Mobile Communications Research Group
Tokyo Institute of Technology

2014

ANNUAL REPORT

Contents

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. The Institute has 3 schools with 23 departments, 6 graduate schools with 45 departments, and many research institutes spread over its Ookayama, Suzukakedai and Tamachi Campuses. Of the approximately 10,000 students, half of them are undergraduates and the other half are graduate students. International students number 1,200. There are 1,200 faculty and 600 administrative staff members. In the 21st century, the role of sci-tech universities has become increasingly important. Tokyo Tech continues to cultivate 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 sci-tech 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.

(Source: Tokyo Institute of Technology Profile 2014-2015, http://www.titech.ac.jp)

Main building

Institute library

Tokyo Tech Seal

The Seal of Tokyo Institute of Technology was designed by Prof. Shinji HORI in 1948. The white portion represents the Japanese character '工', which is the first character of 'Engineering (工業)'. The black figure represents the Japanese character '大', which is the first character of 'University (大学)'. This figure also symbolizes a swallow, which has long been esteemed as a bird of luck in Japan.

Tokyo Tech Logo

"Tokyo Tech Pursuing Excellence" was adopted as a now strategic catchphrase with this logo in 2007. This strong message expresses our philosophy which is directed towards enhancing and strengthening our international reputation.

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. Signal Processing Laboratory
(Prof. Hiroshi Suzuki and Prof. Kazuhiko Fukawa)
2. Propagation and Antenna Laboratory
(Prof. Jun-ichi Takada)
3. System Laboratory
(Associate Prof. Kei Sakaguchi, Assistant Prof. Gia Khanh Tran and Emeritus Prof. Kiyomichi Araki)

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.

Laboratory Introduction
&
Annual Report 2014

SUZUKI-FUKAWA LABORATORY

Website: http://www.radio.ce.titech.ac.jp

Professor Hiroshi Suzuki

received the B.S. degree in electrical engineering, the M.S. degree in physical electronics, and the Dr. Eng. Degree in electrical and electronics engineering, all from the Tokyo Institute of Technology in 1972, 1974, and 1986, respectively. He joined the Electrical Communication Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Japan, in 1974. He was engaged in research on devices in millimeter-wave regions. Since 1978, he has been engaged in fundamental and developmental researchers on digital mobile communication systems. He was an Executive Research Engineer in the Research and Development Department, NTT Mobile Communications Network, Inc. (NTT DoCoMo) from 1992 to 1996. Since September 1996, he has been a Professor at the Tokyo Institute of Technology. He is currently interested in various applications of the adaptive signal processing to radio signal transmission: adaptive arrays, multiuser detection, interference canceling, and MIMO-OFDM for future advanced multiple access communication systems. Prof. Suzuki is a member of the Institute of Electronics, Information, and Communication Engineers (IEICE) of Japan, and of IEEE. He received the Paper Award in 1995, 2007, and 2009, and received the award of IEICE Fellow in 2006, and the IEICE Achievement Award in adaptive space signal processing for mobile communications in 2009.

Associate 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 in 1985, 1987, and 1999 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. Since April 2000, he has been an Associate Professor at the Tokyo Institute of Technology. Prof. Fukawa is a member of IEEE and the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan. He received the Paper Award in 1995, 2007, 2009, and 2012, and the Achievement Award in 2009 from IEICE.

Researcher 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. 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.

SUZUKI-FUKAWA LABORATORY

Our Research Interests

At Suzuki-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 and 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)
- *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-bit rate mobile communications*
    - 8×16 MIMO multi-Gbps systems

Multiple Access

- *Interference mitigation*
    - Spatial filtering
    - MBER precoding for cochannel interference environment
- *Access scheme*
    - IDMA with iterative detection
    - Random packet collision solution

Modulation and Demodulation for Cognitive Radio

- *Gaussian multicarrier (GMC)*
- *SSB*

Millimeter Wave 10 Gbps

- *Phase noise compensation*
- *I/Q imbalance compensation*
- *Real zero coherent detection*

In-House Simulator Design and Implementation

- *FPGA on-board system simulators*
- *4×4 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.

Multipacket-per-Slot Reservation-Based Random Access Protocol with MD and ARQ [1]

Recently, random access (RA) schemes have been adopted in almost all wireless communication systems and will be employed by various kinds of future wireless communication systems. In addition to a connection establishment and a packet transmission in cellular systems, RA is used as the basic access scheme in the distributed wireless communication systems represented by IEEE 802.11 wireless local area networks (WLANs).

This paper proposes a multipacket-per-slot reservation-based random access protocol with multiuser detection (MD) and automatic repeat request (ARQ), called MPRMD, and analyzes its performance by computer simulations. Almost all conventional RA schemes in recent studies are based on single-input single-output (SISO), that is, they try to improve the throughput in the time-frequency domain. MPRMD is also based on SISO and tries to improve the throughput by introducing MD to a reservation-based RA protocol. The use of spatial resources due to multiple-input multiple-output (MIMO) is the next step of MPRMD.

Figure 1 shows packet exchange sequences of MPRMD. In MPRMD, each frame starts with a beacon (BCN) sent by a base station (BS). Upon receiving BCN, each active user terminal (UT) randomly selects both a minislot from the predetermined number of minislots M1 and a preamble sequence from the set of the orthogonal preamble sequences $C_p(l)$, $0 \leq p < N_C$ where p is the index of the preamble sequences and N_C is the maximum number of preamble sequences. Then it transmits the access request packet (AP) composed of the orthogonal preamble sequence and a user terminal identifier (UT-ID) in the selected minislot during the AP transmission period (APP). BS detects the transmitted AP by matched filters for the preamble part and then extracts each UT-ID after separating each AP by MD. In the assignment period (ASP), BS assigns a slot by transmitting an assignment information packets (AIP) including the UT-ID, an index of the assigned preamble sequence and an index of the assigned slot.

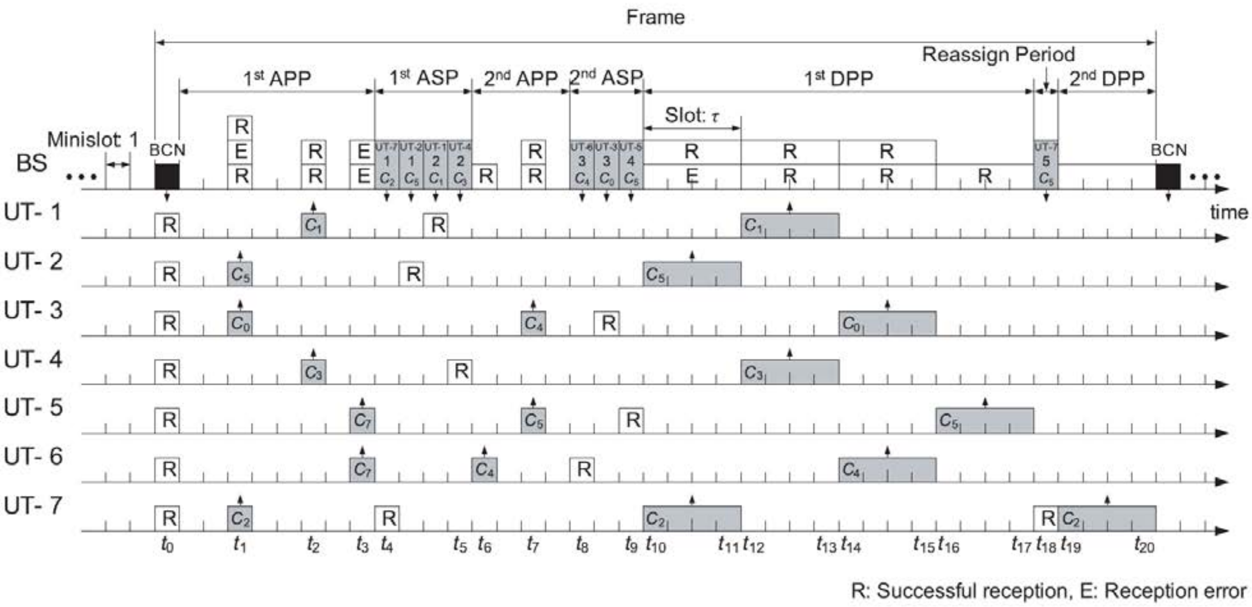


Figure 1. Principle and an example of the packet exchange sequence of MPRMD

The second APP is arranged for each UT that fails to transmit the AP in the first APP. The number of minislots of the second APP is predetermined as M2. Each UT that does not receive the AIP in the first ASP retransmits the AP with the randomly reselected preamble sequence in the randomly reselected minislot in the second APP. BS detects the AP in the same way as in the first APP and assigns a slot by transmitting the AIP in the second ASP.

The proposed protocol enables BS to maximally detect access request packets from UTs by assigning transmission opportunities efficiently and by receiving small packets with minimum overhead through the use of MD. The proposed protocol can further enhance the efficiency by assigning one data slot to multiple UTs.

Suzuki-Fukawa Laboratory

Signal Detection for EM-Based Iterative Receivers in MIMO-OFDM Mobile Communications [2]

Orthogonal frequency-division multiplexing (OFDM) is an effective multicarrier modulation technique for high bit-rate transmission over multipath radio channels, because it can transform a frequency-selective fading channel into a set of parallel frequency-flat subchannels. The multiple-input multiple-output (MIMO) technique can further increase spectrum efficiency of the OFDM system by spatial multiplexing. The optimal receiver for the MIMO-OFDM system is one based on the maximum a posteriori (MAP) criterion and should be capable of performing joint signal detection and channel estimation. The reason for this is that signal detection cannot be performed without using the information on channel parameters, while channel estimation cannot be performed without using the information on transmitted signals. An ideal receiver of this kind, however, would involve prohibitive computational complexity because it would need to perform channel estimation for all hypothetical transmitted signal sequences. What is needed then, is a suboptimal receiver that can drastically reduce complexity, but without increasing the packet error rate (PER).

One solution to the problem of realizing such a suboptimal receiver is to apply the expectation-maximization (EM) algorithm. The EM algorithm, which approximates the MAP estimation in an iterative manner, involves feasible computational complexity, and has been applied to several estimation problems, such as channel estimation, and carrier frequency offset estimation.
For improving the accuracy of the channel estimation in an EM-based receiver, channel estimation that avoids the repetitive use of unreliable subcarriers for consecutive channel estimation and signal detection was proposed. However, the receiver performs the signal detection using the obtained channel estimates, and then uses the same received signals for the next channel estimation. During this process, unreliable received signals continue to be used repetitively.

In order to make the signal detection suitable for the EM-based receiver in MIMO-OFDM mobile communications, this paper proposes spatial removal from the perspective of a message-passing algorithm on factor graphs. The spatial removal performs the channel estimation of a targeted antenna by using detected signals that are obtained from the received signals of all antennas other than the targeted antenna. It can avoid the repetitive use of the unreliable received signals for consecutive signal detection and channel estimation. To exploit both the removal effect and the spatial diversity, appropriate applications of the spatial removal are discussed. Note that the idea of the spatial removal was presented in a recent study for single-input multiple output (SIMO) OFDM communications. This paper extends the spatial removal to MIMO-OFDM, and investigates its performance by computer simulations.

The factor graph of MIMO-OFDM is shown in **Figure 2**, where black squares and white circles symbolize local functions and variables, respectively. The EM algorithm can be interpreted as a message passing algorithm on the factor graph. In **Figure 2**, the dotted arrows and the solid arrows represent messages for channel estimation of the EM algorithm and those for signal detection, respectively. On the basis of this factor graph, the subcarrier removal aims to avoid the repetitive use of unreliable subcarriers for consecutive channel estimation and signal detection. In contrast with the channel estimation of the normal EM algorithm which uses all subcarriers, the subcarrier removal performs the signal detection of a targeted subcarrier by using the channel frequency response that are obtained from all the subcarriers other than the targeted subcarrier. Although the subcarrier removal is for single-input single-output (SISO) OFDM communications, that for MIMO-OFDM can be derived in the same way.

