Mobile Communications Research Group
Tokyo Institute of Technology

2009 Annual Report

MCRG Tokyo Tech

Contents

TOKYO INSTITUTE OF TECHNOLOGY

Leading the world in science and technology, Tokyo Institute of Technology continues to evolve.

Tokyo Institute of Technology, or Tokyo Tech in short, was founded by the Japanese Government, Department of Education, as the Tokyo Vocatioanl Shool in 1881, and then renamed Tokyo Kogyo Daigaku (Tokyo Institute of Technology), in 1929. Following a brilliant history and tradition spanning over 126 years, Tokyo Institute of Technology continues to evolve as one of the world leading science and technology universities of the 21st century.

To be recognized as one of the world-class science and technology universities, Tokyo Tech fosters world-class graduates, develops new frontiers of world-class knowledge, and benefit society through transfer of knowledge by having:

- Three Undergraduate Schools: School of Science, School of Engineering, School of Bioscience and Biotechnology
- Graduate Schools: Graduate School of Science and Engineering, Graduate School of Bioscience and Biotechnology, Interdisciplinary Graduate School of Science and Engineering, Graduate School of Information Science and Engineering, Graduate School of Decision Science and Technology, and Graduate School of Innovation Management.
- Other Research Laboratories.

Tokyo Tech is committed to the following missions:

1. Producing world-class graduates
2. Creating world-class knowledge
3. Contributing to society through the utilization of knowledge

Tokyo Tech seeks to maintain the highest standard in its every mission.

(Information resources:http://www.titech.ac.jp/ and 2006 profile of Tokyo Institute of Technology.)

Tokyo Tech Logo

The logo 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 new strategic catchphrase with this logo in 2007. This strong message expresses our philosophy which is directed towards enhancing and strengthening our international reputation.

School Color

In 2004, Tokyo Tech resolved that its school color would be royal blue, the color that stands for advancement and evolution.

Mobile Communications 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
(Staff: Prof. Hiroshi Suzuki, Associate Prof. Kazuhiko Fukawa, and Assistant Prof. Satoshi Suyama)
2. System laboratory
(Staff: Prof. Kiyomichi Araki, and Associate Prof. Kei Sakaguchi)
3. Propagation and Antenna laboratory
(Staff: 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 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 our 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.

MCRG members

In the 2009 Open House, five invited lectures were held and we would like to take this opportunity to express our thanks and appreciation to Prof. Hiroyuki MORIKAWA of University of Tokyo, Mr. Motoya IWASAKI of NEC, Dr. Sean CAI of ZTE, Dr. Osamu KAGAMI of NTT, and Prof. Akira MATSUZAWA of Tokyo Tech for their valuable contributions to the Open House.

Visit our website at http://www.mcrg.ee.titech.ac.jp/

Laboratory Introduction
&
Annual Report 2009

TAKADA LABORATORY

Professor Jun-ichi TAKADA

was born in Tokyo, Japan, in 1964. He received the B.E., M.E., an D.E. degrees from the 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 the 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. He is currently the co-chair of Special Interest Group on Body Communications in European COST Action 2100 "Pervasive Mobile & Ambient Wireless Communications," and assistant secretary of URSI Japan National Committee. His current research interests are wireless propagation and channel modeling, cognitive radio, and application of wireless communication and information technology for regional/rural development. He is a member of IEEE, IEICE, ACES, ECTI Association Thailand, JASID.

Assistant Professor Minseok Kim

was born in Seoul, Republic of Korea. He received the B.S degree in Electrical Engineering from Hanyang University, Seoul, Korea, M.E. and Ph.D. degrees in Division of Electrical and Computer Engineering, Yokohama National University (YNU), Japan in 1999, 2002, and 2005, respectively. He was with a startup company from 2005 and has experienced H/W and S/W development of various embedded systems. He was also with YNU as a postdoctoral research fellow shortly in 2006. He joined Tokyo Institute of Technology (Tokyo Tech) as an assistant professor from July 2007. His research interests include digital signal processor implementation, radio propagation measurement, array processing, smart antenna system, software defined radio/cognitive radio. Now he is most active in Body Area Network (BAN) channel modeling and spectrum sensing for cognitive radio networks. He is a member of IEEE and IEICE.

Assistant Professor Mir Ghoraishi

received his BSc. from Isfahan University of Technology, Esfahan, Iran, and his MSc. from Amirkabir University of Technology, Tehran, Iran, both in electrical engineering in 1993 and 1999 respectively. From 1993 to 1996 he worked for a hardware company as a service engineer and in 1999 started working as a research engineer in a major Telecom company but he soon received the admission for the PhD course from Tokyo Institute of Technology. From 1999 he is with the Tokyo Institute of Technology where after getting the PhD degree he was a senior researcher and then assistant professor from April 2009. From December 2009 his work is dedicated to the "Research and Development Project for Expansion of Radio Spectrum Resources" of the Ministry of Internal Affairs and Communications, Japan, where he is responsible for the wireless channel analysis. His research interests are radio channel analysis and modeling, array signal processing, parameter estimation, positioning and tracking of wireless nodes and objects and adaptive and statistical signal processing. He has been an active member of the European Cooperation in Science and Technology, COST Action 273, and is representing Tokyo Tech in COST Action 2100. He is a member of IEEE, IEICE and EURASIP.

Members of Takada Laboratory

TAKADA LABORATORY

Recent Research Topics

- **Mobile Communication Systems**
  - Channel Sounder Architecture for Microwave Broadband Mobile Communication Systems
  - Experimental Analysis and Modeling of Dual-Polarized MIMO Channel [29][31]
  - MIMO Channel Analysis for Outdoor Mricro Cell System at 3 Ghz-Band [32]
  - Analysis of the Radio Channel in Interaction to Vegetation [16]
- **Body Area Network (BAN)**
  - Dynamic Channel Model for 4.5-Ghz On Body Propagation With Specific Actions [14][15]
  - Channel Measurement using Network Analyzer in UHF band [47]
  - Observation of Physical Mechanism of On-Body Channel Fluctuation [26]
  - Motion Analysis of On-body Antennas for BAN Channel Modeling
- **Specific Wireless Systems**
  - Application of Reflection on Curved Surfaced and Roughness on Surface in Ray Tracking in Tunnel Propagation[66][69]
  - Double-Directional Channel Modeling using Spherical Harmonics

Channel Characterization and Modeling for Wireless Communication Systems

Fig1BAN Channel Measurement

Cognitive Radio Systems and Networks

- Radio Spectrum Management System for Emergency Radios in Post Disaster Scenario [62]
- Spectrum Sensing Techniques [28]
- Prototype Implementation with Open Source Software Defined Radio Platform using GNU radio and USRP (universal software radio peripherals) [44][65]

Measurement and Signal Processing

- UWB Ranging [30]
- Remote Sensing of Heartbeat using Microwave
- Evaluation of EMC Semi Anechoic Chamber [61]
- Channel Estimation in MIMO Antenna Selection Systems [5]

Fig2. GNU Radio/USRP

ICT Applications for International Development

- ICT application for sustainable development of world heritage site of Luang Prabang, Lao PDR [38][10]
- ICT Applications for teacher training in rural schools of Mongolia

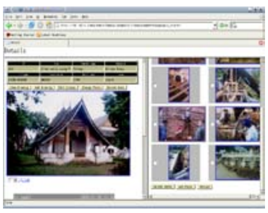


Fig.3 Heritage database

Fig.4 Local ICT center

Fig.5 VCD teacher training

Channel Sounder Architecture for Microwave Broadband Mobile Communication Systems

[This work is supported by "The research and development project for expansion of radio spectrum resources" of The Ministry of Internal Affairs and Communications, Japan.]

The ultimate goal of this project is to investigate the future broadband mobile communication system operating at microwave frequency. The project team consists of NTT DOCOMO, Tohoku University and Tokyo Tech. Takada Lab is responsible for the measurement and analysis of the propagation channel. For this purpose Takada Lab has been developing a channel sounder utilizing the software radio architecture, which is developed in Suzuki-Fukawa Lab, and array antennas.

The operating frequency is 11 GHz with a bandwidth of 400 MHz for the transmitter multitone signal. The channel sounder under development is operating with full MIMO in which each antenna is connected to individual transmitter or receiver module as is illustrated in Fig.6 below. This is in contrast with most existing channel sounders in which a single RF unit is shared in consecutive time-slots. The new sounder has a modular configuration. One transmitter or receiver unit consists of 4 to 8 RF ports, and multiple units can cooperate to one another in a scalable manner.

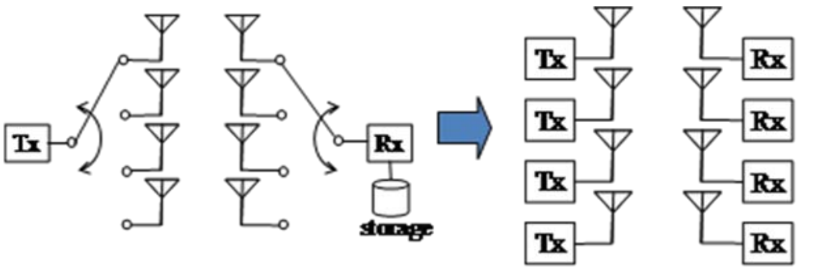


Fig.6 MIMO Channel Sounder Structure

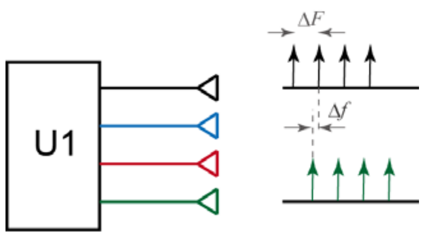


Fig.7 FDM Sounding Scheme

Reference local signal is either shared among the units or generated by atomic oscillator for the synchronization. Clock timing and RF phase are calibrated whenever the unit is turned on. The first prototype consisting one transmitter unit and one receiver unit with each unit consisted of four RF ports. Before the over-the-air test utilizing dual-polarized antennas, baseband, RF and array antenna calibrations will be required. By the year of 2012, 24 × 24 MIMO software radio channel sounder is planned to be ready, and the field measurements in microcell and picocell are planned.

The proposed sounder utilizes frequency-division multiplexing (FDM) among the channels within a unit and time-division multiplexing (TDM) among the units. One TDM symbol consists of multitone signal with the length equal to inverse of the FDM tone separation and its cyclic prefix with the length longer than the maximum delay spread. This signal format is advantages over full FDM in the scalable format with respect to the change of the number of receiver units. It is noted that switching of the weights of all the transmitter units instead of just switching among the units is advantageous in TDM to increase the total transmission power proportional to the number of the units.

TAKADA LABORATORY

Body Area Network Channel Measurement and Modeling

Introduction

As response to the great interests among researchers to body area network (BAN) and high demands of this candidate technology especially in medical health-care, IEEE 802.15.6 working group has been established for BAN standardization. From the beginning, we have studied a statistical channel model at 4.5 GHz for dynamic scenarios [14, 15], and it has been approved as a standard reference channel model[*]. In channel models proposed so far, the effects of the body which is a most significant difference between the BAN and general wireless systems were characterized deterministically or stochastically. However, the models highly depend on the measurement condition, especially antenna. Hence it should be required to improve the flexibility of the model implementation as well as its accuracy and reliability. Our research aims at developing more flexible BAN channel model by antenna de-embedding and channel decompositions.

Decomposition of Antenna Effect from BAN Channels

Since some aspects of BAN channel were not characterized individually in the current standard model, this research tried to decompose those aspects by some approaches. Our initial results were presented the radiation pattern of on-body antenna at various body locations and effect of the antenna distance from the body surface, frequency and test subject dependencies. Further the effect of antenna rotation in the dynamic BAN was tried to be characterized by employing two-antenna holder with the result as shown in Fig. 8. More advanced study of on-body antenna movement was conducted by a set of motion capture equipment (Fig. 9). Now, we are challenging to model the effect of the body motion including the transmission distance, antenna rotation, and velocity to the BAN channel. The study will also be enhanced by using electromagnetic simulation tools.

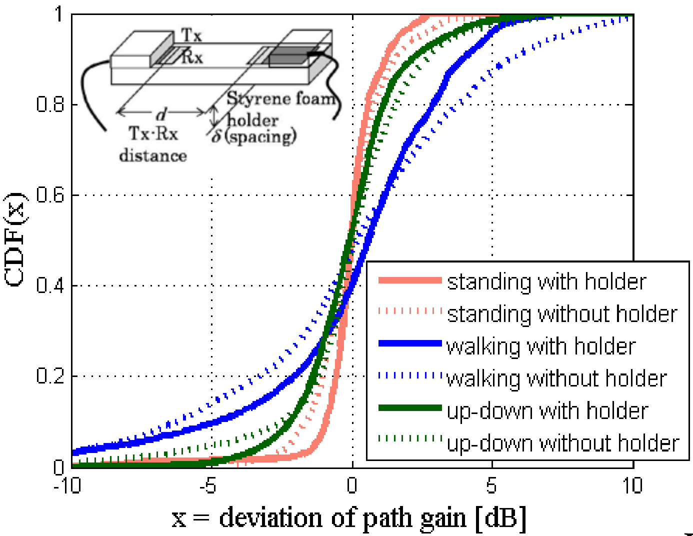


Fig. 8 Effect of antenna rotation was decomposed by two-antenna holder.

