2013

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 2013-2014, 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 Associate Prof. Kazuhiko Fukawa)
2. System Laboratory
   (Prof. Kiyomichi Araki, Associate Prof. Kei Sakaguchi and Assistant Prof. Gia Khanh Tran)
3. Propagation and Antenna Laboratory
   (Prof. Jun-ichi Takada and Assistant Prof. Minseok Kim)

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 2013

ARAKI-SAKAGUCHI LABORATORY

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. Since 1995 he has been 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.

Associate Professor Kei Sakaguchi

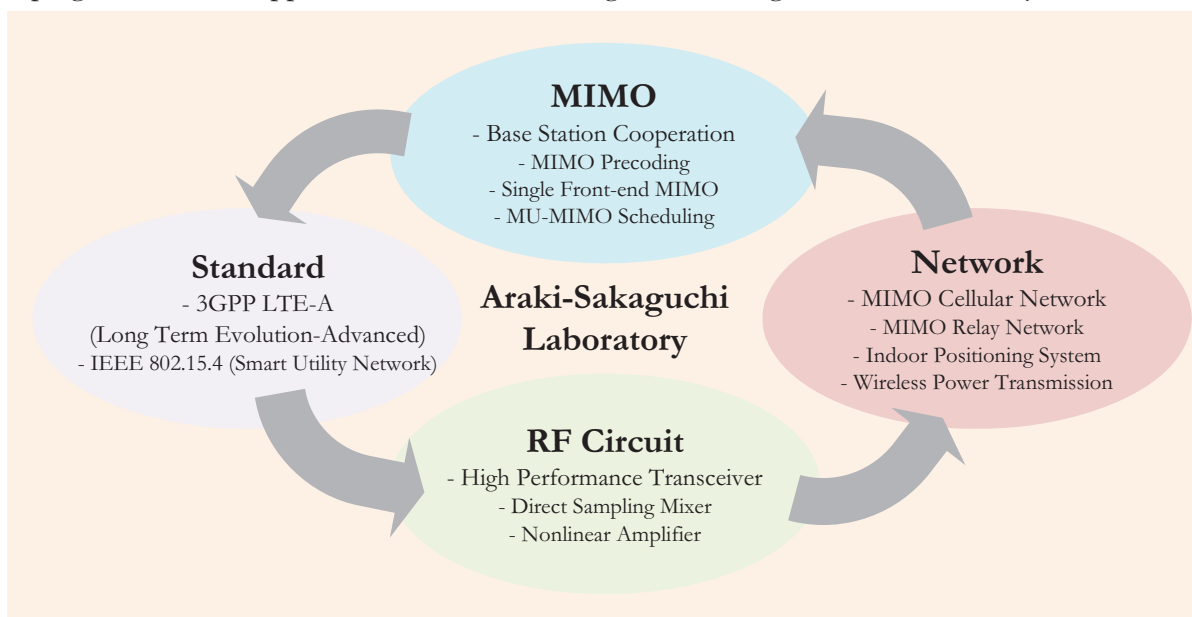Assoc. Prof. Kei Sakaguchi received the M.E. degree in Information Processing from Tokyo Institute Technology in 1998, and the Ph.D. degree in Electrical & Electronics Engineering from Tokyo Institute of Technology in 2006. From 2000 to 2007, he was an Assistant Professor at Tokyo Institute Technology. 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.

The Araki-Sakaguchi laboratory was established in 1995. Founded on wireless communication system, the lab has been extended widely from theoretical analysis to hardware implementation, measurement system construction and empirical experiments. Moreover, not only academic works within the university but also co-works with various industrial companies have been conducted for developing new wireless applications and contributing to the next generation wireless system standards.

MIMO
- Base Station Cooperation
- MIMO Precoding
- Single Front-end MIMO
- MU-MIMO Scheduling

Standard
- 3GPP LTE-A
(Long Term Evolution-Advanced)
- IEEE 802.15.4 (Smart Utility Network)

Araki-Sakaguchi Laboratory

Network
- MIMO Cellular Network
- MIMO Relay Network
- Indoor Positioning System
- Wireless Power Transmission

RF Circuit
- High Performance Transceiver
- Direct Sampling Mixer
- Nonlinear Amplifier

www.mobile.ee.titech.ac.jp

Research and Development of Technologies for Highly Efficient Millimeter Wave Channel Usage [13][42]
The Multiplexing and Compensation/Cancelation 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 phase noise self-cancelling technique to decrease the ICI level; and a digital pre-distortion compensation scheme is also proposed to compensate the nonlinearity of the PA and the IQ imbalance effects of the RF circuits simultaneously.
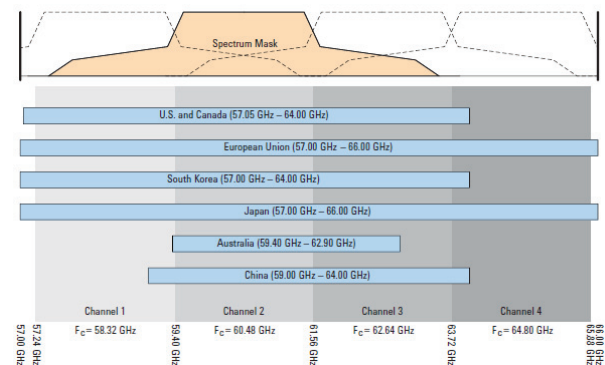

Fig. 1. 60 GHz band plan and frequency allocations by region. (Agilent Technologies Application Note, "Wireless LAN at 60GHz – IEEE 802.11ad

Compensation of RF imperfection
A Mitigation Method of Local Oscillator Phase Noise

Orthogonal frequency division multiplexing (OFDM) has been one of the important technologies for the realization of very high data transmission in micro wave wireless communication systems. In millimeter wave wireless communications, however, local oscillator phase noise deteriorates the orthogonality of OFDM subcarriers, a key property that makes the OFDM suitable for high data rate transmission, resulting in common phase error (CPE) and inter-carrier interference (ICI).

Our group has mathematically investigated the effect of local oscillator phase noise in OFDM systems. It was revealed that the ICI can be eliminated by introducing a periodic structure to the sampled phase noise sequence using a novel RF structure. The performance of the proposed scheme was confirmed by numerical simulation in SISO settings. It is also shown that the scheme can be implemented in MIMO OFDM systems.
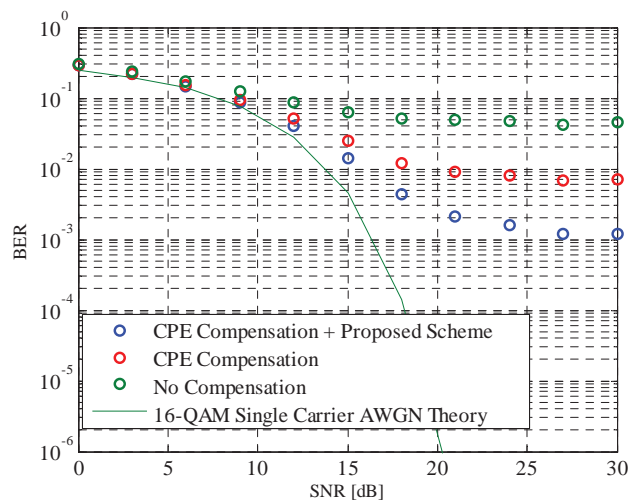
Fig. 2. BER Performance

Beamforming for Multiuser MIMO OFDM System
Investigation of Beamforming using Parasitic Antenna Element (PAE)

In millimeter wave wireless communication systems, large path loss attenuates the propagating signal power and line of sight (LOS) 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.

PAE is similar to general antenna element but terminated with capacitance variable capacitor, say varactor, instead of RF frontend. To create beam patterns, PAEs are located around the driven antenna element. The beam shape is controlled with changing the value of capacitance. PAE beamforming has advantage in low power consumption and small space arrangement compared with other schemes. Our group has investigated controllability of PAE beamforming and effect of beamforming in millimeter wave multiuser MIMO OFDM system.
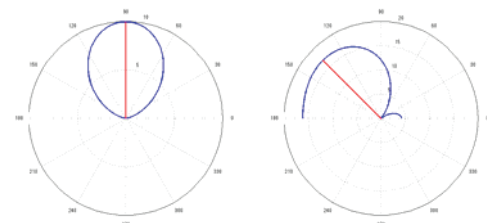
Figure 4 shows the capacity per user in the multiuser MIMO OFDM system. It is shown that the coverage of multiuser MIMO OFDM with PAE beamforming is increased by more than 5 m from that of without beamforming at our target of channel capacity (4 bps/Hz/user) that provides higher than 6 Gbps data rate for each user.
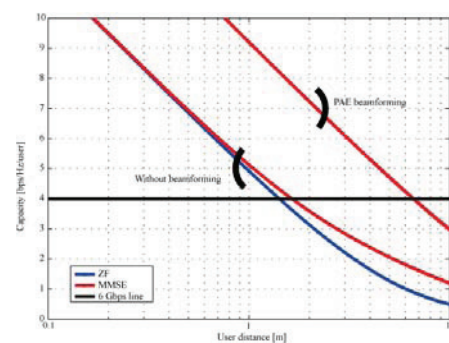

Fig. 3. Beam patterns

Fig. 4. Performance of beamforming

Dual-Band Digital Predistortion on Concurrent Amplification of Dual-Band Signals   [6][12][22][24][32][40]
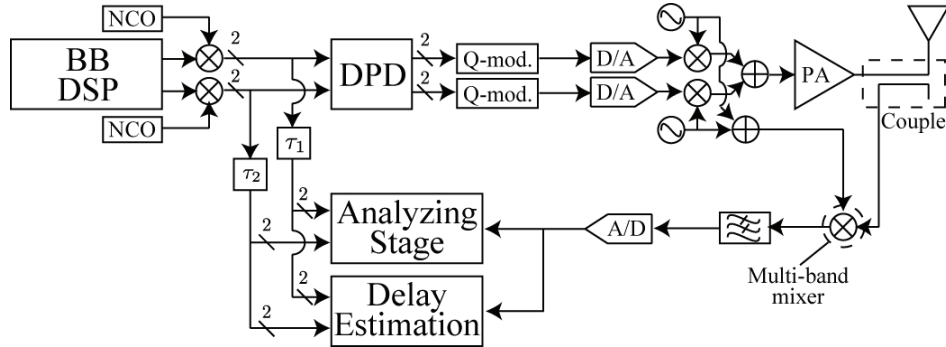

Fig. 5. Bock diagram of a dual-band adaptive DPD system with a concurrent dual-band mixer for feedback loop

To realize User-Centric Wireless Networks which integrates various wireless systems on a unified hardware platform toward easy and flexible network connections for users, we examine a multi-band power amplifier (PA) and digital predistortion (DPD) to compensate for nonlinear distortion. DPD is needed to track nonlinear time-varying characteristic of PA due to a change over time or a change in temperature. To compensate for this time-varying characteristic, adaptive predistorter which updates and optimizes coefficients of a polynomial expression is often used. However, each feedback path for each band is needed to compensate for PA noninearity on concurrent amplification of multi-band signals. It results in the increase of the number of RF circuits and the degradation of the system's flexibility. Therefore, we propose a single feedback system employing multi-band mixer which can concurrently convert multi-band signal centered at separated RF frequencies into intermediate frequencies (IF). Fig. 5 shows this proposed architecture. To verify this feedback system, experiment is conducted. Fig. 6, Fig. 7 and Fig.8 shows the experiment system and experiment results respectively.

Fig. 7 and Fig. 8 shows spectrum regrowth can be reduced and DPD performance in the proposed feedback system is equivalent to that in the conventional feedback system. Thus, our experimental results demonstrate the validity of this feedback system
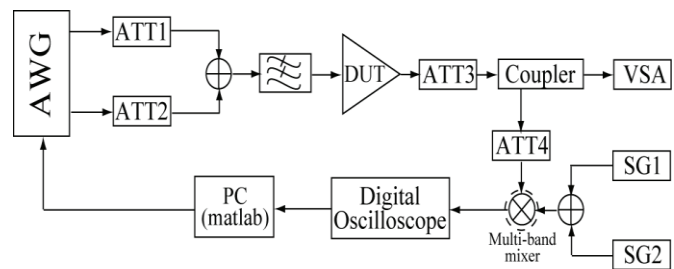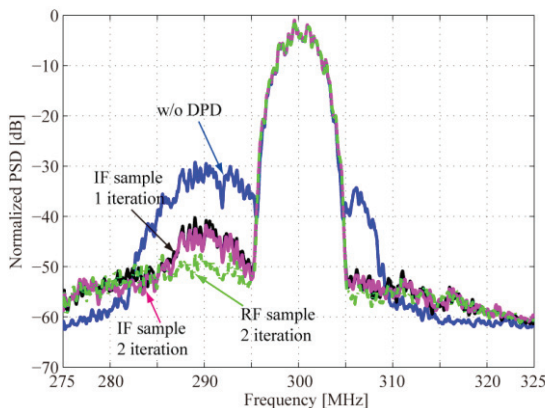

Fig. 6. Experiment system.