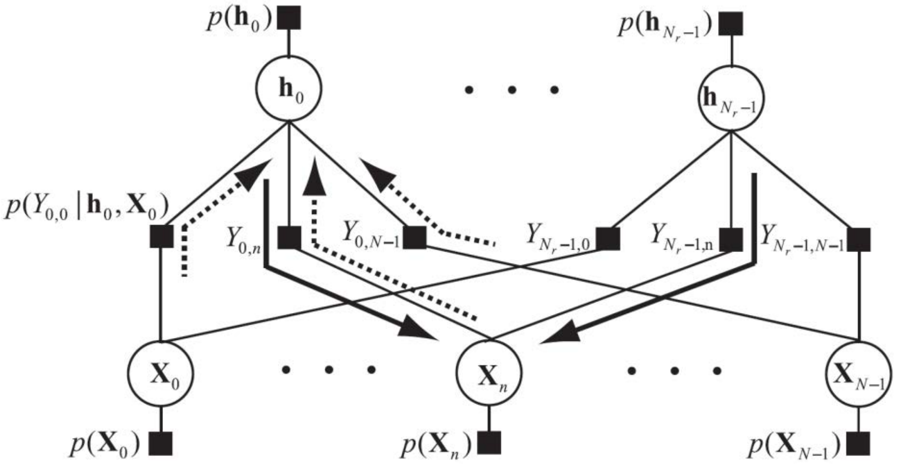


Figure 2. Factor graph of MIMO-OFDM

10 Gbps Outdoor Mobile Communication Experiment Employing CoMP in 11 GHz Band [3]

Recently, the traffic of mobile communications is growing rapidly by the appearance of smartphones, and future mobile communication systems require higher bit rate. This paper investigates a suitable system configuration for an 11 GHz band 10 Gbps mobile communication employing coordinated multipoint (CoMP) transmission and reception. For verifying the effectiveness of the system configuration, an outdoor CoMP transmission experiment was conducted. This paper introduces the outdoor experiment where a base station (BS) with 16 receive antennas in the 8×16 MIMO-OFDM experimental system was divided into two BSs with eight antennas for the CoMP reception. It is also shown that the CoMP reception can expand a coverage area of over 10 Gbps throughput compared with 8×16 MIMO with one BS.

In order to improve spectral efficiency and user throughput in cell-edge, enhanced MIMO and CoMP technologies are being investigated by theory and experimentation. In addition, 3GPP heterogeneous network (HetNet) introduces a pico cell inside a macro cell to offload the increasing traffic. Since the higher frequency bands increase a path loss, the macro cell should be replaced with the pico cell or a micro cell.

BS with 16 receive antennas in the 8×16 MIMO-OFDM experimental system is divided into two BSs with eight antennas such as BS1 and BS2. As shown in **Figure 3**, MS with eight transmit antennas is installed inside a measurement vehicle, and omni-directional antennas are mounted on the roof of the vehicle. BS1 operates as BS for the micro cell, and eight receive antennas are located on the balcony of an apartment house in **Figure 3**. In addition, BS2 operates as BS for the pico cell, and both eight omni-directional receive antennas and the receiver (Rx) box are located on the road.

As shown in **Figure 3**, MS moves along the measurement course at an average speed of 9 km/h in Ishigaki city, Okinawa prefecture, Japan, and both BS1 and BS2 store the received signals. BS1 is located at position A where the distance from a starting point of the measurement is almost 30 m, while BS2 is at position B where the distance is almost 65 m. MS passes through position B, and then it moves toward an ending point of the measurement which is almost 90 m away from the starting point. Since the directivity of the BS1 directional antennas is pointed toward position C, the received power at

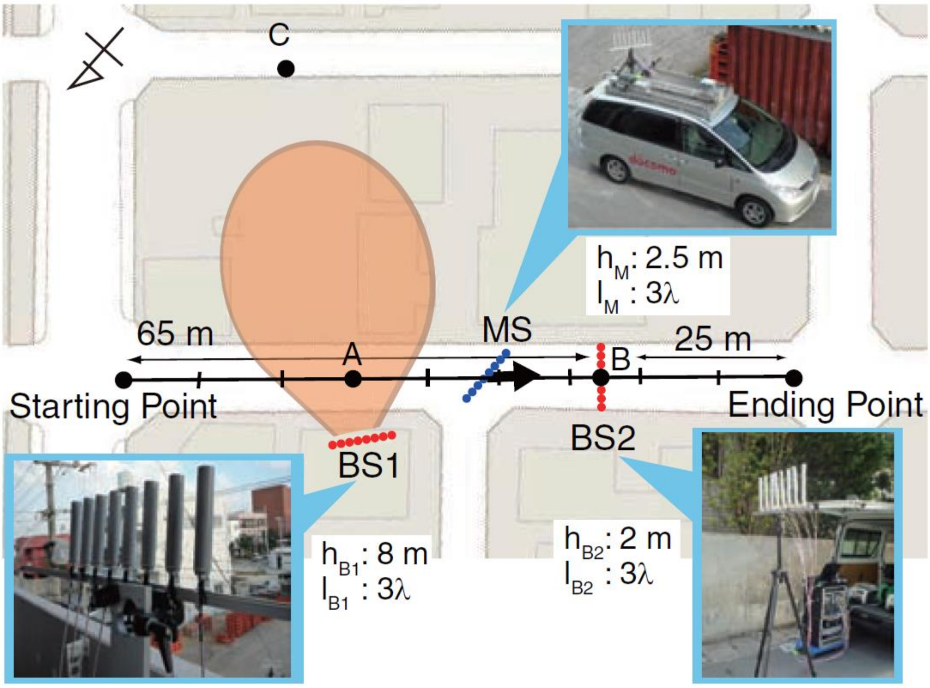


Figure 3. Measurement course in CoMP outdoor experiment.

position A is not relatively high due to the narrow beam width of the BS1 antennas in the vertical plane. The reflected wave from position C causes a large number of multipath components in the area from the starting point to position A. Note that the MS transmit antennas are horizontally tilted at 45 degrees to the traveling direction as shown in **Figure 3**.

This paper has presented the suitable CoMP system configuration employing the micro and pico cells for super high bit rate mobile communications using the higher frequency bands. This paper has briefly introduced the specifications and the geographical configuration for the 11 GHz band uplink CoMP outdoor experiment using 8 x (8 x 2) MIMO. Moreover, the experiment results have demonstrated that the CoMP system configuration can improve the total SNR in the wide area compared with 8×16 MIMO without CoMP for the micro cell. It has been also shown that the system configuration can expand the coverage area of over 10 Gbps throughput to 1.4 times.

Evaluation of 30 Gbps Super High Bit Rate Mobile Communications Using Channel Data in 11 GHz Band 24×24 MIMO Experiment [4]

Sophisticated mobile terminals such as smartphones are rapidly fueling the demand for higher bit rate transmission, and fourth-generation mobile communication systems target the maximum bit rate of 1 Gbps. In order to verify the feasibility of the 30 Gbps transmission for future mobile communications, this paper presents the performance of 30 Gbps MIMO-OFDM eigenmode transmission based on computer simulations using channel data measured using the 11 GHz band 24×24 MIMO channel sounder. Specifically, this paper presents the throughput of a 30 Gbps transmission in a measurement course used in outdoor propagation experiments, when adaptive modulation and coding (AMC) is employed and a channel state information (CSI) error at the transmitter exists.

Figure 4 shows the propagation experiment environment. The Tx is mounted inside a measurement vehicle, and the Tx antenna array is fixed on the roof of the measurement vehicle. In addition, the Rx is established in a room on the third floor of an apartment house, and the Rx antenna array is located on a balcony of that room. The Tx and Rx antenna array employ a 12-element antenna array with dual polarization (pol.), i.e., vertical (V) and horizontal (H) polarization. The Tx antenna array comprises an omni-directional antenna in the H plane with the antenna gain of 4 dBi.

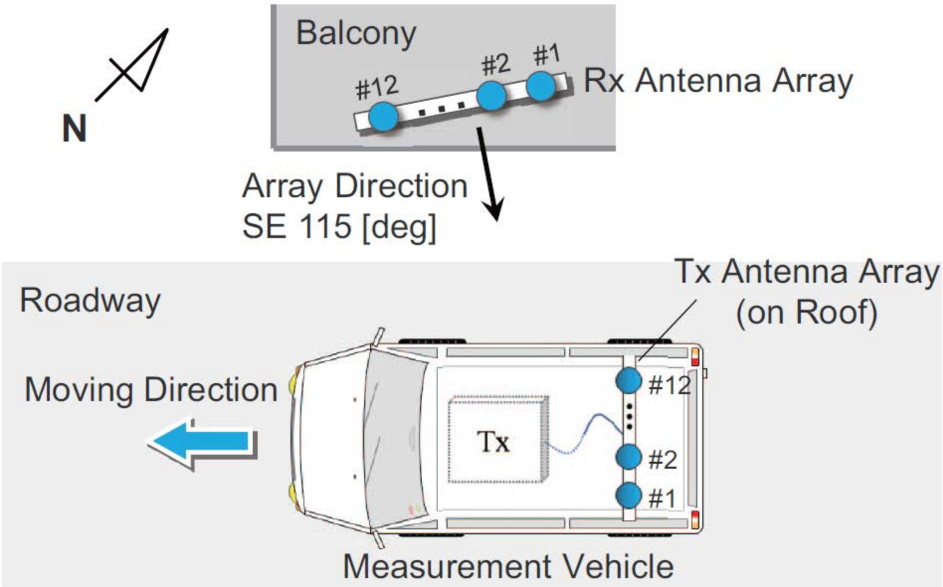


Figure 4. Propagation experiment environment

In order to verify 30 Gbps super high bit rate mobile communications, computer simulations were conducted in 24×24 MIMO-OFDM eigenmode transmission by utilizing the channel data collected using an 11 GHz band 24×24 MIMO channel sounder. This paper introduced specifications and a hardware configuration for the 24×24 MIMO channel sounder, and showed the propagation experiment conditions and a measurement course. Moreover, we showed that with the mean of the average SNRs for the entire measurement course, Γ_c, of 20 dB, 30 Gbps throughput exceeding 30 Gbps is achieved in an area where the average SNR is higher than 18 dB and the delay spread is larger than 100 ns. We also showed that AMC significantly expands the area where 30 Gbps throughput is available with Γ_c of 20 dB, and that the 30 Gbps throughput requires a CSI error at the Tx that is 10 dB lower than the noise power.

Low Complexity Signal Detection Employing Multi-Stream Constrained Search for MIMO Communications [5]

Multiple-input multiple-output (MIMO) is a promising technique for high bit-rate transmission over wireless channels because it can increase channel capacity in proportion to the number of antennas without expanding frequency bands. Therefore, MIMO has been adopted in the wireless LAN, Long Term Evolution (LTE) of the 3rd Generation Partnership Project (3GPP), or LTE-advanced (LTE-A).

The optimal signal detection for the MIMO system is the maximum likelihood detection (MLD) [5]. However, the computational complexity of MLD is prohibitive when the modulation order or the number of transmit antennas are large. This is because the complexity increases exponentially with the modulation order or the number of transmit antennas. For example, LTE-A supports eight transmit antennas, which can be considered comparatively large. Therefore, the demand for MIMO signal detection methods that can achieve excellent transmission performance with low computational complexity has increased. Thus, many suboptimal detection methods have already been proposed. As nonlinear detection, sphere decoding (SD) and QR decomposition with M algorithm (QRM)-MLD transform a channel matrix into an upper triangular matrix by QR decomposition and reduce the number of signal candidates in order to reduce complexity. These nonlinear methods still need a lot of signal candidates so as to maintain sufficient transmission performance. On the other hand, the linear detection methods such as zero forcing (ZF) and minimum mean-squared error (MMSE), linearly transform the received signal for detection and thus require much less complexity than that of MLD. However, their transmission performance degrades severely owing to the noise enhancement.

