OFDM | Channel Estimation | DFT Interpolation

Technology Reports

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

Channel Estimation by 2D-Enhanced DFT Interpolation Supporting High-speed Movement

Targeting broadband mobile communications by MIMO-OFDM, we have developed a channel estimation method based on 2D-Enhanced DFT Interpolation that can perform high-accuracy channel estimation in environments featuring high-speed movement. We have shown this method to be effective by a testbed.

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1. Introduction

In wireless channels, the accurate estimation of channel information that indicates attenuation and phase rotation in the transmit signal is critical for decoding the receive signal without errors. Furthermore, given that future systems as typified by IMT-Advanced will need to increase the number of antennas in Multiple Input Multiple Output (MIMO)[*1] transmission to achieve even higher spectral efficiency [1], channel estimation[*2] will have to be even more accurate since, in some MIMO signal detection methods, errors in signal detection caused by errors in channel estimation will affect signal detection in other antennas.

The use of high carrier frequencies and wide bandwidths in future systems is also expected to make a system more vulnerable to variations in selective fading[*3] in both the frequency domain and time domain. In general, channel estimation makes use of pilot signals[*4] that have a known pattern and that are discrete with respect to time and frequency. In data demodulation, the system performs two-dimensional interpolation on channel information estimated at each pilot signal position and then applies the channel-estimated values obtained by the above interpolation at the data positions to demodulate.

Conventional channel estimation methods based on Two Dimensional-Linear Interpolation (2D-LI) or its enhanced scheme, while easy to implement, can not necessarily achieve sufficient estimation accuracy especially in environments featuring high-speed movement. On the other hand, Two Dimensional-Discrete Fourier Transform Interpolation (2D-DFTI)[*5] [2][3] can perform interpolation while retaining multipath channel[*6] characteristics, i.e. the Doppler spectrum[*7], and the delay profile[*8] enabling high-accuracy estimation even during high-speed movement. However, for packet trans-

*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 **Channel estimation**: The process of estimating the amount of attenuation and phase rotation acquired by the signal while propagating via the wireless channel. Estimated values so obtained (channel information) are used on the receive side for separating MIMO signals and performing demodulation as well as for optimizing the transmit signal.

*3 **Selective fading**: Signal fading in which fluctuation in amplitude and phase differs by frequency and time due to multipath effects in which time-delay differences are large and high mobility.

mission by Orthogonal Frequency Division Multiplexing (OFDM)[*9], virtual subcarriers, Direct Current (DC) components, and signal burst characteristics make it impossible to prevent signal discontinuities in the frequency and time domains. On applying a Fourier transform or inverse Fourier transform to such a discontinuous signal, the signal will oscillate about the discontinuous points due to the Gibbs phenomenon (Gibbs artifact) causing the accuracy of channel estimation to drop.

In response to this issue, we developed Two Dimensional-Enhanced Discrete Fourier Transform Interpolation (2D-EDFTI) with the aim of preventing this performance degradation caused by the Gibbs phenomenon and demonstrated its effectiveness through simulations and experiments. This research was performed as part of the Adaptive Packet Radio Transmission (APRT) project at DOCOMO Beijing Labs.

In this article, we first outline a channel estimation method based on 2D-EDFTI that can prevent degradation in the accuracy of channel estimation under high-speed movement. We then describe its implementation on a testbed and present the results of an evaluation experiment.

2. MIMO-OFDM System Model

The configuration of a Single-User (SU)-MIMO-OFDM testbed is shown in **Figure 1**. Here, the MIMO system uses four antennas at both the transmitter and receiver and adopts open-loop spatial multiplexing[*10]. The data flow is the same for each antenna: pilot signals are inserted, OFDM modulation is performed, and data is transmitted independent of the other antennas. The wireless channel is affected by two-dimensional selective fading in the frequency and time domains due to multipath propagation and mobility. Transmission is performed in bursts, and on the receive side, processing begins with frame synchronization using preamble[*11] signals at the beginning of each frame. The system then performs a DFT on the signal at each antenna, extracts the pilot signals, and performs channel estimation and interpolation. Finally, it uses the results so obtained to detect the MIMO signals.

