Cluster Polarization Behavior of a MIMO System: Measurement, Modeling and Statistical Validation of the Correlation of its Channel Parameters

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Abstract—This paper presents clusterwise polarization characteristics based on an estimated MIMO channel of a small urban macrocell at 4.5 GHz. Polarization path gain, cross-polarization ratio, and co-polarization ratio characteristics as influenced by channel parameters such as delay, azimuth and elevation angle of arrival were investigated. Hypothesis testing was used as a verification of the results. This statistical verification clarifies the independence of polarization characteristics from an azimuth angle of arrival, whereas some correlation was found between the cross-polarization ratio and the elevation angle of arrival. The results also confirmed a log-normal cross-polarization ratio.

I. INTRODUCTION

Multiple-input-multiple-output (MIMO) wireless systems have attracted a lot of attention as a key technology to achieve high data rates [1], [2]. However, using only spatial diversity has disadvantages in terms of the size limitations especially at the mobile terminal. In this regard, the adoption of dual-polarized arrays has been proposed to enable polarization diversity as well [3], [4]. Moreover, since advantages of MIMO systems are exploited in multipath-rich environments, knowing the multipath channel, including the effect of depolarization through the channel, plays a key role in realistic system design. Given the above, polarimetric measurement results have been presented so far (e.g. [5], [6]). Although existing models provide some information about depolarization, validation of the results were not sufficient. In this paper, relations between polarization characteristics of an estimated MIMO channel and other channel parameters are presented together with their statistical validations. In particular, the polarization path gain and polarization ratio are examined. The estimated channel was derived from a small urban macrocell at 4.5 GHz and it is based on the double-directional channel model [7]. Multipath cluster parameters are the primary consideration of the analysis since their polarization behavior is also seen as an effect on the interaction of multipaths with scatterers in the environment. The rest of the paper is organized as follows. Section II describes the measurement scenario and the equipment used, followed by a brief description of the channel estimation and clusterization performed. In Section III the results are presented and analyzed and afterwards conclusions are drawn in Section IV.

TABLE I
RUSK-FUJITSU WIDEBAND MIMO CHANNEL SOUNDER [8]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>4.5 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>120 MHz</td>
</tr>
<tr>
<td>BS antenna array</td>
<td>Uniform rectangular array</td>
</tr>
<tr>
<td>BS patch element</td>
<td>3-dB VP beamwidth: 101° / 89°</td>
</tr>
<tr>
<td></td>
<td>3-dB HP beamwidth: 86° / 94°</td>
</tr>
<tr>
<td></td>
<td>Main lobe gain: &gt; 5 dBi</td>
</tr>
<tr>
<td></td>
<td>XPD: 13-15 dB</td>
</tr>
<tr>
<td>MS antenna array</td>
<td>Stacked uniform circular array</td>
</tr>
<tr>
<td>MS patch element</td>
<td>3-dB VP beamwidth: 122° / 86°</td>
</tr>
<tr>
<td></td>
<td>3-dB HP beamwidth: 61° / 89°</td>
</tr>
<tr>
<td></td>
<td>Main lobe gain: &gt; 4 dBi</td>
</tr>
<tr>
<td></td>
<td>XPD: 10-14 dB</td>
</tr>
<tr>
<td>Transmit signal</td>
<td>Wideband multitone</td>
</tr>
<tr>
<td>Max. delay setting</td>
<td>3.2 μs</td>
</tr>
<tr>
<td>No. of MIMO channels</td>
<td>1536</td>
</tr>
<tr>
<td>V / H vertical / horizontal polarization</td>
<td>V-polarized port / H-polarized port</td>
</tr>
<tr>
<td>V / H beamwidth</td>
<td>V-plane</td>
</tr>
<tr>
<td>V / H col. beamwidth</td>
<td>H-plane</td>
</tr>
</tbody>
</table>

II. MEASUREMENT

A. Channel Sounder and Environment

Channel sounding was performed using the RUSK channel sounder. Important specifications of this sounder are placed in Table I. The antenna arrays that were used were carefully calibrated in an anechoic chamber. This channel sounder has a switched-array architecture, which uses fast switches at both ends of the channel. Reference clocks at both base station (BS) and mobile station (MS) ensure timing and switching synchronization throughout the measurement.

Figure 1 shows the small urban macrocell environment that was considered. The BS antenna was placed on top of the highest building in the measurement area, where the average building height around it was less than half its height. For the MS positions, they were placed along the street. Details of the measurement setup are shown in Table II.
### TABLE II
**SMALL URBAN MACROCELL SCENARIO**

| BS height | ∼85 m |
| MS height | ∼1.80 m |
| BS-MS distance | ∼230 m - 400 m |
| Structure type | residential and industrial |
| MS status | static; moving (slow walk) |
| Measurement condition | after midnight; clear spring weather |

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**B. Parameter Estimation and Multipath Clusterization**

The complex polarimetric path weights ($\gamma_{VV}$, $\gamma_{VH}$, $\gamma_{HV}$, $\gamma_{HH}$), diffuse components, delay ($\tau$), azimuth ($\phi$) and co-elevation ($\theta$) angle of departure (AoD) and angle of arrival (AoA) were estimated by a gradient-based maximum likelihood multidimensional parameter estimation approach [9]. After the parameter estimation, automatic clustering was done jointly in all the spatial and temporal dimensions. For the sake of brevity, details of the clustering algorithm are not presented here. Interested readers are referred to [10]. Only static multipath estimates were used in clustering since the goal was to examine clusters due to multipath mechanisms. So paths that represent the line of sight (LoS) were removed using the single path estimate. In the analysis that follows, the centroids of the clustered path parameters were used.