In this paper, we propose multi-stream constrained search (MSCS) that constrains multiple streams and that searches for signal candidates without the eigenvalue decomposition. When one stream is constrained, MSCS is equivalent to multi-dimensional search (MDS) with all dimensional search. Therefore, MSCS is a more efficient algorithm than MDS. In addition, MSCS can further improve the transmission performance when multiple streams are constrained although the computational complexity increases. In order to reduce the increased complexity, this paper also proposes stream selection-MSCS (S-MSCS) that selects constrained streams under the criterion of small equivalent amplitudes of channels caused by the MMSE detection. The limited pattern of constrained streams can reduce the complexity, and the stream selection based on the equivalent amplitude can maintain excellent transmission performance.

This paper also proposes Stream Selection MSCS (S-MSCS) that can drastically reduce computational complexity compared to MSCS. In this paper, we have proposed a MIMO signal detection method that sets an MMSE detection result to the starting point and that searches for signal candidates in multi-dimensions of the noise enhancement. In the search, some streams of the signal candidates are fixed to constellation points. When one stream is constrained, the proposed method is equivalent to the best case of MDS and requires less complexity. In addition, it has been shown that multiple constrained streams can extremely improve the transmission performance. Furthermore, this paper has investigated another version of the proposed method that selects the constrained streams under the criterion of small equivalent amplitudes of channels caused by the MMSE detection. This process can drastically reduce the computational complexity. Computer simulations under 8 × 8 MIMO flat fading conditions with 16QAM have evaluated the transmission performance and computational complexity of the proposed and conventional methods. When two streams are constrained, although large computational complexity is required, the proposed method can achieve almost the same average BER performance as MLD. In addition, the proposed method with the stream selection and three constrained streams can maintain only 0.5 dB degradation of the average BER performance from MLD while reducing the computational complexity to about one third of that of QRM-MLD.

Figure 6 shows the average BER performance over the uncorrelated channel. The proposed MSCS with $N_K = 1, 2$ were investigated and indicated by MSCS-1 and MSCS-2, respectively, where N_K is the predetermined number of constrained streams. S-MSCS with $N_K = 1, 2, 3$ were investigated, and indicated by S-MSCS-1, S-MSCS-2, and S-MSCS-3. Since MSCS-1 is equivalent to MDS without

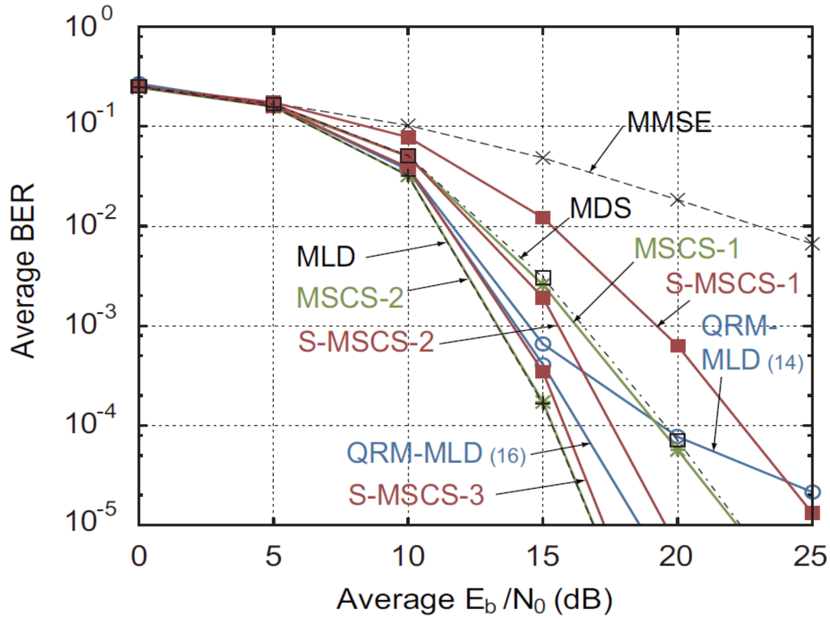
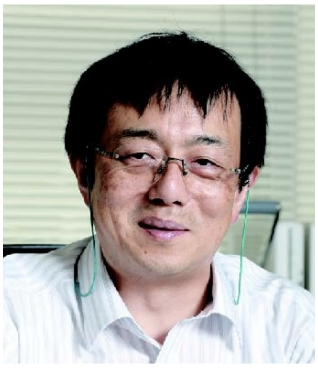


Figure 6. Average BER performance over uncorrelated MIMO channel

approximations, MSCS-1 is a little superior to MDS. The performance of MSCS-1 is 4 dB worse than that of MLD at the average BER of 10−3. In contrast, MSCS-2 achieves almost the same performance as MLD because it searches for much more signal candidates than MSCS-1. However, the computational complexity of MSCS-2 is very large, which will be shown in the next subsection. S-MSCS-1 is about 3 dB inferior to MSCS-1 because of less signal candidates. Similarly, the performance of S-MSCS-2 is also worse than that of MSCS-2. In contrast, S-MSCS-3 can achieve the excellent performance in which the degradation is only 0.2 dB in comparison with MLD. This is due to the increased number of signal candidates and because the nonlinear candidate search is carried out for the streams of which the equivalent amplitudes are small.

In this paper, we have proposed a MIMO signal detection method that sets an MMSE detection result to the starting point and that searches for signal candidates in multi-dimensions of the noise enhancement. In the search, some streams of the signal candidates are fixed to constellation points. When one stream is constrained, the proposed method is equivalent to the best case of MDS and requires less complexity. In addition, it has been shown that multiple constrained streams can extremely improve the transmission performance. Furthermore, this paper has investigated another version of the proposed method that selects the constrained streams under the criterion of small equivalent amplitudes of channels caused by the MMSE detection. This process can drastically reduce the computational complexity.

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



Professor Jun-ichiTakada

Prof. Jun-ichi Takada was born in 1964, Tokyo, Japan. He received the B.E., M.E., and D.E. degree from Tokyo Institute of Technology in 1987, 1989, 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 currently belongs to the Department of International Development Engineering, Graduate School of Science and Engineering. 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, 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).

< Takada Lab members (June 2014) >

Department Profile: What is International Development Engineering?

International development engineering is an interdisciplinary field of engineering that takes in the fields of economics, political science, environment, and social science, in addition to engineering-related fields. By integrating a wide range of knowledge related to international development in addition to the expertise in the existing engineering fields, it strives to use science and technology while considering sustainable development in order to solve a variety of globally affecting issues that cannot be dealt by an individual country or region.

Recent Research Topics

- **Double directional channel sounding and modeling for millimeter wave (60 GHz)**
  - Development of 60 GHz 3-D directional channel sounder [45]
  - Dynamic model of shadowing effects on indoor millimeter propagation channel due to human motion [41]
- **MIMO channel sounding and modeling for microwave (11 GHz)**
  - Development of geometry based clustering approach in double directional channel [17]
  - Identification of indoor scattering mechanism using the measurement and ray tracing simulation
  - Gradient based channel parameter estimation [39]
- **Development of channel sounder using GNU Radio/USRP**
  - Development of fully synchronized channel sounder [24, 46]
  - Development of channel sounder for distributed wireless network [40]
- **Channel sounding and modeling for body area network (BAN)**
  - Antenna de-embedding from BAN channel [22]
  - FDTD-based channel prediction for antenna evaluation
  - Development of tri-polarized dynamic channel sounder [23]
- **Modeling of radio propagation channel represented by spherical vector waves [31]**
- **Propagation channel interpolation for localization of illegal radios [35]**
- **Electromagnetic scattering from foliage obstacles [37]**
- **Electromagnetic scattering simulation on point cloud data using physical optics [42]**
- **Propagation loss model for evaluation of interference area for TV white space systems [4]**
- **Performance comparison between spatial MIMO and polarized MIMO [33]**

Millimeter Wave (60 GHz) Propagation Channel Study: Overview

Escalation of the carrier frequency in order to meet the forecasted data rate demands in future mobile network is being seriously considered since past few years. Among the probable frequency candidates the 60 GHz band with about 5 GHz of continuous bandwidth is very attractive. This band has been traditionally avoided because of the atmospheric attenuations due to oxygen absorption and the large free space path loss; however in the proposed use in pico cells of the future heterogeneous mobile network the cell radius is small enough for the atmospheric attenuations to be negligible. The large free space path loss though necessitates the use of very directional high gain antennas or antenna array and beam steering. In order to study the characteristics of the 60GHz propagation channel including its directional properties we have built a 3-D directional channel sounder based on our previous 11 GHz sounding system. Due to the millimeter scale wavelength of the 60 GHz radio waves, shadowing of the radio waves by human body before it reaches the receiver is not negligible as in lower frequencies. The shadowing by human body when both the UE and the body are in motion is therefore being studied.

Development of 60 GHz 3-D Directional Channel Sounder [45]

To measure and study the properties of the 60 GHz propagation channel for use in future heterogeneous cellular network we have built a channel sounder based on our existing 11 GHz sounding system. The system reuses the baseband and signal processing hardware from the 11 GHz system. A commercially available 60 GHz RF unit is used to up convert the baseband signal to 60 GHz band. The system is capable of operating in frequencies from 57 GHz to 63 GHz with 400 MHz signal bandwidth. It has a delay resolution of up to 2.5 ns, and provides a dynamic range of up to 123 dB with 24 dBi gain and 12 deg beamwidth on both the receiver and the transmitter side. Figure 1 shows the developed system along with the external signal generator of the RF unit. Figure 2 shows the measured angular power spectrum in both the elevation and azimuth plane of the UE and for both configurations of H-H and H-V polarization of the transmitter and the receiver antennas. For H-H polarization unlike in lower frequencies the angular spread is very small and the strongest paths are the direct LOS path and the reflection from wall facing the transmitter antenna. On the other hand for the H-V polarization the strongest paths are located quite differently to that of the H-H polarization suggesting that interaction with scatters considerably affect the polarization of the propagating wave.

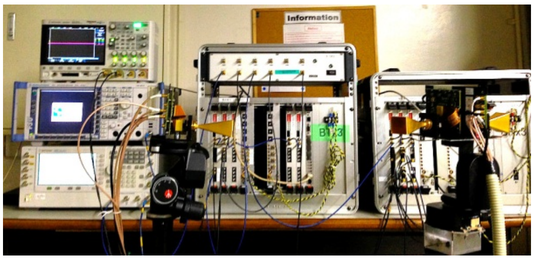


Fig. 1. Channel sounder hardware

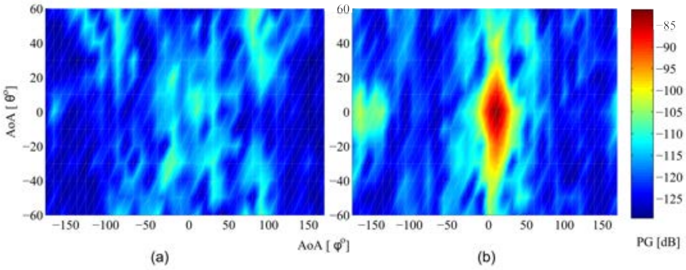


Fig. 2. Power profile in AoA domain

Dynamic Model of Shadowing Effects on Indoor Millimeter Wave Propagation Channel Due to Human Motion [41]

Due to the large propagation loss, millimeter-wave bands are expected to be used mostly in the indoor environment where the shadowing effect on propagation path by human body is very significant. The existing works have mainly evaluated the effects of human body when the UE is static; however the model when UE is dynamic has not been reported. This research aims to evaluate the effect of human body on indoor millimeter-wave propagation channel when user terminal is dynamic, by extending the existing model.

