DOCOMO Beijing Labs | Radio Transmission Technology | MIMO

Technology Reports

Special Articles on Multi-dimensional MIMO Transmission Technology — The Challenge to Create the Future —

Highly-efficient Multi-dimensional Adaptive Packet Radio Interface Technology

The DOCOMO Beijing Labs are conducting research for IMT-Advanced and future mobile communication systems, focusing on multi-dimensional adaptive packet radio interface techniques in the adaptive packet radio transmission project.

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1. Introduction

For future communication system design, the diverseness of services and applications demands further improvements in transmission throughput and reliability. Mobile communication has special features different from fixed communication in terms of mobility, broadcasting, interference and randomness in channel (propagation-paths) fluctuation. Mobility and broadcasting provide the user with the convenience of mobile communication, but, along with interference and random channel fluctuations, they are also signal distorting factors that require particular consideration in the design of mobile communication systems. The transmission scheme has a major effect on cost as well as on the transmission characteristics in terms of throughput and reliability.

The elements considered in radio transmission cover multiple dimensions, including frequency, time, space (beam), power and coding. Accurate measurement of channel fluctuation and interference parameters is a precondition to optimal adaptation of the multi-dimensional transmission elements. The Adaptive Packet Radio Transmission (APRT) project of the DOCOMO Beijing Labs carries out R&D on the efficient adaptation of these multi-dimensional transmission elements for the radio interface. The results of the work are intended to contribute to the IMT-Advanced, which is currently in the process of standardization by the International Telecommunication Union (ITU), and to the development of prototypes.

In this article, we describe an overview of multi-dimensional adaptive radio interface technology and the related issues. We also explain the Multiple Input Multiple Output (MIMO)*1-Orthogonal Frequency Division Multiplexing (OFDM)*2 verification platform that was developed in this project.

2. Requirements and Key Technologies for Future Radio Systems

The maximum spectrum efficiency required by the Long Term Evolution (LTE)-Advanced*3[1] currently being discussed by the 3rd Generation Part-

*1 **MIMO**: A signal transmission technology that uses multiple antennas at both the transmitter and receiver to perform spatial multiplexing and improve communication quality and spectral efficiency.

*2 **OFDM**: A digital modulation method where the information is divided into multiple orthogonal carrier waves and sent in parallel. It allows transmission at high frequency usage rates.

*3 **LTE-Advanced**: The name for IMT-Advanced in 3GPP. IMT-Advanced is the successor to the IMT-2000 Third-Generation mobile communication system.

nership Project (3GPP) is 30 bit/s/Hz for the downlink and 15 bit/s/Hz for the uplink. Furthermore, the mean spectrum efficiency per cell is a maximum of 3.7 bit/s/Hz/cell for the downlink and a maximum of 2.0 bit/s/Hz/cell for the uplink. The user throughput on the cell edge is 0.12 bit/s/Hz/cell/user for the downlink and a maximum of 0.07 bit/s/Hz/cell/user for the uplink (targets are for the 3GPP Case 1 model). LTE-Advanced targets realization of these specifications mainly by increasing the number of antennas by a factor of from two to four relative to LTE. Also, a target maximum rate of 1 Gbit/s or more will be achieved by expanding the frequency bandwidth to a maximum of 100 MHz. For mobility, on the other hand, the supported maximum movement speed is 350 km/h, the same as in LTE. To achieve these goals, NTT DOCOMO has proposed Layered Orthogonal Frequency Division Multiple Access (OFDMA)[*4] and other relevant technical plans [2].

3. Overview of the Research Items

The work being done at the DOCOMO Beijing Labs builds on aforementioned points and has focused mainly on the following four research items.

1) High-performance Complexity-scalable MIMO signal detection Technology

Improvement of spectrum efficiency requires an increase in the number of MIMO antennas, but that also increases the computational complexity of signal detection. It is therefore important to establish technology for achieving both lower computational complexity and higher accuracy in signal detection. In addition, an effective way to achieve a higher transmission efficiency with MIMO is optimized precoding[*5] to exploit space and multiple-user diversity according to channel conditions. Further research on increasing transmission efficiency is necessary.