The frame structure used in the experiment is shown in **Figure 2**. One frame consists of 32 OFDM symbols with the first three symbols being preambles for Automatic Gain Control (AGC)[*12] and synchronization. Eight of the remaining 29 symbols are pilot symbols with the rest being data symbols.

It is common in OFDM transmission systems to set the output of the subcarriers at either end of the band to 0 and to not use them for actual signal transmission to suppress out-of-band

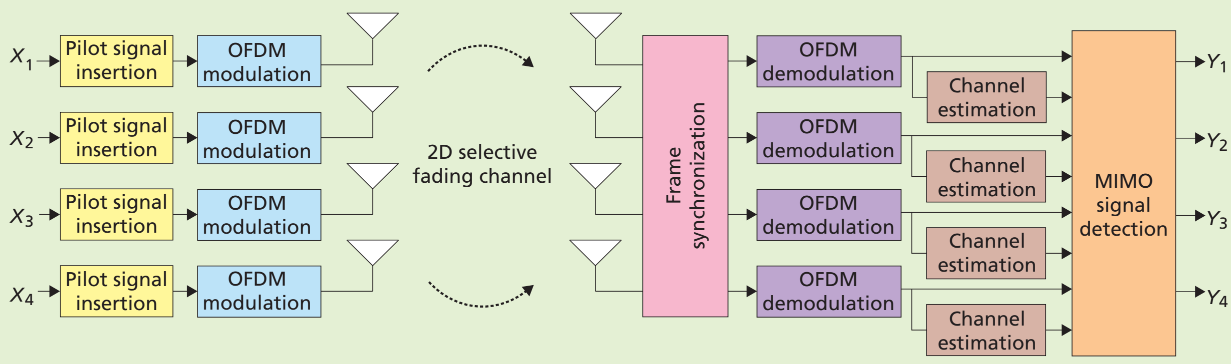

Figure 1 4×4 SU-MIMO-OFDM testbed configuration

*4 **Pilot signal**: A signal having a pattern decided on beforehand between the transmit and receive sides. The receiver uses that signal to estimate channel information (amount of attenuation and phase rotation). The symbols transmitted in the pilot signal are called pilot symbols.

*5 **2D-DFTI**: An interpolation method using a Discrete Fourier Transform (DFT) and IDFT (see *14) in the two dimensions of time and frequency.

*6 **Multipath channel**: Radio waves emitted from a transmitter include waves that directly arrive at the receiver plus other waves that arrive later after reflecting off the ground, buildings and other objects. A radio channel in which radio waves reach the receiver via multiple paths in this way is called a multipath channel.

*7 **Doppler spectrum**: In a multipath channel, each path has a different direction of arrival, and as a result, the Doppler shift, which occurs due to movement, takes on a broad distribution. The power distribution of this Doppler shift is called the Doppler spectrum.

*8 **Delay profile**: In a multipath channel, delay has a temporally broad distribution since the paths of reflected waves differ in length. The power distribution corresponding to this delay time is called a delay profile.

radiation[*13]. These are called virtual subcarriers (or guard subcarrier). The center subcarrier is also not used with its output set to 0 to prevent a DC component. The relationship between these virtual subcarriers, DC component, and subcarrier number is shown in **Figure 3**. Here, the subcarrier number corresponds to k in the following equation for an Inverse Discrete Fourier Transform (IDFT)[*14] in accordance with the image of IDFT implementation. For $k = 0$, it can be seen that the exponential term is 1 resulting in a DC component.

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k)\, e^{j\left(\frac{2\pi}{N}\right)nk} \qquad (1)$$

In equation (1), n is a sampling point in the time domain, N is number of samplings, $x(n)$ is time-domain data, and $X(k)$ is frequency-domain data. In terms of actual frequencies, frequencies increase in the order of 1 - 450 and decrease in the order of 574 - 1,023 centered about subcarrier number 0.

The pilot signal arrangement pattern is shown in **Figure 4**. Pilot signals are transmitted separately from the four antennas using different subcarriers to prevent mutual interference. Data signals are transmitted simultaneously from the four antennas. To apply DFT interpolation, pilot signals must be arranged at fixed intervals in both the time and frequency directions.