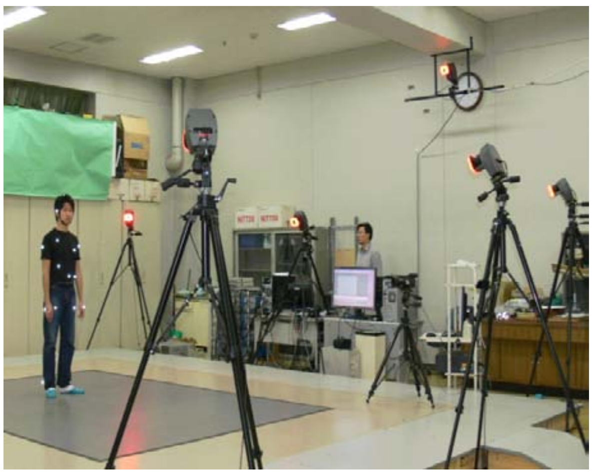


Fig. 9 Measurement of on-body channel fading with motion capture equipment.

[*] M. KIM, etal., IEEE P802.15-08-0489-01-0006, Sept. 2008.

Smart Radio Challenge 2009: Radio Spectrum Management System for Emergency Radios in Post Disaster Scenario

Introduction

Smart Radio Challenge (www.radiochallenge.org) is a worldwide competition organized by Wireless Innovation forum (SDR Forum Version 2.0). In the 2009 challenge seven teams including a team from Takada Laboratory (Tokyo Tech) have been qualified for the final competition.

After a disaster like earthquake/ terrorist attacks in a metropolitan area, rescue operations must be quick and collaborative. Rescue teams setup their own emergency networks urgently. It is quite impossible to manually adjust the wireless channels inside the whole disaster area. A spectrum sensing network that detects the location and frequency of active emergency radios in the disaster area can help to avoid the interference among the rescue teams.

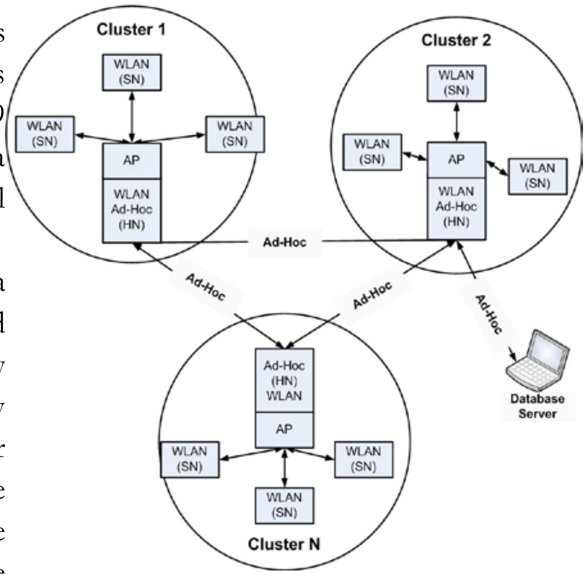


Fig.10 Cluster based Sensor Networks

System Architecture

The System consists of five subsystems. 1) **Spectrum Sensing**, 2) **Modulation Recognition**, 3) **Geo-location**, 4) **Emitter Identification** and 5) **Database maintenance.** All these subsystems are individual research topic carried out by some of the members of Takada Laboratory. Integration of these subsystems is the final outcome of the research [62].

Following figures 11 and 12 show the performance of the Spectrum sensing using the USRP and GNU radio. Performances of both hard and soft cooperation have been tested for three USRP spectrum sensors.

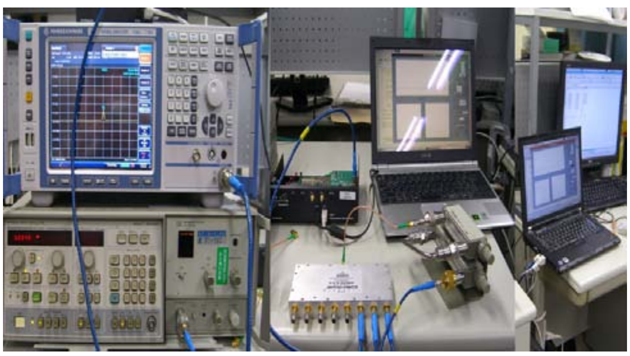


Fig.11 Spectrum sensing system setup

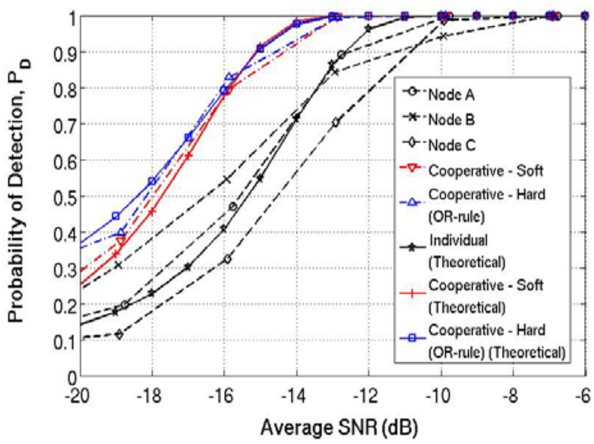


Fig.12 Spectrum sensing system performance

TAKADA LABORATORY

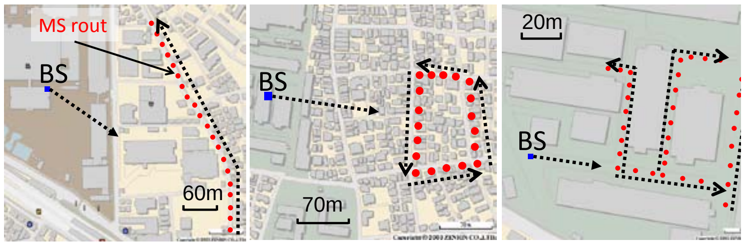
Experimental Analysis and Modeling of Dual-Polarized MIMO Channel

Introduction

The Dual-polarized MIMO system is considered as a solution for the issue of MIMO system: increase of equipment size. However, how the transmitted polarized waves rotate through the channel is not yet thoroughly explored. The aim of this study is to clearly answer the following questions, based on the measurements in three different environments [29].

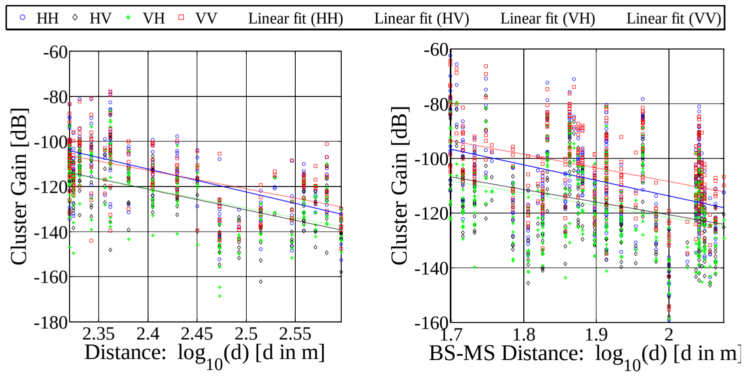
- Do the different polarization pairs suffer same path loss?

- What are the causal factors of depolarization in the environment?



(a) Kawasaki (b) Tokyo (c) Titech campu

Fig. 13 Measurement scenarios



(a) Kawasaki, macrocell (b) Campus, microcell

Fig. 14 Cluster gain vs. BS-MS distance

Channel Measurements

Measurements were conducted in three different scenarios (two macrocell and one microcell scenario).

Results and Discussion

Microcell scenario

The power of horizontal transmission falls off faster than vertical transmission. This is due to the reflection from vertical building walls. Since the building canyon propagation is only the significant mechanism, the results are easy to understand from the theory.

Macrocell scenario

The decay factors of horizontal and vertical transmissions are almost same. The dominant propagation mechanisms are considered as over-rooftop diffraction and reflection from houses' walls. But the results do not much with this theory. The results imply that there are unknown but influential propagation mechanisms. Indeed, the powers from above and below the horizon are clearly different.

Conclusion

This study focuses on understanding the depolarization mechanisms thorough the channel. The comparative analysis from three different scenarios indicated the existence of unknown but influential propagation mechanisms in the small urban Macrocell environment.

Modeling of Reflection on Curved Surface and Rough Surface in Ray Tracing for Tunnel Propagation Prediction

In ray tracing simulations, it is difficult to handle curved surfaces and edges. The approximation by dividing the curved surface into smaller flat plates is not so accurate if the size of smaller plates may not satisfy geometrical optics assumption, and the reflection point which satisfies Fermat's principle may not exist.

In this work, a new ray tracing method which models the reflection on the curved surface was implemented. Path gain simulation results are then compared with measurements made inside an arched tunnel. Next, the effect of rough surface is introduced in the ray tracing simulation, and simulation results are compared with measurement data.

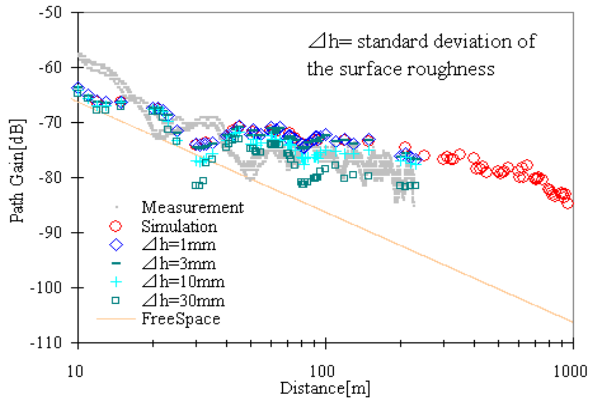
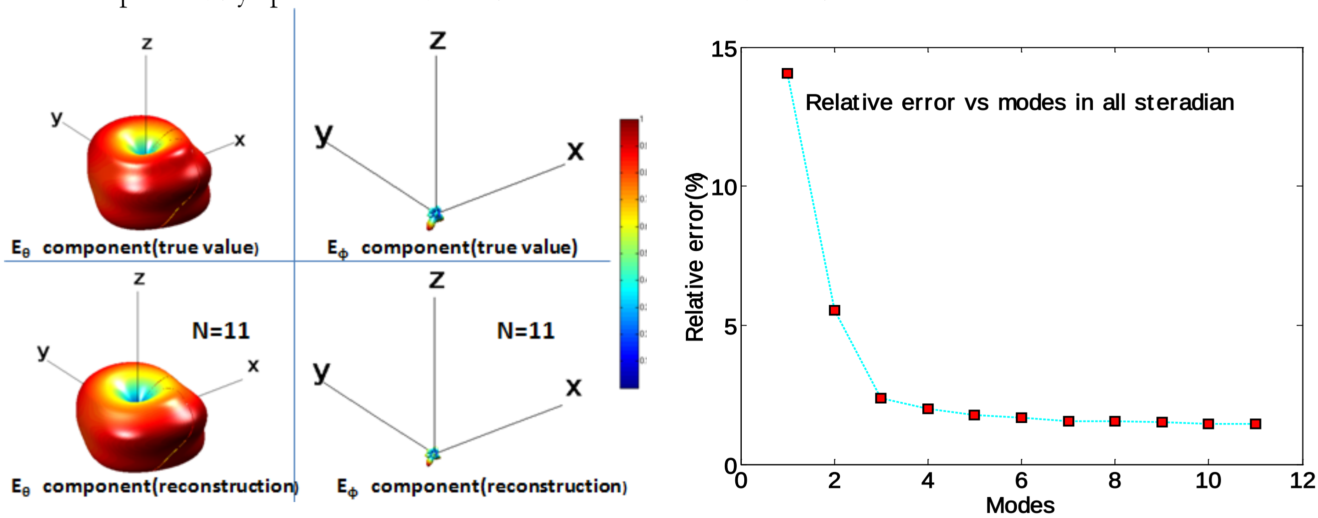


Fig.15 Path gain results with the rough surface.

Double-directional channel model making use of spherical harmonics

In double-directional channel model, transmitting and receiving antennas, which are the parts of communication devices, can be de-embeded from wireless channel for antenna-independent propagation model. Conventionally, this modeling has been expressed as the superposition of plane waves around the antennas. However, the plane wave modeling is not always valid due to diffuse scattering, proximity of scatterer etc. This study investigates an alternative model expressed as finite sums of spherical harmonics at both antennas. Figure 16 shows an example of antenna radiation pattern vs number of spherical harmonics. In the similar manner, we are going to model the multipath channel expressed by spherical modes at both transmitter and receiver antennas.



(a) (b)

Fig.16 (a) Comparison the measured and reconstructed pattern at the number of a mode, (b) Relative Error VS N for measurement

TAKADA LABORATORY

Measured MIMO Channel Capacity in Outdoor Macro Cell at 3 GHz-Band

This study investigates the outdoor MIMO channel characteristics through the measurement using a 2×2 MIMO channel sounding system at the center frequency of 3.35 GHz in urban environment [32]. In this measurement system, the 9-stage PN signals are transmitted by controlling the transmission timing in each transmitter, and hence, the complex MIMO channel impulse responses can be obtained in spite of using same PN sequence in the receiver Fig. 17. From the measured MIMO channel matrix, we computed the channel capacity via singular value decomposition (SVD). The channel capacities are compared for line-of-sight (LOS) and non-line-of-sight (NLOS) environments, as well as for different antenna separation.