2) Adaptive Radio Resource Allocation to Multiple Users

Channel and interference fluctuate within the space and frequency domains. Full adaptation of transmission to those factors is important to improve spectrum efficiency. Additionally, channel and interference conditions vary from user to user and Quality of Service (QoS)[*6] varies from application to application, so satisfying the respective user requirements while at the same time enhancing overall system efficiency is now a crucial and challenging issue.

3) High-accuracy in Channel Estimation

In MIMO transmission, channel estimation accuracy has a decisive impact on the detection accuracy. In reality, the pilot symbols[*7] for channel estimation are generally discontinuous in time, space and frequency, so interpolation[*8] of the estimated values is necessary. Interpolation and estimation errors degrade transmission performance, particularly at high mobility speeds.

Therefore, high-accuracy in channel estimation is an important issue affecting the overall transmission performance.

4) Interference-mitigation and Cell-cooperation Technology

To achieve a high system capacity in IMT-Advanced, space division multiplexing in the same frequency band within a single cell and in multiple cells is desirable. However, system capacity is limited by interference. In such an environment, inter-cell and intra-cell interference must be effectively suppressed. For this purpose, cooperation among cells to avoid or mitigate interference by distributed cells or centralized control is believed to be effective. Cell cooperation by simultaneous transmission from multiple cells is also effective for improving communication quality for cell-edge users.

In this project, specifically, the five key technologies described in the following sections have been studied.

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*4 **Layered OFDMA**: The LTE-Advanced radio access concept advocated by NTT DOCOMO. It allocates transmission bandwidth according to the capability of the mobile terminal and provides adaptive access according to radio environment.

*5 **Precoding**: A technique to improve system performance by performing linear or non-linear processing of each transmitted data stream of the MIMO transmission based on channel information.

*6 **QoS**: A level of quality on the network that is set for each service. Delay, packet loss and other quality factors are the main parameters.

*7 **Pilot symbol**: A pre-determined signal pattern between the transmitting and receiving sides used for channel estimation (attenuation and amount of phase).

*8 **Interpolation**: Estimation of intermediate values from discrete-time samples.

3.1 Overview of DSFDMA

Dynamic Space and Frequency Division Multiple Access (DSFDMA) [3] is a method to which multi-dimensional parameters are optimized collectively and simultaneously.

Adaptive allocation of radio resources to multiple users and the control of inter-cell interference is carried out to improve spectrum efficiency and reliability. In the design, attention has been given to two points. The first is space-frequency selectivity and diversity of individual radio channels, which depends on the location of the transmitting and receiving stations, the carrier frequency, and time. Spectrum efficiency can therefore be increased by fully exploiting the diversity of the selectivity in the three dimensions of space, frequency and time. The second point is diverseness of applications and their distinct requirements. It is also necessary to consider fairness among users while satisfying individual requirements such as transmission rate, packet error rate, and delay/jitter specification (QoS).

Considering those factors, the features of DSFDMA for allocation of uplink space and frequency resources to multiple users are listed below.

- Subcarriers, space (beam) and transmission power are allocated dynamically to each user.
- These values are not determined sequentially, but are optimized simultaneously as parameters of a single target function[*9].
- The target function is a summation of the user transmission capacities for all users weighted by priority according to the individual QoS control policy for each user. The maximum transmission power and restrictions on number of antennas can be set and observed respectively for each user in the optimization.
- Fast and stable optimization by the multi-step gradient-based method[*10]

The results of a simulation show that better characteristics than by conventional methods for future uplink Multi-User (MU)-MIMO can be expected.

3.2 Overview of DOM

Dynamic Ordering M-path MIMO detection (DOM) [4] is a successive interference canceling MIMO signal detection method that uses dynamic m-path canceling order selection.