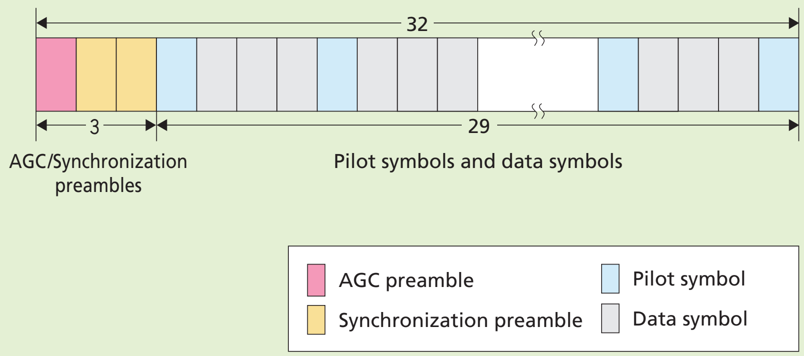

Figure 2 Frame structure used in experiments

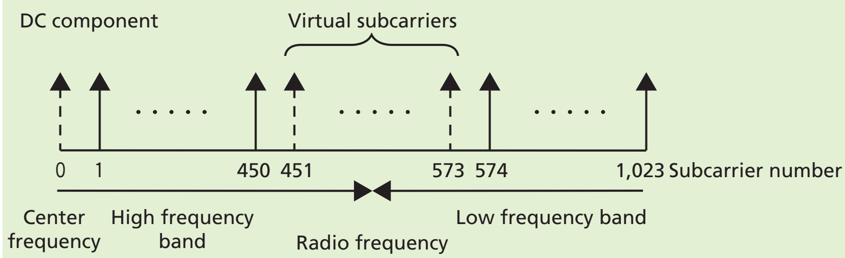

Figure 3 Arrangement of virtual subcarriers

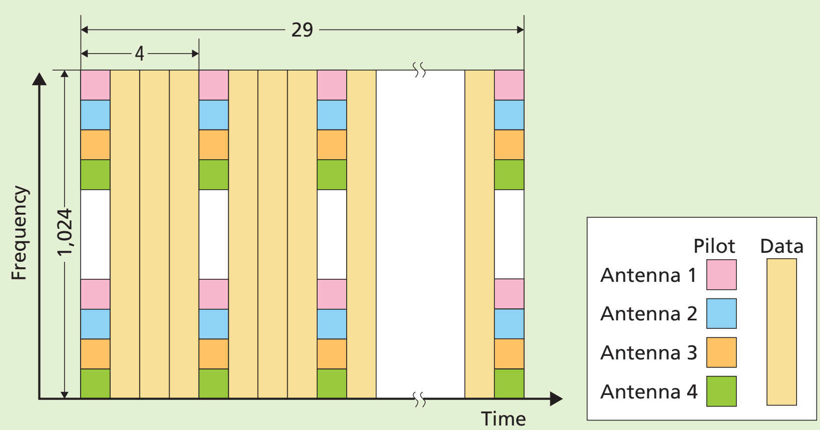

Figure 4 Pilot signal arrangement pattern

*9 **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.

*10 **Open-loop spatial multiplexing**: MIMO transmission using spatial multiplexing with no feedback system.

*11 **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.

*12 **AGC**: A function for automatically adjusting amplification so that the amplitude of the output signal is constant.

*13 **Out-of-band radiation**: Emission of power outside the frequency band allocated for communications.

*14 **IDFT**: An inverse discrete Fourier transform used to convert discrete data in the frequency domain to discrete data in the time domain.

3. 2D-EDFTI

Performing signal detection in a 4×4 MIMO system requires that channel estimation be performed on 16 independent wireless channels corresponding to all possible combinations of transmit and receive antennas.

Channel estimation is first performed at pilot signal positions arranged intermittently with respect to time and frequency. Here, the effects of noise and interference can give rise to errors. With 2D-DFTI, the multipath channel characteristics, i.e. the Doppler spectrum and the delay profile, will be retained, while the effects of noise and interference can be suppressed by deleting these factors on the channel impulse response[*15], which results in high estimation accuracy.