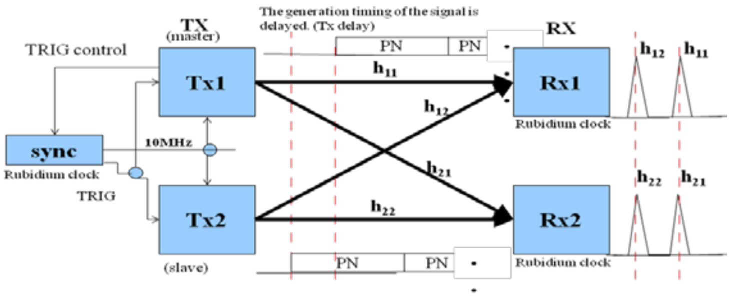


Fig.17 TDM MIMO channel sounder using PN sequence

Analysis of the Radio Channel in Interaction to Vegetation

(Joint Research with NTT DOCOMO)

This project aims at modeling the interaction of vegetation with the radio channel, specifically looks into *dispersive effects* of this interaction. We have accomplished a channel sounding campaign with a MIMO-OFDM channel sounder at 2.2 GHz in a densely vegetated area. Primary results indicate the radio waves penetrate well into the vegetation but the penetrated path is dispersed in space [16]. The dispersion of the received radio waves in azimuth as well as in the delay is analyzed by computing the mean and standard deviation of the azimuth-of-arrival and excess-delay in several transmitter antenna heights.

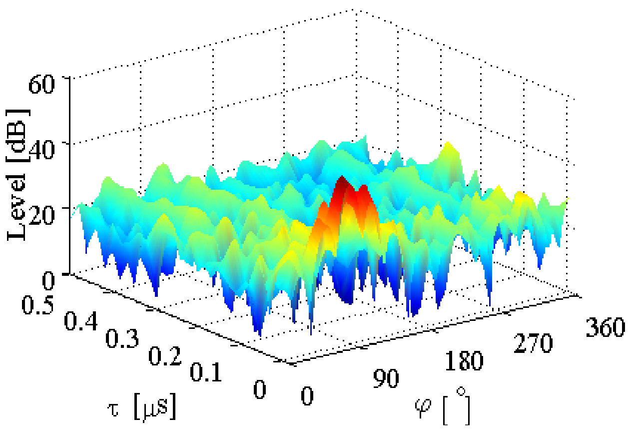


Fig.18 Received Signal Dispersed in Delay and Azimuth

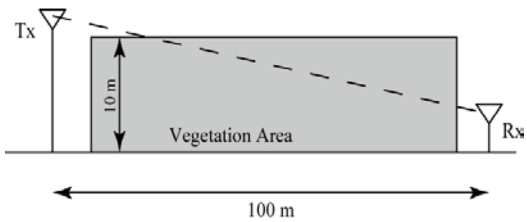


Fig.19 Measurement Scenario

Fig.20 Sample of the Foliage

Introduction of GIS to Promote Sustainable Development of World Heritage Site: Luang Prabang, Lao PDR

Introduction

GIS (Geographical Information System) is a system which captures, stores, analyzes, manages and presents data which are linked to geo locations. Poor planning of GIS can lead to failure cases due to high expenses and lack of human resources. Luang Prabang of Lao PDR (Figure 21 and 22), a World Heritage site, is facing rapid building construction due to high increase of tourists and development pressure. In collaboration with Local Heritage Department (Department of Patrimoine Luang Prabang, DPL) we are going to develop a feasible GIS prototype to analyze the impact caused by the change of constructions on the historical urban landscape [38]. The trend and severity of illegal construction in the past is highlighted in Figure 23.

Fig.21 Map of Luang Prabang

Source: Texas University Larary, 2007

Fig.22 Luang Prabang Landscape

Soure: ICT Center, 2006

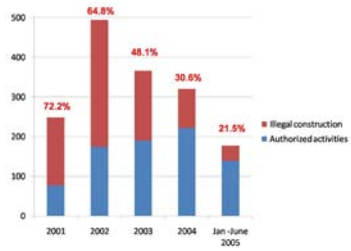


Fig.23 Rate of illegal construction

Soure: MdP Construction report (2001-2005)

Development of GIS Prototype

Feasible introduction of GIS is essential to effectively reflect local needs and continuously utilized by local officials. Needs assessment was conducted to study the needs local from 11 government departments and identified the crucial components to be incorporated into the prototype (Figure 24). One of the major challenges faced is the adequate and updated data on the buildings built. Hence, current work in developing prototype is to build databases for authorized and unauthorized buildings. The buildings are monitored in accordance preservation regulations.

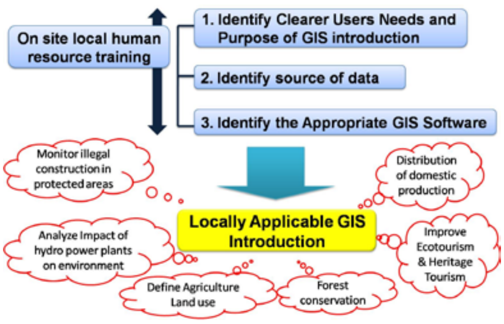


Fig.24 Pre-requisite for development of GIS prototype

Source: JASID 19th Confecence, 2008

ARAKI-SAKAGUCHI LABORATORY

Professor Kiyomichi Araki

Prof. Araki (left) 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. Sakaguchi (right) was born in Osaka, Japan, on November 27, 1973. He received the B.E. degree in electrical and computer engineering from Nagoya Institute of Technology, Japan, in 1996, and the M.E. degree in information processing and the Ph.D. degrees in electrical & electronic engineering both from Tokyo Institute of Technology, Japan, in 1998 and 2006, respectively. In 2000-2008, he was an Assistant Professor at Tokyo Institute of Technology, and from 2008, he has been an Associate Professor at the same university. He received the Young Engineer Awards both from IEICE and IEEE AP-S Japan chapter in 2001 and 2002 respectively, and Outstanding Paper Award both from SDR Forum and IEICE in 2004 and 2005, respectively and Tutorial Paper Award from IEICE communication Society in 2006. His current research interests are in MIMO propagation measurement, MIMO communication system, distributed MIMO network, and cognitive radio. Assoc. Prof. Sakaguchi is a member of IEICE and IEEE.

ARAKI-SAKAGUCHI LABORATORY

"Mobile Communications System Laboratory"

RESEARCH AGENDA

Digital RF

Nonlinear Distortion in Power Amplifiers (p. 16)
Direct Sampling Mixers (p. 17)

RF – MIMO

MIMO Front-end and MIMO Antennas (p. 18)
Single-user and Multi-user MIMO (p. 19)

Distributed MIMO

MIMO Two-way Relay Networks (p.20)
Performance of MIMO Relay Networks (p. 21)
Wireless Smart Grid (p. 22)
Base Station Cooperation MIMO (p. 23)

SYSTEM DEVELOPMENT

Digital RF

CMOS Implementations of
Direct Sampling Mixer

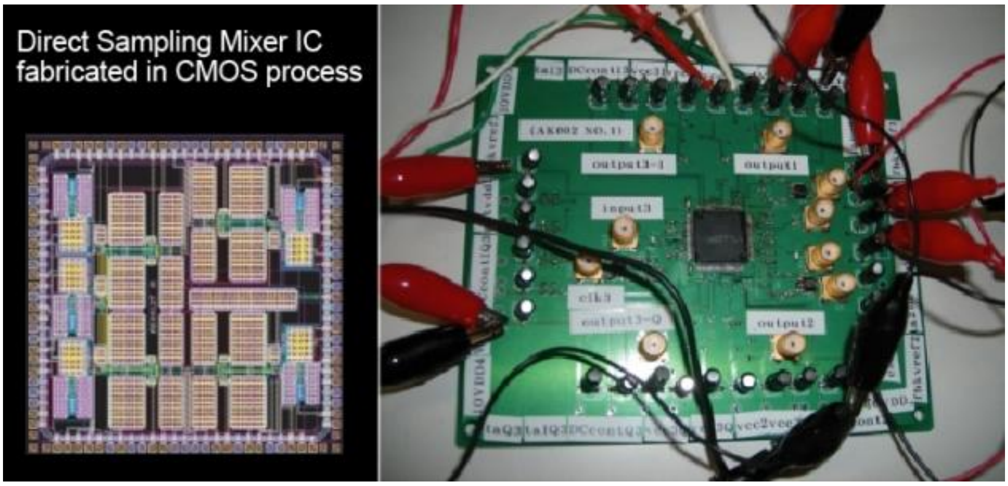
RF – MIMO

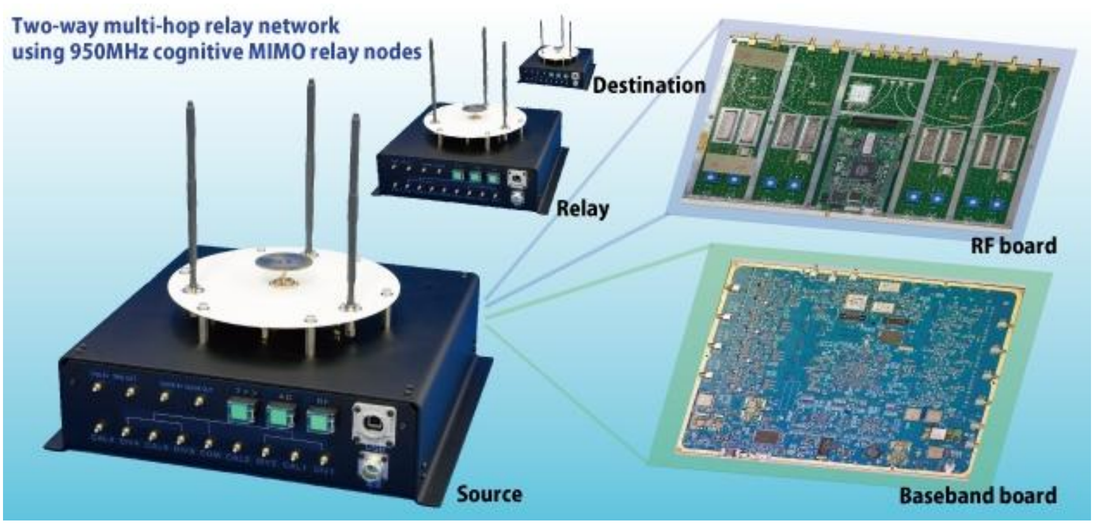
4x4 MIMO fading simulator for LTE,
Mobile Wi-MAX, and 802.11n W-LAN

Distributed MIMO

Prototype hardware for MIMO relay
networks at 950 MHz band
LTE and LTE-Advanced Simulators

The TokyoTech Mobile Communications System Laboratory was established in 1995 by Prof. Araki. Since 2008, the laboratory has been co-led by Assoc. Prof. Kei Sakaguchi. www.mobile.ee.titech.ac.jp

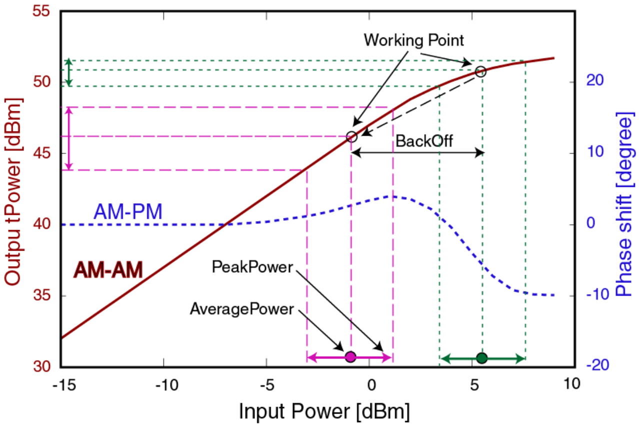




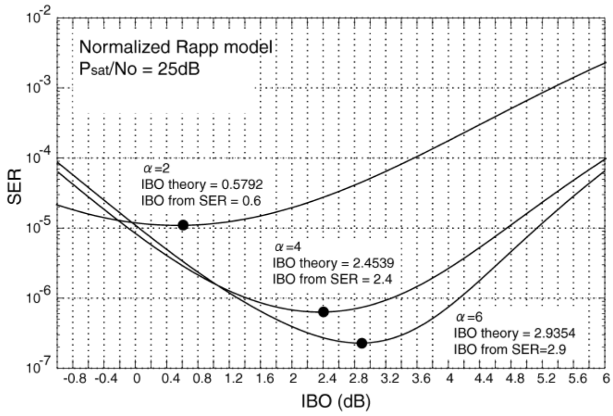
Nonlinear Distortion in Power Amplifiers

Performance evaluation of 16QAM under PA Nonlinear Distortion [29]

We investigate the performance of 16QAM in the presence of nonlinear amplifiers. We propose a detection method named as max-min-point method which is the best method among methods using orthogonal boundaries for decision. We also provide a flow to find optimal Input Back-Off (IBO) point under minimum SER criterion considering various kind of power amplifier nonlinear models.



