Polarimetric Beamforming Comparison of the Multipath Clusterization of ML Estimates and the Measurement Data of a MIMO Macrocell Channel

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Abstract—Clusters produced by multipath clusterization were comparatively evaluated using the directional power spectrum of the measured channel, which was obtained by polarimetric beamforming due to the dual-polarized nature of the channel sounding data. The clusters were from the results of the clusterization of maximum-likelihood-based path parameter estimates of a macrocell channel. The approach provides a way to render the physical meaning of clustering results in line with the measured data. The result shows some slight offset from the measured data, nevertheless, the cluster locations were comparable.

I. INTRODUCTION

The wireless channel plays an important aspect in multiple-input multiple output (MIMO) communication systems. Channel models that have been verified to describe the channel could contribute then to the better utilization of the wireless medium. However, as noted in [1], the verification aspect has somehow received the least attention, resulting in the limited understanding of the channel behavior. Since channel models are usually derived after several treatments of the source data (channel sounding, ray-tracing, simulations, etc.), inclusion of the verification in each treatment is also significant if a realistic channel model is the goal. For each treatment, the better approach is to compare it with the source channel. Among the steps after channel measurements is the estimation of the path parameters (e.g. [2], [3]), and then their clusterization (e.g. [4]–[6]), from which various channel models and properties can be derived by the subsequent treatments. The data treatment, however, depends on the goals. Thus, the angular power spectrum, the fading correlation, the scatterers distribution, and various propagation mechanisms can also be modeled from the parameter estimates or the measurements.

In a similar way, path-wise or cluster-wise channel descriptions must be verified, especially their physical meaning, since these path- or cluster-channel parameters could be seen as building blocks in the modeling process. In this paper, the focus is on verifying the clusters identified from the multipath clusterization of path estimates. These clusters were compared with the measured channel through the directional power spectrum seen at the mobile station (MS), which was obtained by polarimetric beamforming. The measured channel, the parameter estimation, and the clusterization are described next, and then the polarimetric beamforming approach, which is followed by the results.

II. MIMO CHANNEL DATA

A. Channel Sounding

The considered environment is a small urban macrocell in Kawasaki City, Japan, where the base station (BS) was placed on top of a building whereas the MS was moved along a street. Details of this measurement site could be found in [6]. The channel sounding campaign was done with the use of the RUSK-Fujitsu channel sounder [7]. Important details of this sounder are placed in Table I.

B. Maximum-Likelihood Estimation and Multipath Clusterization

From the measurements, the path-wise: delay (τ), BS azimuth direction (ϕBS), BS co-elevation direction (θBS), MS azimuth direction (ϕMS), MS co-elevation direction (θMS), and the four complex polarimetric weights (γHH, γVV, γHV, γVH) were extracted by maximum-likelihood (ML) estimation [8], [9]. The diffuse components were also estimated. Afterwards, the clusterization of these paths was determined by the approach proposed in [6], where the best multipath grouping were verified by the corresponding physical cluster scatterers.

III. POLARIMETRIC BEAMFORMING

In order to verify the multipath clusterization results against the measured data, the directional directional power spectrum was used since it could provide the spatial reality of the clustering structure, which would then be manifested by the measured data if the clusters were true. For this goal, a polarimetric beamforming approach is presented, which is due to the dual-polarized nature of the measured channel. Actually, the majority of the current literature treats only the vertical or a single polarization. However, [10] has shown that
biased angular spreads could be avoided if both the V and H polarizations are considered in the channel characterization.

In the following, the background in [11] is adopted. It is noted that the spatial spectrum is viewed at the locality of the MS since this is where the clusters were identified. The approach could then be outlined as follows.

- Strongest path filtering
- Cluster delay matched filtering
- Cluster BS direction spatial filtering
- Cluster polarimetric path filtering at the MS

A. Considered MIMO System Function

From the measurement, transfer functions of the channel are stored. This measured data could be represented as a dual-polarized, double-directional angle resolved, time-variant MIMO channel transfer function

$$ H_{\text{meas}}(t, f, \Omega_{\text{MS}}, \Omega_{\text{BS}}) = G(f) \sum_{l=1}^{L(t)} A_{\text{MS}}(\Omega_{\text{MS},l}) \Gamma_l A_{\text{BS}}(\Omega_{\text{BS},l}) e^{-j2\pi f \tau_l(t)} \quad (1) $$

