MUTUAL INFORMATION OF MIMO SYSTEM IN A CORRIDOR ENVIRONMENT BASED ON DOUBLE DIRECTIONAL CHANNEL MEASUREMENT

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Abstract—Double directional channel measurements were made in a corridor environment with a channel sounder. A multidimensional high resolution algorithm was used to extract channel parameters for calculating the mutual information of a special Multiple-Input Multiple-Output (MIMO) system. This system utilized bidirectional dual-polarized antennas at both ends of the communication. In a corridor environment, the mutual information of this system was 12 b/s/Hz higher than that of the other MIMO system equipped with traditional 1λ horizontally-spaced vertically-polarized dipole array antennas. Depolarization of the vertical polarization transmission degraded the mutual information of the dipole array antennas in this environment. The angular spread of the incoming signals at the receiver ranged from 0.9° to 3.8° depending on the distance between the transmitter and the receiver.

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1. INTRODUCTION

Multiple-Input Multiple-Output (MIMO) systems play an important role in high speed wireless communications since it can increase data rate without increasing the frequency spectrum or transmitted power [1–5]. They usually use spatially separated antennas with single polarization, but large separation between antennas is needed to achieve uncorrelated channels. When space is limited, small, spatially separated antennas can not provide significant independent channels; hence, polarization diversity antennas are introduced to solve the problem [6,7]. Additionally, as far as radiation pattern is concerned, dipole antennas with omnidirectional radiation pattern are used successfully in many wireless communication systems. However, for certain types of area such as in a corridor, where it is desirable to be able to communicate effectively along its maximum distance, omnidirectional radiation pattern does not give satisfactory result. Therefore, the use of transmitting antennas with bidirectional radiation pattern is proposed.

To assess the performance of MIMO systems in real propagation channel, accurate characteristics of the channel are required. A number of research studies have tried to explain the behavior of corridor channel. Most of them used ray optical models based on electromagnetic simulation [8,9]. However, since the real propagation environments can not be completely modeled by electromagnetic simulation, the environment can be modeled by propagation measurement. The double directional channel measurement was proposed which the properties of the propagation channel were independent of the measurement antennas [10]. The parameters of multipath can be accurately estimated by parametric estimation algorithms. The results of corridor channel characteristics by double directional measurements were reported in [11] where the number of multipath clusters, angular and delay spreads in the environment were presented. Since the application of polarization diversity antennas in MIMO system design proves to be useful, it is necessary to study its polarization behavior in a corridor environment.

In this paper, we present a double directional channel measurement in a corridor. Multipath parameters including polarimetric path weight matrix, Direction of Departure (DoD) at the transmitting site, Direction of Arrival (DoA) at the receiving site, and path delay are extracted from the sounding measurement data. Depolarization of signal was studied in terms of cross polarization power ratio ($XPR$) [12,13]. Angular power spectrum and angular spread of incoming signal in a corridor environment
were also investigated. The extracted multipath parameters can be used in combination with the directivity of any assessed antennas to create a complete channel model like the evaluation approach in [14]. Consequently, the mutual information that corresponds to these channel responses can be obtained. Here, the mutual information of a MIMO system with $0^\circ/90^\circ$ dual-polarized bidirectional antenna and $1\lambda$ horizontally-spaced vertically-polarized dipole array antennas are compared with each other.

2. MATERIAL AND METHOD

2.1. Double Directional Channel Measurement

The channel measurement was conducted in a corridor. The layout and photograph are shown in Fig. 1(a) and Fig. 1(b), respectively. The width of the corridor is 2 m and the length is 64 m, with lecture rooms along both sides. The walls along the corridor and between the rooms were made of reinforced concrete with wooden office doors. The floor was rubber sheets on concrete and the ceiling was covered with metal grid (approximately 50 cm gap between the metal grid and the concrete layer). The height of the corridor was 2.45 cm. There were metal pipes beneath the metal grid. A wideband measurement was performed in the 5 GHz band using the Medav RUSK-Fujitsu MIMO channel sounder [15]. The periodic multi-frequency test signal used in the measurement had a repetition period of 0.8 $\mu$s and a bandwidth of 120 MHz. The measurement was based on MIMO channel with a polarimetric rectangular array antenna as the transmitting antenna (Tx) and a stacked uniform polarimetric circular patch array antenna as the receiving antenna (Rx). For every position in the measurements, the transmitting antenna height is 180 cm and the receiving antenna height is 115 cm. The transmitted power in all measurements was fixed at 30 dBm and the time interval of the MIMO switch was 1 ms. Because the transmitting power was restricted by the transmission license, the Tx and Rx were separated only at a maximum distance of 26 m. All of the locations measured represented the Line-of-Sight (LoS) scenarios where the Tx-Rx separation varied from 26 m to 16 m. These separations corresponded to Rx1 to Rx4 in Fig. 1. The Tx was fixed at the location marked as “Tx” in Fig. 1. It should be noted that there was an emergency door 5 m behind the Tx. The Rx azimuth equals $0^\circ$ was pointing at the Tx at all locations. For all measurements, dual-polarized elements were used in both transmitting and receiving array antennas to obtain a polarization matrix of the environment. The complex frequency responses were computed on-line and stored into the sounder’s hard disk for subsequent off-line post-
processing. At each point in the measurement, 500 snapshots were taken. During the measurement, people were not allowed to move around in order to keep the channel static. The Tx and Rx antennas were de-embedded from the channel response for estimation of the parameters. In order to obtain a correct extraction of the multipath parameters, the Tx and Rx had to be properly synchronized in time and frequency. This was done by connecting the Tx and Rx units via optical fibers. Moreover, the effect of signal propagation through the cable and the signal processing delays were eliminated by doing back-to-back calibration. The complex frequency response data from the sounding measurement was processed off-line by using the RIMAX algorithm [16], a multi-dimensional maximum likelihood algorithm, to extract the multipath parameters.