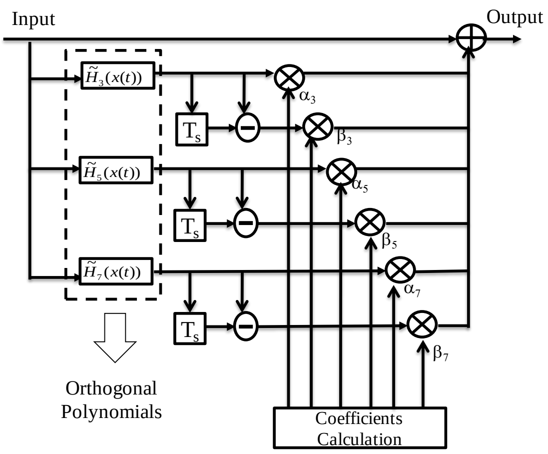
PA and Non-linearity Characteristic



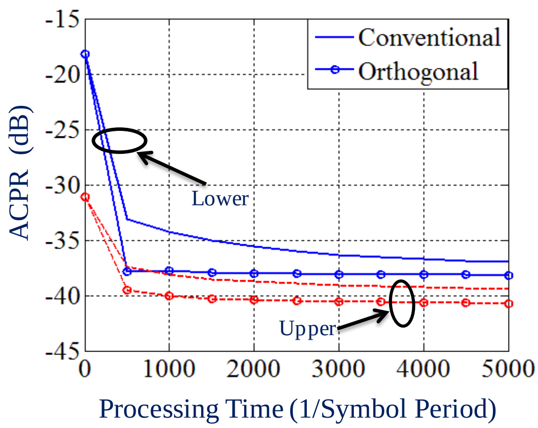
Normalized Rapp model: optimal IBO

Compensation for Nonlinear PA Distortions in OFDM Communication Systems [6], [30]

We present a novel predistorter design using a set of orthogonal polynomials to increase the convergence speed and the compensation quality. Because OFDM signals are approximately complex Gaussian distributed, the complex Hermite polynomials which have a closed-form expression can be used as a set of orthogonal polynomials for OFDM signals. A differential envelope model is adopted in the predistorter design to compensate nonlinear PAs with memory effects. This model is superior to other predistorter models in parameter number to calculate. We inspect the proposed predistorter performance by using an OFDM signal referred to the IEEE 802.11a WLAN standard. Simulation results show that the proposed predistorter is efficient in compensating memory PAs. It is also demonstrated that the proposal acquires a faster convergence speed and a better compensation effect than conventional predistorters



Proposed predistorter design

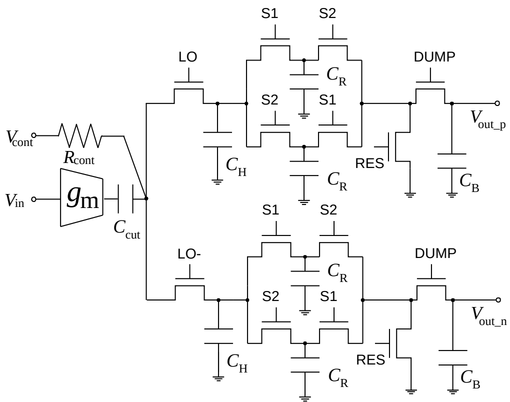


Convergence performance

Direct Sampling Mixers

Characteristic improvement of Direct Sampling Mixer [8], [20]

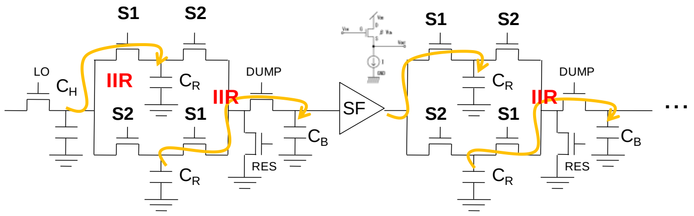
Recently, RF circuits have been migrated to deep-submicron CMOS processes. The Direct Sampling Mixer (DSM) is friendly with CMOS technology since it consists of MOS switches and capacitors. Moreover, DSM is one of essential elements in Software Defined Radio (SDR) receiver. Down-conversion and finite-impulse-response (FIR) anti-aliasing filtering are done by charge-sampling along with decimation. Infinite-impulse response (IIR) channel selection filtering is provided by charge sharing in a discrete charge domain. These operations are reconfigurable, and can reduce power consumption and cost of manufacturing in SDR receiver. In other words, DSM is appropriate for the SDR receiver. However, there are still some problems. We have improved them in several ways.



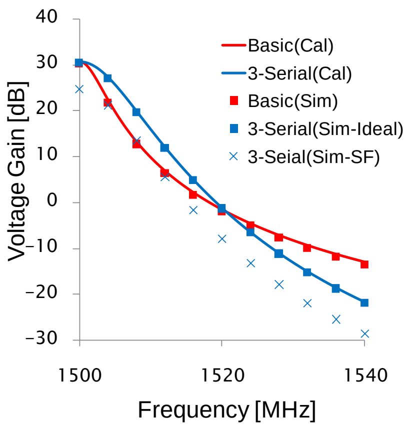
Direct Sampling Mixer

Design of Complex Pole Switched Capacitor Networks with Active Elements

A serialized structure of switched capacitor networks in the DSM is proposed. Utilizing this structure with active elements, source followers, we can obtain higher order filtering which enables wider bandwidth. Therefore, an excellent attenuation characteristic against adjacent blockers can be achieved.



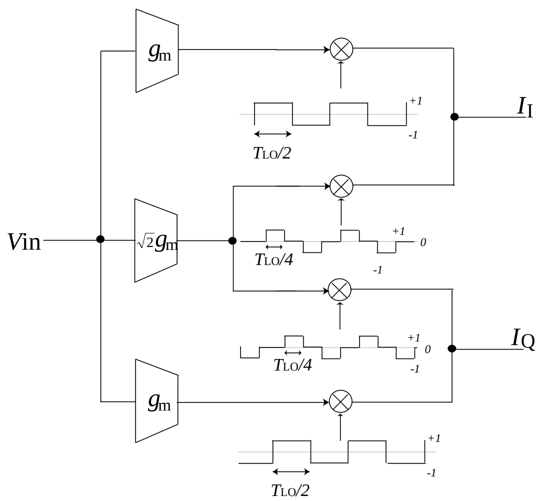
Serialized Direct Sampling Mixer



Frequency Characteristic

Design and Measurement of Harmonic Rejection Direct Sampling Mixer

When DSM is utilized in multi-standard receivers for channel selection, interference can be caused by signals at odd multiple frequencies of the desired signal. We propose a novel structure for DSM including harmonic rejection with pseudo-sinusoidal pulses and show the measured result of a test-chip we implemented in TSMC 0.18μm process. Around 20 dB higher 3rd HRR was achieved.

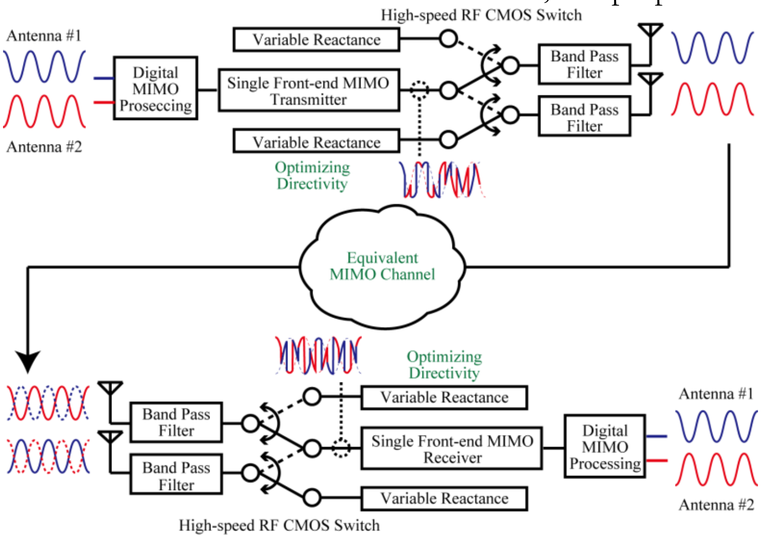


Harmonic Rejection DSM

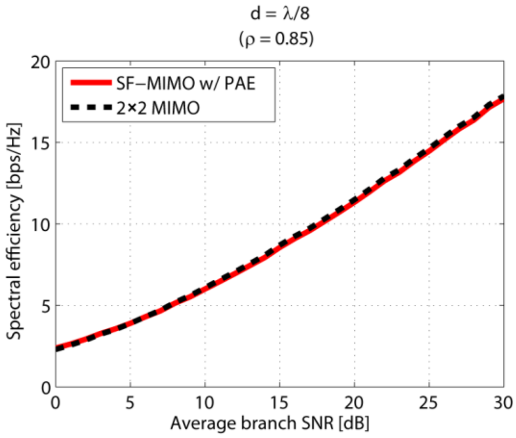
MIMO Front-end and MIMO Antennas

Single Front-end MIMO with Parasitic Antenna Elements [33]

MIMO system requires transceivers at each antenna branches and low spatial correlation environment. Therefore, conventional architecture of MIMO transceivers doesn't realize miniaturization of terminal and reduction of RF circuit cost. We propose a novel architecture realizing single RF front-end for reduction of RF circuit cost. Furthermore, the proposed architecture uses parasitic antenna elements for adaptive beamforming which enhance channel capacity.



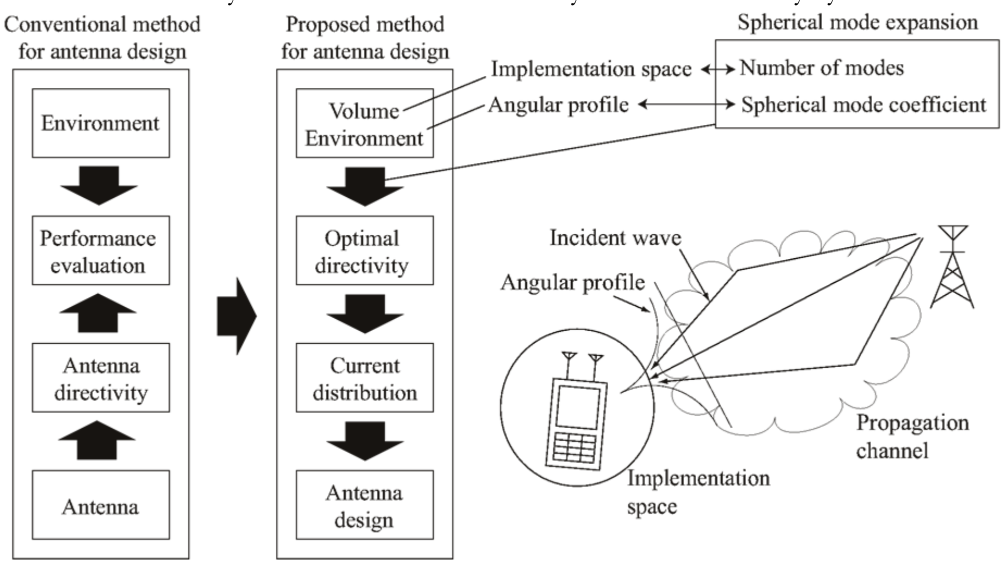
Single Front-end MIMO Concept



Spectral Efficiency vs. Average branch SNR

Design of Diversity Antenna Directivity based on Spherical Mode Expansion [7]

We propose a new array antenna design scheme to achieve best performance under a given propagation environment. For that purpose, Spherical Mode Expansion (SME) of antenna directivity is introduced. In SME, an electrical and magnetic field is expanded into orthogonal spherical wave functions with their weights of Spherical Mode Coefficients (SMCs). In a fixed size or volume of array antenna, the number of effective SMCs to be radiated from the volume is limited. Therefore, optimal antenna directivity in a given volume of array antenna can be achieved by designing limited SMCs. Our research is design of antenna directivity based on SME for SISO system and diversity system.

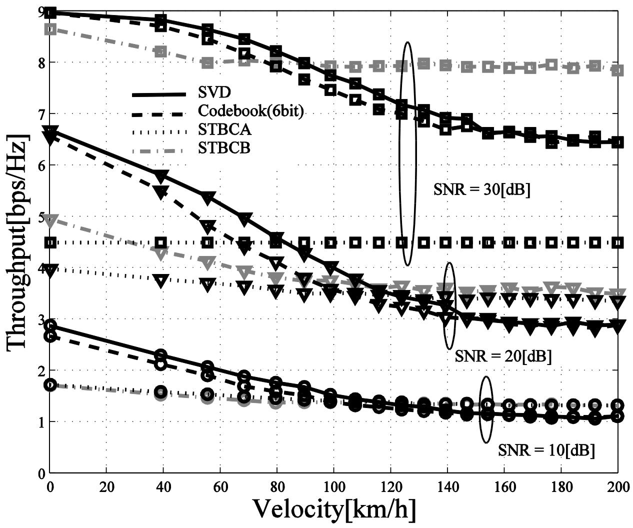


Spherical Mode Expansion – based diversity antenna design

Single-user and Multi-user MIMO

Performance Comparison between Open Loop and Closed Loop MIMO-OFDM Schemes in Cellular Environment

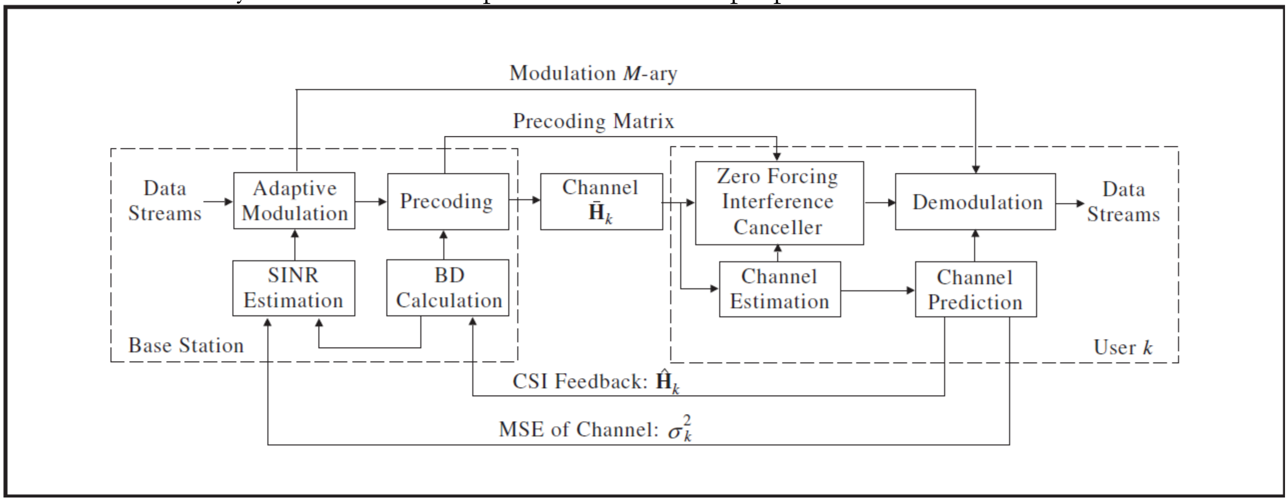
We consider Multiple-Input Multiple-Output (MIMO) systems by the existence of channel state information (CSI) feedback. SVD-MIMO (Singular Value Decomposition) system is the optimal Single User (SU) MIMO transmission by means of transmit (Tx) and receive (Rx) beamforming based on the knowledge of the CSI both at the transmitter and receiver. In practical systems, the performance is degraded due to quantization of feedback information and the time variation of the wireless channel, causing the CSI to be outdated. We analyze the various trade-offs of performance of SU MIMO precoding systems with realistic MIMO parameters.