Equation (1) is the superposition of $L$ paths described by their $\Omega_{\text{MS},l}$ and $\Omega_{\text{BS},l}$ directions, $\tau_l$ delays, and $\Gamma_l$ polarimetric path weight matrices

$$ \Gamma_l = \begin{bmatrix} \gamma_{HH,l} & \gamma_{HV,l} \\ \gamma_{HV,l} & \gamma_{VV,l} \end{bmatrix} \in \mathbb{C}^{2 \times 2}, \quad (2) $$

where $\Omega_l : (\phi_l, \theta_l)$. These path parameters $\Gamma_l$, $\tau_l$ $\Omega_{\text{MS},l}$, and $\Omega_{\text{BS},l}$ are properties of the channel. Due to the limitations of the channel sounder that was used, the Doppler-shift is not included in (1). The properties of the channel sounder are introduced to these path parameters by the $G(f)$ frequency response and the antenna array response $A_{\text{BS}}(\Omega_{\text{BS},l})$ and $A_{\text{MS}}(\Omega_{\text{MS},l})$ at the BS and MS, respectively. Their H and V polarization responses are the two vector entries as follows

$$ A_{\text{BS}} = [a_{\text{BS},H} \ a_{\text{BS},V}] \in \mathbb{C}^{M_{\text{BS}} \times 2} $$

$$ A_{\text{MS}} = [a_{\text{MS},H} \ a_{\text{MS},V}] \in \mathbb{C}^{M_{\text{MS}} \times 2} \quad (3) $$

where narrowband transmission was considered. The channel representation in (1) considers far-field propagation at $c$, which is inherently a plane-wave assumption. Thus the paths are specular in nature. In line with this, (1), however, does not explicitly reflect the diffuse components. Although the channel sounder could still capture them to some degree despite its finite resolution.

It is noted that the steering matrices (3) that were used are based on measurement and calibration in an anechoic chamber. To ensure their dual-polarized nature when used for beamforming, their H and V components are orthogonalized by thin QR factorization. So

$$ Q_{\text{MS}}(\Omega_{\text{MS}}) = [Q_{\text{MS},H} \ Q_{\text{MS},V}] $$

$$ Q_{\text{BS}}(\Omega_{\text{BS}}) = [Q_{\text{BS},H} \ Q_{\text{BS},V}] \quad (4) $$

where $Q$ is the orthogonal matrix in the decomposition of $A$.

B. Beamforming Approach

To obtain the the multipath cluster directional power spectrum, the presence of the strong or LoS (Line-of-Sight) component $l_\text{s}$ in (1) is filtered out in order to have the measured channel transfer function that represents the multipath components. Given a certain observation at the measurement time $t = m_t$, (1) becomes

$$ H(f, \Omega_{\text{MS}}, \Omega_{\text{BS}}) = H_{\text{meas}}(m_t, f, \Omega_{\text{MS}}, \Omega_{\text{BS}}). \quad (5) $$

It is assumed that the delay of $l_\text{s}$ occurs at the peak channel impulse response. So

$$ \tau_{l_\text{s}} = \arg \max_{\tau} \left\{ ||H_{\delta}(\tau, \Omega_{\text{MS}}, \Omega_{\text{BS}})||^2 \right\} \quad (6) $$

where $H_{\delta}(\tau, \Omega_{\text{MS}}, \Omega_{\text{BS}}) = F^{-1}(H(f, \Omega_{\text{MS}}, \Omega_{\text{BS}}))$. By matched filtering, the channel transfer function corresponding only to $\tau_{l_\text{s}}$ is obtained as

$$ H_{l_\text{s}}(\Omega_{\text{BS}}, \Omega_{\text{MS}}) = \xi_{l_\text{s}} H^*(f, \Omega_{\text{MS}}, \Omega_{\text{BS}}) e^{-j2\pi f \tau_{l_\text{s}}} \quad (7) $$

with $||\xi_{l_\text{s}} \cdot e^{-j2\pi f \tau_{l_\text{s}}}|| = 1$ to remove the scaling [12]. Since the interest of the comparison is the directional spectrum at the MS, the BS direction of $l_\text{s}$ is localized from its multiple-input single-output (MISO) directional spectrum