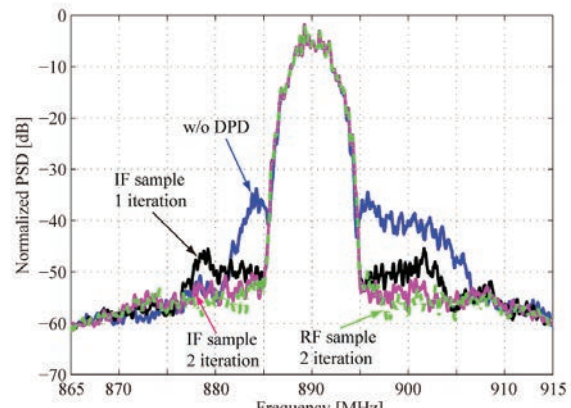

Fig. 7. Spectra comparison for lower channel

Fig. 8. Spectra comparison for higher channel

Transmission efficiency improvement of wireless power transmission

In recent years, mobile devices have been widely used. Because of long time for charging the devices, a wireless power transmission system is required as home appliance system. For supplying transmission power for a certain range, the magnetic field resonance system has been used. Power transmission efficiency as axial deviation and distance from transmission terminal for the magnetic field resonance system shows in Fig. 9. As the coupling coefficient between Tx/Rx coils varies, the transmission efficiency fluctuates on the simulation parameters. Therefore, we propose to optimize the load impedance of the receiver in order to improve the transmission efficiency. Figure 10 shows the result of the optimization of the receiver load impedance. Deference from no optimization system, the optimization one can expand the range of the high transmission power efficiency compensating the insufficient efficiency close to the transmission terminal.
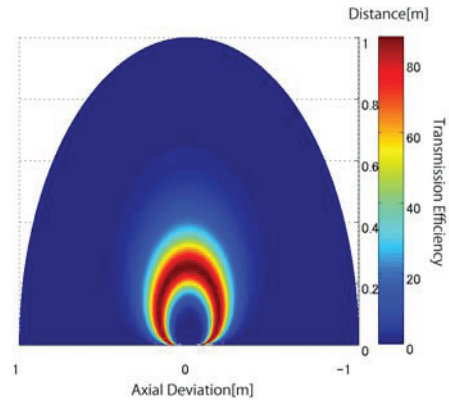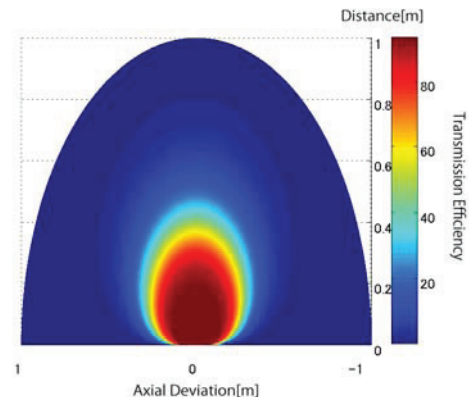

Fig. 9. Efficiency without optimization

Fig. 10. Efficiency with optimization

Low noise matching design for realization in compact MIMO receivers

This study considers a feasible matching circuit for maximizing capacity for compact MIMO receiver system. We present a complexity-reduced low noise matching design (Fig. 11) and its equivalent circuit using practical L/C based circuit components (Fig. 12). Our analysis result shows the superiority of the even-odd mode matching method with optimal performance and feasible implementation. Furthermore, the optimal case is determined through performance comparison in lossy condition of the matching circuit. The minimum required Q-factor Q_{min} for evaluating the necessity shows that the proposed matching is effective for closely antenna spacing with high mutual coupling (Fig. 13).
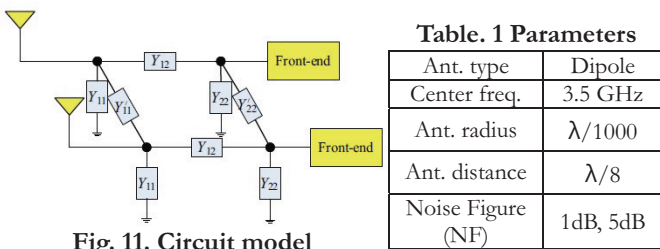

Fig. 11. Circuit model

Table. 1 Parameters

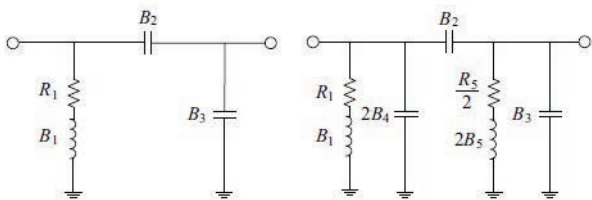| Ant. type	Dipole
Center freq.	3.5 GHz
Ant. radius	λ/1000
Ant. distance	λ/8
Noise Figure (NF)	1dB, 5dB

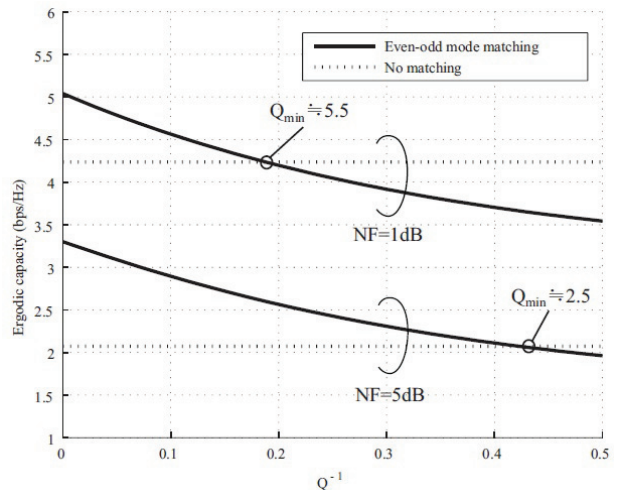**Fig. 12. (a) Even mode   (b) Odd mode**

Fig. 13. Ergodic capacity in different lossy condition

9

Cell Association Method for Multi Band Heterogeneous Networks [5] [8] [11] [38]

Extreme growth of cellular network traffic is a big issue in recent years. To tackle this problem, heterogeneous cellular network (HetNet) which is a new type of cellular network topology constructed by mixture of the conventional large coverage macro base station (BS) and low power with small coverage BSs (pico BSs), was proposed and standardized in 3rd generation partnership project (3GPP) and higher frequency band will be exploited e.g. 3.5GHz band and 60GHz band. Multi band HetNet uses these two features by allocating the lower band to macro BSs and higher band to pico BSs. Our group firstly analysed the effect of the cell association method for multi band HetNet and proposed novel call association method considering the

Fig. 14. System rate gain

received signal strength and traffic demand of each user equipments (UEs). Figure 14 shows the system rate gain with respect to that of the macro-only homogeneous cellular network. Dashed lines are conventional cell association method and solid lines are proposed method respectively. The result reveals that proposed association method provides great benefits in any cases and achieves as well or better performance in 60GHz case.
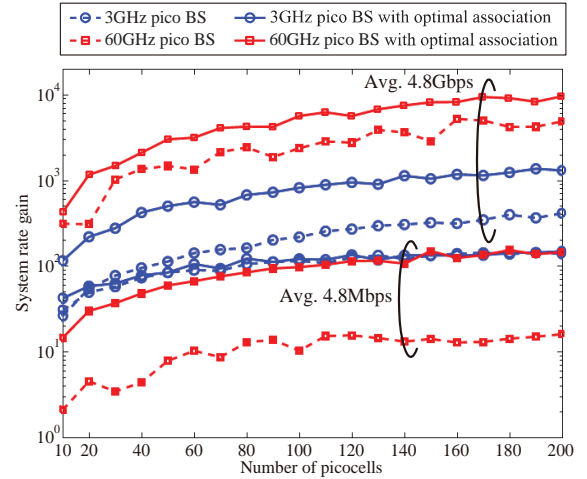
Large Scale Cooperation in Cellular Networks with Non-uniform User Distribution [14]

In real-world networks, user density and traffic demand depend on the time of the day. Traditionally, networks are designed for the worst case or the busiest time. Quite the contrary, our idea is to dynamically transfer network resources from sparse areas to dense areas. To realize this, we employ large-scale CoMP (coordinated multipoint) with flexible coverage control. Coverage control is accomplished through antenna vertical/ horizontal beam direction. Our idea is to focus on user dense areas and form large clusters around them to borrow idle base stations (BS) from vacant areas (Fig. 15). To implement this, we have to solve an optimization problem, which selects best BSs for the cluster and finds their optimum beam direction/pattern subject to maximizing the overall network sum rate. Our results show that the system rate can be multiplied several times with the proposed scheme (Fig. 16).
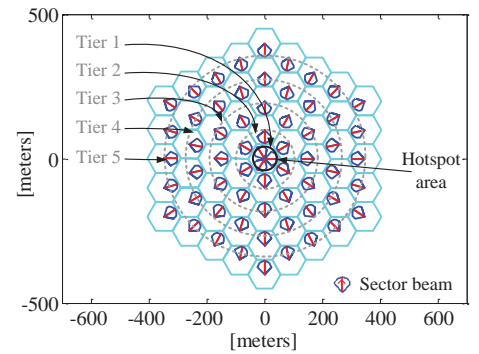
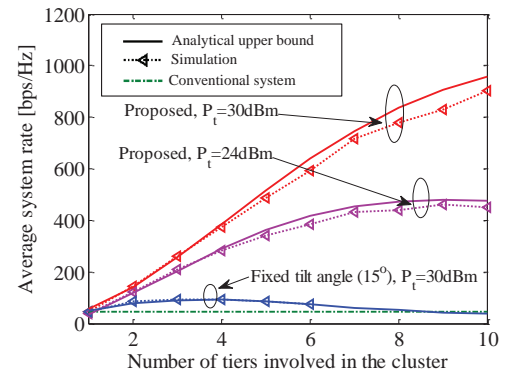**Fig. 15. A 5-Tier Cluster Around a Single Hotspot Zone**

Fig. 16. System Rate

Wireless Sensor Networks   [4] [7] [17] [20] [21]

Recently, Wireless Sensor Networks (WSNs) have been expected for the employment in autonomous systems. In current situation of WSNs, two main issues, i.e. wireless energy transmission and optimal relay placement, have long been hot research topics. In this fiscal year, we aim to realize battery-less sensor in wireless energy transmission systems to improve the energy coverage, and propose a methodology to find the relay placement to enhance the network coverage as well as reduce error rate.

Battery-less Sensor Network with Wireless Energy Transmission

We propose multi-point wireless energy transmission with carrier shift diversity, which can avoid dead spots occurring in conventional wireless energy transmission by creating artificial fading in indoor environment as shown in Fig. 17. The artificial fading is realized by allocating different frequencies to multiple transmitters. To verify the effectiveness of the proposed scheme, we developed battery-less sensor node, which requires -4dBm power consumption. The experiment is performed along the straight line of 6 m between Tx 1 and 2 to measure the received power and verify sensor activation. The proposed scheme can mitigate the deadspots as shown in Fig. 18 (red line). The coverage of single-point and simple multi-point energy transmission are limited to 44% and 70% respectively, while that of the proposed method can achieve 100% to activate the battery-less sensor in the experimental environment.
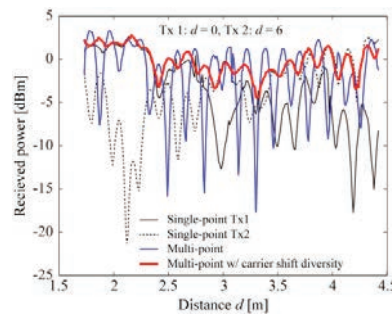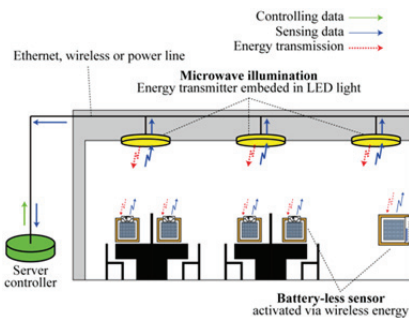