This method is based Successive Interference Cancellation (SIC)[*11], which has relatively low computational complexity. It selects the stream layers that have high received signal reliability and takes multiple most reliable surviving symbols paths to execute the cancellation-ordering comparison. The evaluation shows that this method requires much less computation than Maximum Likelihood Detection (MLD)[*12], but has detection capability that can approach MLD. This method can also easily accommodate diverse complexity scaling and antenna number. It also has the merit of being easily implemented in hardware by a pipeline structure[*13], and so is suitable for device with a strict complexity-constraint. By using it together with Adaptive SElection of Surviving Symbol replica candidates based on the maximum reliability (ASESS)[*14] [5] for the quadrant decision, a further reduction of the computational complexity can be expected. This method is explained in detail in another paper in this Special Article [6].

3.3 Overview of 2D-EDFTI

2D-EDFT extends channel estimation using two-dimensional Discrete Fourier Transform (DFT) interpolation with an enhanced signal processing. Generally, channel estimation includes estimating propagation attenuation and the amount of signal phase rotation, as well as interference and noise characteristics. The accuracy of channel estimation directly affects the symbol detection error-rate, as MIMO system relies on the channel information to optimize the transmission and to separate the multiple signal sources, so highly accurate channel estimation is mandatory for high system perfor-

*9 **Target function**: A function that represents the target quantities for multiple parameters (communication capacity, cost, etc.) to be optimized. The optimization is performed by finding the parameters maximizing or minimizing the function.

*10 **Gradient-based method**: A numerical computation algorithm for optimization. Computation is iterated in a direction to make a target function increase or decrease from an initial value and obtain the parameters that give the maximum or minimum value of the function.

*11 **SIC**: A MIMO signal separation method in which the multiple signals mixed in received signals are detected one by one and separated by a canceling process. Usually, it has a higher performance than the ZF (*24) or Minimum Mean Square Error (MMSE) method.

*12 **MLD**: A MIMO signal detection method in which the transmission signal pattern with a maximal likelihood is searched. It offers the highest performance, but the computation is usually of infeasible complexity for a high-dimension MIMO system.

mance.

As described in Chapter 2, the channel estimation value applied to the data symbol is obtained by interpolation. Discrete Fourier Transformation Interpolation (DFTI)[*15] outperforms simple linear interpolation, particularly in an environment of high-speed mobility where Doppler effects exist, because it can reserve the impulse response information. However, with Inverse Fast Fourier Transform (IFFT)[*16] and Fast Fourier Transform (FFT)[*17], discontinuities of pilot signals in the time and frequency domains cause the edge effect, which degrades the estimation accuracy. Our proposed 2D-EDFTI scheme takes into account the extrapolation[*18] and mitigates the effects due to pilot signal discontinuities, allowing DFTI to be applied to an actual system [7]. This method is explained in detail in another paper in this Special Article [8].

3.4 Overview of Highly Efficient Burst Frame Synchronization Technology

Random access communication systems that use short bursts, such as wireless LANs, are highly efficient in handling data packets, which is increasingly important with the convergence of future cellular networks and wireless LAN. When short bursts are received, burst detection, timing synchronization and frequency offset compensation[*19] must be completed within a short time-duration as compared to the burst. The points listed below are important aspects in the design of the synchronization method.

- Highly accurate timing synchronization/frequency offset compensation through exploiting a short preamble[*20]
- Feasible computational complexity
- Sufficiently low preamble Peak to Average Power Ratio (PAPR)[*21]
- Avoidance of interference between synchronization signals between users
- Facilitating the channel estimation and Signal to Noise Ratio (SNR) estimation

In this project, we developed a new synchronization method that combines delay correlation and symmetry correlation on the basis of those design policies [9]. We also verified the feasibility and effect with testbed. This method is explained in detail in another paper in this Special Article [10].

3.5 Overview of Adaptive MIMO Precoding

Link adaptation[*22] is already used to improve channel efficiency in radio systems. In MIMO transmission, even greater transmission efficiency can be achieved by adaptively changing the precoding method according to channel conditions.

Adaptive transmission generally requires information feedback from the receiving side. In the system design, the following points have to be considered.