Throughput vs. Velocity

Robust Design for Multiuser Block Diagonalization MIMO Downlink System with CSI Feedback Delay [10]

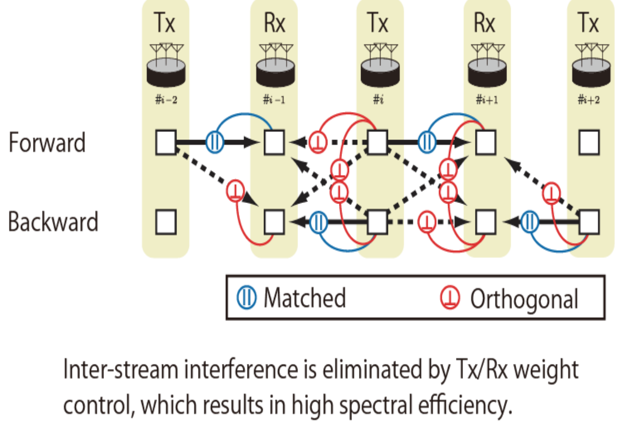
For a system with multiple antenna users, block diagonalization (BD) is a technique, where multiuser interference can be completely canceled. To realize BD, the base station should accurately know the CSI of users. However, the CSI fed back to the base station becomes outdated due to the time-varying nature of the channels. Channel prediction is an efficient approach to combat the performance degradation due to feedback delay in single user MIMO system, but in a BD system, the multiuser interference still remains. We analyzed the effects of imperfect CSI caused by feedback delay on BD MIMO downlink system with channel prediction. We also propose a robust scheme for this.



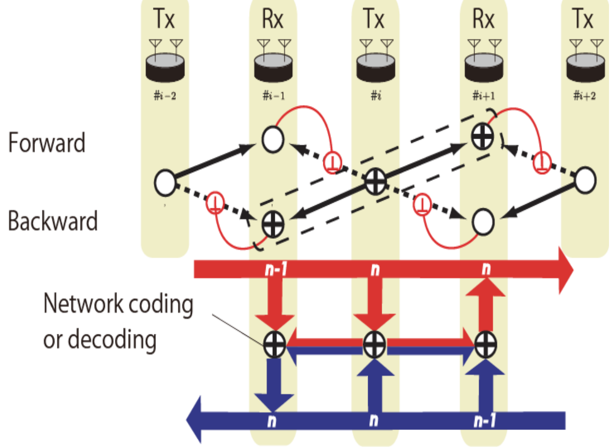
System design for robust multiuser block-diagonalization

MIMO Two-way Relay Networks

The MIMO two-way relay (MTR) is a topology we have proposed to realize highly efficient multi-hop relay networks. In a MIMO two-way relay network, the transmit and receive weights at the relay nodes are aligned to remove the intercell interference from the adjacent nodes. The weights are also aligned at the receiver to match with the desired transmitted signals. We also propose network coding schemes to the MIMO Two-way relay to further increase the capacity of the forward and backward flows. [1], [5]



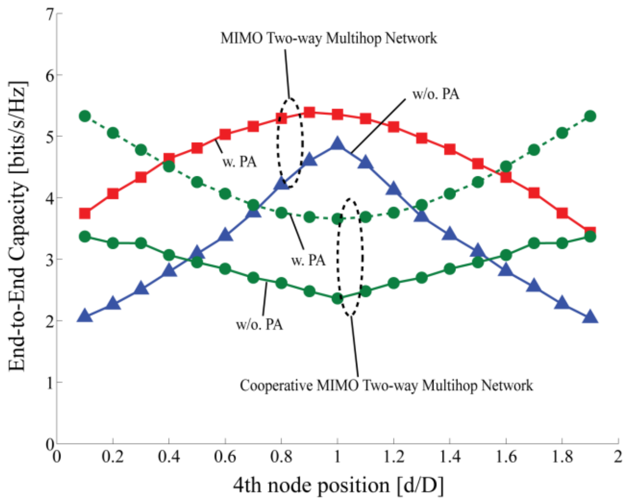
Tx/Rx weight control



MIMO network coding

Power Allocation vs. cooperative relaying for MTR [9], [34]

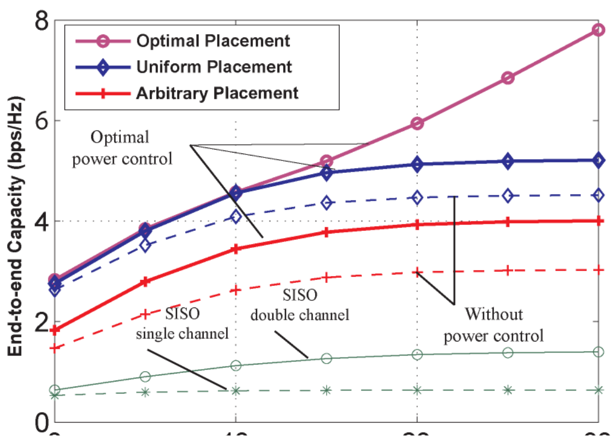
Previous works in MIMO two-way relay network have focused on a uniform topology of the relay nodes. However such a topology rarely exists in a practical situation. In a non-uniform topology, the end-to-end network capacity degrades severely due to the bottleneck link caused by uneven SNR. To combat this problem, we propose several schemes: power allocation and cooperative relaying.



End-to-end capacity vs. central node position

Optimal Routing and Power Allocation in MTR [21]

MIMO two-way relaying can enable highly efficient multihop networks. We analyzed the effect of the routing, i.e. relay locations, on the network performance of such wireless networks assuming an optimal power allocation. We then modeled and solved the joint optimization of node placement and power allocation using a geometric programming framework. Our results showed a significant capacity gain of the optimal placement at high SNR. Also, it achieved a large power reduction although the optimization did not explicitly minimize the total power consumption.

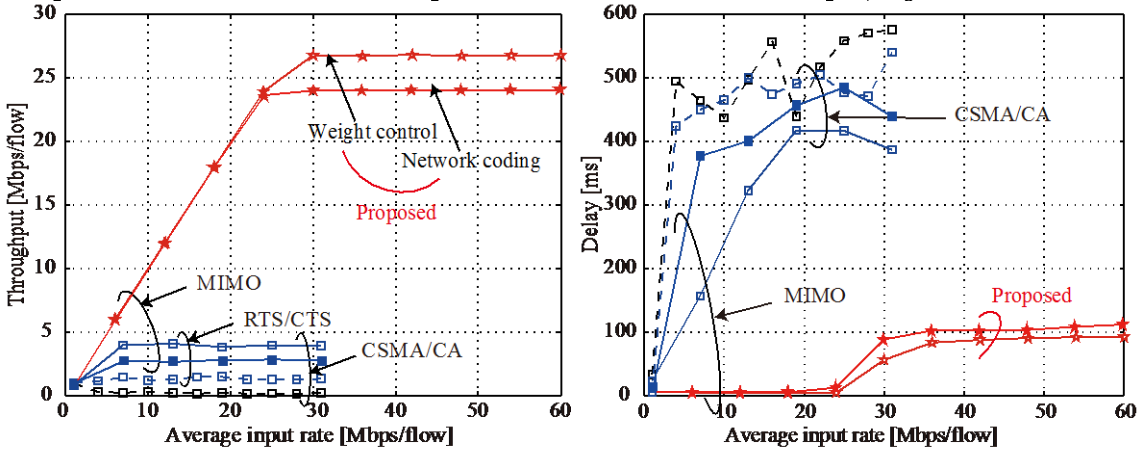


End-to-end capacity vs. Max Tx. Power

Performance of MIMO Relay Networks

Wireless mesh network performance: MIMO two-way relay vs. CSMA/CA based protocols [12], [35]

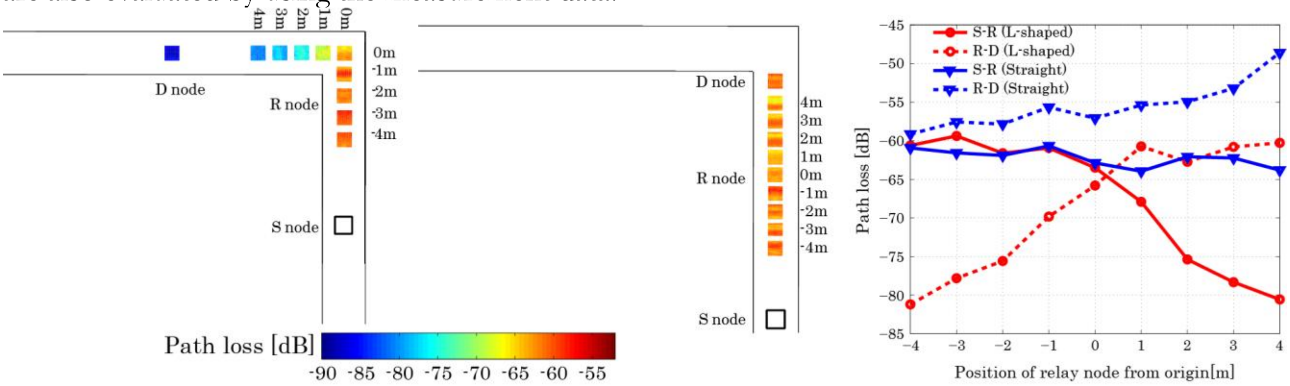
IEEE 802.11 Medium Access Control (MAC) is considered as the standard MAC for the current generation of wireless networks. While simple to use and efficient for local one-hop transmission, 802.11 MAC does not scale to higher size networks and presents a serious loss of performance in terms of delay, fairness and most critically, throughput. In this research, we consider the MIMO two-way multi-hop relay as a PHY/MAC cross-layer design protocol for mesh network. We implemented network simulators and provided details about the architecture of the network simulators including packet format, frame format, retransmission mechanism. Network performance of the proposed protocol was evaluated in comparison with mesh networks employing CSMA/CA.