Fig. 17. Battery-less sensor networks

Fig. 18. Experiment result

Table 2: Experiment parameters

EIRP	35dBm
Center frequency	920.4MHz
Carrier offset	50Hz
Antenna hight	1.5m

Network planning methodology for wireless multi-hop networks

We propose a relay placement optimization methodology for multi-hop relay networks in practical environments. Fig. 19 shows the target factory environment considered in this research, where the locations of sink and sensor nodes are pre-assigned. Here, red dots illustrate the sensor nodes that can connect to the sink at the middle of the target environment, while blue dots illustrate the sensor nodes that need relay to help them connect to the sink. By using our proposed method, we can estimate the minimum number of relay nodes to cover all sensor nodes and packet loss as well as delay can be minimized as shown in Fig. 20.
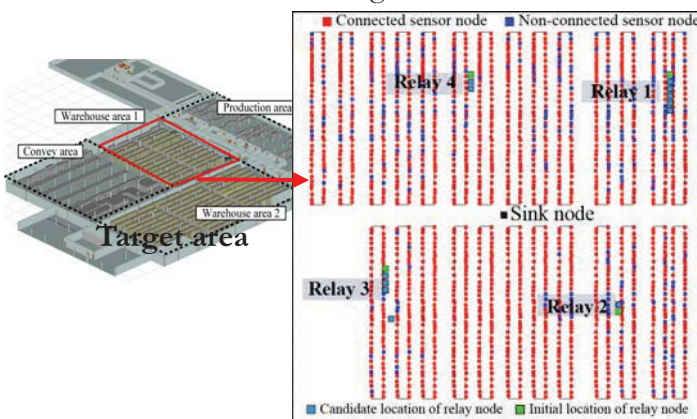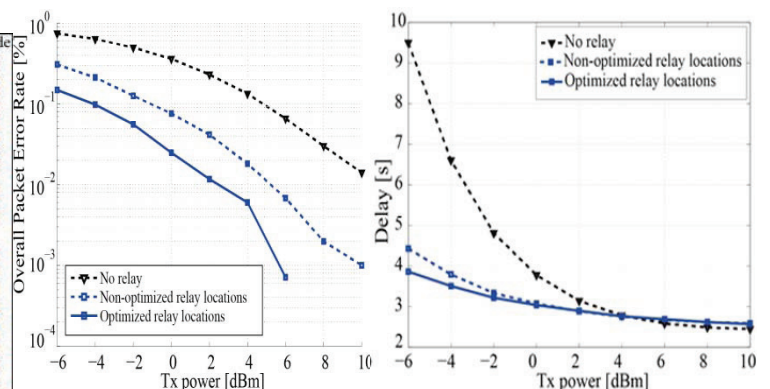

Fig. 19. Factory environment

Fig. 20. Packet loss and delay

Araki-Sakaguchi Laboratory
Location Estimation for Illegal Cell-phone Use in Indoor Environment [18][29]

With the increasing popularity of cell-phone usage, there is a great demand for high accuracy location estimation methods in indoor environment, for example to detect illegal usage in prohibited area, to track the movement of consumers, or provide push services based on user's location. For these purposes the grid based indoor localization method is introduced, especially for illegal cell-phone use case such as cheating in the exam.

For indoor location estimation system, some multi sensor methods are proposed. The well-known metrics of conventional location estimation methods are Received Signal Strength Indicator (RSSI), Time Different of Arrival (TDOA), and Direction of Arrival (DOA). These methods often assume ideal scenarios such as LOS; however indoor environment where there are a lot of obstacles is typically a Non-Line of Sight (NLOS)

Fig. 21. System model

environment with severe multi path fading. Thus conventional methods are hard to be applied in realistic indoor environments as they always achieve low accuracy.

The proposed method invokes the nature of the received signal cross-correlation between sensors. The cross-correlation of the received signal consists of the convolution of the auto-correlation of the transmit signal and the cross-correlation of the channel responses thus fully contains information of the transmitter property and the channel responses. It suggests that employing the cross-correlation can generalize conventional location fingerprint methods using RSSI, TDOA and DOA. The conventional location fingerprint method also has problems of the requirement of the fine grid measurement and the static environment. So that we introduce statistical scheme into location fingerprint technique to conquer the problems of locality and dynamic environment.

We conducted an experiment to validate the superiority of the proposal method in indoor environment. The propose method statistically learns location fingerprint from the cross-correlation of the recorded signals and estimates the transmitter position by the metric of the likelihood of the cross-correlation between learned and illegal. The proposal location estimation accuracy improves by 10-fold compared to the conventional methods (RSSI, TDOA). As a result, we can more correctly specify the location of illegal radio emitter.
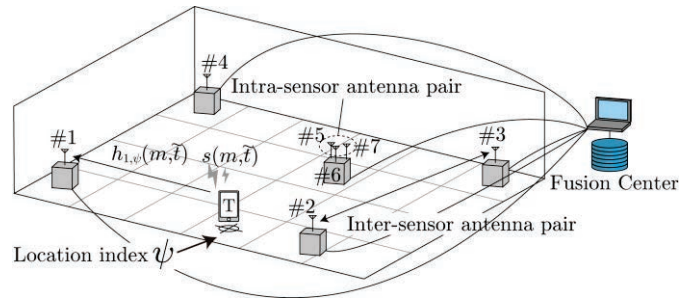

Fig. 22. Experiment settings
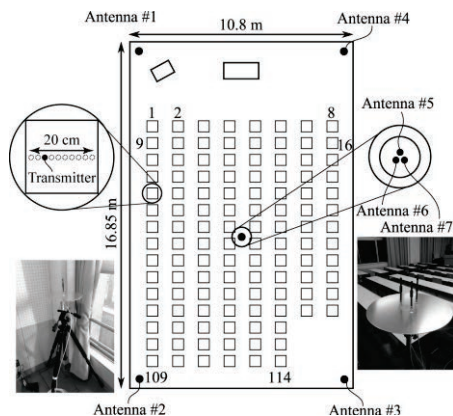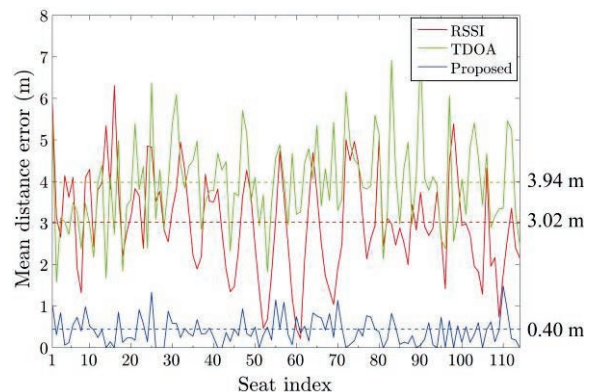

Fig. 23. Mean distance error vs position index

MIMO Cognitive Radio System using Transmit/Receive Beamforming [9][26][32]

MIMO Cognitive Radio System (MIMO-CRS) is one of cognitive radio systems which avoids interference from/forward other nodes using MIMO beamforming technique (Fig. 24). To perform beamforming, MIMO-CRS nodes first obtain Channel State Information (CSI) and design beam pattern by calculating beamforming weight. In practice, CSI is always obtained with errors and the beam created may causes severe residual interference. To evaluate performance degradation caused by such contaminated CSI, we implemented MIMO-CRS on our 950MHz MIMO prototype hardware (Fig. 25) and also developed a corresponding demonstration system. In the demonstration, we

Fig. 24. MIMO-CRS.

assume 2 existing nodes which communicate with each other in Time Division Duplex (TDD) manner and 2 MIMO-CRS nodes try to communicate with each other without disturbing the existing nodes by using MIMO beamforming. To obtain CSI at Receiver side (CSIR), which is necessary to perform receive beamforming, MIMO-CRS nodes overhear existing nodes' training sequence embedded in the transmitted signal. On the other hand, to obtain CSI at Transmitter side (CSIT), which is necessary to perform transmit beamforming, we convert CSIR of the previous timeslot into CSIT by taking advantage of channel reciprocity principle (Fig. 26).
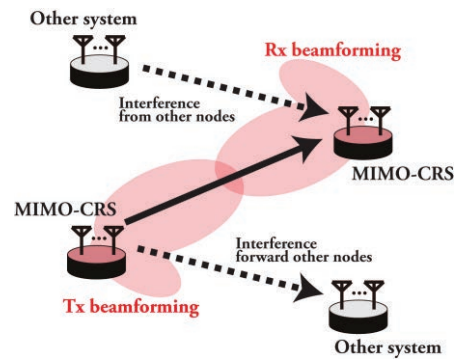
Fig. 27 shows example of demonstration results. The left side shows the transmitted signal from the

Fig. 25. Hardware.
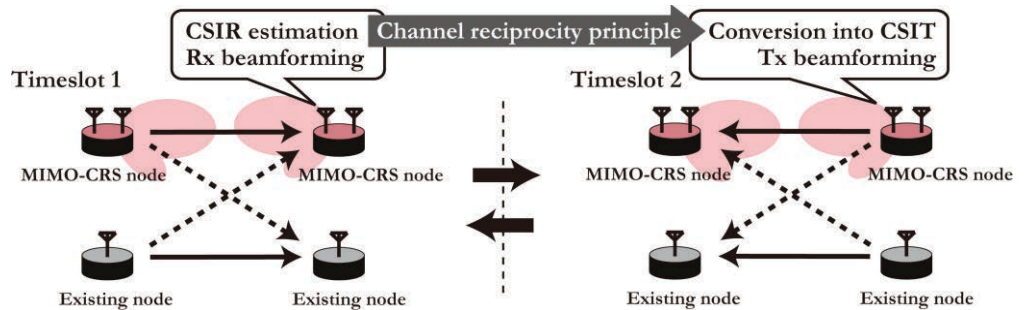
Fig. 26. Demonstration scenario.

MIMO-CRS node and the existing node, and the central and right side show the received signals without and with beamforming respectively. In the case that MIMO-CRS nodes does not perform transmit/receive beamforming, we can see severe interference in both nodes' constellations and decoded images. However, in the case that MIMO-CRS nodes do perform transmit/receive beamforming, residual interference can be eliminated and the correct images are decoded.

Fig. 27. The effectiveness of beamforming.

SUZUKI-FUKAWA LABORATORY

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

Professor Hiroshi Suzuki

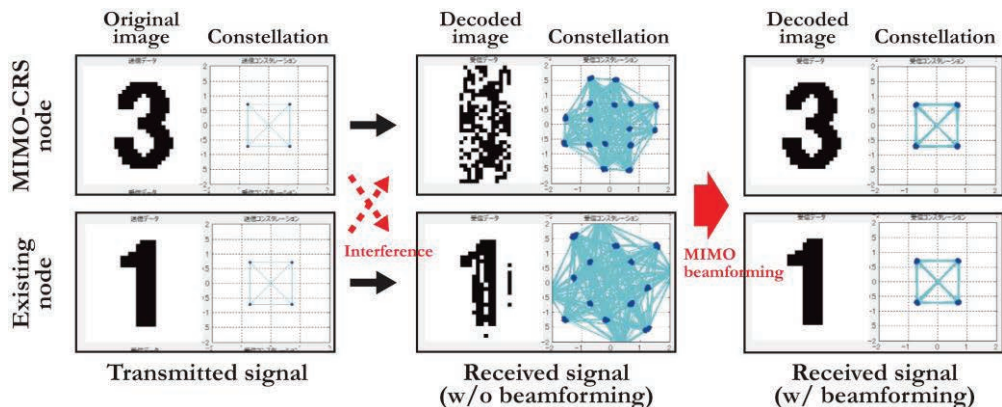received the B.S. degree in electrical engineering, the M.S. degree in physical electronics, and the Dr. Eng. Degree in electrical and electronics engineering, all from the Tokyo Institute of Technology in 1972, 1974, and 1986, respectively. He joined the Electrical Communication Laboratories, Nippon 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.

10 Gbps Millimeter-Wave OFDM Experimental System with Iterative Phase Noise Compensation [1]

60 GHz millimeter-wave systems have been extensively studied, and 60 GHz wireless personal area network (WPAN) standardization in IEEE 802.15.3c has employed OFDM transmission because of multipath channels. Moreover, single-chip RF-CMOS ICs based on silicon (Si) technology for the 60 GHz transceiver have been developed to reduce power consumption and cost. However, it is difficult to make a frequency synthesizer with sufficiently low-level phase noise over 8 GHz bandwidth of the

60 GHz band, and it is well known that OFDM is much sensitive to the phase noise. In order to solve this problem, decision-directed phase noise compensation (DD-PNC) has been proposed for the OFDM transmission, and has been verified by 60 GHz radio frequency (RF) experiment using 64QAM with coding rate R = 1/2 (2.96 Gbps).
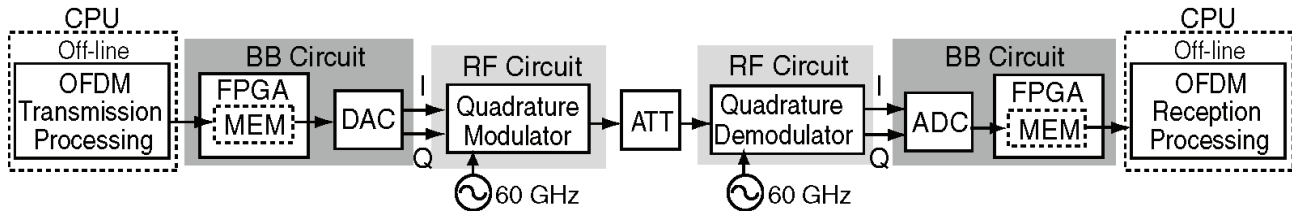

Fig. 1. 60 GHz-band 10 Gbps OFDM experimental system

This paper presents a 10 Gbps millimeter-wave OFDM experimental system that employs 64QAM and LDPC code with R = 14/15 in order to realize 10 Gbps bit-rate. The experimental system also applies combination of DD-PNC, decision-directed channel estimation (DDCE) and packet interleaving (P-IL) to OFDM reception processing for coping with the influence of the phase noise in such highly efficient modulation and coding scheme.