In this study, the whole channel is decomposed into many paths. Ray-tracing method is used to calculate the propagation paths due to the reflections from walls. The shadowing probability of each path is calculated based on the population density in the room, human body size and path length. In the same simulation, the path shadowing state transition also is calculated. From obtained data, the relationship between path shadowing probability and path shadowing state transition probability is plotted. Fig.3 shows that relationship, where $\boldsymbol{P}_{\mathbf{bg}}$ represents transition probability from un-shadowed state to shadowed state and $\boldsymbol{P}_{\mathbf{gb}}$ represents transition probability in the opposite direction. These results agree with the case when user terminal is static. Threfore, this state transition model depends on only the path shadowing probability, and not the mobility of the user.

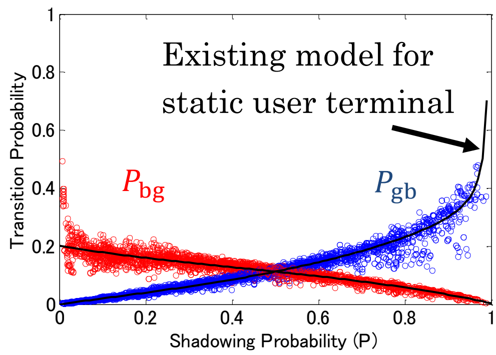


Fig. 3. Path shadowing state transition probability model

Microwave (11 GHz) Propagation Channel Study: Overview

(The project was funded by the Ministry of Internal Affairs and Communications in FY2009-2012.)

The demand for the data traffic in future mobile services has been increasing exponentially, and exploring new frequency bands above 5 GHz is an inevitable choice to accommodate such demand. The radio propagation channels properties at higher frequency bands have not been sufficiently justified from the view point of the requirements for current mobile data transmission. A large path-loss is not always a disadvantage, but is rather advantageous when designing small cell or hot spot systems within a confined coverage area where very high-speed data transmission can be realized because a very wide frequency bandwidth is available. Also, the antenna size is decreasing with the increase of the frequency, array antennas can be deployed for MIMO transmission and/or beam steering.

This work aims at the fundamental studies of radio propagation properties of 11 GHz with bandwidth of 400 MHz. We have developed a 24×24 multiple-input and multiple-output (MIMO) channel sounder system to exploit new frequency bands [3]. The comprehensive indoor and outdoor environments have been conducted in 2012 for the double-directional property and eigen-structure of the channels, and the detailed analyses are still ongoing.

Fig. 4. Double directional channel measurement in 24 × 24 MIMO configuration

Development of a Geometry-Based Clustering Approach [17]

In this work, a novel clustering approach is proposed by inputting the scattering point in x- and y-coordinates into a power weighted K-means clustering algorithm as opposed to conventional approach where multipath delay and angular dimensions are utilized. In conventional clustering approach, the interaction objects (IO) in the environment are overlooked and may result in the mixture of different IO within a cluster. Proposed clustering approach is intended to solve this problem. Figure 5 shows the comparison between conventional and proposed clustering approach in the Centennial Hall. The x- and y- coordinates of scattering points are obtained by the Measurement-based ray tracer where the measurement results are inputted into ray tracing algorithm. This approach is now being used to validate the COST2100 channel model which is based on geometry based stochastic channel model (GSCM) at 11 GHz.

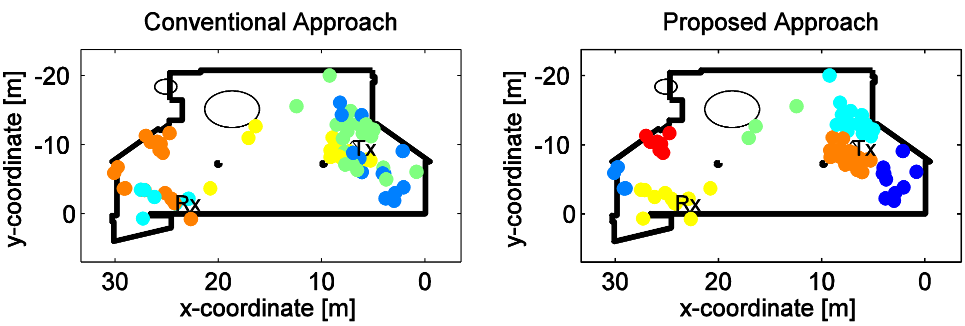


Fig. 5. Clustering comparison between conventional and proposed approach

Identification of Indoor Scattering Mechanism Using the Measurement and Ray Tracing Simulation

This work investigates the dominant propagation mechanisms in indoor line-of-sight (LOS) environments from channel measurement and ray tracing simulation. Double-directional channel sounding was performed using 24×24 MIMO channel sounder at 11 GHz with 400 MHz bandwidth to get the MIMO channel transfer function. Path parameters from ray tracing simulation and antenna response were used to reconstruct the ray tracing based channel transfer function. Beamforming was applied to both channel transfer functions to get angle resolved power spectrum. Then the angular and delay power spectra were used to identify the dominant propagation mechanisms. Figure 6 shows double directional angular delay power spectra obtained from measurement. Along with LOS component, walls and window reflected paths were found to be the dominant propagation mechanisms observed in both measurement and simulation. But ray tracing failed to predict the scattering power from the long and thin metal objects such as window frame and metal pillar edge which are the significant objects observed in measurement.

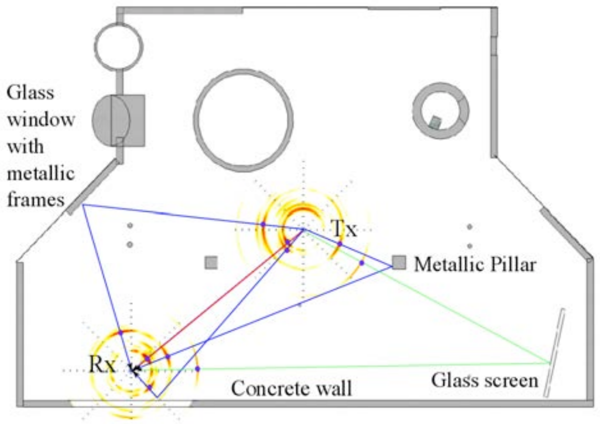


Fig. 6. Angular delay power spectra from measurement

Gradient Based Channel Parameter Estimation [39]

The wideband double-directional channel characteristic can be represented by the path parameters, such as direction of departure, direction of arrival, time delay of arrival, path gain. The estimation of these parameters from the channel sounding data is an important process of double directional channel characterization to de-embed the influence of antennas from the propagation channel. Maximum likelihood parameter estimation and expectation-maximization algorithm for computational reduction are commonly used, but search-based optimization is very time-consuming process. In this work, the hybrid approach of rough global search and conjugate gradient method is deployed to maximize the likelihood function with faster convergence and smaller error than conventional search based approach. Figure 7 shows a simulation result to a test channel with 6 paths. The proposed method performed a good accuracy with lower than 1 % residual power after the estimation. To avoid the local maxima of likelihood function due to the initialization and side lobes of matched filter, rough global search is introduced.

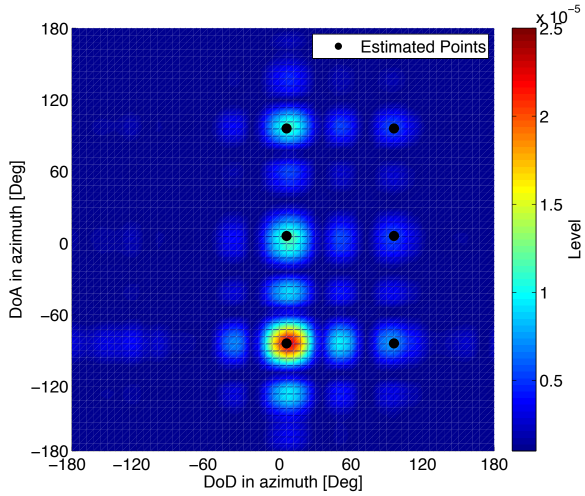


Fig. 7. Double-directional angular power profile

Development of Channel Sounder Using GNU Radio/USRP

Development of Fully Synchronized Channel Sounder [24, 46]

Channel sounding has long held importance for wireless communication system design, but it is restricted by large cost and workload. Therefore, we have developed a channel sounder using very low cost hardware (USRPs) and free software (GNU Radio). USRP is a reconfigurable hardware peripheral that provides a general purpose radio with high variety of RF board at various frequency bands. In our hardware, the bandwidth of 12.5MHz within 400-4400 MHz is used. The frequency and timing synchronization between Tx and Rx are realized by using 10 MHz signal and pulse per second signal both from external rubidium clock respectively. Also, phase alignment is realized by introducing timed command to tune the phase of signals at the same timing. Figure 8 shows the appearance of USRP channel sounder and the Table 1 shows the parameters of the channel sounder. The dynamic range (DR) is approximately 83 dB.

Fig. 8. USRP N200

Table 1. Specification of channel sounder

RF frequency Range	400-4400 MHz
Transmit signal	Multitone signal (128 Tones)
Sample rate	12.5 MSps I/Q
Bandwidth	12.5 MSps
Sync reference signal	10 MHz from Rb atomic clock
Delay Resolution	80 ns
Transmitted power	20 dBm max

Development of Channel Sounder for Distributed Wireless Network [40]

To implement cooperative algorithms in distributed wireless networks (DWNs) where the devices in the network are able to communicate each other independently, the correlation model of distributed channels are crucial. Although traditional channel sounders were utilized in the existing works to measure and construct the correlation model for distributed channels, it is difficult to implement such a system in large scale of distributed measurement which requires the numerous transmitter and receiver nodes. Therefore, the well-suited channel sounder prototype for the outdoor DWNs is developed by adopting the standalone system which combines GNU Radio and standalone USRP Embedded Series E110. To customize the device to be the distributed channel sounder, the solutions are provided for the following issues: 1) the limited communication rate between the embedded PC and FPGA, 2) the synchronization among the nodes, and 3) the protocol and procedure of the communications among the nodes.

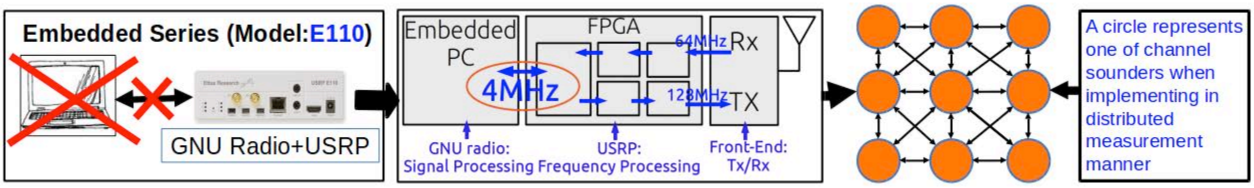


Fig. 9. Architecture of distributed channel sounder using USRP E110

Radio Propagation in Body Area Network (BAN) for Wearable Devices

Introduction

Body area network (BAN) is a network of sensors or actuators in the vicinity human body. There is an enormous potential for application of BAN in health-care and other fields. The BAN propagation channel, however, is suffered from the absorption and time-varying shadowing by the human body, which may degrade reliability. To overcome this issue, we are working on antenna de-embedding, channel prediction for antenna evaluation, and a tri-polarized dynamic channel measurement system.