After the system performs 2D-DFTI in the time domain and frequency domain using the estimated values obtained from the positions of each pilot signal, channel-estimation values at each data position can be obtained. In 2D-DFTI, interpolation is performed while effectively raising sampling frequency by 0 insertion, and as this has no effect on IDFT or DFT values, interpolation can be performed at high accuracy while retaining the Doppler spectrum and delay profile. However, when discontinuities exist in the time and frequency domains, estimation accuracy drops due to the Gibbs phenomenon as mentioned earlier. To solve this issue, we proposed and developed 2D-EDFTI [4][5] in the APRT project. The process flow of 2D-EDFTI is shown in **Figure 5**. The entire process consists of the following four steps.

1) Step 1: Compensate for Discontinuities (Frequency Domain)

We first perform a DFT and then apply the Least Squares (LS)[*16] method to each pilot signal for channel estimation. Letting P_t denote the number of pilot symbols within one frame and P_f the number of pilot signals for each antenna within one pilot symbol, the estimated value is the $P_f \times P_t$ matrix denoted as CFR_{Pilot}.

Next, to compensate for the discontinuities in the frequency domain, we interpolate virtual channel estimated values by linear interpolation at the

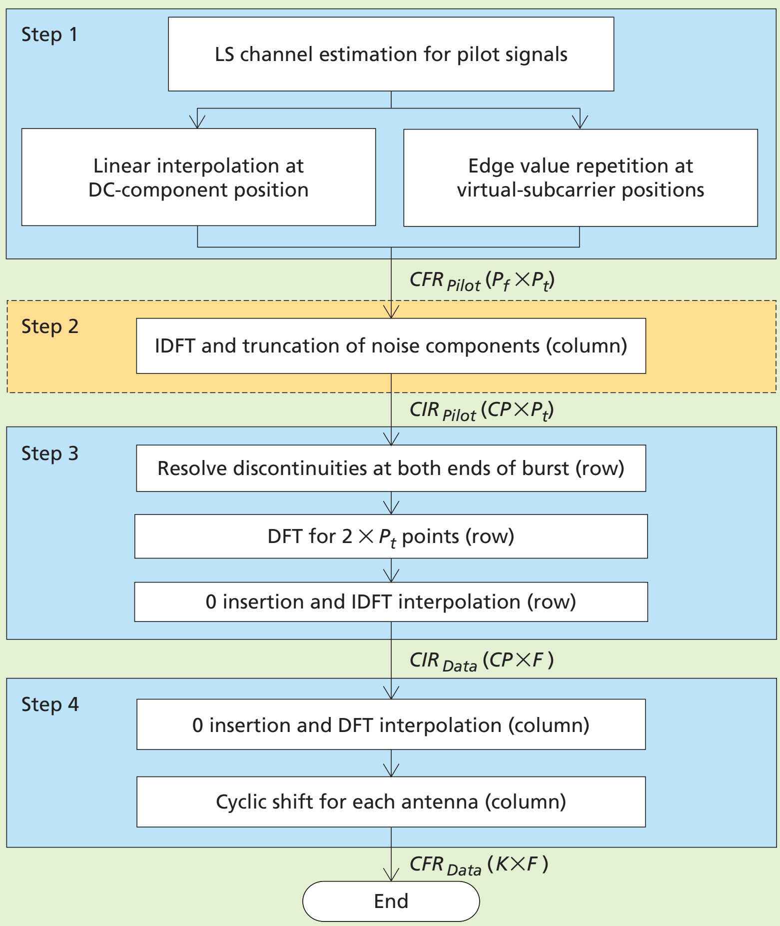

Figure 5 2D-EDFTI process flow

*15 **Channel impulse response**: The signal response when inputting an impulse signal in a multipath channel; multiple impulses each corresponding to a different path and having its own delay time, attenuation, and phase rotation can be measured in the time domain.

*16 **LS**: A method for determining an estimated value by minimizing the sum of squares of offsets between that value and measured values.

position of the lost DC-component and by edge value repetition at the positions of the virtual subcarriers (**Figure 6**). This mitigates the effects of distortion by the Gibbs phenomenon on meaningful signal sections.

2) Step 2: Truncate Noise Components

Each column of the CFR_{Pilot} indicates the channel frequency response within the same OFDM symbol. Performing an IDFT at P_f points against this vector enables the channel impulse response to be obtained. In general, the power of a delayed wave attenuates exponentially with time. The accuracy of channel estimation can therefore be raised even higher by extracting only the wave's leading portion and truncating the remaining portion governed by noise. Letting Cyclic Prefix (CP) denote the number of extracted time samples, we get a $CP \times P_t$ matrix denoted as CIR_{Pilot}.