Figure 1. Location of sounding measurements. (a) Layout. (b) Photograph.

2.2. Mutual Information Calculation

Since mutual information is a random variable that depends on instantaneous channel, the Cumulative Distribution Function (CDF) of mutual information can be obtained from measurements with slightly displaced arrays or with temporally varied scatterer arrangement. However, these complex measurement techniques can be replaced by...
a simple evaluation method that requires only a single measurement (single snapshot) of the channel [14]. This method uses the fact that different realizations of the channel are generated as the phases of multipath components change. These phases are uniformly distributed random variables that occur when the transmitter, receiver, or scatterers move in the channel. The transfer function of a $2 \times 2$ MIMO system with single polarization is shown in [14]. However, for a $2 \times 2$ MIMO system with dual-polarized antennas at both ends, the different realizations of the transfer function of the different polarized transmitting and receiving antennas are

\[ H(t, \tau) = \int \int \int \int E_R(\Omega_R) \times \Gamma(t, \tau, \Omega_R, \Omega_T) \times E_T^H(\Omega_T) d\Omega_R d\Omega_T \]

\[ = \sum_{l=1}^{L} \begin{bmatrix} e_{R\theta_1}(\Omega_{Rl}) & e_{R\varphi_1}(\Omega_{Rl}) \\ e_{R\theta_2}(\Omega_{Rl}) & e_{R\varphi_2}(\Omega_{Rl}) \\ \vdots & \vdots \\ e_{R\theta_N}(\Omega_{Rl}) & e_{R\varphi_N}(\Omega_{Rl}) \end{bmatrix} \cdot \begin{bmatrix} \gamma_{pp}^{\varphi} & \gamma_{pq}^{\varphi} \\ \gamma_{qp}^{\varphi} & \gamma_{qq}^{\varphi} \end{bmatrix} \cdot \begin{bmatrix} e_{T\theta_1}^{*}(\Omega_{Tl}) \\ e_{T\varphi_2}^{*}(\Omega_{Tl}) \end{bmatrix} \]

(1)

$l$ is the index of estimated paths and $L$ is the total number of estimated paths. $\Gamma$ is the different path weights which are complex polarimetric path weights $\gamma_{pp}^{\varphi}$, $\gamma_{pq}^{\varphi}$, $\gamma_{qp}^{\varphi}$, and $\gamma_{qq}^{\varphi}$ for the different transmitting and receiving polarizations. The first and second subscripts indicate the polarization at the receiver and transmitter ends, respectively, where $p$ and $q$ are the vertical and horizontal polarizations. $E_R$ and $E_T$ are the complex radiation patterns of the receiving and transmitting antennas, respectively. $\Omega = (\theta, \varphi)$ where $\theta$ and $\varphi$ are the azimuth and elevation directions. $\tau$ is the delay different multipath number $k$.

Referring to [2, 17], the uncorrelated channels for the MIMO system can be found by using the Singular Value Decomposition (SVD) of the channel matrix $H$. It should be noted that water filling was not used to calculate the uncorrelated channels of the channel matrix $H$ since power assigned to the channel remains unaltered whether channel conditions are favorable or not. From Shannon’s theorem [18], the mutual information of a uniform power transmission per unit frequency or the spectral efficiency measured in b/s/Hz of parallel channels can be calculated [1, 2, 17].
3. RESULTS

3.1. Channel Characteristics

To investigate the depolarization of the signal in the corridor environment, we used the cross polarization power ratio (XPR) [12, 13] term of each detected path. The centroid of the cross polarization power ratio (XPRC) and the spread of the cross polarization power ratio (XPRS) were calculated at each measured point and used to evaluate the depolarization of the environment.