Fig.1 shows 10 Gbps millimeter wave OFDM experimental system using a highly efficient modulation and coding scheme where iterative phase noise compensation can drastically alleviate performance degradation due to phase noise. 60 GHz frequency synthesizer in a silicon RF-CMOS IC suffers from relatively large phase noise, which severely degrades the performance of the 10 Gbps OFDM using 64QAM and LDPC code with coding rate of 14/15. In order to alleviate this impairment, the experimental system applies combination of decision-directed phase noise compensation (DD-PNC), decision-directed channel estimation (DDCE) and packet interleaving (P-IL) to OFDM reception processing as explained in **Fig.2**.
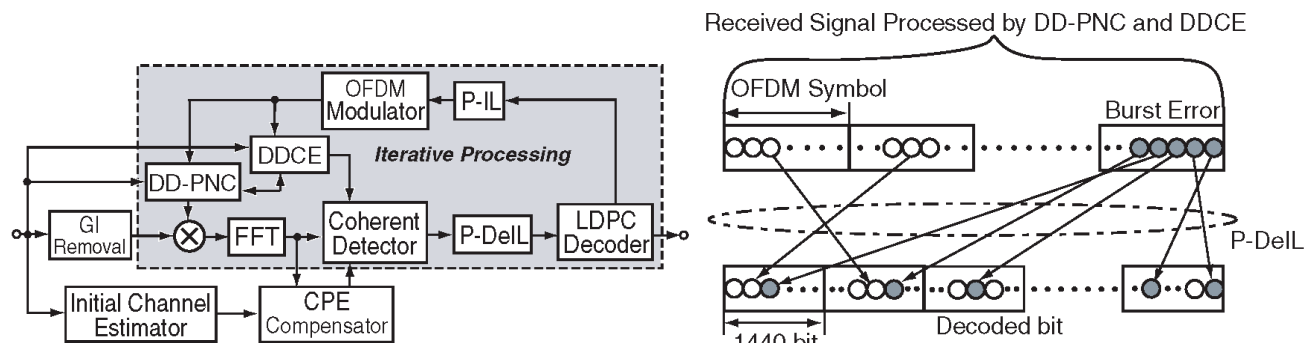

Fig. 2. Reception processing with DD-PNC and DDCE

Fig. 3. Synergistic effect of iterative processing

The sophisticated combination of iterative processing provides a synergistic effect on coping with the influence of the phase noise by exploiting outputs of the LDPC decoder. Experimental results of the 10 Gbps OFDM with 60 GHz cable connection demonstrate that the combination can achieve 10 Gbps throughput at SNR of 25.8 dB when the phase noise level is -89 dBc/Hz at 1 MHz offset.

The OFDM transmission processing divides information bits into some blocks of 1,344 bit, and generates LDPC code blocks of 1,440 bit. Next, P-IL permutates the coded bit sequence over one packet. Then, it maps the coded bits into modulation signals at data subcarriers and inserts pilot signals

at pilot subcarriers. Finally, IFFT converts the modulation and pilot signals into time-domain signals and guard interval (GI) is inserted.
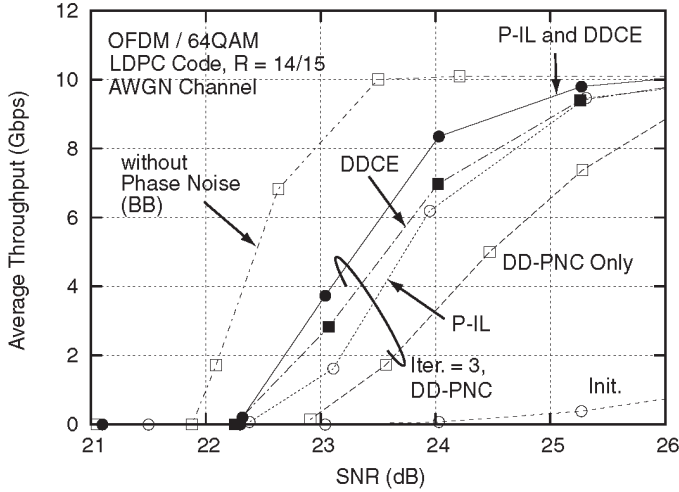

Fig. 4. Measured throughput performances

Fig.3 (p.17) shows the synergistic effect of the iterative processing which includes DD-PNC, DDCE, P-IL, the LDPC decoding. Since the length of the LDPC code block is much shorter than the packet length, it is difficult to sufficiently correct burst errors due to the phase noise, even if the outputs of the LDPC decoder are fed back to DD-PNC and DDCE without P-IL. Applying P-IL to the iterative processing can exploit the outputs of the LDPC decoder for the high-coding-rate LDPC code, and the synergistic effect of the iterative processing can drastically alleviate the degradation due to the phase noise.

Average throughput performances were calculated from packet error rate measured by the experimental system and were shown in **Fig.4**. For comparison, average throughput of a BB experimental system was also plotted. This figure demonstrates that the average throughput of the initial processing (Init.) severely degrades, while three iterations of the reception processing can considerably improve the throughput performance. Moreover, it can be seen that the average throughput of the combination of DD-PNC and DDCE outperforms that of DD-PNC only, and that it is almost the same as that of the combination of DD-PNC and P-IL. This is because P-IL can avoid burst errors by permutating the LDPC code blocks over one packet. In addition, this figure shows that the sophisticated combination of the DD-PNC, DDCE and P-IL can achieve 10 Gbps throughput at the received SNR of 25.8 dB.

The experimental results have demonstrated that three iterations of the combination can achieve 10 Gbps throughput at the received SNR of 25.8 dB by coping with the phase noise whose level is -89 dBc/Hz at 1 MHz offset.

Approximate Channel Block Digitalization for Open-Loop Multiuser MIMO Communications [2]

In mobile communications, multiuser multiple-input multiple-output (MIMO) in which plural users share the same frequency band has attracted much attention. A major problem of the multiuser MIMO is cochannel interference among users. Block diagonalization (BD) is one of the most promising techniques to cope with the interference. BD generates a precoding matrix by using channel state information (CSI) of all users and multiplies a transmitted symbol vector by the precoding matrix so that a channel matrix multiplied by the precoding matrix can be block diagonalized.

This paper proposes an approximate block diagonalization (BD) method that does not require feedback of channel state information (CSI) by using the second-order statistics of channels for multiuser MIMO mobile communications.

On the assumption that an incidence angle distribution in the uplink channel is the same as the angle of departure in the downlink channel, the proposed scheme estimates the autocorrelation matrix of the downlink channel from the average and variance of incidence angles in the uplink. Since the proposed scheme uses the estimate of the autocorrelation matrix of the downlink channel, it performs eigenvalue decomposition of the autocorrelation matrix whereas the conventional BD performs singular value decomposition of the channel matrix. To verify the effectiveness of the proposed scheme, computer simulations are conducted. It is shown that the proposed scheme, which does not need CSI feedback, is little inferior in the channel capacity to the conventional BD precoding that requires CSI feedback. BD generates a precoding matrix by using channel state information (CSI) of all users and multiplies a transmitted symbol vector by the precoding matrix so that a channel matrix multiplied by the precoding matrix can be block diagonalized.
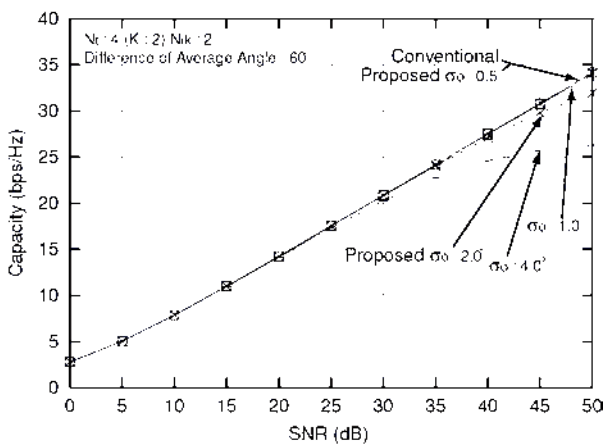

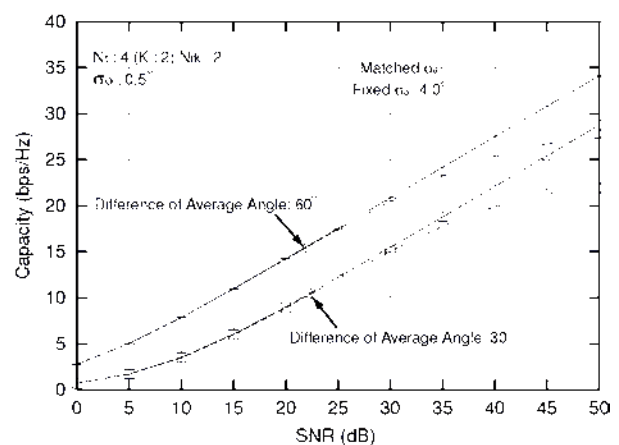**Fig. 5 Average channel capacity with average angle difference of 60°**

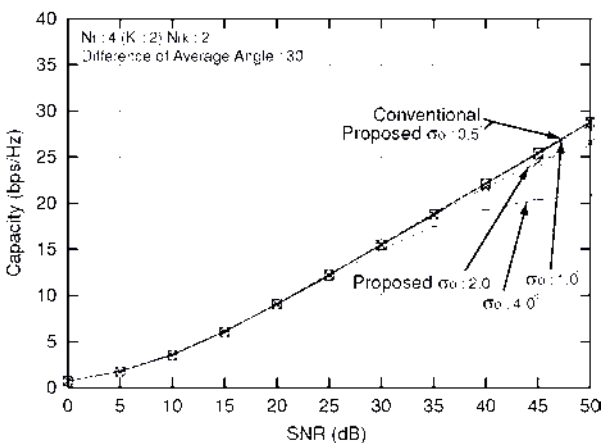**Fig. 6 Average channel capacity with estimation errors of σ_ϕ**

Fig. 7 Average channel capacity with average angle difference of 30°
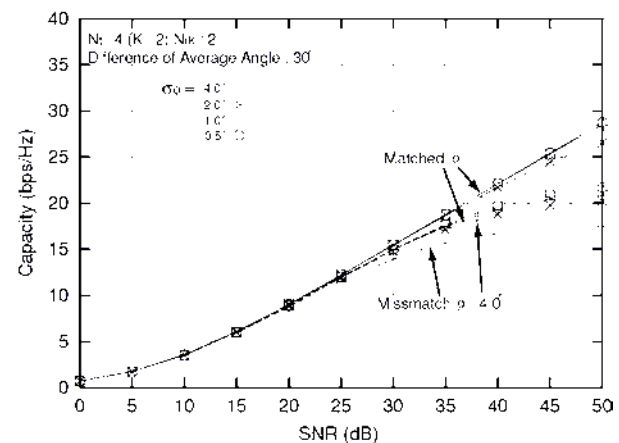

Fig. 8 Average channel capacity with estimation errors of the mean of ϕ_k

Figs.5-8 show results of computer simulations under two MSs and Rayleigh fading condition that have demonstrated that the proposed scheme can achieve almost the same channel capacity as the conventional BD which requires CSI feedback when SNR is less than 30dB. It was also shown that the proposed scheme is robust against estimation errors of the average and standard deviation of incidence angles when SNR is less than 30dB.