Throughput and delay performance

Propagation Measurement of MIMO Relay Network in Strong Shadowing Indoor Environment at 5 GHz Band [17], [22]

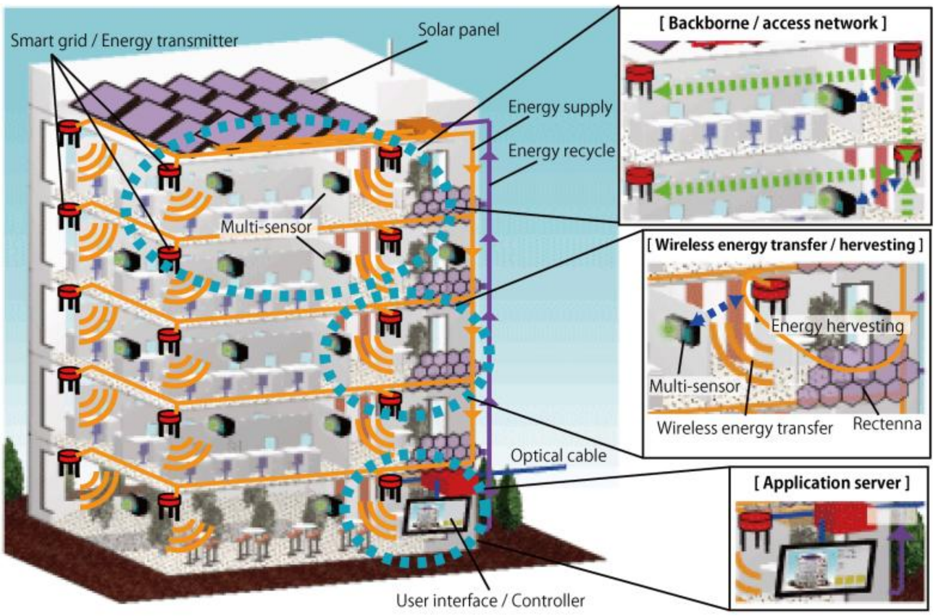
The problem of shadowing caused by the obstacles degrades the performance of wireless communication systems. Relaying technique is one of the solutions to deal with this problem. We conducted MIMO wideband propagation measurements in an L-shaped corridor with various relay positions where shadowing is dominant. In order to study how shadowing degrades the signal strength, measurements were also done in straight corridor, where shadowing can be neglected. Analysis results shows the benefits of relay technique in a realistic shadowing environment and the optimum position for relay node can be determined. Furthermore, the performance of various relaying schemes including decode-and-forward, two-way relay network employing network coding and cooperative relay schemes are also evaluated by using the measurement data.



a) L-shaped corridor b) Straight corridor c) Average pathloss at relay position

Wireless Smart Grid

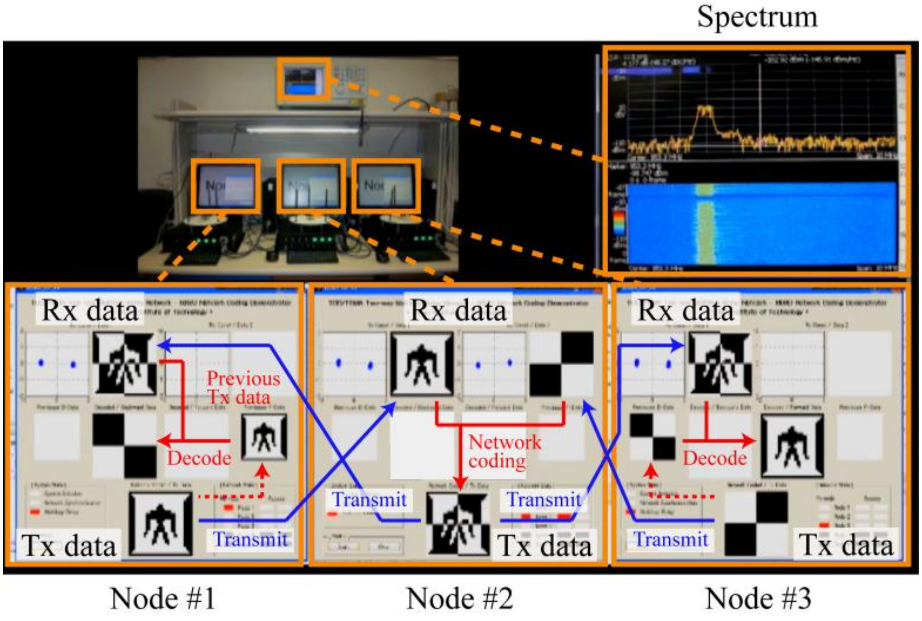
[41] We propose a wireless grid in which wireless sensor network technology, RFID, and smart mesh networks are combined. The building control system is shown in the figure below as an application of smart grid. This system consists in sensor nodes which have wireless energy battery, and mesh networks which have wireless energy transmission and data relay functions. By using the wireless smart grid, multiple of sensors and controller can work without battery. Furthermore, scalable and high reliable wireless network can be realized by high data rate and high reliable relay functions of smart mesh networks such as MIMO mesh networks.



Building control system by wireless grid

Prototype Hardware for Wireless Smart Grid [15, 37-39]

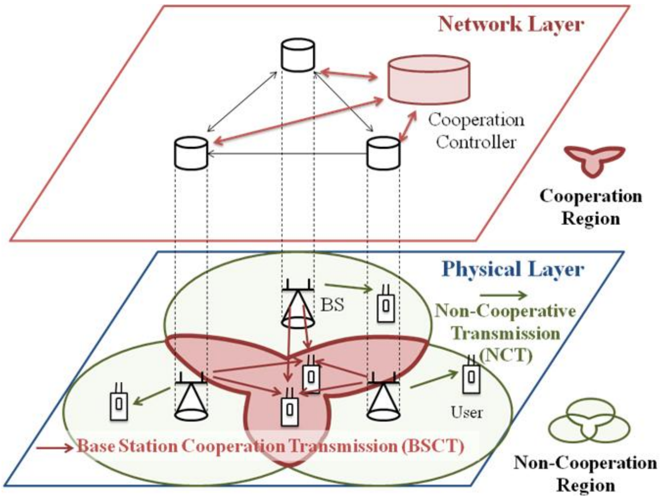
In the MIMO mesh networks, MIMO beam-forming or network coding are used for interference cancel and flow multiplexing. We are developing prototype hardware for MIMO mesh networks at the 950MHz band. The figure below shows an overview of MIMO two-way multi-hop relay network.



MIMO two-way multi-hop relay network demonstrator with MIMO network coding using 950MHz band

Base Station Cooperation MIMO

Fractional Base Station Cooperation Cellular Network (FBSC-CN) [14, 42, 43]



Communication quality degradation at cell-edge areas is an important problem in conventional cellular systems. Base station cooperation (BSC) has been considered to solve the cell-edge problem by coordinating the transmissions between BSs. However, BSC requires a high-speed backhaul bandwidth and increases the complexity in the user scheduling. FBSC-CN is a cellular network in which a combination of non-cooperative transmission (NCT) and BSC BSC Transmission (BSCT) is performed in order to achieve the gains both at the cell-inner and cell-edge with limited complexity. FBSC-CN gives the better spectral efficiency and requires less backhaul bandwidth than full BSC MIMO.

User Combination Selection Method for Base Station Cooperation Multi-user MIMO (MU-MIMO) [24, 25]

The performance improvement through BSC-MU-MIMO depends on the combination of selected user locations. We propose user combination selection from the aspects of both statistical and instantaneous characteristics of propagation channels in order to reduce user selection complexity.

Theoretical Analysis of Base Station Cooperation MIMO Channel by Using Eigenvalue Theory [19, 40]

We develop a theoretical analysis of BSC-MIMO using eigenvalues of Wishart matrix. The distributions of the eigenvalues considering unbalanced pathloss are obtained and the average channel capacity of BSC-MIMO by using these distributions are derived.

Partial Protection Coordinated Beamforming for LTE-Advanced [23]

Coordinated Beamforming (CB) is a category of coordinated multi-point schemes for LTE-Advanced, where there is no requirement of tight base station synchronization or exchange of user data. In conventional CB, MIMO precoding is performed to form full spatial nulls in the direction of other-cell users to eliminate intercell-interference. However, the spatial nulls limit the spatial diversity to the in-cell user which lead to relatively low throughputs when the other cell user is far from the in-cell user. We have developed partial protection coordinated beamforming (PPCB), in which partial spatial nulls are formed to maintain relatively high throughput at all locations. Under PPCB, transmit antenna weights are formed to limit the maximum interference power to UEs of cooperating cells, while MIMO transmission is performed to in-cell UEs. PPCB was shown to give improvements in throughput over conventional null-beamforming under an LTE-advanced simulation scenario.

Deterioration of capacity due to propagation delay difference in Base Station Cooperation [31]

Propagation delay difference between BS and mobile station (MS), inter-symbol interference and inter-carrier interference degrade channel capacity in spite of OFDM symbol with Guard Interval. In this research, a method to determine reception at MS when signals are simultaneously transmitted from different BSs is proposed, and the research also studies channel capacity degradation with respect to the ideal case without propagation delay.

SUZUKI FUKAWA LABORATORY

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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, Tokyo, 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 the Institute of Electronics, Information, and Communication Engineers (IEICE) of Japan, and of IEEE. He received the Paper Award in 1995, 2007, and 2009 the award of Fellow in 2006, and the Achievement Award in 2009 from IEICE.

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Assistant Professor Satoshi Suyama
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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, and RF circuit impairment compensation techniques. 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 with factor graphs
    - MMSE detection avoiding noise Enhancement [8]
  - Adaptive blind method for heterogeneous streams
  - Soft decision-directed channel estimation (SDCE) [1]

- *MIMO-OFDM system optimization*
  - BER improvement
    - Subcarrier phase hopping (SPH)
    - Minimum BER (MBER) precoding [2]
  - PAPR reduction
    - Block diagonalization with selected mapping (BD-SLM) [9], [15], [18]
    - Partial transmit sequence (PTS)
  - Joint BER and PAPR improvement
    - SPH-SLM
    - Eigenmode transmission with PAPR reduction [6], [19]
  - Relaying system improvement
    - Amplify-and-Forward (AF) / Decode-and-Forward (DF) switching

Multiple Access

- *Interference mitigation*
  - Spatial filtering [3]
  - MBER precoding for cochannel interference environment

- *Access scheme*
  - IDMA with iterative detection [11], [12], [17], [23]
  - Random packet collision resolution [13], [16]

Modulation and Demodulation for Cognitive Radio

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

RF Impairment Compensation

- *Phase noise compensation* [4], [5], [7], [10], [20], [21], [24]
- *I/Q imbalance compensation*
- *Real zero coherent detection*

In-House Simulator Design and Implementation

- *FPGA on-board system simulators* [14]
- *4x4 MIMO fading simulators*

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

Decision-Directed Phase Noise Compensation for Milimeter-Wave Single Carrier Transmission Systems with Frequency-Domain Equalization [7]

Wireless personal area network (WPAN) systems in the 60-GHz millimeter-wave band have been extensively studied, and the 60-GHz WPAN standardization in IEEE 802.15.3c investigates single carrier (SC) transmission employing frequency-domain equalization (FDE), which is called SC-FDE. Moreover, single-chip RF-CMOS ICs based on the silicon (Si) technology for the 60-GHz WPAN transceiver have been developed to lower power consumption and cost. However, the relatively large phase noise from the phase locked loop (PLL) synthesizer occurs. SC-FDE suffers from severe performance degradation due to the phase noise. This is because it is difficult to compensate the phase noise for SC-FDE before FDE, and the phase noise in the FFT severely degrades the post-FFT received signal. A combination of decision-feedback equalization and phase noise compensation for SC transmission has been investigated, however it cannot be directly applied to SC-FDE. On the other hand, decision-directed phase noise compensation (DD-PNC) for the OFDM transmission has been proposed, and it can compensate relatively large phase noise. Thus, we propose a SC-FDE receiver employing DD-PNC that can cope with multipath delay and phase noise for the 60-GHz SC transmission.

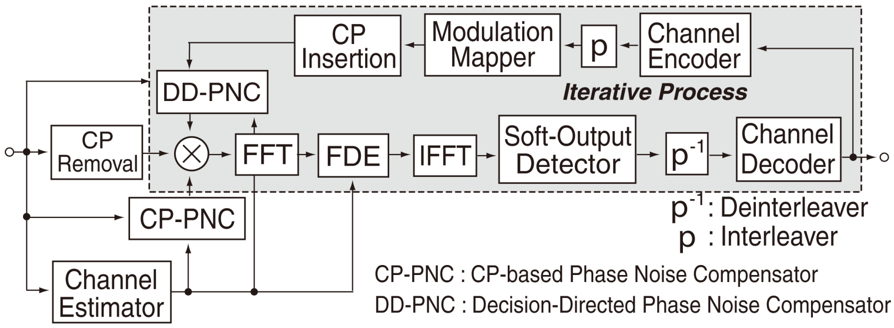


Fig. 1 SC-FDE receiver employing DD-PNC

Fig. 1 shows a block diagram of the proposed SC-FDE receiver employing DD-PNC. The receiver iterates the phase noise compensation and signal detection by exploiting an output of the channel decoder. In an initial process, a channel estimator first estimates a channel impulse response by using the preamble, and then a cyclic prefix (CP) based phase noise compensator (CP-PNC) removes the phase noise from the time-domain received signal by using CP of the Golay code and the channel estimates. After FFT converts the compensated received signal into the frequency-domain one, the MMSE-based FDE is performed, and then the equalized output is transformed into the time-domain signal by IFFT. Next, the soft-output detector provides soft decision from the equalized signal, and after deinterleaving the soft decisions, a soft-decision Viterbi decoding is performed. If a decision error is detected from the decoded bits, the receiver shifts the initial process to an iterative process.

In the iterative process, the receiver first generates a transmitted signal replica from the decoded bits. Next, DD-PNC recursively estimates the phase noise by the one-tap least-mean-square (LMS) algorithm using the replica, and then it removes the estimate from the time-domain received signal. After that, the coherent detection is also conducted for the compensated signal. The receiver repeats the iterative process until the number of iterations exceeds a predetermined threshold or no decision error is detected.

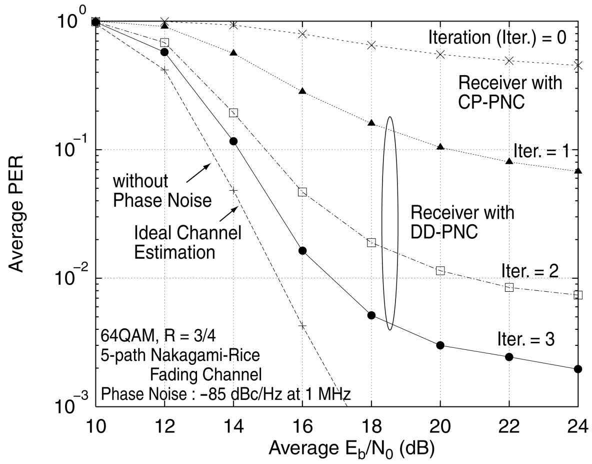


Fig. 2 Average PER performance with 64QAM

Computer simulations following the IEEE 802.15.3c standard were conducted to verify the effectiveness of the proposed receiver. When the phase noise level is −85 dBc/Hz, average packet error rate (PER) performance is shown in **Fig. 2**. For comparison, PER of the SC-FDE receiver with ideal channel estimation under the phase-noise-free condition was also plotted (ideal performance). **Fig. 2** demonstrates that the phase noise severely degrades PER of the receiver with CP-PNC, and that PER cannot reach 10^{-1} even in the high E_b/N_0 region. On the other hand, the proposed receiver with DD-PNC can achieve PER = 10^{-2} at the E_b/N_0 = 16.8 dB, and it can reduce the E_b/N_0 degradation from the ideal performance to 1.4 dB.