Fig. 10. BAN channel measurement example: chest-navel link

Antenna De-embedding [22]

Although it has been known that the type of antenna greatly affects the BAN channel behavior, no channel modeling has successfully separated the contributions of the antennas and other factors. In other word, the antennas are still *embedded* in the channel. Therefore, this work proposes *antenna de-embedding,* where the contribution of the antennas to the channel response is explicitly and quantitatively modeled. Antenna de-embedding brings various benefits such as fast antenna evaluation, comparison among different measurement campaigns, and antenna-independent channel models and transmission simulations. The proposed approach applies channel modeling using spherical vector waves into the BAN channel. For validating the concept, the proposed approach was implemented by the finite-difference time-domain (FDTD) method. It was shown that the proposed approach can generate the same channel responses with the conventional approach. This work is the first and only successful antenna de-embedded BAN channel modeling.

FDTD-based Channel Prediction for Antenna Evaluation

As an application of antenna de-embedding, FDTD-based antenna evaluation is proposed. The proposed method predicts the channel responses during a specific body motion for arbitrary small antennas. Figure 11 shows the process of the proposed method which combines the quasi-static FDTD simulation and the antenna model approximated as the summation of six orthogonal electric and magnetic dipoles. Figure 12 shows the mean path gain of various antenna pairs during a walking motion, where good agreement is observed between the measurement and prediction.

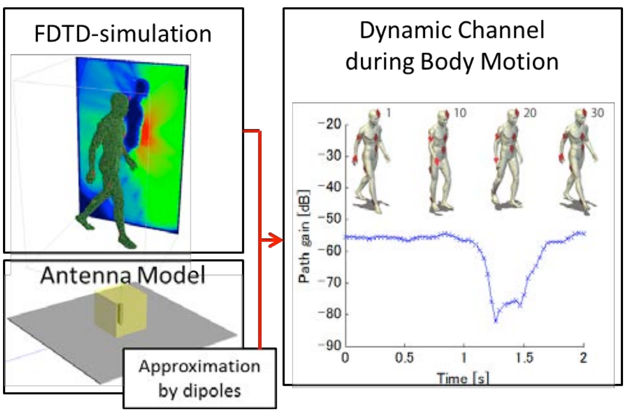


Fig. 11. FDTD-based Channel Prediction

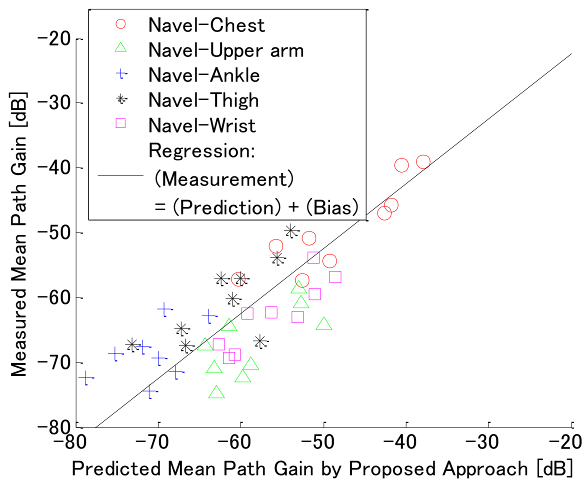


Fig. 12. Comparison between the measurement and prediction for a walking

Development of Tri-Polarized Dynamic Channel Sounder [23]

This channel sounder is developed to capture time-varying 3×3 channels during body motion. The measurement data is expected to contribute to antenna de-embedding, evaluation of diversity techniques, and analysis of the propagation mechanism. In antenna de-embedding, the channel response of arbitrary antennas is predicted by the weighted sum of the measured 3×3 channels. In the evaluation of diversity techniques, the diversity gain with different combining schemes and antennas pairs can be compared. The schematic of the channel sounder is shown in Fig. 13. In order to measure 3×3 channels simultaneously, the sounder utilizes a three-port RF switch for time division multiplexing, tri-polarized dielectric resonator antennas, and a multi-port oscilloscope. The proposed system has been validated by experiments, where sufficient frame-rate and path gain accuracy to capture dynamic nature of the BAN channel were confirmed.

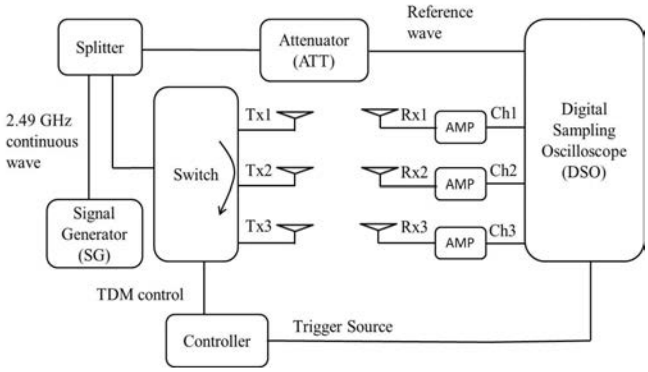


Fig. 13. Schematic of channel sounder

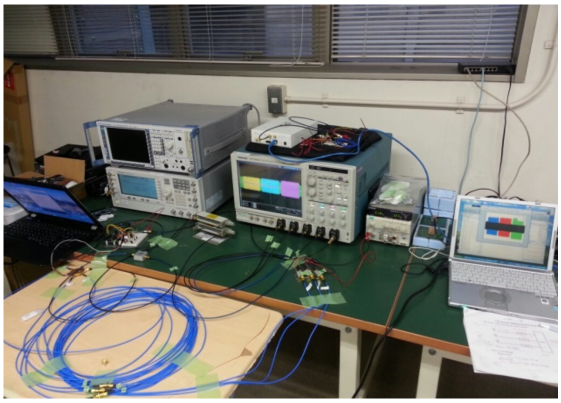


Fig. 14. Developed channel sounder

Modeling of Radio Propagation Channel Represented by Spherical Vector Waves: Parameter Estimation with Spherical Virtual Array [31]

A typical MIMO wireless communication system contains antennas at both ends and a propagation channel. While antennas radiate/receive electromagnetic waves and are designable, propagation channel describes how electromagnetic waves interacts with physical environment and is uncontrollable. Hence the separate modelling of them is necessary and crucial for a better antenna-channel combination.

Propagation channel can be modelled by using a finite number of spherical vector waves, where this finite number can be determined according to electrical size of transmit/receive antennas. Practically, propagation channel represented by spherical vector waves can be estimated from radio channel response by dedicated design of antennas at both ends. Spherical array with certain configuration, whose expanded spherical wave coefficients form a good condition of linear inverse, is designed. Practically, virtual array whose antenna elements have the mode of electric/magnetic dipoles can be used. The above proposed approach is being examined by both simulation and measurement.

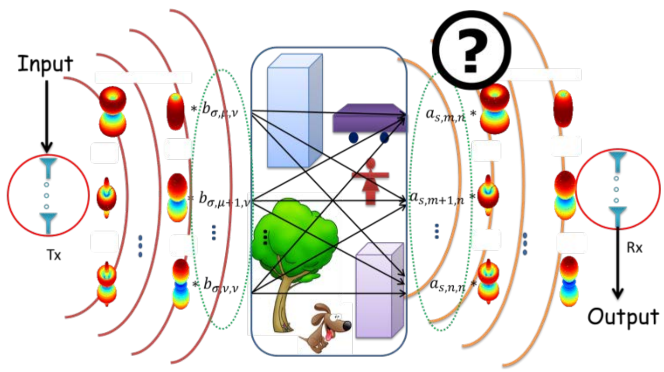


Fig. 15. Channel modeling by spherical vector waves

Propagation Channel Interpolation for Localization of Illegal Radios [35] (The project is funded by Koden Electronics Co., Ltd.)

Conventional localization techniques such as triangulation and multilateration are not reliable in non-line-of-sight (NLOS) environments such as dense urban areas. Although fingerprint-based localization techniques have been proposed to solve this problem, we may face difficulties when we do not know the parameters of the illegal radio when creating the fingerprint database. This research proposes a novel technique to localize illegal radios in an urban environment by interpolating the channel impulse response stored as fingerprints in a database. The proposed interpolation technique consists of interpolation in the bandwidth (delay), frequency and spatial domains. A localization algorithm which minimizes squared error is employed in this research, and the proposed interpolation technique is evaluated using location fingerprints obtained from ray-tracing simulations. Results show that the proposed interpolation technique is superior to conventional localization techniques.

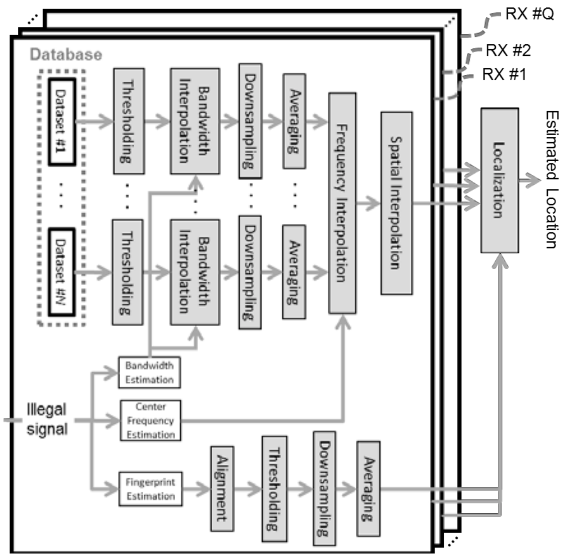


Fig. 16. Flowchart of proposed interpolation technique

Electromagnetic Scattering from Foliage Obstacles [37]

Foliage is one of the most dominant types of obstacles that are present in rural propagation environments. These foliage obstacles, with their leaves, branches, and trunks act as complex scatterers to the propagating radiowaves. This interaction between the propagating radiowaves and the foliage obstacles may affect the performance of radio systems operating in such environments. Proper understanding of such interactions is necessary to predict their effects on radio systems to ensure the performance of such systems in these environments. The complex and random nature of these foliage structures provides a significant challenge in predicting their effects on radio waves. The scattering from individual leaf element is evaluated using generalized Rayleigh- Gans (GRG) approximation. The total scattered fields from multiple leaves are then evaluated using a far field superposition approximation from each of the individual scatterers. Multiple scattering effects are also investigated. Radar cross section of multiple leaves is evaluated by using the proposed approximation and is compared with numerical solution of method of moments in Fig. 17. They show good agreement.

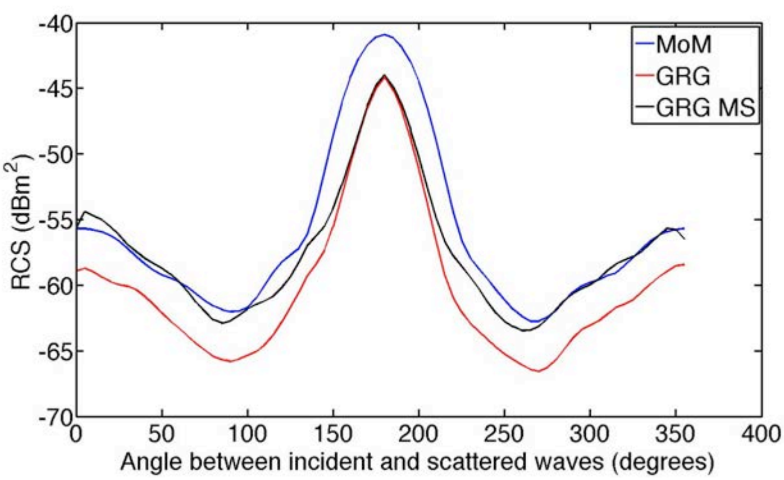


Fig. 17. Radar cross section of multiple leaf scatterers

Electromagnetic Wave Scattering Simulation Using Physical Optics on Point Cloud Data [42]

For the prediction of the multipath propagation channel characteristics, it is necessary to simulate the scattered wave from objects. However, it is necessary to create the geometrical model of scatterers accurately when performing the scattering simulations. 3D CAD is often used to create the geometrical model of the object. However, 3D CAD has difficulty to deal with the complex objects in the real world. Recently, representation of geometrical surface using point clouds has been gaining attention due to its accuracy and speed for arbitrary shape, in particular through the measurement by using laser profiler. Physical optics approximation (PO) is one of the high frequency approximation methods, which is applicable to deal with large complicated objects with the good accuracy in the back scattering region. We implemented the electromagnetic wave scattering simulation using PO on point cloud data, and a sphere which is chosen for the evaluation of accuracy since it is a canonical electromagnetic scattering problem with rigorous solution for comparison. Figure 18 shows the point cloud model for a sphere.

