Multi Site MIMO Channel Analysis at 4.85GHz in Outdoor Environment

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Abstract—Multiple-Input Multiple-Output (MIMO) system has been actively investigated to enhance wireless data transmission in outdoor environments. Micro/Macro-cell services such as WLAN/WiMAX have been much attention because they achieve a high throughput. Since proliferation of these services are expected, base stations (BSs) need to be located at various heights and locations in outdoor environments. Although many publications have reported measurements of the channel state information (CSI) in outdoor environments, the relationship between the BS heights or locations and the transmission performance in MIMO systems has not yet been fully investigated. Moreover, when the number of BSs increases per area, inter-cell interference problem occurs. Such an interference deteriorates the communication quality. In this paper, the experiment is conducted in urban area, in Japan, and the CSI was obtained using 4x4 MIMO-OFDM signals. We present signal to noise ratio (SNR), channel capacity and eigenvalues in MIMO channels, when the BS heights and locations are changed. We clarify that eigenvalues are one of important parameters for not only the channel capacity in MIMO channels but also inter-cell interference by the analysis using the measured MIMO channels.

Keywords-component: MIMO, outdoor environment, base station height and location, inter-cell interference, capacity, SNR, eigenvalue, cellular system,

I. INTRODUCTION

Multiple-Input Multiple-Output (MIMO) is expected to enhance wireless data transmissions even without increasing the bandwidth [1],[2]. MIMO can increase the channel capacity in proportion to the number of antennas in a multipath environment [3],[4]. However, a multipath-rich environment generates strong fading. To mitigate this fading effect, the combination of orthogonal frequency division multiplexing (OFDM) and MIMO technologies (MIMO-OFDM) has emerged. References [5]-[7] present MIMO OFDM system designs and measurements.

As outdoor wireless communication systems, the cellular systems are well known. On the other hand, the use of WLAN and WiMAX of micro/macro-cell wireless systems has recently become more popular. Hence, various scenarios should be considered in outdoor MIMO systems. There have been reports on measurements concerning outdoor MIMO system [8]-[11]. However, the relationship between the base station (BS) heights or locations and transmission performance has not yet been clarified.

Furthermore, the conventional studies for MIMO channel measurements generally deal with only single cell environment. As the microcell wireless systems become widespread, inter-cell interference among the multiple BSs increases. Thus, investigation of inter-cell interference corresponding to the deployment at BS (e.g., height and location) is also required for the future outdoor MIMO systems.

In this paper, as a basic study into multi-site scenarios, a MIMO channel analysis is conducted at several BS heights for two BS sites. A Channel State Information (CSI) measurement experiment is conducted in urban area, in Japan. We use four transmitter antennas and four receiver antennas: 4x4 MIMO scenario is considered. The BSs are located in two places and the channel measurements are conducted corresponding to three heights for each BS. The CSI between the Mobile Terminals (MTs) and BSs is obtained using 4x4 MIMO OFDM transmission with 104 subcarriers in a 1.56 kHz bandwidth. The center frequency is 4.85 GHz, which is near frequency with wireless LAN systems such as IEEE802.11a/n. We analyzed the SNR, channel capacity, and eigenvalues of the channel matrices. Moreover, we evaluate the effect of the interference to a neighboring cell by evaluating the eigenvalues, which are obtained by the CSI in a MIMO channel.

This paper is organized as follows. In Section II, the measurement environment is described. Section III shows the signal to noise ratio (SNR) characteristics in two different BSs and three different antenna heights at each BS. Section IV presents the analysis of the channel capacity and eigenvalue characteristics for mitigating inter-cell interference. Finally, our conclusions are given in Section V.

II. MEASUREMENT ENVIRONMENT

This section describes the measurement testbed and a definition concerning the results which are obtained by using the measured CSI. Fig.1 shows the configuration of MIMO measurement testbed. Since the transmitter and receiver comprise four antennas each, and we obtain 4x4 MIMO-OFDM channel matrices. The transmitter continuously transmits short and long preambles based on the IEEE802.11a standard. The preambles are modified for an outdoor
environment. The length of the guard interval (GI) is four times that specified in the IEEE802.11a standard and a 128-point Fast Fourier Transform (FFT) is used. The received signal is stored by the receiver and the channel matrices are obtained through offline processing.

A. Measurement Site and Equipment

To analyze the MIMO channel based on different BS heights and locations, an experiment is carried out in the Yokkaichi area using the MIMO-OFDM testbed. Fig.2 shows a map of the measurement area. BS1 and BS2 are located at the southern and northern edges of the measurement course, respectively. The channel matrices are obtained using a vehicle along courses A and B. Fig.3 shows photographs of the BS configuration, MT and measurement site as viewed from the BS1. The BS antennas are placed at the height of 7, 13, or 19 m. The BS antennas are patch antennas configured in a straight line array, the 3-dB beamwidth is 90 degrees, and the BS antenna spacing is one wavelength. The MT antennas are mounted on top of the vehicle at the height of 2 m. The MT antenna comprises monopole antennas in a circular array and the MT antenna spacing is 0.5 wavelengths. Both the BS and MT emit vertically-polarized waves. Table I gives the experiment parameters. The frequency of 4.85 GHz is used for this measurement and the 4x4 channel matrices are obtained with 104 subcarriers. The bandwidth for each subcarrier is 157.5 KHz.