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### III. RESULTS AND DISCUSSIONS

The results of the analysis are described in terms of polarization path gain, polarization ratios, and the behavior of polarization ratios as influenced by the delay, azimuth AoA and elevation AoA.

#### A. Polarization Path Gain

For each polarization pair, the cluster path gain is plotted against the distance between the MS and BS in Fig. 2. Their best-fit curves are obtained by linear least squares. The fitted path gains in dB could be expressed as follows.

$$ P_{VV} = -22.55 \log_{10}(d) - 4.88 \quad (1) $$

$$ P_{HH} = -27.57 \log_{10}(d) + 8.21 \quad (2) $$

$$ P_{VH} = -25.81 \log_{10}(d) - 1.14 \quad (3) $$

$$ P_{HV} = -28.28 \log_{10}(d) + 5.12 \quad (4) $$

It was observed that the path gain of HH polarization pairs decay faster than that of VV polarization pairs. These copolarized path gains were 4.65 dB higher than the cross-polarized ones. Quite similar observations are reported in [11].
and [12] for different macrocell scenarios. In particular for indoor scenarios, [5] and [13] report that the HH path gain decays faster than the VV path gain. In [11], co-polarized pairs have been observed to be 4 to 10 dB higher than cross-polarized ones, whereas [12] observes a median value in this range.

**TABLE III**

<table>
<thead>
<tr>
<th>Parameter 1</th>
<th>Parameter 2</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>XPR(_{V}^{MS})</td>
<td>(\theta^{\text{AoA}})</td>
<td>-0.37</td>
</tr>
<tr>
<td>XPR(_{H}^{MS})</td>
<td>(\theta^{\text{AoA}})</td>
<td>-0.04</td>
</tr>
<tr>
<td>CPR</td>
<td>(\theta^{\text{AoA}})</td>
<td>-0.14</td>
</tr>
<tr>
<td>XPR(_{V}^{MS})</td>
<td>XPR(_{H}^{MS})</td>
<td>0.00</td>
</tr>
<tr>
<td>CPR</td>
<td>XPR(_{H}^{MS})</td>
<td>0.03</td>
</tr>
<tr>
<td>XPR(_{V}^{MS})</td>
<td>(\tau)</td>
<td>0.15</td>
</tr>
<tr>
<td>CPR</td>
<td>(\tau)</td>
<td>0.04</td>
</tr>
</tbody>
</table>

\(* \theta^{\text{AoA}} \) and \(\tau\) dependence: Linear-Liniar coefficient.
\(* \phi^{\text{AoA}} \) dependence: Linear-Circular coefficient.

**B. Cluster Polarization Ratios**

The cross-polarization ratio (XPR) indicates how much the polarization of the paths changes, whereas the co-polarization ratio (CPR) shows the degree of vertical polarization with respect to the horizontal polarization. The cluster XPRs and CPR were computed respectively as follows.

\[
XPR_{V}^{BS} = 10 \log_{10} \left( \frac{\sum_{l \in C_{k}} |\gamma_{VV,l}|^2}{\sum_{l \in C_{k}} |\gamma_{HV,l}|^2} \right) \quad (5)
\]

\[
XPR_{H}^{BS} = 10 \log_{10} \left( \frac{\sum_{l \in C_{k}} |\gamma_{HH,l}|^2}{\sum_{l \in C_{k}} |\gamma_{HV,l}|^2} \right) \quad (6)
\]

\[
XPR_{V}^{MS} = 10 \log_{10} \left( \frac{\sum_{l \in C_{k}} |\gamma_{VV,l}|^2}{\sum_{l \in C_{k}} |\gamma_{HV,l}|^2} \right) \quad (7)
\]

\[
XPR_{H}^{MS} = 10 \log_{10} \left( \frac{\sum_{l \in C_{k}} |\gamma_{HH,l}|^2}{\sum_{l \in C_{k}} |\gamma_{HV,l}|^2} \right) \quad (8)
\]

\[
CPR = 10 \log_{10} \left( \frac{\sum_{l \in C_{k}} |\gamma_{VV,l}|^2}{\sum_{l \in C_{k}} |\gamma_{HV,l}|^2} \right) \quad (9)
\]

In the notation in (5)-(8), XPR\(_{V}^{MS}\) for example, is the XPR at the MS for paths \(l\) in the \(k\)th cluster \(C_{k}\) that originated with V polarization, with the channel assumed to be reciprocal.