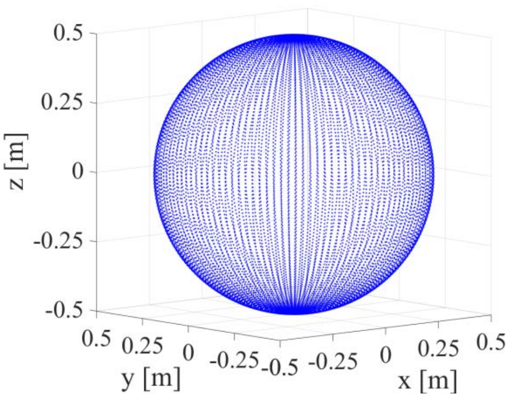


Fig. 18. Point cloud data for a sphere

Propagation Loss Model for Evaluation of Interference Area for TV White Space Systems [4] **(This work is under the joint research with NICT.)**

TV white space (TVWS) is expected to be widely used to realize efficient frequency utilization. When utilizing TVWS, secondary users (SU) must guarantee that they will not cause any harmful interference to primary users in the band, such as TV broadcasting. In order to accurately estimate the interference area, propagation channel model for the SU is required. We propose a propagation loss model for usage of TVWS by SU. Conventional propagation models in UHF band were developed for high-rise base station antenna and for long distance. Therefore, those models do not match the conditions when a SU is operating in TVWS with low antenna height and for short propagation distance. We then conduct outdoor channel measurements in TV band using low height antenna and within the short distance (Fig. 19), and developed a propagation loss model based on two-path model.

Proposed propagation loss model to evaluate the interference area is as follows.

$$L_{\mathrm{I}}\ [\mathrm{dB}] = \begin{cases} 20\log_{10}\left(\dfrac{4\pi d}{\lambda}\right) - 6, & \text{for } d \le R_{\mathrm{bpp}} \\ 20\log_{10}\left(\dfrac{d^2}{h_{\mathrm{b}} h_{\mathrm{m}}}\right), & \text{for } d > R_{\mathrm{bpp}} \end{cases}$$

$$R_{\mathrm{bpp}} = \frac{2\pi h_{\mathrm{b}} h_{\mathrm{m}}}{\lambda}$$

The proposed model is effective for estimating interference area of SU.

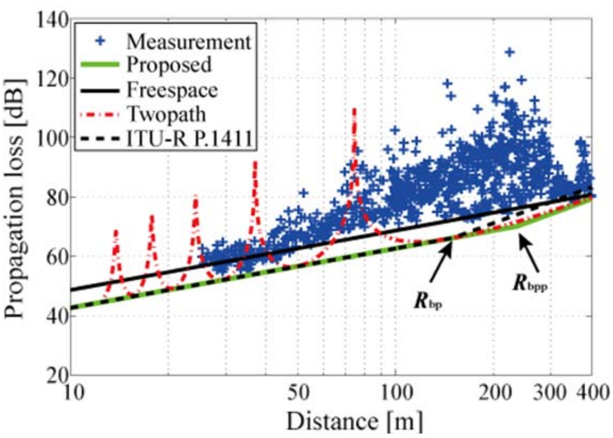


Fig. 19. Propagation loss versus distance

SAKAGUCHI LABORATORY

Associate Professor Kei Sakaguchi

Assoc. 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 of Technology in 2006. From 2000 to 2007, he was an Assistant Professor at Tokyo Institute Technology. Since 2007, he has been an Associate Professor at the same university. In April of 2012, he also joined Osaka University as an Associate Professor, namely he has two positions in Tokyo Institute of Technology and Osaka University. He received the Outstanding Paper Awards from SDR Forum, IEICE, and IEICE communication society in 2004, 2005, 2012, and 2013 respectively. He also received the Tutorial Paper Award from IEICE communication society in 2006. He served as a TPC co-chair in the ICST CrownCom in 2011 and as a General co-chair of IEEE WDN-CN in 2012. His current research interests are MIMO cellular networks, smart grid, and wireless energy transmission. He is a member of IEICE and IEEE.

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.

Project Researcher Ebrahim Rezagah Roya

Roya E. Rezagah received B.Sc. in Electrical Engineering from Sharif University of Technology, Tehran, Iran in 2002, and M.Sc. and Ph.D. in Communications systems from Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran, in 2006 and 2011 respectively. During her study in Tehran Polytechnic, she joined several industrial projects as a researcher and system designer. Those industrial experiences cover a wide range from RFID to cell planning and DVB-T implementation. In 2011, she joined Araki-Sakaguchi lab. in the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Tokyo, Japan and on September 2014, she received Dr. Eng. from Tokyo Institute of Technology. Since 2011, she has been working on coordinated multipoint (CoMP) in cellular networks in Araki-Sakaguchi lab. with close collaboration with industry and mobile service providers.

Sakaguchi Laboratory

Research and Development of Technologies for Highly Multiplexing of Millimeter Wave Channels [10][18][22][23][24][25]

The Multiplexing and Compensation Techniques

For the spread of multimedia applications, high speed wireless communication techniques are necessary to transmit a large amount of data within a very short time period. Millimeter wave wireless system, WiGig (Wireless Gigabit Alliance), provides multi-gigabits per second (multi-Gbps) data rate in short distance transmission scenarios. The channel allocation is as shown in Figure 1 that the license free frequency band from 57 to 66 GHz is divided into 4 channels; and for each channel, 2 GHz band width is allocated for broad band wireless applications. Here we employ multiple-input and multiple-output (MIMO) and multiuser MIMO (MU-MIMO) techniques with orthogonal frequency-division multiplexing (OFDM) schemes to further improve the efficiency of the millimeter wave channel. The goal of our team is the development of system to support 4 single antenna users simultaneously in one channel and provide maximal 6 Gbps data rate for each user. The maximal capacity of the multiband and multiuser system will be 16 users (4 channels by 4 users) with totally 96 Gbps data rate.

However, there are several issues for the development of millimeter wave wireless systems: 1) the large path loss and straightness property of millimeter wave; 2) the interference from other millimeter wave wireless systems; 3) the high phase noise of millimeter wave RF local oscillator (LO) signals; and 4) the nonlinearity of the power amplifiers (PA). The straightness property will decrease the capacity of point to point MIMO systems, but for MU-MIMO systems the capacity is guaranteed by the spatial and multiuser diversity. Conventionally, directional high gain antennas are employed to compensate the path loss; however, that will limit the benefit of the multiuser scenario, for the coverage is limited by the beam width of antenna. Parasitic antenna element (PAE) is proposed to solve this issue, for its controllable beam pattern and high antenna gain. There is also an extra issue about the base band signal processing, which is that the high data rate induces the huge calculation effort for the de-multiplexing of the MU-MIMO system; therefore, the complexity of the solutions for the development also should be considered. The employment of PAE can roughly separate the information for different users that can reduce the calculation complexity for the de-multiplexing. Because the license is not necessary for using the millimeter channels, there may be some other millimeter wave systems, say, the near-field system, mmFlash, existing in the service area of the targeted system, which using the same frequency band that will induce the interference. The employment of PAE also can reduce the effect of the interference from different kind systems.

The phase noise of LO and the nonlinearity of PA induce the inter-carrier interference (ICI) in OFDM systems that decreases the system performance; and the nonlinearity of PA also induces the interference to adjacent channels. We develop a frequency domain ICI cancellation technique to decrease the ICI level; and a dual-channel concurrent digital pre-distortion (DPD) compensation scheme is also proposed to concurrently compensate the nonlinearity of the PA.

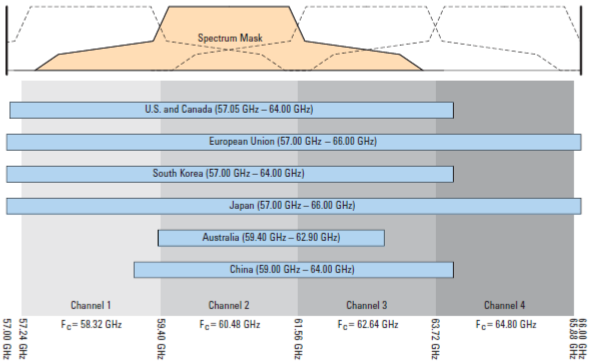


Fig. 1. 60 GHz band plan and frequency allocations by region. (Agilent Technologies Application Note, "Wireless LAN at 60GHz – IEEE 802.11ad

Low-Complexity Phase Noise Compensation

Orthogonal frequency division multiplexing (OFDM) modulation has been a key technology for fast data communications because it can mitigate the effect of multipath delay by dividing the channel into hundreds of narrowband channels. OFDM, however, is sensitive to the phase noise due to the imperfect local oscillators. It is because the phase noise causes interference among signals in the subcarriers, as known as ICI, as well as the rotation of the received signal, CPE. To address this issue, several techniques have been proposed. Some scheme take advantage of an iterative OFDM receiver employing phase noise tracking by adaptive algorithms and error correction codes. While this technique effectively mitigates the effect of phase noise, the fact that the iterative process incorporates the generation of transmit and receive replica, may pose computational burden on the receiver. To address this issue, a low-complexity inter-carrier interference (ICI) and common phase error (CPE) mitigation method for millimeter-wave OFDM systems in the presence of local oscillator phase noise is proposed in this paper. The frequency domain received signals are simply added to each other with complex coefficients which are estimated by least-mean-square (LMS) algorithm utilizing pilot signals in each OFDM symbol. Numerical analysis showed that the numerical complexity is reduced by 1/30 compared to one of the time-domain phase noise compensation scheme.

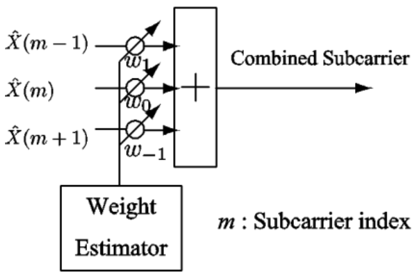


Fig. 2. Diagram of Phase Noise Compensation

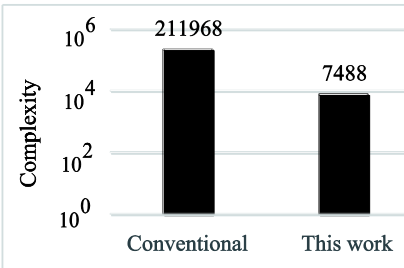


Fig. 3. Numerical Complexity

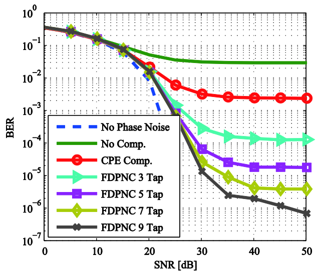


Fig. 4. BER vs SNR

User Selection Algorithm with RF beamforming

In millimeter wave wireless communication system, large path loss attenuates the propagation signal power and line of sight communication environment is more preferred. Beamforming is a useful technology for millimeter wave wireless communications and suitable for the realization of multiuser system and mitigation of interference from or toward other system.