3) Step 3: Compensate for Discontinuities and Interpolation (Time Domain)

Each row of the CIR_{Pilot} obtained in Step 2 indicates channel changes in the time domain, but if data is transmitted in units of frames, discontinuities will appear at both ends of the frame. To obtain a periodic signal here, we splice the original vector with a vector of reverse order (as if reflecting the original vector in a mirror) and then perform a DFT on $2 \times P_t$ points (**Figure 7**). We now perform 0 insertion followed by IDFT to obtain time sampling equivalent to F number of symbols excluding preamble within one frame. Since the zero insertion performed here has no effect on IDFT values, Doppler spectrum information is retained as is. The results of this processing gives a $CP \times F$ matrix denoted as CIR_{Data}.

4) Step 4: Interpolation in the Frequency Domain

Finally, to interpolate in the frequency domain, we perform zero insertion so that each column of CIR_{Data} has the same number of subcarriers K and perform a DFT. We then perform a cyclic shift for each antenna in accordance with pilot signal position and obtain a $K \times F$ matrix denoted as CFR_{Data} thereby completing all channel estimation and interpolation. Delay profile information is retained as is in this process.

4. Evaluation Experiment

Basic system parameters used in the experiment are shown in **Table 1** and the hardware configuration implement-

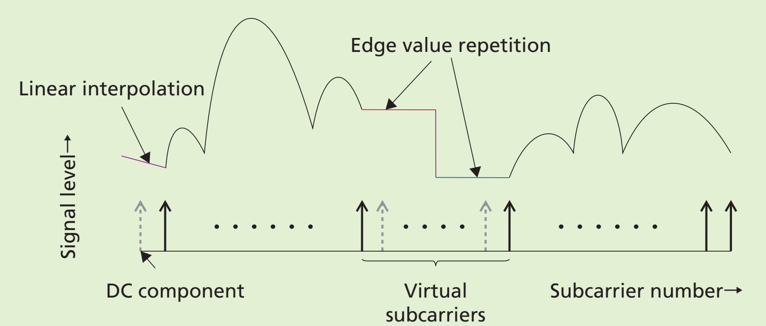

Figure 6 Resolving discontinuities in frequency domain

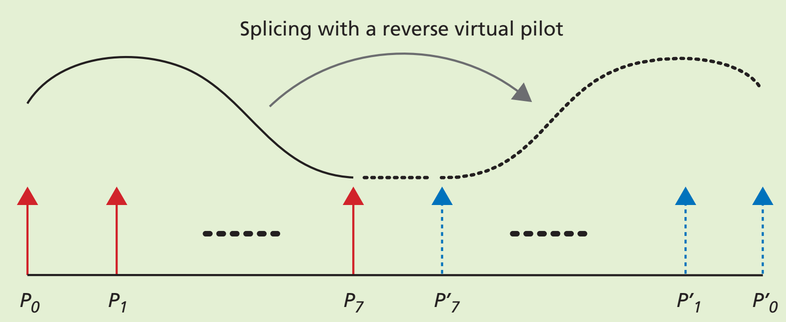

Figure 7 Resolving discontinuities in time domain

ing 2D-EDFTI is shown in **Figure 8**. In this evaluation, we used 3GPP TR 25.996 [6] Case 2 as the channel model. We modularized the processing part for DFT/IDFT - the core of the algorithm - for the sake of design efficiency and reliability. We also used techniques like parallel processing, pipeline processing[*17], and multiplexed signal processing[*18] to reduce process delays and use hardware resources more efficiently. Images of 16 Quadrature Amplitude Modulation (QAM) data symbol constellations[*19] after MIMO signal separation are shown in **Figure 9**. Here, we used Zero Forcing (ZF)[*20] in signal separation and compared results between two channel estimation methods: the widely used 2D-LI and the proposed 2D-EDFTI.