- Trade-off between amount of feedback and transmission characteristics
- Feedback delay and channel fluctuation compensation
- Robustness against channel estimation error and interference
- Balance of minimum unit of resource allocation and quantity of allocation control messages
- Meeting the requirements of the duplex[*23] scheme (Time Division Duplex (TDD)/ Frequency Division Duplex (FDD))

The methods that have so far been proposed in this field include a rank adaptation method that uses adaptive spatial-time coding [11], a method that increases the time or frequency domain diversity effect [12], and a feedback signal optimization method when Zero Forcing (ZF)[*24] precoding is applied to downlink MU-MIMO [13].

4. Overview of the MIMO-OFDM Testbed

In addition to evaluating the methods described above by theoretical

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*13 **Pipeline structure**: A structure that allows parallel processing for efficient use of multiple processing units by each unit successively working as a pipeline in each clock cycle. That allows more efficient use of hardware resources and improved processing throughput.

*14 **ASESS**: A MIMO signal detection method developed by NTT DOCOMO that can reduce the computational complexity of conventional QRM-MLD to about 1/4.

*15 **DFTI**: A method of obtaining interpolation via a DFT.

*16 **IFFT**:A fast algorithm for converting discrete frequency domain data into discrete time domain data.

*17 **FFT**: A fast algorithm for converting discrete time domain data into discrete frequency domain data.

*18 **Extrapolation**: Using discrete data obtained by measurement or other means to estimate values that lie outside the range of that data.

*19 **Frequency offset compensation**: Processing that compensates deviation from the reference frequency/phase caused by radio propagation.

analysis and computer simulation, we also tested the feasibility and effects of the DOM, 2D-EDFTI and high-performance burst-frame synchronization techniques in real-time operation on a MIMO testbed.

The testbed allows evaluation in a more realistic environment. The results are also obtained faster than with computer simulation, rich and valuable information for a further improvement of the algorithms can be obtained from experimental data. Implementation in hardware also makes it possible to precisely re-evaluate the implementation complexity for the proposed algorithm.

This testbed has the following features.

- A general-purpose Field Programmable Gate Array (FPGA)[*25]/Digital Signal Processor (DSP)[*26] board is used for the baseband digital signal processing. Also, the development environment runs on Windows®[*27], and the transmitting and receiving methods can be replaced instantly by downloading a design file to the FPGA boards.
- Having a development environment with Graphical User Interface (GUI) entry methods allows a more efficient module design of the required sophisticated functions than a conventional hardware design environment, and reduces the skill level required on the developers.
- Some of control parameters can be set on-line in real time. The intermediate results at each stage of the signal processing can be displayed on a host computer and on some instruments in real time, and recorded on a hard drive as well.

The basic configuration of the testbed is shown in **Figure 1**. The transmitter consists of a source data generator, source encoder, transmitter baseband processing unit and transmitter Radio Frequency (RF) unit. The receiver has an RF unit, baseband processing unit, source decoder, packet error-rate monitor (for analyzing and measuring the quality of the received signal) and a received data display. In the experiment, the channel simulator[*28] can emulate 4×4 MIMO channels with up to 24-paths per channel. In addition to developing the MIMO transmitter and receiver, we developed functions for real-time measurement and display of the received signal constellation[*29],