SUZUKI-FUKAWA LABORATORY

Iterative Signal Detection of EM-based Receivers with Multiple Antennas for OFDM Communications [3]

Joint signal detection and channel estimation based on the expectation-maximization (EM) algorithm has been investigated for orthogonal frequency-division multiplexing (OFDM) mobile communications over fast-fading channels. In order to make the signal detection suitable for the iterative EM-based receiver with multiple antennas, 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 unreliable received signals for consecutive signal detection and channel estimation. Computer simulations under fast-fading conditions demonstrate that appropriate application of the spatial removal can exploit such a removal effect and the spatial diversity, resulting in improvement of the packet error rate (PER).
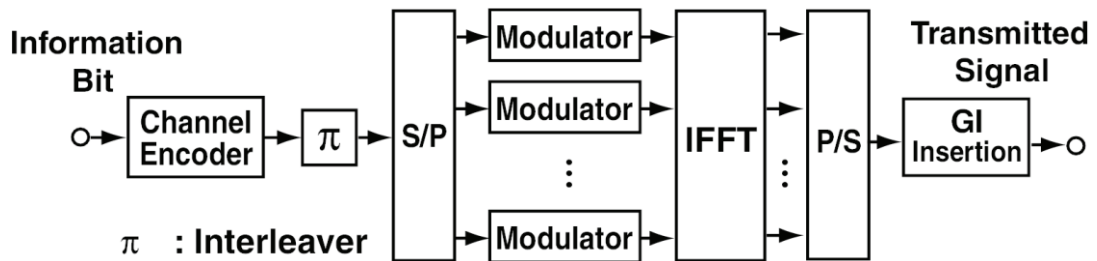

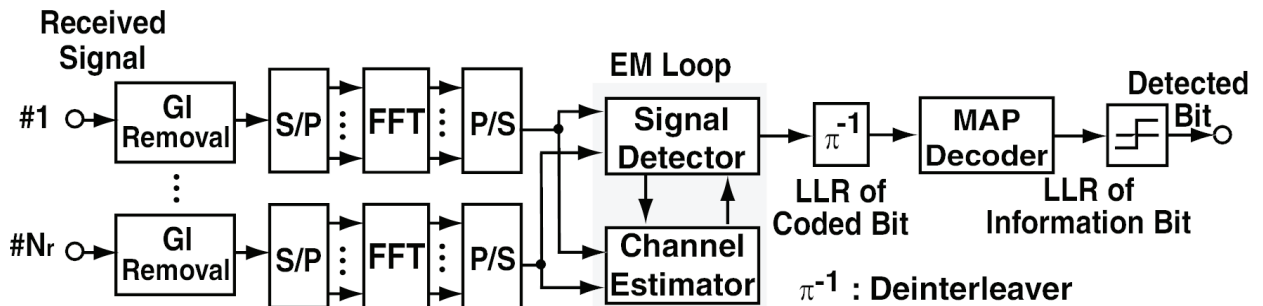Fig.9 Structure of an OFDM transmitter

Fig. 10 Structure of an OFDM receiver

The optimal receiver for the OFDM system is one based on the maximum *a posteriori* (MAP) criterion. Since an ideal receiver of this kind would involve prohibitive computational complexity, a suboptimal receiver is investigated to drastically reduce complexity, but without increasing the packet error rate (PER). The expectation-maximization (EM) algorithm, which approximates the MAP estimation in an iterative manner, involves feasible computational complexity, and has been applied to joint signal detection and channel estimation.

In order to make the signal detection suitable for the EM-based receiver with multiple antennas, 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 application of the spatial removal is discussed.

Fig.11. shows the average PER performance versus the EM iterations with average EM iteration for the spatial removal through overall channel realization in computer simulations. The spatial removal can improve the convergent PER for both the channel estimation methods. **Fig.12** shows the average PER performances versus the average E_b/N_0, where the number of EM iterations, L is 8; and the channel estimation with the subcarrier removal was adopted. It can be seen that SPR(2,3) reduces the error floor by more than half. Application of the spatial removal was discussed to exploit both the removal effect and the spatial diversity. Computer simulations with $f_{DTS}=3.0\times10^{-2}$ demonstrated that appropriate application of the spatial removal can improve the PER performance, and the combination of the spatial removal and the subcarrier removal reduces PER to 7.6×10^{-4}.
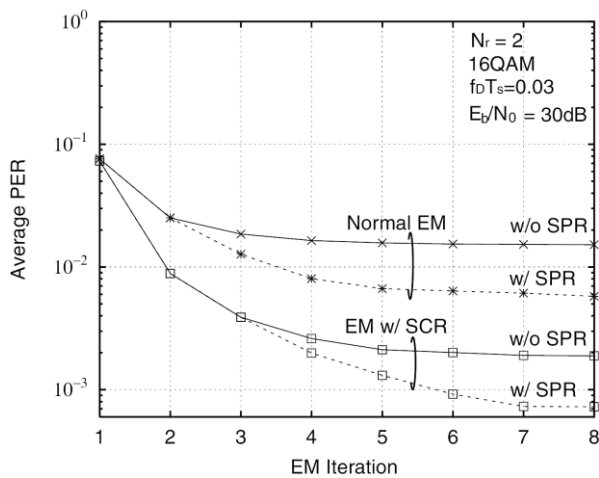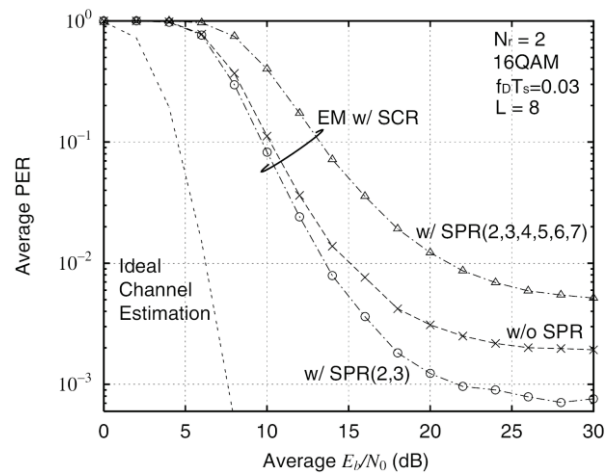

Fig.11. PER performance versus *L*

Fig.12. PER performance versus E_b/N_0

11 GHz Band 8×16 MIMO-OFDM Outdoor Transmission Experiment for 10 Gbps Super High Bit Rate Mobile Communications [4]

Sophisticated mobile terminals such as smartphones are rapidly growing the demand for higher bit rate transmission, and fourth-generation mobile communication systems target the maximum bit rate of 1 Gbps. In experiments to verify a higher bit rate, 12×12 MIMO transmission with the signal bandwidth of 100 MHz achieved 5 Gbps. In addition, 10 Gbps transmissions using higher frequency bands over 5 GHz were discussed at a 3GPP workshop focusing the post LTE-Advanced era.
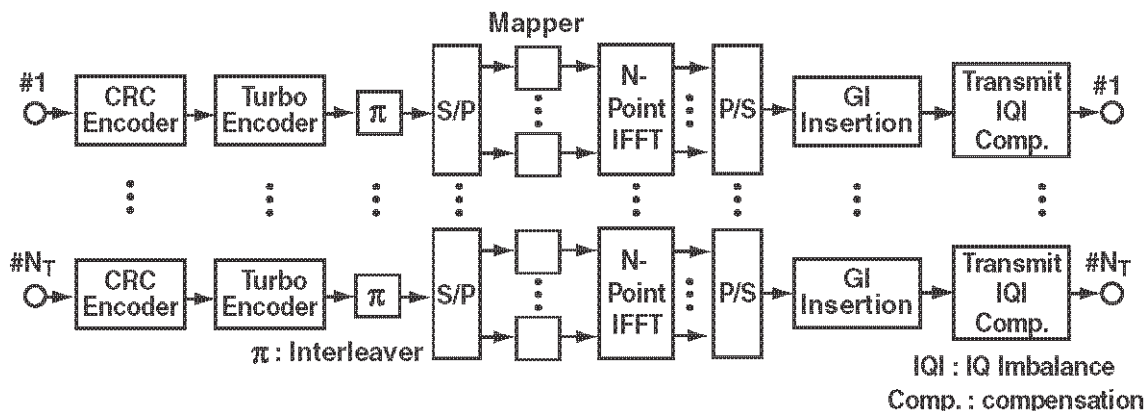

Fig. 13. MIMO-OFDM transmission processing (N_T = 8)

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In order to achieve even higher bit rates, super high bit rate mobile communications attaining a bit rate of greater than 10 Gbps have been investigated. A 10 Gbps 8×8 MIMO-OFDM experimental system was developed to verify the feasibility of the super high bit rate by experimentation. The experimental system consists of baseband (BB) circuits that support the signal bandwidth of 400 MHz and 11 GHz band radio frequency (RF) circuits. The basic performance of the experimental system has been evaluated in laboratory experiments.
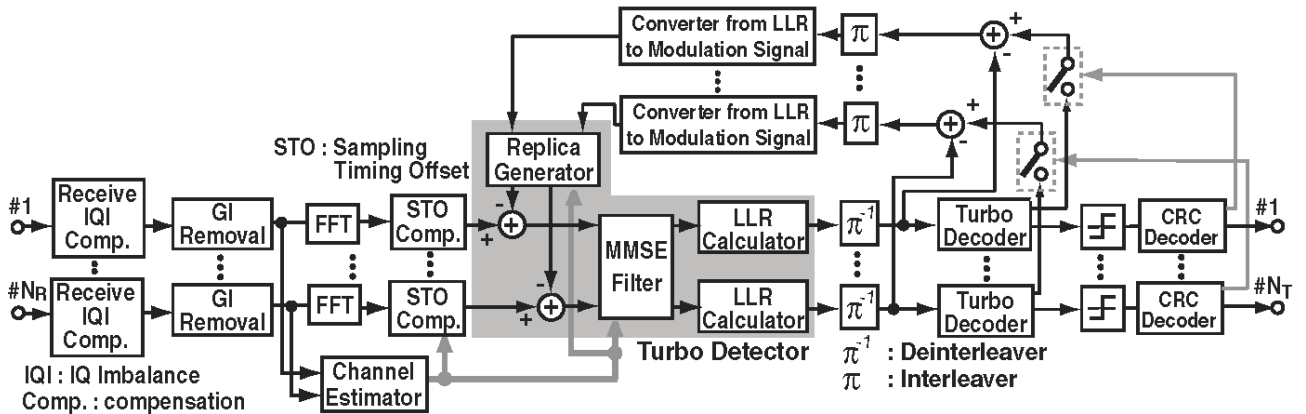
Fig. 14. MIMO-OFDM reception processing ($N_R = 16$)
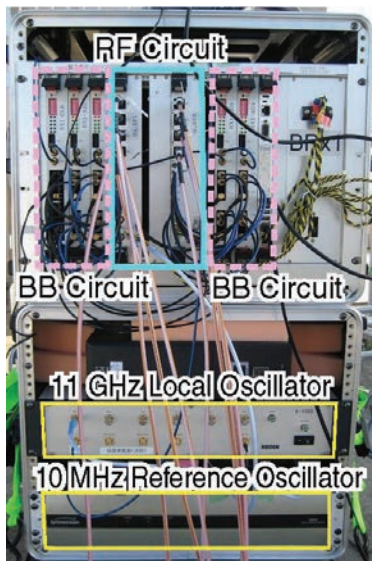
Fig.15. Rx box.
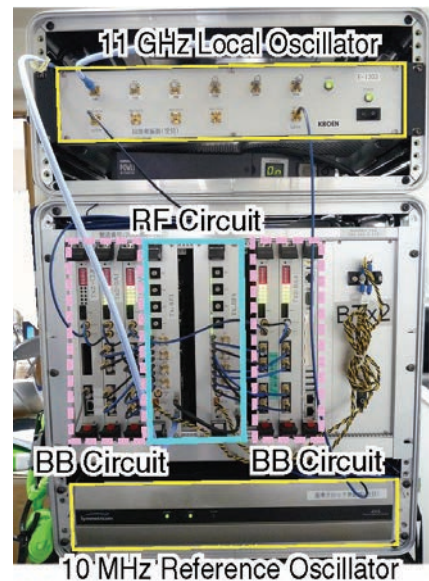
Fig.16. Tx box.

A novel experimental system for achieving 10 Gbps in 11 GHz band outdoor mobile environments including line-of-sight (LOS) propagation channels, that extends 8×8 MIMO to 8×16 MIMO and combines a high power amplifier (HPA), was developed. In addition, outdoor transmission experiments were performed in Ishigaki City in Okinawa Prefecture, Japan in December 2012. A mobile station (MS) with 8 transmitter (Tx) antennas traveled along a measurement course while a base station (BS) with 16 receiver (Rx) antennas stored the received signals, and then the throughput performance levels were evaluated by demodulating them in an off-line mode. Hardware configuration for the 11 GHz band 8×16 MIMO-OFDM experimental system is shown in **Fig.15** and **Fig.16**.