As can be seen in Fig. 9, signal points when using 2D-LI start to collapse as the speed of movement increases and become hardly recognizable at 120 km/h. In contrast, signal points when using 2D-EDFTI exhibit little degradation at 30 km/h and are still recognizable at 120 km/h. One reason why the accuracy of channel estimation degrades when using 2D-LI is that severe undulation in the fluctuation of doubly-selective fading during high-speed movement degrades the accuracy of timing synchronization. With 2D-EDFTI, on the other hand, estimation accuracy can be maintained since timing synchronization errors will not affect characteristics greatly as long as they are within the CP. Furthermore, 2D-EDFTI can suppress more noise

Table 1 System parameters

Parameter	Value
Carrier frequency	2.35 GHz
Bandwidth	6.25 MHz, 12.5 MHz
MIMO	4×4 spatial multiplexing
Frame length	32 symbols
Number of subcarriers	1,024
Number of virtual subcarriers	128
CP	96 samples
P_f	256
P_t	8
Modulation system	BPSK (pilot) 16QAM (data)
Channel estimation	2D-LI, 2D-EDFTI
MIMO detection method	ZF, DOM
Channel model	3GPP TR 25.996 Case2 3 km/h, 30 km/h, 120 km/h

BPSK: Binary Phase Shift Keying

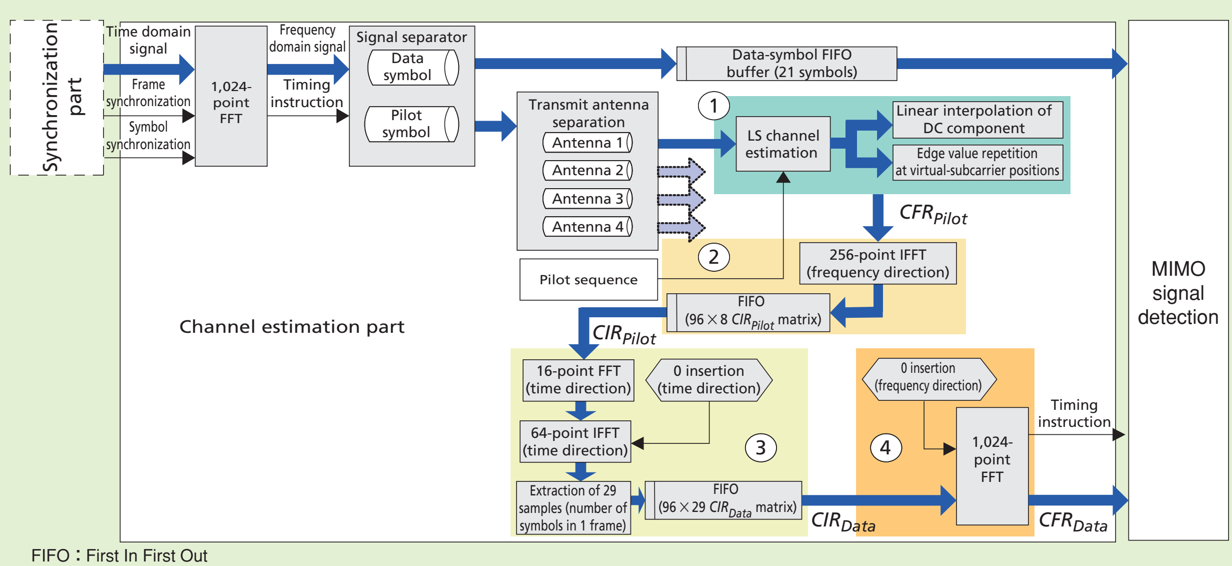

Figure 8 Hardware configuration of channel estimation part based on 2D-EDFTI

*17 **Pipeline processing**: The insertion of an instruction in each unit of a processor every clock cycle to achieve parallel execution, which achieves more efficient use of hardware resources and faster processing.

*18 **Multiplexed signal processing**: In this article, the processing of modules having different clocks by a single FPGA to use hardware resources more effectively.

*19 **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.

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

than 2D-LI in channel estimation.