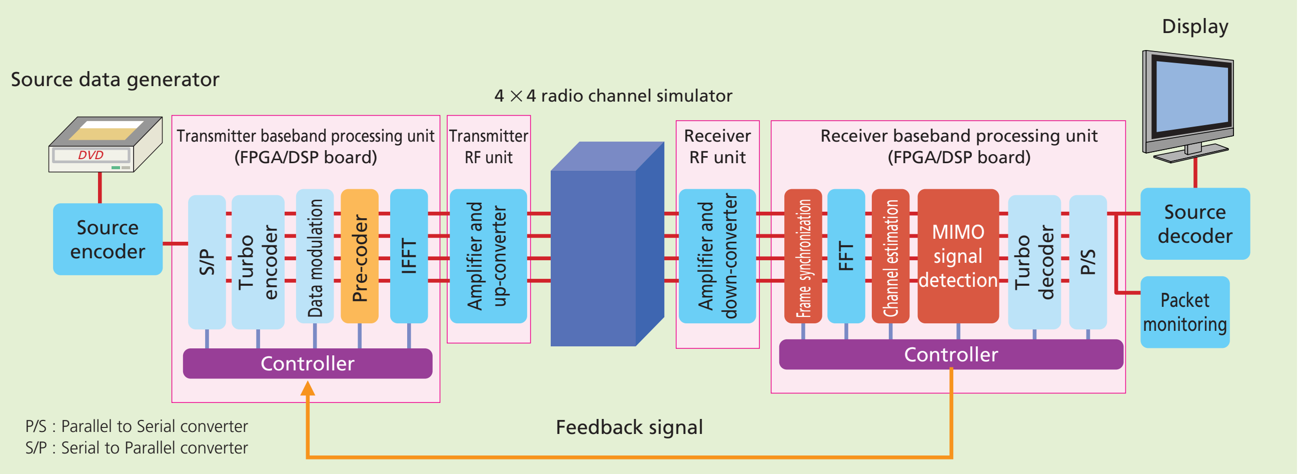

Figure 1 MIMO-OFDM testbed configuration

*20 **Preamble**: A fixed signal pattern that is placed at the beginning of a packet. On the receiving side, it is used for packet detection, gain control, frame synchronization, and frequency synchronization, etc. to prepare for reception of the data part.

*21 **PAPR**: The ratio of the maximum power to the average power. If this value is large, the amplifier power back-off has to be large to avoid nonlinear distortion, which is particularly problematic for mobile terminals.

*22 **Link adaptation**: A technique with adaptive transmission parameters such as number of multi-value modulation values, coding rate, power and MIMO precoding, according to radio channel conditions and QoS requirements.

*23 **Duplex**: A communication methodology for bidirectional communication. Schemes include TDD and FDD, according to the multiplexing method.

*24 **ZF**: A detection method that multiplies the received signal by the inverse of the wireless channel matrix.

*25 **FPGA**: An LSI whose logic can be freely designed.

*26 **DSP**: A processor specialized for processing digital signals.

SNR and error rate. We also designed special data exchange functions for high-volume data and control signal exchange between the boards.

The setup of the MIMO-OFDM testbed is shown in **Photo 1**. So far, we have implemented 4×4 MIMO-OFDM transmission with Quadrature Amplitude Modulation (16QAM)[*30] on the testbed, with a maximum spectrum efficiency of 14 bit/s/Hz. We implemented the proposed technologies, such as MAP-DOM, 2D-EDFTI and burst-frame synchronization described in Chapter 3, verifying these techniques, discovering new issues and further improving the algorithms.

5. Conclusion

There are many important issues to be studied in the radio interface design of IMT-Advanced and future mobile communication systems. Among them, the DOCOMO Beijing Labs have been focusing on advanced MIMO signal detection techniques, multiple-user radio resource allocation methodology, accurate MIMO channel estimation and enhanced cell cooperation techniques. We have also developed a MIMO radio verification platform for 4×4 MIMO-OFDM transmission and continued on to verification testing for original MIMO signal detection, channel estimation and synchronization techniques.

In future work, we will continue to

Photo 1 Testbed external view

*27 **Windows®**: A registered trademark or trademark of the Microsoft Corporation in the United States and other countries.

*28 **Channel simulator**: A device that simulates radio channels in real time.

*29 **Constellation**: The digitally modulated symbol pattern, usually represented in a two-dimensional plane with the X axis for the in-phase component and the Y axis for the orthogonal (Quadrature phase) component.

*30 **16QAM**: A digital modulation scheme in which the signal is transmitted in symbols defined by a 16-pattern set. Each component is of different phase and amplitude.

develop the hardware verification platform, to verify techniques for closed-loop MIMO precoding, MU-MIMO, and base station cooperative MIMO*31, contributing to future mobile communication systems.

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*31 **Base station cooperative MIMO**: MIMO transmission method in which multiple base stations cooperate to improve communication quality, particularly, for users on the edge of the cell.