This paper shows the results of distribution of SNR, delay spread and Eigenvalues of the measured channels. It is found that the throughput performance is related to the 8th eigenvalue and that the spatial correlation among the BS antennas is high due to the small 8th eigenvalue. **Fig.17** and **Fig. 18** demonstrate that are calculated by demodulating the received signals in the off-line mode. The throughput is calculated based on the block error rate. In **Fig.17** the maximum number of iterations in the turbo detection is set to 2, and in the case of coding rate, $R = 2/3$, the peak throughput becomes 10.5 Gbps. Since $R = 2/3$ improves the error correcting capability of the turbo code, throughput of greater than 10 Gbps is stably attained. **Fig. 18** shows the throughput performance with 64QAM and $R = 3/4$. 2 iterations of turbo detection improve the throughput performance in the whole area of the measurement course. It was shown that throughput greater than 10 Gbps is achieved using 11 GHz band broadband MIMO transmission in an area where the average SNR is greater than 9.4 dB and rich multipath delayed waves are observed. It was also shown that 2 iterations of turbo detection expand the area where 10 Gbps throughput is available and that $N_R \geq 12$ achieves the throughput of 10 Gbps.
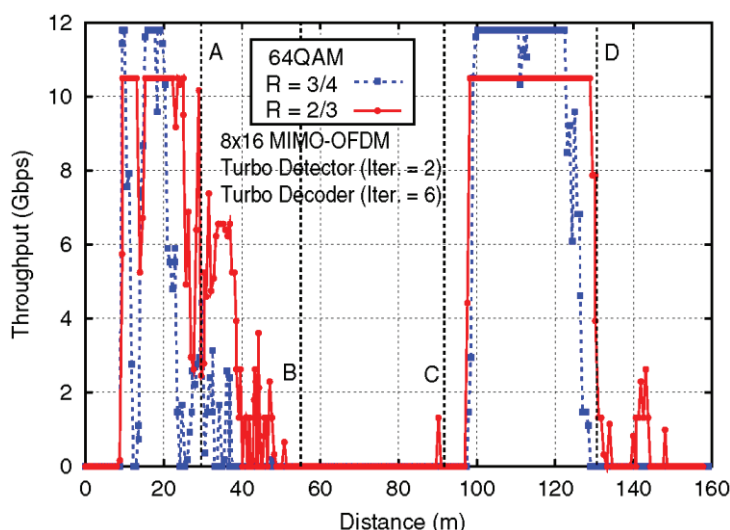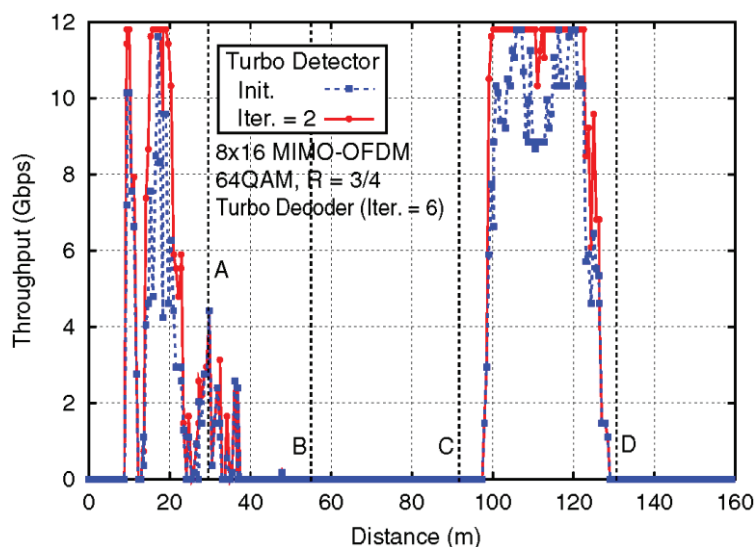

Fig. 17. Effect of coding rate on throughput performance

Fig. 18. Throughput performance with 64QAM and $R = 3/4$

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., 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 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, regulatory issues of white space and spectrum sharing, and information technology for regional/rural development. He is fellow of IEICE, senior member of IEEE, and member of JASID.

Assistant Professor Minseok Kim

Prof. Kim was born in Seoul, Republic of Korea. He received the B.S degree in Electrical Engineering from Han Yang University, Seoul, Korea, M.E and Ph.D degrees in Division of Electrical and Computer Engineering, Yokohoma National University (YNU), Japan in 1999, 2002, and 2005, respectively. He joined Tokyo Institute of Technology (Tokyo Tech) as an assistant professor from July 2007. He has been on leave to Georgia Institute of Technology as a visiting scholar in 2010. From April 2014, he joined Niigata University as an associate professor. His research interests include digital signal processor implementation, radio propagation measurement, array processing, smart antenna system, software defined radio/cognitive radio. He is a member of IEEE and IEICE.

< Takada Lab members >

- ▪ **MIMO Channel Sounding and Modeling for Super High Bit-Rate Mobile Communications**
  - ➢ Spatio-temporal channel characterization of indoor and outdoor environments [5]
  - ➢ Visualization of the propagation mechanism [24]
  - ➢ Measurement-Based Ray Tracer for Double-directional Propagation Analysis
  - ➢ Propagation Mechanisms by Comparing the Measurement Results and Ray Tracing
  - ➢ Channel parameters estimation using SAGE algorithm and cluster-based analysis [46]
- ▪ **Body Area Network (BAN)**
  - ➢ Antenna De-embedding [25]
  - ➢ Evaluation of Multi-link UWB BAN Channel [38]
  - ➢ Cooperative relaying in Narrowband BAN
- ▪ **Stochastic Modelling of Double-Directional Channel in Spherical Wave Domain [41]**
- ▪ **Radiowave Propagation through Foliage [42, 49]**
- ▪ **Interpolation of Location Fingerprint Database for Radio Localization [13, 54]**
- ▪ **MIMO Antenna Evaluation Utilizing Instant LTE Throughput Estimation [45, 53]**
- ▪ **Development of Channel Sounder using GNU Radio and USRP**
- ▪ **Propagation Characteristics of UHF Band for TV White Space [36]**

MIMO Channel Sounding and Modeling for Super High Bit-Rate Mobile Communication Systems

(This work was supported by The Ministry of Internal Affairs and Communication Japan.)

(1) Introduction (Challenge for Future Mobile Systems)

As the data traffic in future mobile services will be continuously increasing, conventional cellular networks covering large cell area cannot be expected to provide sufficient capacity and satisfactory data rates due to the lack of sufficient bandwidth. Because of the serious congestion of the frequency spectrum at lower microwave bands (below 5 GHz), exploring new frequency bands above 5 GHz is an inevitable choice in the future. These higher frequency bands were previously neglected because of their high path-loss with distance, deep shadowing due to weak diffraction, and higher Doppler frequency. However, the radio propagation properties at higher frequency bands have not been sufficiently justified from the view point of the requirements for current mobile data transmission. In fact, 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.

This work aims at the fundamental studies of radio propagation properties of high frequency bands of 11 and 60 GHz with bandwidth of 400 MHz. We developed a fully parallel MIMO channel sounder, and the various measurement campaigns have been conducted. Currently, the spatio-temporal channel properties of various indoor small cell/urban cellular environments are being analyzed.

(2) Path Loss Characteristics of Indoor/Outdoor Environments [5]

The channel measurements were conducted in various indoor environments at Tokyo Tech including the non-line-of-sight (NLoS) (corridor-room; Room A and B) and line-of-sight (LoS) (open spaces in a room and halls; Room C, Hall D and E). The omni-directional antennas were used for the transmitter (Tx) and receiver (Rx) with the height of 1.7 m. Figs 1 and 2 show the path loss versus distance for LoS and NLoS, respectively. The path-loss exponents of the co-polarization for Room A and Room B (Area1) ranged between 2.0 and 2.6. On the other hand, as shown in Fig. 2, the path-loss exponents in the LoS environments range between 0.55 and 1.5 for co-polarization. We see that the LoS path-loss has an exponent less than 2, which indicates a guiding effect of the environments. Further, the larger the area of the environment, the faster is the power fall-off with distance.
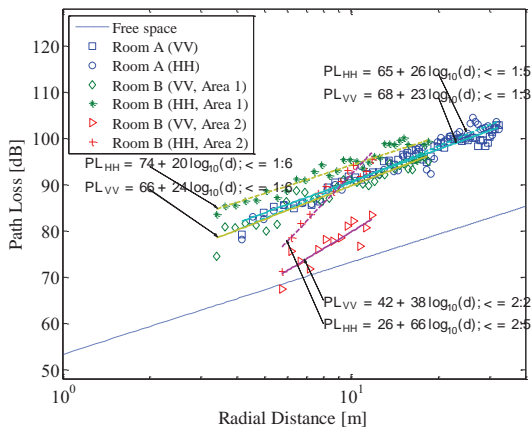

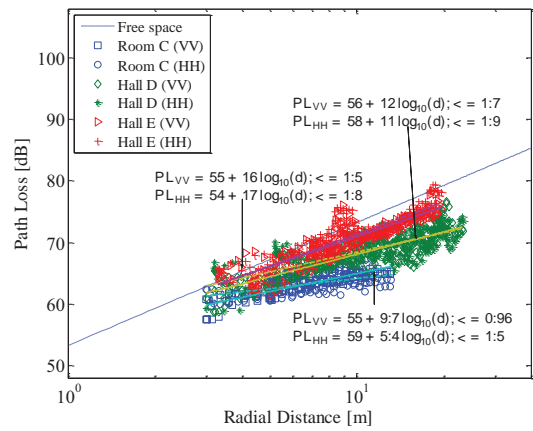**Fig. 1 Path loss: Indoor NLoS (Co-pol)**

Fig. 2 Path loss: Indoor LoS (Co-pol)

The field measurements in various urban cellular environments (macrocell/microcell/street) have been conducted in Ishigaki city, Okinawa. The measurements include the roadway, downtown and residential areas. The dual-polarized 12-element uniform circular arrays (UCA) at Tx and Rx for directional channel measurement. The Rx array was installed in the buildings as a base station (BS) with various height of 2.5 m (street cell), 9 m (microcell), or 28 m (macrocell). The Tx antenna array was installed on the top of the measurement vehicle as a mobile station (MS), and the antenna height at MS was about 2.5 m. The snapshots were taken at constant time interval while MS was moving at the velocity slower than 10 Km/h. Fig. 3 indicates the path gain on the measured area map, and Fig. 4 shows the distance dependency of the path loss, where it was obtained by polarimetric beamforming. From this results, we can see that the path gain in LoS environments well matches free space path loss, but large shadowing loss between L_f and L_f-20 dB can be found when LoS was blocked.
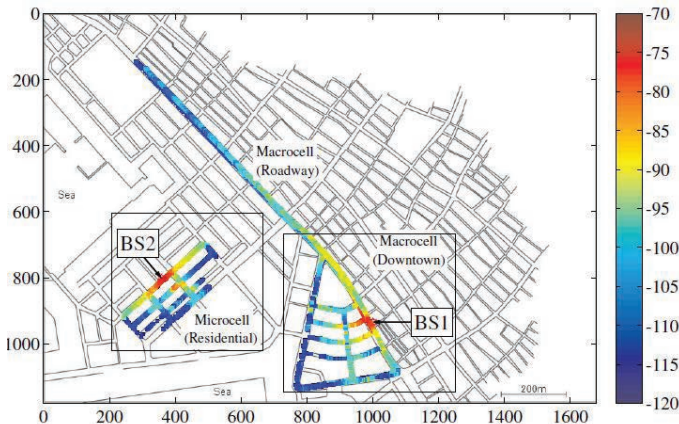

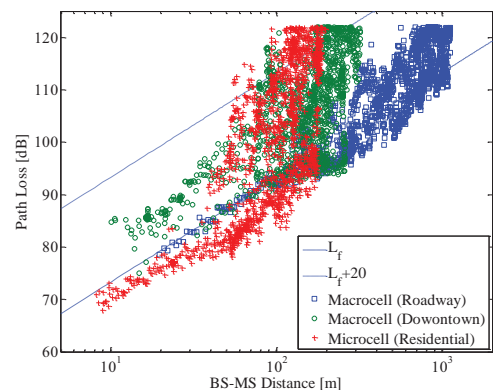
Fig. 3 The measured areas and routes.