Figure 3 shows a comparison of the cluster polarization ratios. Low CPRs were noted to be due to prevalence of horizontal scatters in the environment considered. For the cluster XPRs, they could be considered as log-normally distributed as seen in their log-normal probability plots in Fig. 4(a)–4(c). As could be observed in Fig. 4(c), the CPR may not be log-normally distributed due to the 15% deviation in the lower tail.

To confirm the goodness of fitting between the log-normal fitting and experimental distributions, a Lilliefors test [14] has been applied for each experimental polarization ratios. The Lilliefors test is the modified version of Kolmogorov-Smirnov test (KS-test) which tests the normality of the distribution by comparing the data with a fitted log-normal distribution. This is in contrast to a Kolmogorov-Smirnov test, which requires that the null distribution must be completely specified. In the Lilliefors test, the null hypothesis \(H_{0}\) is that the experimental polarization ratio comes from a distribution in the log-normal family, against the alternative hypothesis \(H_{1}\) that it does not come from a log-normal distribution. This significance level was set to 5%. For XPR\(_{V}^{MS}\) and XPR\(_{H}^{MS}\), their null hypotheses have been satisfied so they could be judged as distributions in the log-normal family. On the other hand for CPR, null hypothesis has been rejected so it could not be judged as log-normally distributed.
C. Influence of Delay and Directions on Polarization Ratios

Figure 5 shows the individual effect of $\theta^{\text{AoA}}$, $\phi^{\text{AoA}}$ and $\tau$ on XPR. It was observed that the influence of $\theta^{\text{AoA}}$ on vertically transmitted components was stronger than their horizontal counterparts, with most of the concentration occurring from $40^\circ$-$140^\circ$. Similar results have been obtained in [15], [16]. For $\phi^{\text{AoA}}$ and $\tau$, no significant effects were observed, which has been seen in [15] and [17] as well. In the same way, the
effects of the same parameters on CPR are presented in Fig. 6. Quantifying the degree of influence among the parameters in Figs. 5 and 6 were done by calculating their correlation coefficients, which are listed in Table III. The linear-circular coefficient $\rho_{LC}$ [18] was computed as

$$\rho_{LC} = a_n \left( \sum_{m=1}^{n} \left[ \frac{m \cos \left( \frac{2\pi}{n} r_m \right) \left( \frac{2\pi}{n} r_m \right) \sum_{n=1}^{m} \sin \left( \frac{2\pi}{n} r_m \right) \right]^2 \right) \right) \right) (10)$$

where

$$a_n = \begin{cases} \frac{1}{\sum_{n=1}^{m} \frac{\sin \left( \frac{2\pi}{n} r_m \right)}{\left[ 1 + \cos \left( \frac{2\pi}{n} r_m \right) \right]^3}} & \text{if } n \text{ is even} \\ \frac{1}{\sum_{n=1}^{m} \frac{\sin \left( \frac{2\pi}{n} r_m \right)}{\left[ 1 + \cos \left( \frac{2\pi}{n} r_m \right) \right]^{2n}}} & \text{if } n \text{ is odd} \end{cases}$$ (11)

$n$ is the observation length, $m$ is the rank of the linear random variable, and $r_m$ is the circular rank of the circular random variable. For the case of this correlation (10), $0 \leq \rho_{LC} \leq 1$. As Table III indicates, most of the correlations were small. Among them, the XPR$_{MS}$ and elevation AoA had a medium correlation. However, since the multipath data that was used in Figs. 5 and 6 was based on a single environment, it would be difficult to give general observations. It should be noted that the correlation coefficient indicates only the ordinal relation. To examine the correlation among the parameters closely, it is necessary to compare the results with statistical hypothesis testing, which is presented next.

To confirm the influence of delay and directions on polarization ratios, T-test has been applied at a significance level of 5%. The T-test is a hypothesis testing used to confirm that the mean value of the experimental sample data is equal to the intended mean value in case of unknown variance. In the T-test, the null hypothesis $H_0$ is that the population correlation coefficient is equal to 0 (independent), against the alternative hypothesis $H_1$ that the parameters are dependent on each other.

Figure 7 shows the results of the T-test. Upper and lower limit indicate the correlation coefficient at a significance level of 5%. Therefore, if the test statistics are outside the limits, corresponding parameters can be judged as dependent on each other. These plots clarify the independence of polarization characteristics from azimuth angle of arrival, whereas some correlation was found between the cross-polarization ratio and the elevation angle of arrival.

IV. CONCLUSION

Multipath cluster polarization characteristics of a small urban macrocell at 4.5 GHz have been presented in this paper. The results indicate that cluster XPRs are log-normally distributed, which was not found to be true for the CPR. With respect to distance, HH polarization path gains were observed to decay faster than their VV counterparts. In the same way, both co-polarized gains were about 4.65 dB higher than cross-polarized gains. The analysis of the behavior of polarization ratios with respect to delay, and to direction shows that they are affected by elevation AoA, whereas delay and azimuth AoA do not show significant impact. These results were validated by using hypothesis testing and it showed the difference of vertical and horizontal polarization characteristics. Consistencies with other published measurements have been observed as well, nonetheless there are differences. Generalizations should be explained from the environment structure, propagation mechanism, and the inclusion of other related measurement results, which should be done in the future.

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REFERENCES