The XPRC and XPRS results are shown in Table 1. The XPRC_V results of vertical polarization were mainly positive except at Rx1 where there was depolarization. As for the results of the XPRC_H of horizontal polarizations, depolarizations could be observed at Rx1 and Rx2 but there were no depolarizations at Rx3 and Rx4. The XPRS of 2 to 7 dB could be observed in both polarizations. The angular spreads at the front of the receiver in the corridor environment, shown in Table 1, varied from 0.9° to 3.8°. This result agreed well with the measurement reported in [11]. These XPRC and angular spread had an influence on the mutual information of the investigated antennas. The discrete azimuth angular power spectrums at Rx1 for vertical and horizontal polarizations are shown in Figs. 2(a) and 2(b), respectively. They have bidirectional patterns which were similar to the shape of the corridor. Hence, it can be concluded that a bidirectional radiation pattern antenna is suitable for this environment. The directions of significant paths, i.e., paths with high path gain, were in the azimuth direction of 0° and 180°. The nearly 180° path was the transmission path whose signals passed over the receiver and then reflected back from the wall behind it. As shown in Table 1, the result on F/B, which are the ratios of the incoming signal in the 0° direction to the incoming signal in the 180° direction, shows that the signal strength in the front direction was significantly strong at all points measured.

Table 1. Angular spread, XPRC, XPRS, and Front-to-Back ratio (F/B).

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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Front</td>
<td>Back</td>
</tr>
<tr>
<td>Rx1</td>
<td>−0.3</td>
<td>−1.8</td>
<td>6.7</td>
<td>7.2</td>
<td>3.8°</td>
<td>4.2°</td>
</tr>
<tr>
<td>Rx2</td>
<td>2.6</td>
<td>−0.9</td>
<td>4.8</td>
<td>5.5</td>
<td>1.2°</td>
<td>3.2°</td>
</tr>
<tr>
<td>Rx3</td>
<td>5.7</td>
<td>2.3</td>
<td>3.4</td>
<td>3.8</td>
<td>1.1°</td>
<td>2.9°</td>
</tr>
<tr>
<td>Rx4</td>
<td>7.2</td>
<td>6.5</td>
<td>2.3</td>
<td>2.1</td>
<td>0.9°</td>
<td>2.7°</td>
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The measured discrete angular power spectrums at Rx2, Rx3, and Rx4 were similar to those in Fig. 2 and so not illustrated.

### 3.2. Bidirectional Dual-Polarized Antenna

A bidirectional dual-polarized antenna was used for evaluation in this corridor environment. The antenna parameters were the ring radius ($a$), ring width ($d$), and probe length ($l$) which was the same for both excited probes as shown in Fig. 3. The angle between the two probes was fixed at $90^\circ$. The maximum gain, return loss, and isolation of the antenna were adjusted by varying the antenna parameters to achieve the desired antenna characteristics [19]. The antenna was equipped with probe 1 on the $+z$-axis to provide vertical polarization and probe 2 on the $-y$-axis to provide horizontal polarization. Both probes were of the same length ($l$) of $0.25\lambda$, following the design in [20]. These two probes excited the two apertures perpendicular to the $x$-axis and provided a bidirectional radiation pattern along the $+x$-axis and the $-x$-axis. When the antenna was placed on the ceiling of the corridor, its bidirectional radiation pattern covered the length of the corridor along the $x$-axis. Maximum gains were required in the directions $\phi = 0^\circ$ and $\phi = 180^\circ$ to provide maximum coverage distance of the area. Ring radius of $0.30\lambda$ (1.73 cm) and ring width of $0.40\lambda$ (2.31 cm) were used to fabricate the prototype antenna.

![Figure 2. Received angular power spectrums at Rx1. (a) Vertical polarization. (b) Horizontal polarization.](image-url)
Figure 3. Configuration of a bidirectional dual-polarized antenna.

Figure 4. Measured S-parameters of the bidirectional dual-polarized antenna.

Figure 5. Radiation patterns in the $xy$-plane of the bidirectional dual-polarized antenna. (a) Probe 1 was excited, probe 2 was terminated. (b) Probe 2 was excited, probe 1 was terminated.

Figure 4 shows the $S$-parameters of the antennas over the 4–7 GHz band. The bandwidth, with VSWR at less than 2:1, was 1600 MHz for this proposed antenna and, consequently, the impedance bandwidth was wide. Specifically, over the operating bandwidth of 5.15–5.25 GHz, the antenna yielded return loss and isolation of more than 40 dB
and 10 dB, respectively. Figs. 5(a) and 5(b) show the measured and simulated radiation patterns in the $xy$-plane of the antenna when probe 1 and probe 2 were excited, respectively. The antenna possessed a bidirectional pattern with cross polarization of less than 10 dB.