PAPR Reduction Methods for Eigenmode MIMO-OFDM Transmission [6]

In mobile communications, MIMO-OFDM can achieve excellent transmission performance over multipath fading channels by the OFDM technique, and can realize space division multiplexing (SDM) using multiple transmit and receive antennas. On the other hand, the transmitted signal has high peak-to-average power ratio (PAPR) because of OFDM characteristics. In the eigenmode MIMO-OFDM transmission that performs linear precoding using CSI, conventional PAPR reduction methods cannot be employed because they disturb the linear precoding. We propose PAPR reduction methods for the eigenmode MIMO-OFDM. The proposed methods, which are referred to as eigenmode transmission SLM (EM-SLM) and eigenmode transmission PTS (EM-PTS), perform a phase shift for PAPR reduction not to affect the eigenmode channels by the linear precoding.

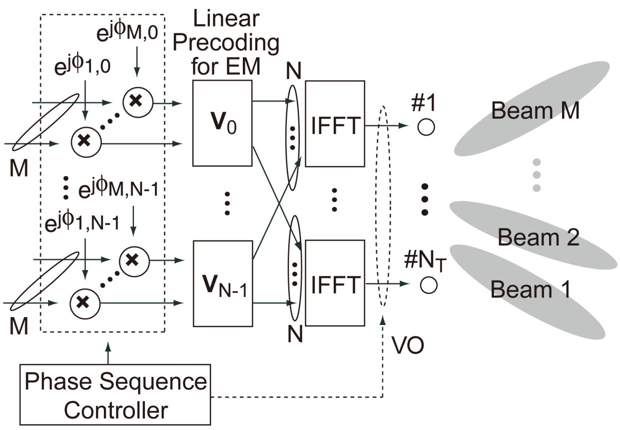


Fig. 3 EM-SLM

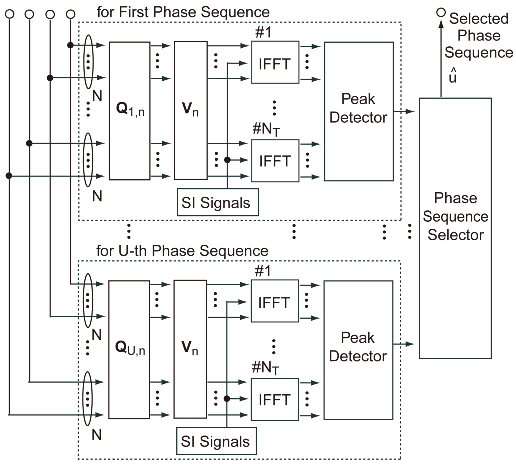


Fig. 4 Phase sequence controller for EM-SLM

The basic configuration of EM-SLM is shown in **Fig. 3**. EM-SLM first performs a phase shift for the modulation signal. After the linear precoding, IFFT converts the precoded modulation signals into a time-domain signal. This configuration can perfectly maintain the precoding effect because any phase shift by EM-SLM does not affect the EM channels at all. Moreover, phase shift to the modulation signals is carried out by using the selected phase sequence. In addition, side information (SI) on the selected phase sequence is modulated into SI-bearing (SI) signals. The configuration of the phase sequence controller for EM-SLM is shown in **Fig. 4**. It parallel calculates the instantaneous power of the transmitted signals corresponding to each phase sequence, and detects the peak power of the transmitted signals during one OFDM symbol. Then, by comparing the *U* peak powers which are generated from the *U* phase sequences, the best phase sequence that minimizes the peak power is selected. We also proposes an enhanced version of EM-SLM using the conventional PTS technique for OFDM, which is referred to as EM-PTS, to reduce the numerical complexity of EM-SLM. The conventional PTS performs the phase shifts for the time-domain signals by employing the same phase shift over some subcarriers in SLM. Moreover, similarly to the conventional PTS, all the subcarriers are divided into B blocks, and the same phase shift in the each block is used. **Fig. 5** shows a block diagram of the EM-PTS transmitter. The process until the modulation signal mapper is the same as that of the EM-SLM transmitter. After that, it carries out the linear precoding, and divides the precoded modulation signals into the B blocks. Then, IFFT generates a time-domain signal of each block, and the time-domain signals of the B blocks are fed into the phase sequence controller. Next, the phase sequence controller selects from the U phase sequences the phase sequence that minimizes the peak power. Finally, the transmitter performs the phase shift corresponding to the selected phase sequence for the time-domain signal of each block, and generates the transmitted signal at each antenna by combining the time-domain signals of the B blocks and a time-domain signal into which IFFT converts the SI signals. Therefore, the EM-PTS transmitter reduces the complexity over the EM-SLM.

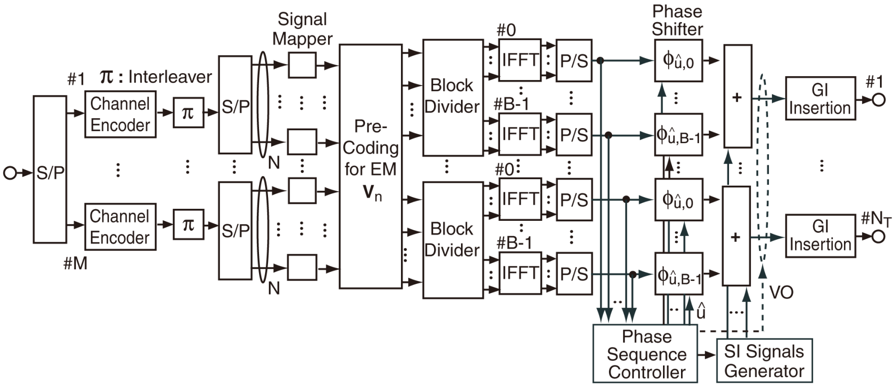


Fig. 5 EM-PTS transmitter

Computer simulations following the 5 GHz-wireless LAN standard were conducted to verify the effectiveness of EM-SLM and EM-PTS in MIMO-OFDM transmission. **Fig. 6** shows the PAPR reduction performance of the low-complexity EM-PTS transmitter with U =16. It can also reduce PAPR, and the PAPR degradation against EM-SLM at CCDF = 10^{-3} is limited to 1.0 dB, 0.3 dB, and 0.2 dB, when B =2, 4, and 8, respectively. On the other hand, EM-PTS can reduce the complexity to $B/(U+1)$ times as much as that of EM-SLM, and with B =4,U =16, the complexity becomes almost 1/4 of EM-SLM..

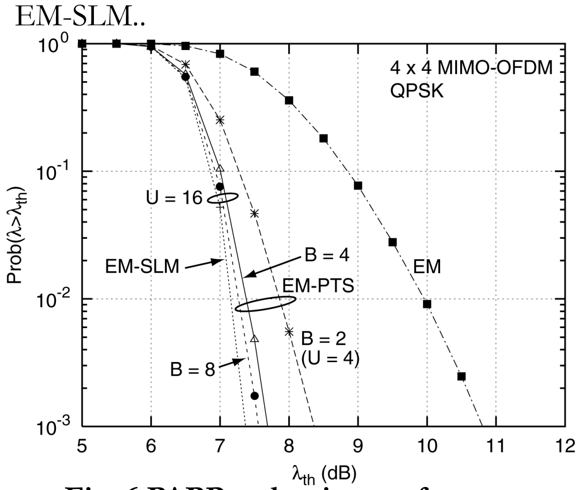


Fig. 6 PAPR reduction performance

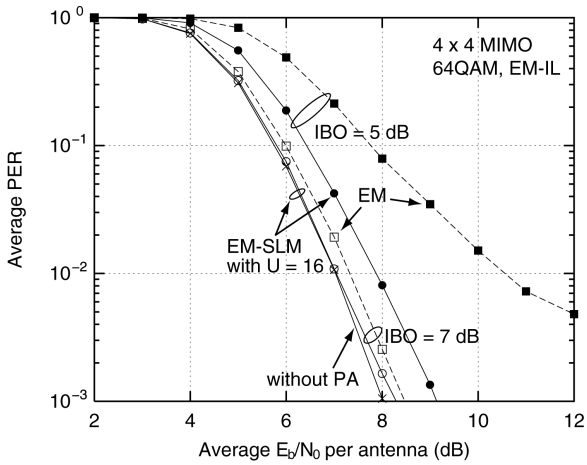


Fig. 7 Average PER performances of EM-SLM with PA

To evaluate the influence of the nonlinear distortion, PER performances of EM-SLM with 64QAM were investigated. The results are shown in **Fig. 7**. It can be seen that with the input backoff (IBO) = 5 dB, the normal EM suffers from the nonlinear distortion by power amplifier (PA), while EM-SLM with U =16 can limit E_b/N_0 degradation at PER =10^{-2} to 0.9 dB, and it can gain 2.7 dB in comparison with EM by the PAPR reduction effect.

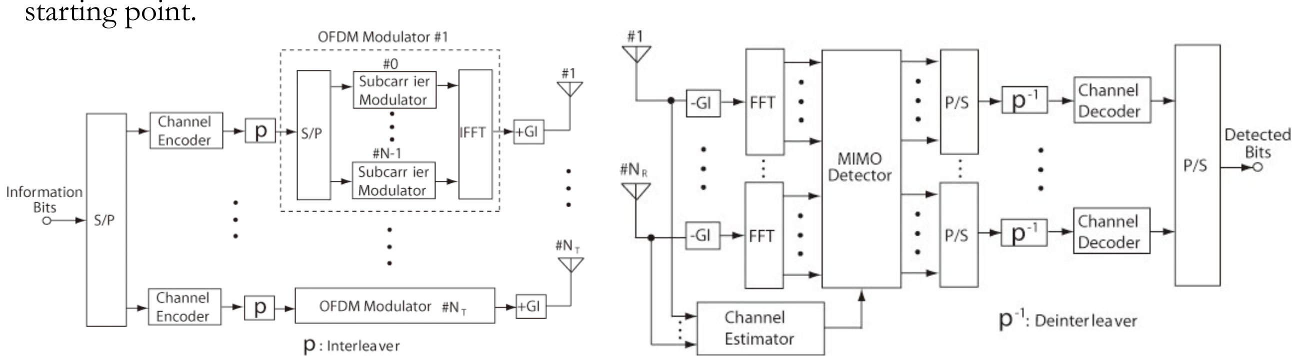
SUZUKI FUKAWA LABORATORY

Low-complexity Algorithm for Log Likelihood Ratio in Coded MIMO-OFDM Communications [8]

Multiple-input multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM) is one of the most promising techniques for future mobile communications because it can efficiently use the spectrum and improve the system capacity. The optimal signal detection for coded MIMO-OFDM systems is based on the maximum a posteriori (MAP) criterion, and requires a prohibitive amount of computational complexity.

To reduce such complexity, an iterative receiver based on the turbo principle can improve reliability of signal detection by exchanging log likelihood ratios (LLRs) of coded bits between soft demodulator and soft channel decoder parts. For obtaining an approximate LLR, the soft demodulator needs to search for a pair of transmitted signal candidates that can maximize the log likelihood function under a constraint that a coded bit be either one or zero. However, this search needs to calculate the log likelihood function for all the transmitted signal candidates, which still requires a large amount of complexity.

To solve such a problem, low-complexity algorithms that simplify the maximum likelihood detection (MLD). The conventional method employs a low-complexity algorithm in order to find the transmitted signal candidate that maximizes the log likelihood function, that is the maximum likelihood sequence (MLS). Then, the method applies another low-complexity algorithm in order to find the transmitted signal candidate that maximizes the log likelihood function under a constraint that a coded bit be inverse to that of the estimated MLS, which is referred to as inverse-bit MLS (IB-MLS). Thus, this conventional method needs to apply the low-complexity algorithm for all the coded bits so as to find IB-MLSs, which requires high complexity. We propose a low-complexity algorithm that can efficiently find MLS and IB-MLS. The proposed algorithm simultaneously searches for MLS and IB-MLS in directions of the noise enhancement with the minimum mean-square error (MMSE) detection as a starting point.



(a) Transmitter **(b) Receiver**

Fig. 8 MIMO-OFDM system

Fig. 8 (a) shows a block diagram of a MIMO-OFDM transmitter with N_T transmit antennas. An information bit sequence is divided into N_T parallel streams. Then each stream is fed into a channel encoder followed by an interleaver. The resultant coded bit sequence is passed into an OFDM modulator that generates OFDM signals having N subcarriers with the guard interval (GI). The OFDM signals are up-converted into RF signals and transmitted. **Fig. 8 (b)** shows a block diagram of a MIMO-OFDM receiver with N_R ($N_R \leq N_T$) receive antennas. Signals received by the N_R antennas are down-converted and signal components corresponding to GI are removed. Each fast Fourier transform (FFT) processor extracts N subcarrier signals from the resultant signals. Using the subcarrier signals and channel frequency responses estimated by a channel estimator, a MIMO detector generates LLRs of the coded bits which are passed into a respective deinterleaver followed by a channel decoder. Each channel decoder performs channel decoding and provides detected bits.