Fig. 4 Path loss versus distance (vertical pol)

(3) Visualization of the propagation mechanism [24]

To gain better insight of the radio propagation mechanism, we have taken the point-cloud and 3-D movie clips of the measured areas using 3-D laser scanning system. By using 3-D movies, the "radiophoto" which is a visualized panoramic photo be superimposed radio parameters is created. Fig. 5 shows a radiophoto produced by the measured channel power distribution obtained from an urban macrocell environment where the simulation path are also indicated by the circles. The simulation is helpful to interpret the fundamental and dominant mechanisms. From this figure, we can easily understand that direct wave is coming from near 0 degree and the reflection wave from the backward building near -180 degree.
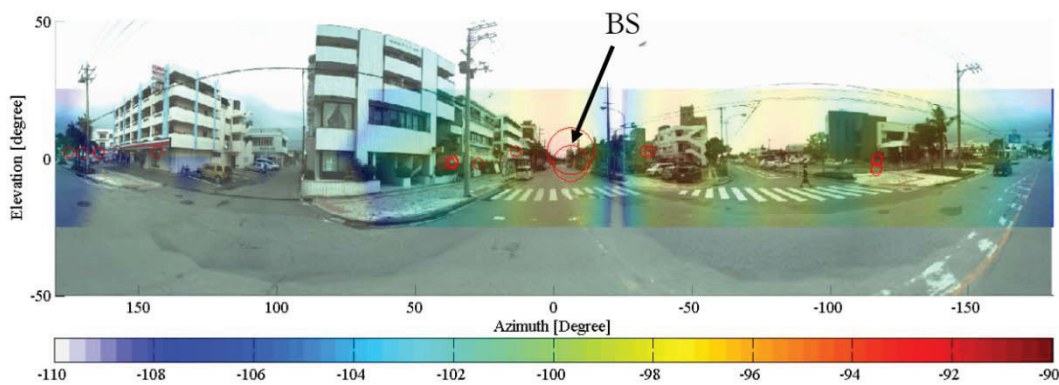

Fig. 5 Panoramic photo of measurement propagation channel and simulation paths

(4) Development of Measurement-Based Ray Tracer for Double Directional Propagation Analysis

Measurement-based ray tracer is a useful tool which predicts the radio wave propagation by using measured data as the input to the ray-tracing algorithm. The measurement path parameters are extracted by using SAGE and beamforming algorithm. This tool is considered to be also useful when analyzing complex measurement results. By inter-connecting the measurement results with the physical environment, it is possible to identify the dominant propagation paths and scattering objects of the multipath components (MPC). Each MPC contains four main parameters which are direction-of-departure (DoD), direction-of-arrival (DoA), both in azimuth and elevation plane, time delay (τ) and path gain or amplitude. Fig. 6 shows the ray tracing result at Centennial Hall (Hall E) which the path parameters are computed by using SAGE algorithm. Currently, this tool is being used to analyze common cluster and inter-link correlation between different links in multi-link COST2100 channel model which is based on Geometry based Stochastic Channel Model (GSCM).
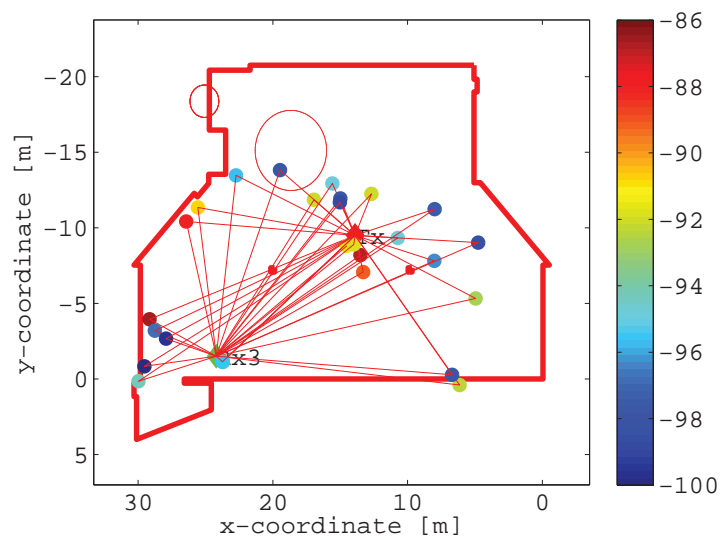

Fig. 6 Ray visualization of Centennial Hall

(5) Study of Propagation Mechanisms by Comparing the Measurement Results and Ray Tracing Simulation

In this work, we compare the large scale channel parameters such as path loss, cross- and co-polarization ratios, delay profile, and angular profile of the channel, which are calculated using the measurement results and simulation performed in corresponding environments. The measurements were conducted in some buildings in Tokyo Tech to study various kinds of indoor environments. For the simulation, corresponding building models were constructed using the CAD tools which were then used to calculate the field in the Ray Tracing Simulator. RapLab is used for the ray tracing simulation which calculates the interacting points and ray paths using image theory and then computes the field at the receiver by taking into account of each propagation path and interacting material.

The output of the ray tracing simulator is the individual paths each with the path gain, delay, angle of departure, and angle of arrival. As the ray tracing results have very high resolution in angular and delay domain, direct comparison with the measurement should not be done as the measurement data resolution is limited by antenna beamwidth and system bandwidth. To make the comparison equivalent, we constructed the channel transfer function using the ray tracing results and

Fig. 7 Angular power spectra obtained from ray tracing

antenna beam pattern. Then beamforming is applied to this transfer function to get the angular power spectra and power delay profile which can be compared directly to the similarly beamformed measurement results. The study now focuses on finding the paths in the measurement which cannot be observed in the simulation and trying to incorporate these paths in the simulation for the better accuracy of simulation results.

(6) Radio channel parameters estimation using SAGE algorithm and cluster-based analysis [46]

A popular method to analyze the behavior of radio channels with high resolution and accuracy is a maximum likelihood based parameter estimation such as the Space Alternating Generalized Expectation Maximization (SAGE) algorithm.

Fig. 8 shows the SAGE detected-paths and the panorama view from the receiver side. We applied an automatic clustering algorithm to each estimated path. The concept of this algorithm is minimizing the total sum of the distance of the paths to their cluster's centroid. After this, the cluster-based statistical channel characterization is performed.

Fig. 8 Cluster Identification using SAGE estimation results

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

Introduction

Body area networks (BAN) is a network of sensors or actuators in the vicinity of (on-body and off-body) or inside a human body. There is an enormous potential for application of BAN in health care, sports, security, military, business and multimedia entertainment among others. A 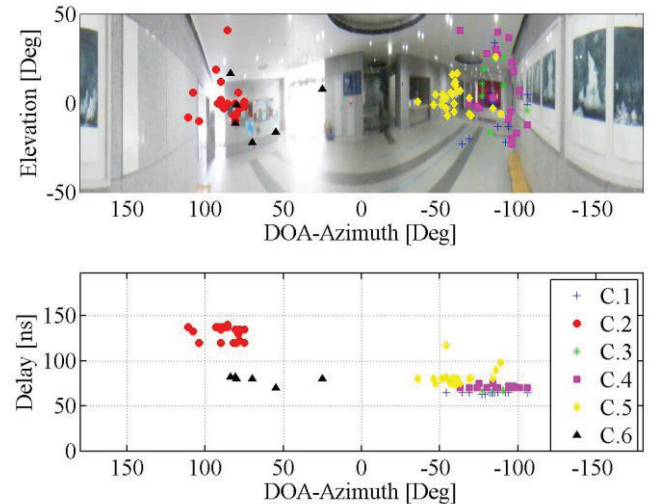BAN needs to be highly energy efficient but compact. It must be robust against severe channel fading conditions arising due to body and body motion as well as due to multi-paths from surround environment and interference from other systems, while at the same time transmitting at low power to keep electromagnetic radiation into the body below a safe limit. In this context, we are working on the radio propagation for on-body channels to get useful insights for BAN designs.
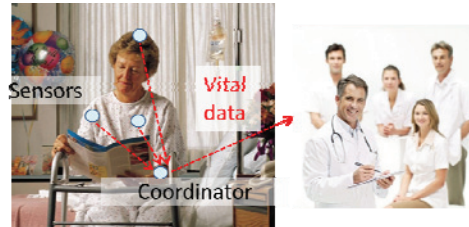

Fig. 9 BAN application example: wireless vital sensor data monitoring for health-care
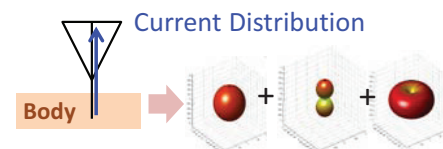
(1) Antenna De-embedding [25]

Spherical Wave Function and the FDTD Method

Due to the coupling of antennas and a human body, antenna-independent channel characterization has not been achieved in BAN context yet. To address this issue, an antenna de-embedding approach using spherical wave function and the finite-difference time-domain (FDTD) method has been proposed. The radiation and reception properties of the antenna are modeled by the finite spherical wave coefficients obtained from the current distribution on the human body. The propagation channel is modeled by the mode-to-mode mapping matrix between the radiated wave and the incoming wave. The proposed approach has been initially validated for the antennas far from the body. The FDTD simulator using GPGPU has been also developed.

(a) Antenna modeled by the summation of spherical waves
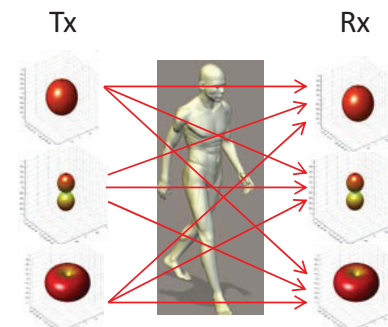
(b) Propagation channel modeled by the mode-to-mode mapping

Fig. 10 Antenna de-embedding approach using spherical waves

2D study near scattering object

2D antenna de-embedding is also studied for examining the effect of nearby scattering objects. In this study, 2D spherical wave expansion and the boundary element method (BEM) were utilized. Mode-to-mode mapping matrix has been derived from the relationship between observation point around transmitter and receiver and a mixed mode wave as the source.

Fig. 11 FDTD simulation during the walking motion

Fig. 12 BEM simulation with the human body modeled by a cylinder

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(2) Evaluation of Multi-link UWB BAN Channel [38]

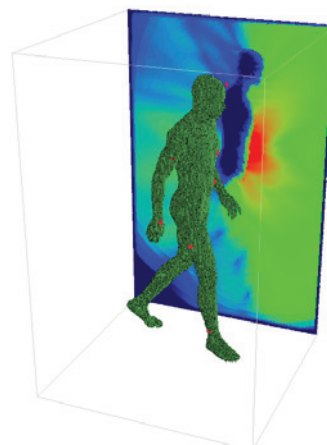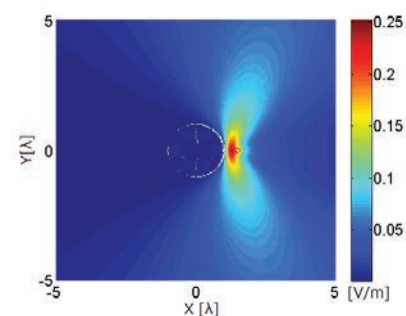In IEEE 802.15.6 standard, ultra-wide-band (UWB) technology is adopted in the wide band PHY specification to enable high data rate transmissions with very low transmitting power. For improving the reliability of UWB systems, rake reception and antenna diversity can be taken into acccount. When deploying such a multi-link system, antennas should be positioned optimally to achieve the best performance. We measured the channel responses for the case when the coordinator has multiple antennas located on the waist belt. The transmit nodes were located on other parts of the body, Fig. 14 shows one such case. From the measurement results, we compared the effect of rake reception and antenna diversity at each position using the outage probability as a performance metric.

Fig. 13 Measurement
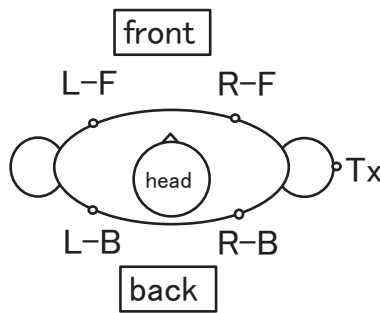
Fig. 14 Antenna position
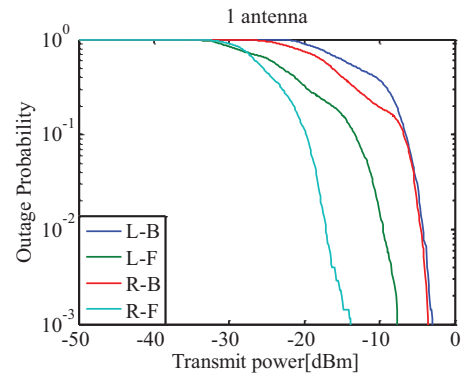
Fig. 15 Outage probability

(3) Cooperative relaying in Narrowband BAN
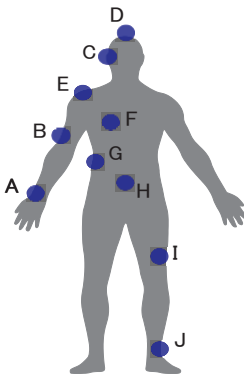
Fig. 16 Node location

The slow fading and quasi-static nature of on-body BAN channels means it could suffer from burst errors that are difficult to be corrected with simple error correcting codes. In addition to difficult channel fading conditions narrow-band BANs operating at the ISM bands are also highly susceptible to interference from other wireless systems operating in this band making it highly unreliable.