But multiuser MIMO (Multiple-Input Multiple-Output) system with RF beamforming need a consideration of both selection of user and selection of beam pattern due to modification of channel matrix by RF beamforming. We propose two types of user selection algorithm. The first one is modified capacity-based selection. The second one is modified SUS (Semi-orthogonal User Selection). Both algorithms are based on already existing algorithms but combined beam pattern selection. To analyze the performance of multiuser MIMO system, we modeled small meeting room channel and simulate multiuser MIMO system. We can achieve 6Gbps per user for each algorithm and achieve higher performance if we use large number of beam pattern.

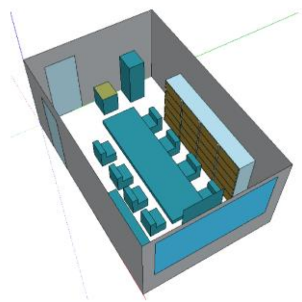


Fig. 5. Target environment

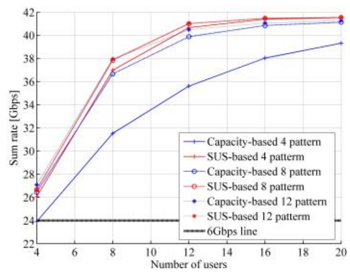


Fig. 6. No. of users vs Sum rate

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5G Cellular Network [3] [4] [6] [8] [15] [20] [26] [27] [28]

~ Millimeter-wave evolution ~

Triggered by the explosion of mobile traffic, 5G (5th Generation) cellular network requires evolution to increase the system rate 1000 times higher than the current systems in 10 years. Motivated by this common problem, there are several studies to integrate mm-wave access into current cellular networks as multi-band heterogeneous networks to exploit the ultra-wideband aspect of the mm-wave band. Sakaguchi laboratory has proposed comprehensive architecture of cellular networks with mm-wave access, where mm-wave small cell basestations and a conventional macro basestation are connected to Centralized-RAN (C-RAN) to effectively operate the system by enabling power efficient seamless handover as well as centralized resource control including dynamic cell structuring to match the limited coverage of mm-wave access with high traffic user locations via user-plane/control-plane splitting.

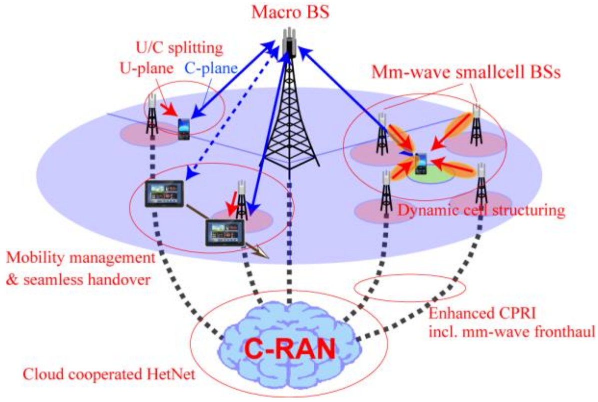

Fig. 7. 5G cellular network architecture

~ System level simulator ~

To prove the effectiveness of the proposed 5G cellular networks, system level simulator was developed by introducing an expected future traffic model, a measurement based mm-wave propagation model, and a centralized cell association algorithm by exploiting the C-RAN architecture.

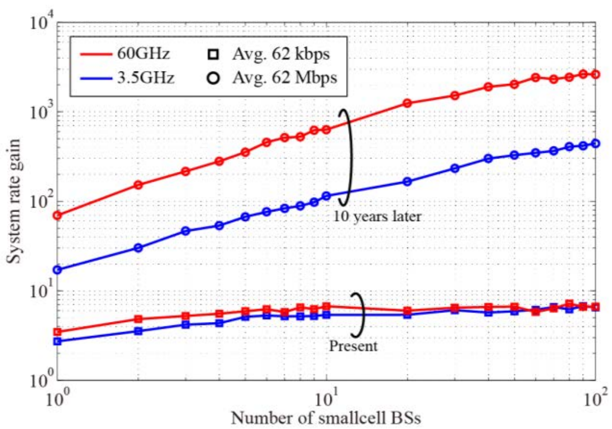

Fig. 8. System rate improvement

Numerical results in Fig. 8 show the effectiveness of the proposed network to realize 1000 times higher system rate than the current network in 10 years which is not achieved by the small cells using commonly considered 3.5 GHz band.

~ Dynamic resource management ~

A framework at control-plane is also established to allow dynamic resource management of the network, including optimal resource allocation, user association, dynamic activation and cell restructuring based on users' traffic. 3GPP-like protocols are also defined to command required measurements and reports for the decision entity which may be the macro-BS, C-RAN or the trace control entity (TCE).

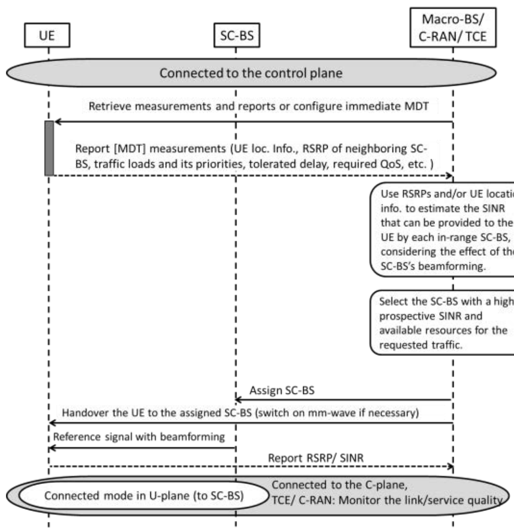

Fig. 9. Control-plane protocol

WiFi Assisted Dual-band MAC Protocol for Coordinated Beamforming among WiGig APs in Indoor Environment [30]

The Wireless Gigabit (WiGig) Access Points (APs) using the 60 GHz unlicensed frequency band are considered as a key enabler for future gigabit Wireless Local Area Networks (WLANs). Beamforming (BF) is tremendously used with WiGig transmissions to enhance the link quality and overcome the channel impairments. The exhaustive search BF protocol, currently used by WiGig APs, causes a lot of collisions when multiple APs tend to work simultaneously using random access. Accordingly, system throughput is highly decreased with a high increase in packet delay and packet dropping rate. We proposed an efficient dual-band (5 GHz/60 GHz) Medium Access Control (MAC) protocol to coordinate the BF operation among the WiGig APs using their wide coverage 5 GHz (WiFi) interfaces. Therefore, concurrent WiGig data transmissions can be successfully accomplished with a low number of packet collisions. Statistical learning, using WiFi fingerprints, is used for finding out the best beams for an AP-User Equipment (UE) link. The bad beams that can collide with the existing data communication links of other APs are eliminated from the estimated beams before the beam training process. Figure 11 shows that the average total throughput achieved by the proposed coordinated BF is always higher than that achieved by the conventional un-coordinated BF.

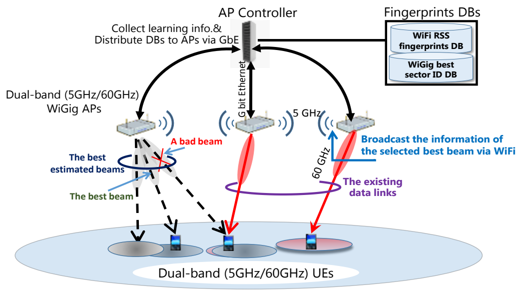

Fig. 10. The proposed system architecture.

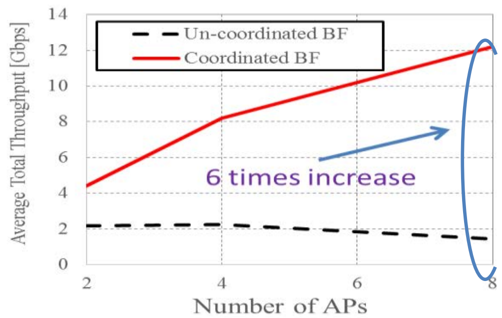

Fig. 11. Total throughput [Gbps].

Delayed Offloading using Cloud Cooperated Millimeter Wave Gates [7][17]

As a contribution to solve the capacity problem of future cellular networks, we proposed the CC-HetNet in which the previously proposed WiFi/WiGig system is distributed in the Macro BS area in the form of millimeter wave (mm-w) Gates. Due to the massive offloading capacity of WiGig gates, and thanks to the fact that most of users' generated traffic is indeed delay tolerable, we investigated the concept of delayed offloading using the gates. Also, an enhanced Access Network and Discovery Function (eANDSF) is proposed to handle the problem of how we can optimally associate a user with delayed traffic to a WiGig gate from his nearby discovered gates to maximize the total system offloading, of which function is not provided by the conventional ANDSF proposed by 3 GPP. Figure 13 confirms the higher performance of using the proposed e-ANDSF using optimal gate selection than using conventional ANDSF in terms of total gates offloaded bytes in tera bytes [TB].

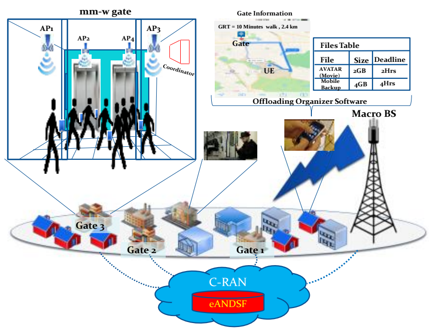

Fig. 12. The proposed delayed offloading CC-HetNet structure.

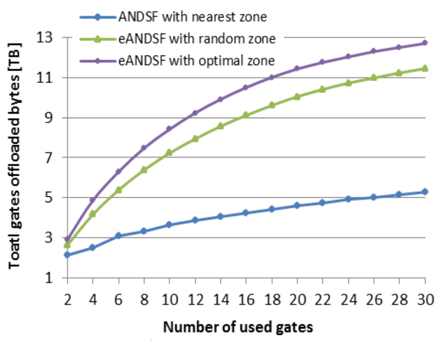

Fig. 13. Total gates offloading.

LED light control system activated by wireless energy transmission [10] [12] [28] [30]

BEMS (Building Energy Management Systems) employ numerous sensors to save the consumed energy of the building. However, the lifetime of the sensor node has long been an issue in wireless sensor networks. In order to deal with the problem, we proposed wireless grid which can permanently activate battery-less sensor nodes by multi-point wireless energy transmission with carrier shift diversity (MPCSD) which can realize seamless supply of energy to the sensor nodes by allocating orthogonal frequencies to the multiple energy transmitters compared with simple multi-point scheme (MP) in which multiple transmitters use the same frequency. As an example of wireless grid applications, LED light control system using human detection sensor is developed in an indoor office environment as shown in Fig. 14. Multiple wireless energy transmitters are embedded in all the LED ceiling lights. To reduce the consumed power of sensor nodes, the sensor network is constructed with access links and backhaul multi-hop network, where the sensing data of human detection are used to reduce energy consumption of the office. To evaluate the developed system, we conduct an experiment to verify the sensor activation. The experimental result shows that 100% coverage of sensor activation is verified in the office environment with the sensor node consumed power of 155 μW as shown in Fig. 15 (c), while the coverage of MP is only 88% as shown in Fig. 15 (b).