$$ \Omega_{\text{BS},l_\text{s}} = \arg \max_{\Omega_{\text{BS}}} \{ P_{\text{MISO},l_\text{s}}(\Omega_{\text{BS}}) \} \quad (8) $$

where $P_{\text{MISO},l_\text{s}}(\Omega_{\text{BS}}) = ||Q_{\text{BS}}^* (\Omega_{\text{BS}}) h_{\text{MISO},l_\text{s}}(\Omega_{\text{BS}})||^2$ is the resulting polarimetric beamforming spectra at the BS towards the MS antenna element where the received $l_\text{s}$ is strongest ($m_{\text{MS},l_\text{s}}$), that is

$$ h_{\text{MISO},l_\text{s}}(\Omega_{\text{BS}}) = H_{\delta, m_{\text{MS},l_\text{s}}}(\tau_{l_\text{s}}, \Omega_{\text{BS}}). \quad (9) $$

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### TABLE I

<table>
<thead>
<tr>
<th>Carrier frequency</th>
<th>4.5 GHz</th>
</tr>
</thead>
<tbody>
<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>2 × 4 × 2 elements (row × col. × pol.)</td>
</tr>
<tr>
<td></td>
<td>3-dB VP beamwidth: 101° / 90°</td>
</tr>
<tr>
<td></td>
<td>3-dB VP beamwidth: 89° / 90°</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>2 × 24 × 2 elements (row × col. × pol.)</td>
</tr>
<tr>
<td></td>
<td>V &amp; H polarized patch antennas</td>
</tr>
<tr>
<td></td>
<td>3-dB VP beamwidth: 122° / 86°</td>
</tr>
<tr>
<td></td>
<td>3-dB VP beamwidth: 61° / 89°</td>
</tr>
<tr>
<td></td>
<td>Main lobe gain: &gt; 4 dBi</td>
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<tr>
<td></td>
<td>XPD: 10-14 dB</td>
</tr>
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<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>
</tbody>
</table>
The spatial matched filtering of $\Omega_{BS,l_s}$ using $Q_{BS,l_s}$ yields

$$H_{l_s}(\Omega_{MS}) = H_{l_s}^*(\Omega_{BS,\Omega_{MS}}) Q_{BS}(\Omega_{BS,l_s}).$$  \((10)\)

Considering all the filtering previously described, the dimension of \((10)\) reflects the dual-polarized spatio-temporal matched filter output. This output is the response of the MS antenna array to the transmit spatio-temporal dimensions of $l_s$, given by $\Omega_{BS,l_s}$ and $\tau_{l_s}$. With this response, the $l_s$ polarimetric path weight is obtained as follows

$$\Gamma_{l_s}(\Omega_{MS}) = Q_{MS}^*(\Omega_{MS}) H_{l_s}(\Omega_{MS}).$$  \((11)\)

The MS direction of $l_s$ is then obtained from the $l_s$ directional spectrum at the MS

$$\Omega_{MS,l_s} = \arg \max_{\Omega_{MS}} \{P_{MS,l_s}(\Omega_{MS})\}$$  \((12)\)

where

$$P_{MS,l_s}(\Omega_{MS}) = |\gamma_{HH,l_s}(\Omega_{MS})|^2 + |\gamma_{HV,l_s}(\Omega_{MS})|^2 + |\gamma_{VV,l_s}(\Omega_{MS})|^2.$$  \((13)\)

The channel transfer function of $l_s$ with its obtained path parameters is then expressed as

$$H_{l_s}(f,\Omega_{MS},\Omega_{BS}) = G(f) A_{MS}(\Omega_{MS,l_s}) \Gamma_{l_s}$$

$$A_{BS}^*(\Omega_{BS,l_s}) e^{-j2\pi f \tau_{l_s}(ms)}.$$  \((14)\)

Thus \((5)\) could be rewritten as follows

$$H(f,\Omega_{MS},\Omega_{BS}) = H_{l_s}(f,\Omega_{MS},\Omega_{BS}) + H_{l_s}(f,\Omega_{MS},\Omega_{BS})$$  \((15)\)

where $H_{l_s}(f,\Omega_{MS},\Omega_{BS})$ is the channel transfer function that could represent the superposition of multipath components. Since the clustering of paths are generally regarded as those due to multipaths, though $l_s$ could also be a cluster \([13]\), it could then be supposed that the cluster of paths are in $H_{l_s}(f,\Omega_{MS},\Omega_{BS})$, i.e.