Measurement results for Bit Error Rate (BER) versus Signal to Noise Ratio (SNR) are shown in **Figure 10**. These results show bit-stream characteristics before channel coding[*21] at speeds of movement from 3 - 120 km/h. It can be seen here that 2D-EDFTI exhibits better characteristics than 2D-LI under all conditions. The two methods also diverge as the speed of movement increases further demonstrating the superiority of the proposed method. Indeed, in a 120 km/h environment, 2D-EDFTI combined with simple ZF detection has better BER characteristics than 2D-LI combined with Dynamic Ordering M-paths MIMO detection (DOM)[*22], a MIMO detection algorithm based on Successive Interference Cancellation (SIC). This shows that the accuracy of channel estimation has a great effect on MIMO-detection characteristics. If accurate channel estimation cannot be performed, even the application of an advanced MIMO detection algorithm will not enable the intrinsic superiority of MIMO systems to be demonstrated.

5. Conclusion

This article described a high-accuracy channel estimation method based on 2D-EDFTI. This method can be applied to actual systems by virtue of suppressing the Gibbs phenomenon. Evaluation experiments performed on a testbed showed that the method can achieve high estimation accuracy even in a doubly-selective fading environment in both the time and frequency domains and that it is robust with

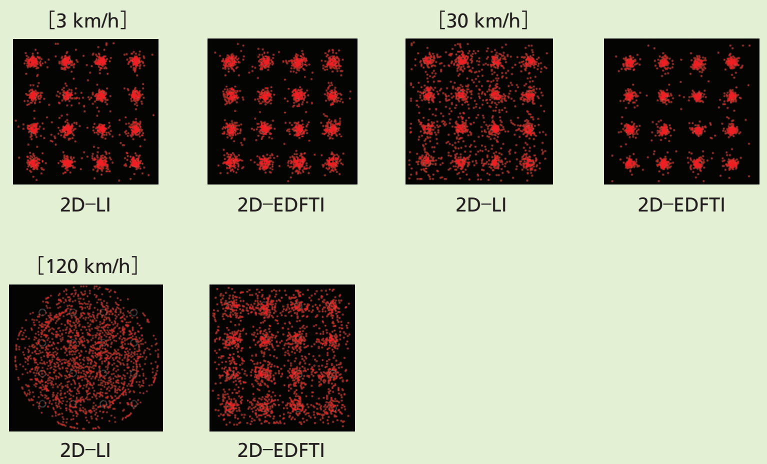

Figure 9 16QAM constellation

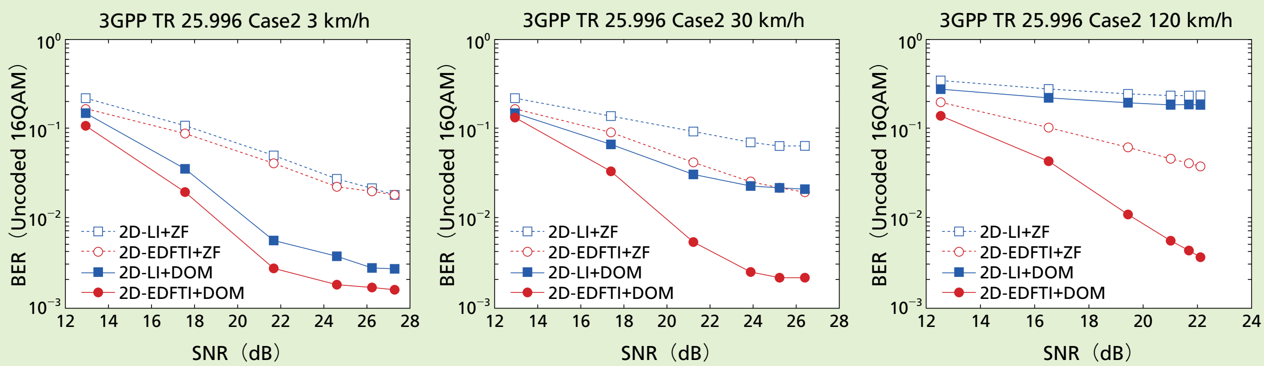

Figure 10 BER vs. SNR for various speeds of movement

*21 **Channel coding**: Transmission-path coding that gives transmit data redundant bits to enable the receive side to perform error detection and correction; typical channel-coding schemes include Turbo and Low Density Parity Check (LDPC).

*22 **DOM**: A MIMO signal detection algorithm developed by DOCOMO Beijing Labs that combines an interference canceller with multi-path searching.

respect to high-speed movement. We expect this technology to be applied to future IMT-Advanced systems to provide high-quality MIMO-OFDM transmission in environments having high-speed movement.

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