The proposed algorithm searches for MLS and IB-MLS simultaneously, and thus is expected to reduce the complexity more drastically. First, this algorithm performs the MMSE detection that requires a very small amount of complexity. The MMSE detection calculates an inverse matrix for obtaining its weight matrix and enhances the noise in directions of eigenvectors having large eigenvalues of the inverse matrix. Thus, decision errors by the MMSE detection are likely to occur in the directions of such eigenvectors. Considering this phenomenon, the proposed algorithms searches for MLS in the directions of the noise enhancement with the MMSE detection as a starting point. Note that IB-MLS can exist in the other directions owing to the intentional decision errors. Therefore, the algorithm searches for MLS and IB-MLS in the directions of plural eigenvectors having considerable eigenvalues. This point is a major difference between the proposed algorithm and the conventional ones. In addition, these conventional algorithms aim to search for only MLS.

Computer simulations were conducted to verify performance of the proposed algorithm. As a conventional algorithm, stream cancelling method (SCM) was also evaluated. SCM is indicated by D_1-D_2, where D_1 and D_2 are the low-complexity algorithms which estimate MLS and IB-MLS, respectively. As D_1 and D_2, the sphere decoding (SD) and the MMSE detection (MMSE) were selected. In addition, we consider the one-dimensional search in the direction of the eigenvector having the largest eigenvalue with the MMSE detection as a starting point, which is indicated by PM. Furthermore, the performance of LLR calculation by MLD were evaluated as a theoretical lower bound. The following simulations assumed that the channel estimation is ideal, and set ζ and N_P to $-1 + 10^{-3}$ and 2, of which validity was justified by another simulation.

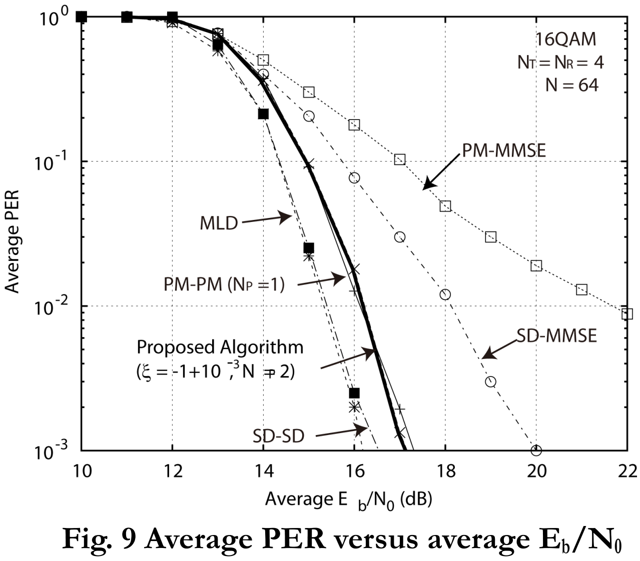


Fig. 9 Average PER versus average E_b/N_0

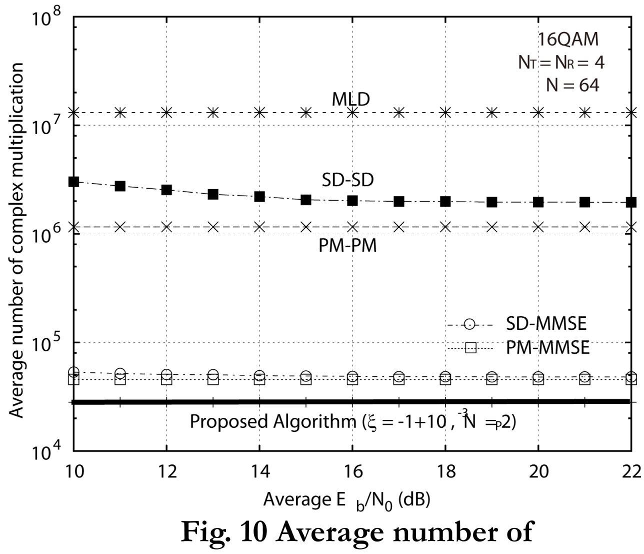


Fig. 10 Average number of complex multiplications

Fig. 9 shows E_b/N_0 average packet error rate (PER) performances of the proposed and conventional algorithms. Average PER of SD-SD is almost the same as that of MLD while average PER of the proposed algorithm is slightly inferior to that of MLD. To achieve average PER of 10^{-3}, the proposed algorithm requires 3.0 dB less E_b/N_0 than SD-MMSE and 1.0 dB more E_b/N_0 than MLD. **Fig. 10** shows the average number of complex multiplications per subcarrier which the proposed and conventional algorithms require. The proposed algorithm needs much less complexity than MLD and SD-SD, which outperform the proposed algorithm. This algorithm can achieve the lowest complexity of all the algorithms and reduce the complexity to about 0.2% of that of MLD.

SUZUKI FUKAWA LABORATORY

Precoding Technique for Minimizing BER of MIMO-OFDM System Employing MLD under Multicell Co-channel Interference [2]

MIMO-OFDM downlink transmission adopted in the mobile communication system is required to use the same frequency channel over closely located cells. This causes mobile stations (MSs), especially ones at cell edges, to suffer co-channel interference (CCI) from more than one base stations (BSs), and thus degrades the overall performance of the system. To overcome this problem, downlink multicell CCI mitigation techniques are necessary. The CCI mitigation techniques can be classified in terms of the interaction between BSs; cooperative and non-cooperative types. The cooperative type assumes that all BSs can obtain channel state information (CSI), even that of different cells, and they can be jointly optimized to mitigate CCI. Although the cooperative CCI mitigation technique can be regarded as the optimal solution for combatting CCI, it is not feasible in practice. Moreover, the requirement of the real time joint optimization among all BSs is still highly difficult to fulfill.

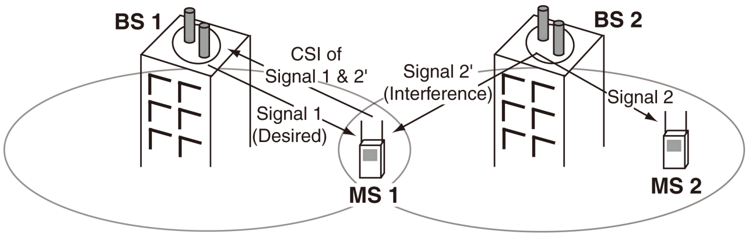
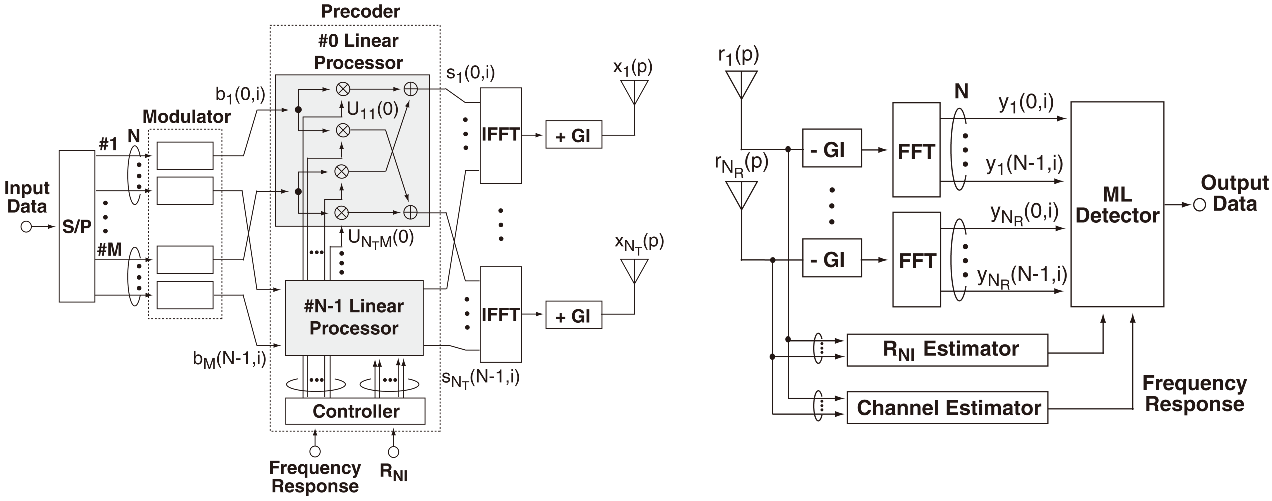


Fig. 11 Downlink system in a multicell environment.

Typically, non-cooperative CCI mitigation techniques perform preprocessing on the transmitted signal using linear precoders. We propose a linear precoder for the noncooperative multicell CCI environment as shown in **Fig. 11** in order to minimize a BER upper bound of the maximum likelihood detector (MLD). Since there is no cooperation among BSs, it is assumed that information on the interference is estimated at the MS and then fed back to the desired BS for the precoder. The proposed precoder exploits the statistical property of CCI to cope with CCI in a multicell environment. **Fig. 12** shows the **(a)** a transmitter and **(b)** a receiver of the MIMO-OFDM system corresponding to BS1 and MS1 in **Fig. 11**, respectively. A precoder that can minimize the BER upper bound of MLD under a non-cooperative downlink multicell CCI environment has been proposed. The upper bound is derived from the pairwise error probability (PEP) which is averaged with respect to the CCI plus noise, and the optimization of the precoding parameters employs the steepest descent algorithm under a transmit power constraint.



(a) Transmitter **(b) Receiver**

Fig. 12 MIMO-OFDM system.

Computer simulations of an uncoded MIMO-OFDM system in the downlink two-cell environment were conducted to verify the effectiveness of the proposed precoding method. For comparison, performances of non-precoded, eigenmode, and MMSE precoded MIMO-OFDM systems were also evaluated. **Figure 12** shows average BER performances with the average SIR of 20 dB. Note that both the non-precoded systems outperform the eigenmode and MMSE precoded transmissions because the former can exploit the spatial diversity from the MIMO channel more effectively than the latter in the uncoded system with CCI being not severe. It can also be observed that the eigenmode outperforms the MMSE precoder at low SNR but its performance degrades at high SNR. This is because at low SNR, adaptive modulation coding (AMC) of the eigenmode alleviates the use of severely degraded subchannels, and thus outperforms the MMSE precoder which attempts to use all subchannels. On the other hand, at high SNR, the limited number of AMC modes of the eigenmode results in worse performance than that of the MMSE precoder.

Figure 13 shows the average BER performance versus average SIR with average SNR of 16 dB. It can be seen that the eigenmode transmission outperforms the non-precoded system when average SIR < 10 dB but becomes inferior to the non-precoded system when CCI diminishes. This is because at large amount of CCI, the eigenmode transmission combined with AMC can mitigate CCI more effectively than MLD of the non-precoded system. On the other hand, when CCI diminishes, the non-precoded system with MLD can exploit the spatial diversity more effectively than the eigenmode transmission. The MMSE precoder operates similarly to the non-precoded system with optimal MLD at low SIR and its performance converges to the CCI-free performance as SIR increases. Evidently from this figure, the proposed MBER precoding method can improve the BER performance more significantly than any other transmission schemes regardless of the average SIR.

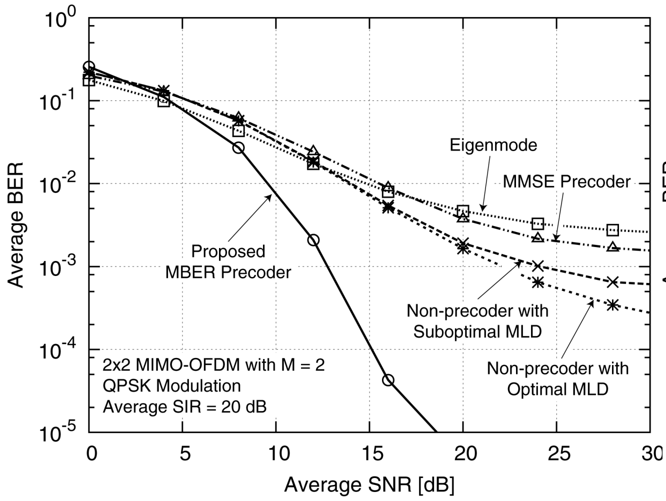


Fig. 12 Average BER performance

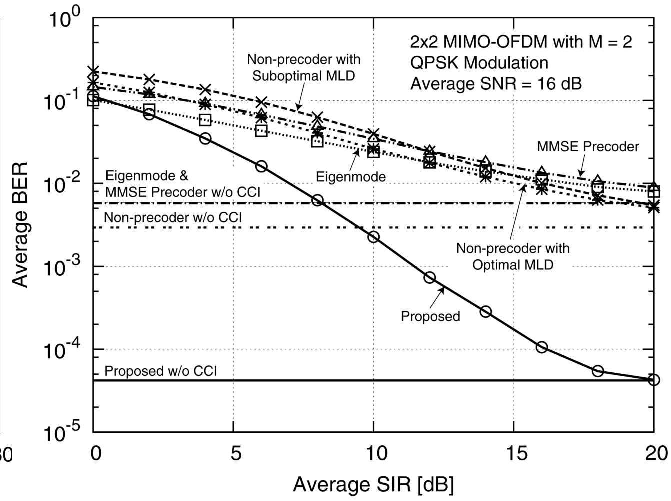


Fig. 13 Average BER versus average SIR

CONTRIBUTIONS

TAKADA LAB

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