<table>
<thead>
<tr>
<th>TABLE I. MEASUREMENT PARAMETERS</th>
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<tr>
<td>Center frequency [GHz]</td>
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<tr>
<td>Bandwidth [MHz]</td>
</tr>
<tr>
<td>BS antenna</td>
</tr>
<tr>
<td>MT antenna</td>
</tr>
<tr>
<td>Sampling rate (A/D) [MHz]</td>
</tr>
<tr>
<td>Sampling rate (D/A) [MHz]</td>
</tr>
<tr>
<td>Number of subcarriers</td>
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<td>Subcarrier interval [kHz]</td>
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</table>

Figure 1. Configuration of measurement testbed

Figure 2. Measurement environment

Figure 3. Photographs of BS, MT, measurement site. (a) BS antenna, (b) MT antenna, (c) MT site, (d) view of course from BS1.
B. MIMO Channel Capacity

We consider a MIMO-OFDM system with four transmitter antennas and four receiver antennas. At the i-th subcarrier, the received signal, \( y_i \in \mathbb{C}^{4 \times 1} \), is given by

\[
y_i = H_i x_i + n_i,
\]

where \( x_i \in \mathbb{C}^{4 \times 1} \) is the transmission signal, \( n_i \in \mathbb{C}^{4 \times 1} \) represents zero mean, the complex Additive White Gaussian Noise (AWGN) with a covariance matrix \( \sigma^2 I \), where \( (.)^H \) denotes the conjugate transpose of the corresponding vector or matrix, and \( I \) represents the identity matrix. Term \( H_i \) is the 4\times4 channel matrix. The expectation and variance of the element of the transmitted signal, \( x_i \), are defined to be zero and one, respectively.

When the respective numbers of the transmitter antennas and receiver antennas are four, the MIMO channel capacity at the i-th subcarrier, \( C_i \), is described using the channel matrix as follows.

\[
C_i = \log_2 \left( \det \left( I + \frac{H_i H_i^H}{4\sigma^2} \right) \right)
\]

where \( \det [A] \) denotes the determinant of \( A \), \( \lambda_{ij} \) is the i-th eigenvalue at the i-th subcarrier, and \( \lambda_{1,1} > \lambda_{2,2} > \lambda_{3,3} > \lambda_{4,4} \). We define the channel capacity using one OFDM signal as

\[
C = \frac{1}{N_c} \sum_{i=1}^{N_c} C_i,
\]

where \( N_c \) is the number of subcarriers. The SNR is calculated as

\[
S = \frac{1}{N_c} \sum_{i=1}^{N_c} \| H_i \|^2_F
\]

where \( \| . \|_F \) denotes the Hermitian transposition.

III. SNR MEASUREMENT RESULTS

A. COST Walfish-Ikegami (COST W-I) model

We evaluated the SNR by using the COST Walfish-Ikegami (COST W-I) model (street canyon model) [12]. The COST W-I model realistically characterizes the ground reflections because it is based on measurements. Although it was originally designed for frequencies up to 2 GHz, we used an extended model which can evaluate 5 GHz band [13].

The key parameter extended in the extended COST W-I model is given by

\[
L = L_0 + L_{\text{rt}} + L_{\text{msd}},
\]

where \( L_0 \) is the free space path loss, \( L_{\text{rt}} \) is the rooftop to street diffraction and scatter loss, and \( L_{\text{msd}} \) is the multiscreen diffraction loss. Each parameter is expressed as

\[
L_0 = 20 \log \left( \frac{4\pi d}{\lambda_0} \right),
\]

\[
L_{\text{rt}} = -16.9 - 10 \log w + 10 \log f + 20 \log (h_{\text{build}} - h_m)
\]

\[
+ \begin{cases} -10 + 0.354\varphi & 0^\circ \leq \varphi < 35^\circ \\ 2.5 + 0.075(\varphi - 35) & 35^\circ \leq \varphi < 55^\circ \\ 4.0 - 0.114(\varphi - 55) & 55^\circ \leq \varphi < 90^\circ \end{cases}
\]

and

\[
L_{\text{msd}} = -18 \log \left( 1 + (h_b - h_m) \right) + 54 + 18 \log d - 9 \log b
\]

respectively, where \( d \) is the distance from the transmitter to receiver, \( \lambda_0 \) is the wavelength, \( w \) is the road width, \( f \) is the frequency, \( h_{\text{build}} \) is the average building height, \( h_m \) is the MT height, \( \varphi \) is the angle between the line of sight (LOS) and the road, \( h_b \) is the BS height, and \( b \) is the building separation. \( h_{\text{build}} \) and \( \varphi \) are given by an actual map information in Fig. 2. Table II gives the extended COST W-I model parameters in the measurement courses.