### 3.3. Mutual Information

Two sets of Tx-Rx antennas are compared in this section, namely, the bidirectional dual-polarized antennas and the dipole array antennas at both the Tx and Rx ends. Uncorrelated paths were obtained from the eigenvalues of the SVD approach. Usually, the MIMO channel mutual information reported by most of the existing studies was investigated under a constant received power condition [1, 6, 17]. However, in order to evaluate the effect of antenna gain on mutual information, power allocation was not used in this calculation. Power in each channel and noise power were calculated from the transmitted power levels and the noise floor of the receiver according to IEEE Std 802.11a [21]. For the 5.15 to 5.25 GHz band, the total maximum output power was equal to 40 mW. Since each transmitter transmitted an independent data stream of power, we have power in each channel equals 20 mW or 13 dBm. According to IEEE Std 802.11a, the noise figure of the receiver was equal to 10 dB, noise power was equal to $-91$ dBm over the 20 MHz bandwidth. Finally, by using power in each channel, noise power and eigenvalues, mutual information was obtained. From the value of above power in each channel and noise power, the calculated Signal to Noise Ratio (SNR) was 104 dB which was rather high from the SNR used in an optimal power allocation system. However, these power in each channel and noise power are actually used in WLAN IEEE 802.11a. In the calculation of mutual information of the bidirectional dual-polarized antenna and the dipole array antennas, the same values of power in each channel and noise power were used.

#### Table 2. Comparison of 10% outage mutual information (b/s/Hz) of the antennas.

<table>
<thead>
<tr>
<th>Rx</th>
<th>Mutual information [b/s/Hz]</th>
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<tr>
<td></td>
<td>Bidirectional Antenna</td>
</tr>
<tr>
<td>Rx1</td>
<td>30.2</td>
</tr>
<tr>
<td>Rx2</td>
<td>31.2</td>
</tr>
<tr>
<td>Rx3</td>
<td>32.1</td>
</tr>
<tr>
<td>Rx4</td>
<td>36.0</td>
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</table>
The mutual information of the bidirectional dual-polarized antenna and the dipole array antennas at 10% outage probability and at all measurement points are shown in Table 2. At Rx1, the bidirectional dual-polarized antenna provided higher mutual information than the dipole array antennas did due to the corresponding radiation pattern with the angular power spectrums. In addition, there was the depolarization of the vertical polarization at Rx1 where the transmitted vertical polarization signals turned into a horizontal polarization in this corridor environment. Hence, the receiving vertical polarization dipole array antennas received cross polarization. At other Rx positions (Rx2, Rx3 and Rx4) the mutual information from the dual-polarized antenna was higher than that from the dipole array antennas since the average angular spread at these Rx positions was very small. The performance of spatially-spaced MIMO systems degrade when their incoming signal angular spread is small such as in a line-of-sight environment [22, 23]. Mutual information increases as the distance between the transmitter and the receiver decreases due to stronger received signal as the receiver approaches the transmitter. It should be pointed out that bidirectional dual-polarized antenna is suitable for a corridor environment where the angular spread is small and depolarization exists.

4. CONCLUSION

This paper presents the results of double directional channel measurements in a corridor environment by channel sounder. Channel properties, especially polarization, in a corridor are determined from $XPRC$, $XPRS$, angular spread and angular power spectrum. The obtained channel multipath parameters, i.e., DoA, DoD, TDoA and polarimetric path weight are calculated with antenna directivity to produce MIMO channel model of arbitrary antenna. Then, mutual information of arbitrary antenna in a corridor environment can be investigated. It can be observed that the reflection along the corridor established the small spread of the incoming signal. Measurement results exhibit the bidirectional shape of the received angular power spectrum. It was found that depolarization of both vertical and horizontal polarizations should be concerned in installing the antenna in the corridor. For instance, traditional dipole antenna may be installed with tilt angle to achieve good communication performance when distance between Tx and Rx is in excess of 20m. A dual polarized antenna is a good candidate to resolve depolarization of vertical polarization in the corridor environment. Furthermore, the bidirectional antenna is suitable for the bidirectional angular power
spectrum in the corridor environment. It was illustrated that the bidirectional dual-polarized antenna provides 66.67% higher mutual information than the dipole array antennas over the same SNR value. It is noted that this result is for $2 \times 2$ array antenna; however, the result maybe different for larger array. This increased mutual information enhances data rate in high-speed modern wireless communications.

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