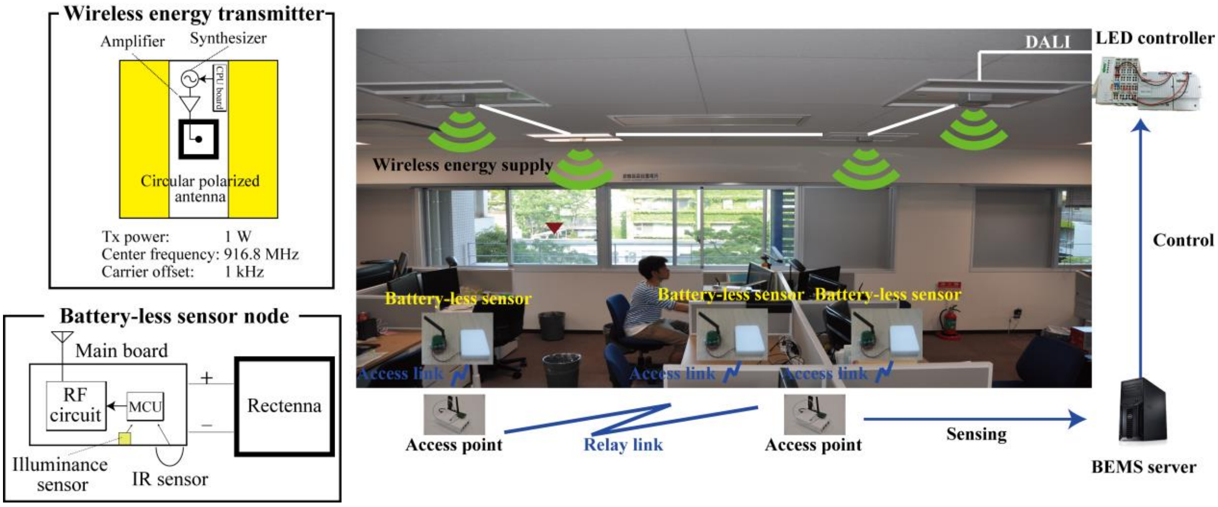

Fig. 14. Developed LED control system using battery-less sensor network.

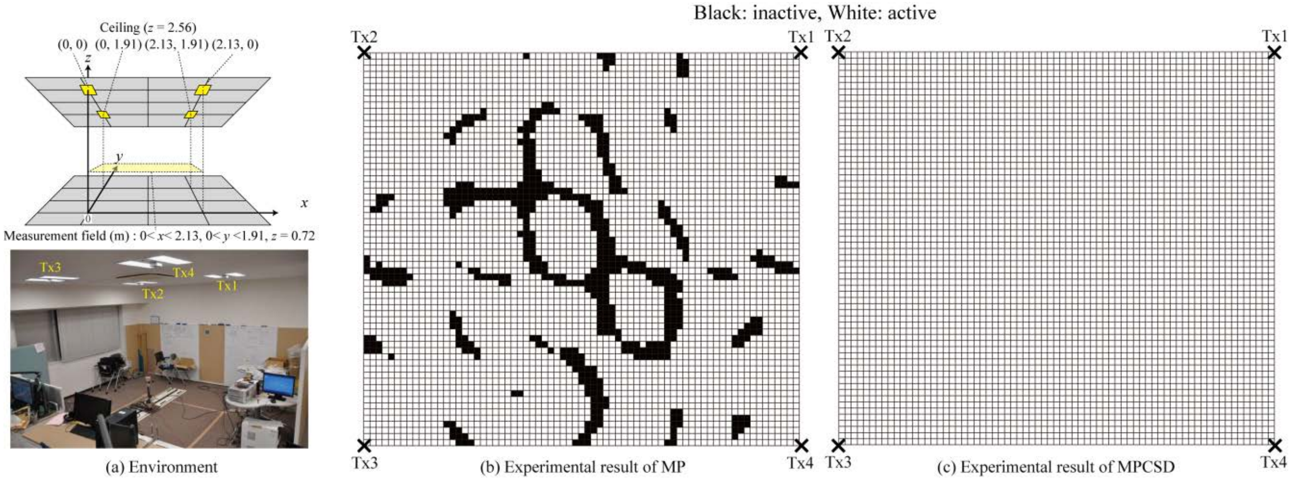

Fig. 15. Experimental results of activation status.

Indoor Wi-Fi Localization System utilizing Location Fingerprinting Technique [14][16]

In recent years, electromagnetic-wave localization systems utilizing Wi-Fi have been proposed in some projects, e.g. PlaceEngine, Skyhook Wireless, Ruckus Wireless etc. The reason why Wi-Fi is preferred to use for localization systems is that Wi-Fi have spread through the market and its module is very low cost. However, the localization performance of such conventional Wi-Fi localization systems is not so good in exchange for cost-efficiency. In order to improve the poor performance of conventional Wi-Fi localization systems, we introduce the location fingerprinting technique into the systems. The location fingerprinting technique is a novel localization technique, in which location dependent propagation parameters, such as Received Signal Strength (RSS) or Channel Impulse Response (CIR) are treated as "fingerprint" of location, and location is identified by its prior-learning and pattern-matching like fingerprint authentication. The concept of location fingerprinting technique is illustrated in Fig. 16.

In this research, we considered how to realize location fingerprinting technique based localization on Wi-Fi system. Specifically, we propose some novel fingerprints which can be calculated from propagation parameters which Wi-Fi system can provide. We also evaluate the localization performance of the fingerprints by practical simulation. The simulation configuration is described in Table 1 and the simulated environment and results are illustrated in Fig. 17 and 18. From the results, we found that fingerprinting technique is improved by more than 50% in terms of the median value of estimation error. Toward experimental validation of the system, we also design a whole system architecture, develop prototype hardware and software based on the design. The architecture of developed system is illustrated in Fig. 19, which includes a dedicated terminal for propagation parameter learning, Wi-Fi Access Points and its controller, and a localization server.

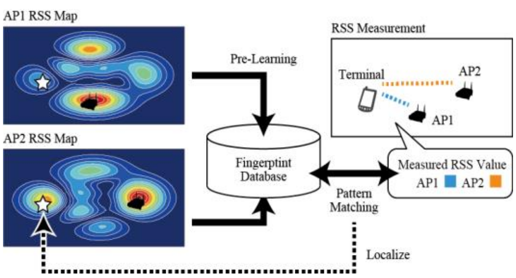

Fig. 16. Example of Fingerprinting technique.

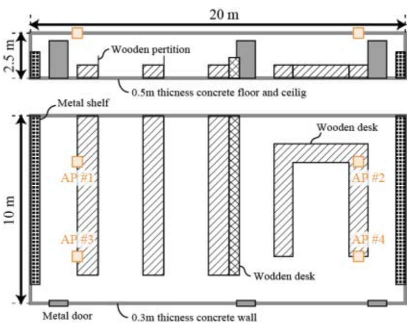

Fig. 17. Simulated environment.

Tab. 1. Simulation configuration.

Wi-Fi Standard	802.11a
Center Freq.	5.0GHz
Bandwidth	20MHz
Antenna Num.	2 (1+ additional 1)

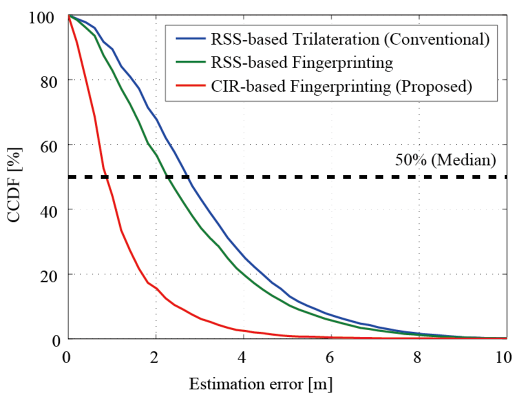

Fig. 18. Simulation result.

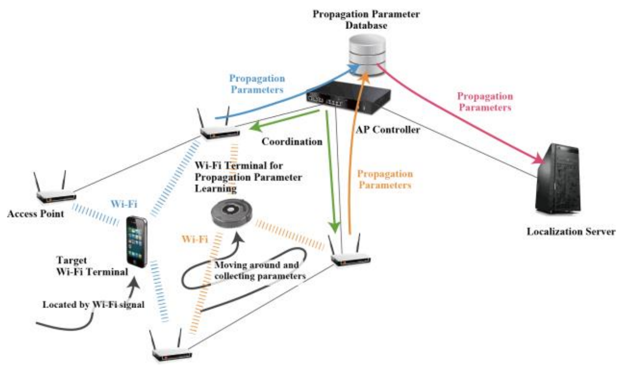

Fig. 19. Proposed System Architecture

CONTRIBUTIONS

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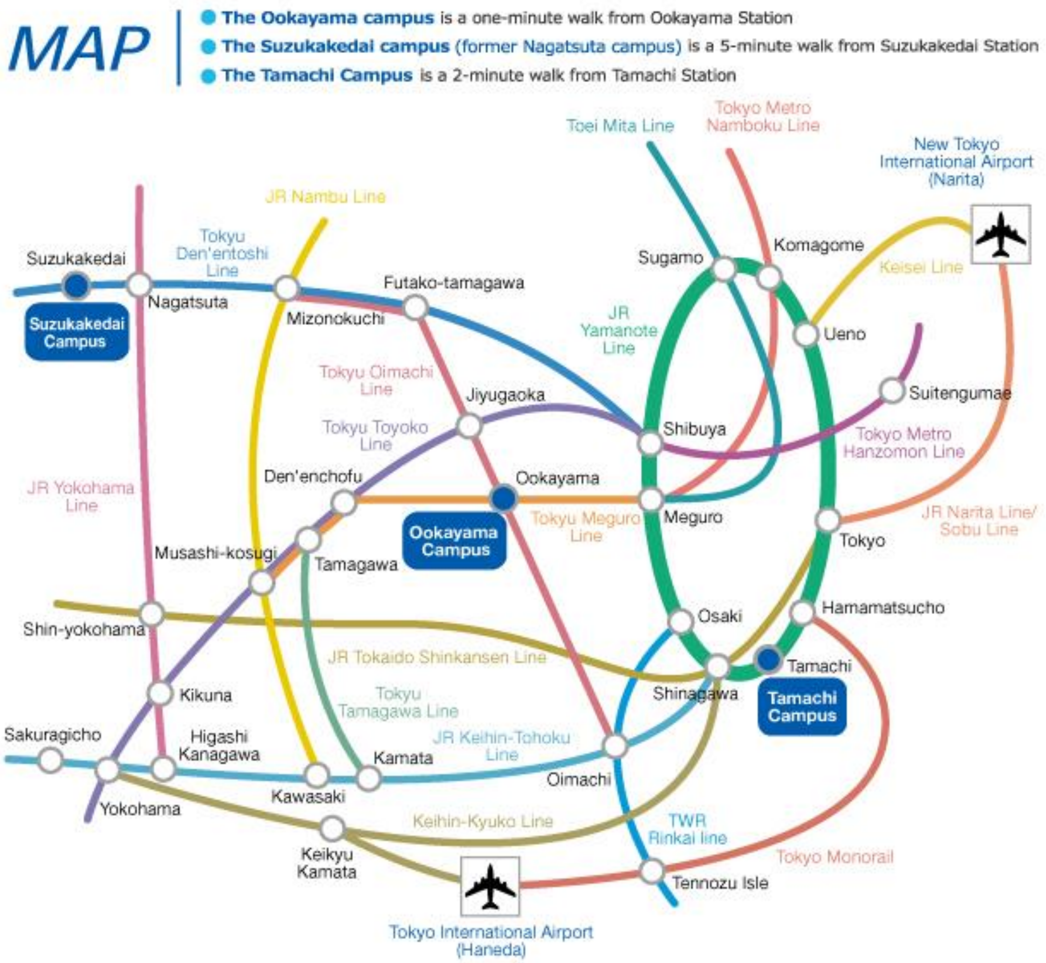

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