B. Evaluation of SNR

Figs. 4 and 5 show the measured SNRs at BS1 and BS2, respectively, corresponding to the BS height of 19 m, 13 m, and 7 m. The SNR distribution derived using the extended COST W-I model is also shown in Figs. 4 and 5 by dotted line. The distance from the respective start points of each course is represented on the horizontal axis. The figures show that the SNR degradation becomes large as the BS height decreases. The SNR distribution Fig. 4 agrees well with the extended COST W-I model. However, Fig. 4 shows that the SNR at the height of 19 m, 13 m, and 7 m stray from the extended COST W-I model when the distance is far than 850 m, 550 m and 400 m, respectively. When the distance between the BS and the MT becomes far, the measured SNR is less than that estimated using the extended COST W-I model. It is this reason that the power of LOS path is decreased. On the other hand

<table>
<thead>
<tr>
<th>Table II. COST W-I Model Parameters in the YOKKAICHI CITY</th>
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<tr>
<td>Type of city</td>
</tr>
<tr>
<td>Frequency [GHz]</td>
</tr>
<tr>
<td>BS height [m]</td>
</tr>
<tr>
<td>Average height of surrounding buildings [m]</td>
</tr>
<tr>
<td>MT height [m]</td>
</tr>
<tr>
<td>Road to radio path [degree]</td>
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<tr>
<td>Road width [m]</td>
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</tbody>
</table>
Fig. 4. SNR for each height of BS1

Fig. 5. SNR for each height of BS2

Fig. 6. Capacity for each height of BS1

Fig. 7. Capacity for each height of BS2

hand, Fig. 5 shows that the propagation environment is strayed from the extended COST 207 model. This is due to two reasons. The first reason is that there is the building in front of BS2. The buildings between the measurement course and BS2 interrupt the LOS path. The second reason is the cable loss. The measured channel matrices at BS2 are much less than those at BS1 due to the long feeding cables.

IV. MIMO CHANNEL ANALYSIS

A. MIMO Capacity Evaluation

Figs. 6 and 7 show the MIMO capacity for BS1 and BS2, respectively. As can be seen in Figs. 6 and 7, we find that the capacity also depends on the BS height similar to the SNR. However, there are some differences between the SNR and the capacity. In Fig. 6, maximum capacity at BS height of 7 m is 5.5 and 7.4 bit/sec/Hz greater than those at the BS height of 13 m and 19 m, respectively, and there are relatively few local peaks compared to the SNR distribution. Since the maximum SNR at the BS height of 7 m is only 3 dB greater than those at the BS height of 13 m and 19 m, the BS at a low location enables multi-cell MIMO systems in LOS environment. Fig. 7 shows that when the BS height is 19 m, the locations at which the maximum capacity is obtained are different from the locations where the maximum SNR is obtained. The capacity at the height of 7 m is less than those at the height of 13 m and 19 m. These figures show that the capacity distribution is very important in the design of communication cells in MIMO-OFDM, because the channel capacity is expressed by not only SNR but also multiple eigenvalues as shown in Eqn.(3). Hence the analysis of eigenvalues is very important.

The SNR and capacity distributions also indicate the inter-cell interference distribution. In other words, these figures show that the cell radius becomes large as the height increases. In the next subsection, we clarify this characteristic by using the analysis of eigenvalues.

B. Evaluation of Eigenvalue Distribution

To investigate the inter-cell interference, the eigenvalues of the channel matrices are calculated. Figs. 9 to 11 show the eigenvalue distribution for BS1 at the height of 19 m, 13 m, and 7 m, respectively. These figures show that the first eigenvalue is strongly correlated to the SNR distribution. However, the second to fourth eigenvalues are not less subject to the local peak of the SNR than the first eigenvalue. Furthermore, the ratio of the first eigenvalue to the other eigenvalues becomes large as the distance increases. These eigenvalues distributions give information concerning inter-cell interference in MIMO communication systems. At the communication cell edge, the second to fourth eigenvalues can
be negligible compared to the noise (0dB). Thus, only first eigenvalue affects on the inter-cell interference to next cell. The channel capacity distribution is insusceptible to local SNR peaks. The eigenvalue analysis shows that only the first eigenvalue is correlated to the SNR distribution and the ratio of the first eigenvalue to the other eigenvalues becomes large as the distance between the BS and the MT increases. These results indicate that the ratio of the first eigenvalue to the other eigenvalues becomes large as the distance increase. Hence, we found that the eigenvalue is an important parameter to consider inter-cell interference. We clarify that eigenvalues are one of important parameters for not only the channel capacity in MIMO channels but also inter-cell interference by the analysis using the measured MIMO channels.

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V. CONCLUSION

In this paper, we presented a MIMO channel analysis using CSI measured in an outdoor environment. The SNR, channel capacity, and eigenvalues were evaluated in two different BSs and three different antenna heights at each BS. We found that the SNR distribution at the height of 19 m agrees well with that derived using the extended COST W-I model. On the other hand, we clarified that the SNR of measured data becomes lower than that of extended COST W-I model at the cell edge.

\[\begin{align*}
\text{Figure 8. Eigenvalue distribution for BS1 at 7m} \\
\text{Figure 9. Eigenvalue distribution for BS1 at 13m} \\
\text{Figure 10. Eigenvalue distribution for BS1 at 19m}
\end{align*}\]