$$\Omega_{MS,l_s} = \Omega_{BS,l_s}.$$  \((16)\)

Since the purpose is to get the directional spectra of multipath clusters attained from the clusterization of ML estimates, as seen at the MS, the spectrum is obtained in a similar way as that of $l_s$ using the obtained cluster delay and BS direction centroids. From \((16)\), the matched filter output of the $k^{th}$ cluster $C_k$ is thus

$$H_{C_k}(\Omega_{MS},\Omega_{BS}) = C_{C_k} H_{C_k}^*(f,\Omega_{MS},\Omega_{BS}) e^{-j2\pi f \tau_{C_k}}$$  \((17)\)

with $\|C_{C_k} e^{-j2\pi f \tau_{C_k}}\| = 1$. Beamforming towards $\Omega_{BS,C_k}$ results in

$$H_{C_k}(\Omega_{MS}) = H_{C_k}^*(\Omega_{MS}) Q_{BS}(\Omega_{BS,C_k}).$$  \((18)\)

From this beamforming output, the dual-polarized, cluster path weight is obtained:

$$\Gamma_{C_k}(\Omega_{MS}) = Q_{MS}^*(\Omega_{MS}) H_{C_k}(\Omega_{MS}).$$  \((19)\)

Accordingly, the cluster directional spectrum viewed at the MS is:

$$P_{MS,C}(\Omega_{MS}) = \sum_{C_k} |\gamma_{HH,C_k}(\Omega_{MS})|^2 + |\gamma_{HV,C_k}(\Omega_{MS})|^2 + |\gamma_{VV,C_k}(\Omega_{MS})|^2.$$  \((20)\)

The directional power spectrum obtained by polarimetric beamforming could provide a physical interpretation of the reality of the clustering results since it could check if the cluster delay and directions would produce the same clusters based on the measurement. In this paper the clusters were identified at the MS. So the cluster delay and BS direction centroids were used in \((17)\) and \((18)\) to see if the clusters at the locality of the MS are present in the measured channel.

**IV. RESULTS**

Physically verified multipath clusters obtained using the clusterization approach in \([6]\), \([14]\) are shown in the plot in Fig. 1. Using the cluster delays and BS directions in the polarimetric beamforming of the measured channel, Fig. 2 shows the resulting cluster directional spectrum at the MS. Comparing these results, the clustered estimates in Fig. 1 could be seen to correspond to the two dominant peaks of the spatial spectrum of the multipath channel, though there is some offset in the cluster shape of the estimates.

There are several reasons that could contribute to the noted difference. In general, the path parameters produced by ML estimation are expected to comb the beamformer resolution. As pointed in \([6]\), there are still gaps that need to be improved in the clusterization of multipaths. Thus, the improvement in the clusterization approach, like estimation, must be done more rigorously, especially the physical meaning of the results. The physical significance is emphasized since it could be seen to correspond to the measurement. Several promising areas and
approaches that could be explored are discussed in [15], [16]. Moreover, the consideration of the diffuse components is a slight explanation of the offset. In the clustering approach used, these diffuse components were not included, though their possible presence could be in the (measured) channel. Since the path estimates are based on the double-directional channel model [17], which assumes discrete waves, the representation of continuous fields from real-world scattering could not be accounted by path-wise parameters. Accordingly, this also points to the limited resolution of the channel sounder like the bandwidth, but more specifically to the antenna array size, which contributes to the spatial resolution. Nevertheless, the results are comparably similar given that the clusterization of the estimates are within the resolution of the spatial filter. The presented polarimetric beamforming approach for obtaining the directional spectrum at the MS is useful then for evaluating cluster directions, especially either at the locality of the MS or BS. In the extraction of the properties of the channel, the approach could be considered as one measure of evaluating spatial channel models and results with respect to the measured channel.

V. SUMMARY

A comparative verification of the multipath clusterization of maximum-likelihood estimates of a small urban channel by polarimetric beamforming was presented. To some extent, the spatial evaluation shows that the directional power spectrum obtained by polarimetric beamforming could verify the clusters from the clustering of path parameters. The difference was accounted to how the channel data is treated by the approaches (parameter estimation and clusterization) in extracting the characteristics of the channel. Improvement in these approaches is seen as a key to minimize the variation. The difference could indicate how they deviate to some degree from the measured channel.

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REFERENCES