Cooperative relaying can be a practical solution address this issue. Cooperative relaying is expected to improve the outage performance for the same transmit power or decrease the required transmit power to achieve the same outage performance. We evaluated performance gains due to simple decode-and-forward (DF) relaying and incremental decode-and-forward (I-DF) relaying with selection combining (SC) at the coordinator node (H in Fig. 16). The performance gains at 10% outage probability with best cooperator is shown in Fig. 17. The best cooperator selected based on channel statistics is also shown to the right. We found that the gains in I-DF were mainly due to path-loss gains due to relaying and not due to diversity combining. With carefully chosen cooperator location up-to 14 dB performance gains can be had with I-DF as opposed to 12 dB for DF.
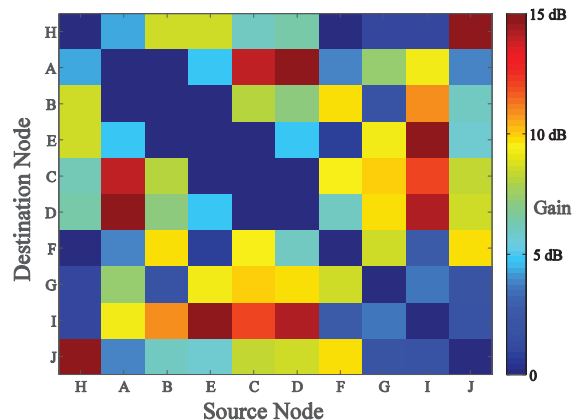
Fig. 17   I-DF Relaying gain with best cooperator

Stochastic Modelling of Double-Directional Channel in Spherical Domain [41, 47]

The double-directional channel (DDC) is introduced to de-embed antennas from both ends of MIMO system and to study the propagation phenomenon itself. DDC model in plane wave domain (PWD) is popular and intuitive to describe the propagation as paths, but its limitation in diffuse scattering makes it unable to perform antenna de-embedding. Alternatively, DDC model in spherical wave domain (SWD) is intuitive for antenna de-embedding since the antenna input in SWD is simply the expansion coefficients of antenna radiation pattern. Also, it is antenna-friendly because the truncation of channel can be directly determined by antenna size. The major contributions of this study are as follows:

1. Statistical parameters of DDC in SWD are investigated by using the channel model parameters in PWD, based on the explicit relationship of model in SWD and the generating model in PWD.
2. To avoid the use of channel model parameters in PWD and to enable the modelling in sheer SWD, a stochastic modelling of DDC in SWD is proposed according to analyzed statistical characteristics.
3. To support the proposed modelling, appropriate array configurations for antenna de-embedding and antenna-channel recombination are discussed.

This research enables the performance estimation and evaluation of different antennas in certain propagation environment.

Radiowave Propagation through Foliage [42, 49]

The propagation of radiowaves is largely dependent on the types of obstacles that are present in the propagation medium. One type of obstacle that is predominant in rural environments, which may also be present in urban and sub-urban environments are foliage obstacles. These foliage obstacles, made up of leaves, branches, and trunks, interact with propagating radiowaves, which may degrade the performance of wireless communication systems operating in such environments. Proper understanding of the effects of these foliage obstacles in the propagation medium is needed to ensure the performance of these wireless systems.
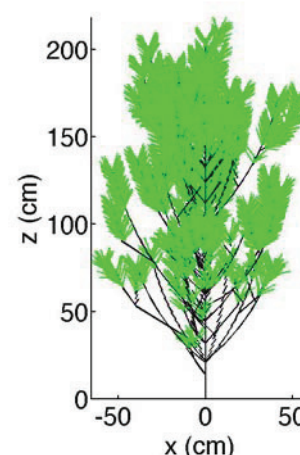
Fig. 18 Simplified tree geometry

In this research, the foliage elements are approximated as simplified geometries, such as thin dielectric disks and cylinders for the leaves and branches. From these simplified structures, the Generalized Rayleigh Gans approximation is used to determine the scattered fields from these foliage elements. From these scattered fields, relevant scattering parameters may be extracted for use with random medium propagation models.

Fig. 19 Scattered electric field from simplified tree structure

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MIMO Antenna Evaluation Utilizing Instant LTE Throughput Estimation [45, 53]

(Joint research with SOKEN Inc,.)

Recently, a research to estimate throughput for MIMO antenna evaluation is very active, such as MIMO-OTA testing. However, most of throughput estimation methods are costly and time consuming, therefore there is a demand for a simple evaluation method.

In this research, we propose that an LTE throughput vs. MIMO channel eigenvalues map is generated in advance using an LTE software simulator as Fig. 20, and LTE throughput is estimated simply by referring to the map from eigenvalues in almost the same manner as the channel capacity estimation. The big advantage of the proposed method is that once the map is created, we do not have to use LTE simulator which needs a long simulation time. Actually, if the map is published, it is possible to estimate LTE throughput without using LTE simulator.
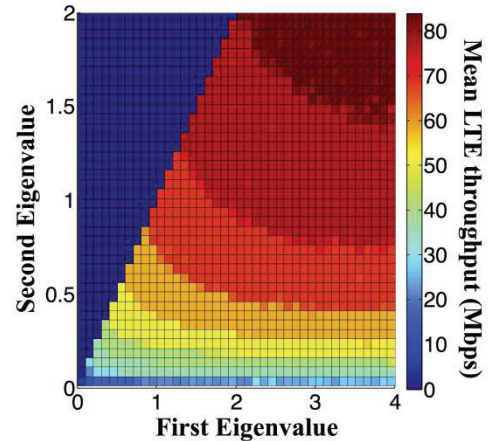
Fig. 20 LTE throughput vs. Eigenvalues Map

Interpolation of Location Fingerprint Database for Radio Localization [13, 54]

Techniques such as triangulation and trilateration have been used along with RSSI, TDOA etc. for localization in outdoor scenarios. However in densely urban areas where many obstacles exist, multipaths are dominant, resulting in the above techniques to be unreliable. Fingerprint-based localization may prove to be advantageous in these scenarios.

In this research, we focus on utilizing RSSI and also the channel impulse response (CIR)

Fig. 21 Comparison between spatial interpolation of RSSI values using various algorithms

as collected from as many locations and frequency bands as possible, but this is not feasible due to time and space constraints. One approach to solve this problem is to perform interpolation on the measured fingerprints along the spectral and spatial domains to estimate the fingerprints at an arbitrary frequency band and location.

In this research, we propose to utilize log-linear regression on each delay tap of the CIR for frequency interpolation. Furthermore, we propose to use a popular geostatistical technique called Ordinary Kriging (OK), which exploits the spatial correlation, for spatial interpolation. Preliminary results utilizing RSSI values obtained from ray-tracing simulation confirmed that OK may result in more accurate interpolated values compared to other commonly used interpolation algorithms.

Development of Channel Sounder using GNU Radio and USRP

Channel impulse response (CIR) measurement is important for communication system design, but it is restricted by large cost and workload. Therefore, we developed a channel sounding system using very low cost hardware (USRPs) and free-software (GNU Radio). USRP, from Ettus Research is a reconfigurable hardware peripheral that provides a general purpose radio with high variety of RF board at various frequency bands (400~4400MHz). In the developed system, the multitone signal with the bandwidth of 25MHz is used. We tested the channel sounder system with a DUT (T-junction circuit). Fig. 22 shows the appearance of USRP (N200) transceiver and the Table 1 shows the parameters of the channel sounder. The transmit power is 20 dBm and the dynamic range (DR) is approximately 83dB.

Table 1 Specification of channel sounder

RF frequency Range	400-4400 MHz
ADC sample rate	100 MSa/s
Transmit signal	Multitone signal (256 Tones)
Length of signal packet	25 MS
Sample rate	25 MSps
Bandwidth	25 MSps
Center frequency	2.4GHz
Sync reference signal	Rb atomic clock (10MHz)
Delay Resolution	40ns
Transmitted power	20 dBm

Fig. 22 USRP (N200)

Propagation Characteristics of UHF Band for TV White Space [36]

(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 TV band, such as TV broadcasting systems. In order to accurately estimate the interference area, propagation channel model for the SU is required. The conventional propagation channel model in UHF band was created under assumptions of high base station antenna height and long propagation distances. Therefore, it does not match the operating conditions of SU in TVWS, where both antenna height and propagation distance are smaller. In this work, we conduct outdoor channel measurements using low height antenna and compare the results with the conventional channel model. As a result, we found that the measurement results under LOS and NLOS are consistent with the ITU-R P.1411 model and the extended Okumura-Hata model respectively.

Fig. 23 Propagation loss versus distance. (Measurements)

CONTRIBUTIONS

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Transactions and Letters

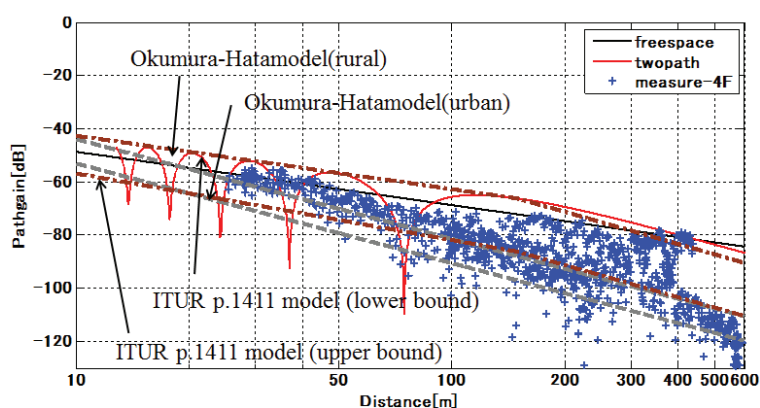[1] Kei Obara, Takayuki Inoue, Gia Khanh Tran, Kiyomichi Araki. ICI reduction technique by split OFDM, IEICE Communications Express, Vol. 2, No. 4, pp. 154-160, Apr. 2013.

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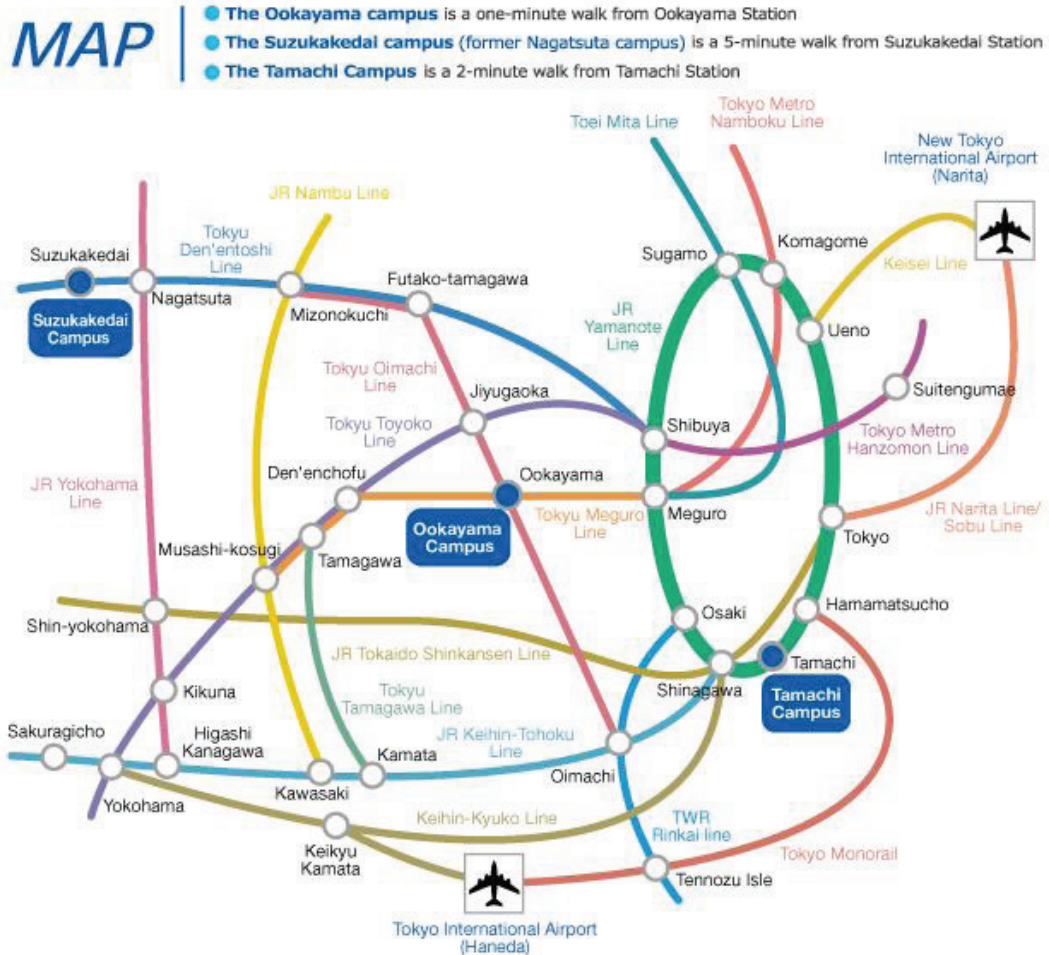
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