Polarization Diversity for Base Station Antennas

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Outline

- Problem formulation
- Model for the radio channel and the antenna reception
- Derivation of the relation between power correlation and far-field coupling
- Simulated antennas: Dual polarized Aperture Coupled Patch and slanted dipoles
- Measured radiation patterns of base station antennas and calculated correlation
- Far-field coupling from amplitude only measurements
- Correlation and diversity gain
- Slant ±45° vs. vertical/horizontal polarization
- Conclusion
Problem Formulation

• Base station antenna used in a Rayleigh fading environment
• We wish to use polarization diversity with equal mean power on both branches; thus the two antenna channels should be symmetrical
• We assume un-correlated envelopes of vertical and horizontal incident field components

What is the output signal correlation from the antenna?
Is there a difference between different antenna configurations?
What is the impact in terms of diversity gain of using different types of base station antennas?
Measurements of the radio channel

<table>
<thead>
<tr>
<th>Environment and source</th>
<th>Mobile Orientation</th>
<th>$\chi$ (dB)</th>
<th>Frequency</th>
<th>Correlation $\rho_{env}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban [1]</td>
<td>Vertical car antenna</td>
<td>4-7</td>
<td>920 MHz</td>
<td>median 0.02</td>
</tr>
<tr>
<td>Urban [2]</td>
<td></td>
<td>7</td>
<td>463 MHz</td>
<td>-0.003</td>
</tr>
<tr>
<td>Sub-urban [2]</td>
<td></td>
<td>12</td>
<td></td>
<td>0.019</td>
</tr>
<tr>
<td>Urban &amp; sub-urban [3]</td>
<td>0°</td>
<td>10</td>
<td>1790 MHz</td>
<td>&lt;0.7 for 95%</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>4.6-6.3</td>
<td></td>
<td>&lt;0.7 for 95%</td>
</tr>
<tr>
<td>Urban [4]</td>
<td>70±15° in- and outdoor</td>
<td>1-4</td>
<td>1821 MHz</td>
<td>&lt;0.2 for 90%</td>
</tr>
<tr>
<td>Sub-urban [4]</td>
<td></td>
<td>2-7</td>
<td></td>
<td>&lt;0.1 for 90%</td>
</tr>
<tr>
<td>Urban &amp; sub-urban [5]</td>
<td>0°</td>
<td>4-7</td>
<td>1848 MHz</td>
<td>&lt;0.5 for 93%</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>0</td>
<td></td>
<td>&lt;0.5 for 93%</td>
</tr>
<tr>
<td>Urban [6]</td>
<td>Car mounted monopole</td>
<td>7.6 ± 2.1</td>
<td>970 MHz</td>
<td>0.09 ± 0.09</td>
</tr>
</tbody>
</table>


Antenna model

The channel vectors $\mathbf{a}, \mathbf{b}$ are projected onto the polarization ellipse of axial ratio $\chi^{0.5}$.
Derivation of Power Correlation from Far-field Coupling

Incident field:

\[ E_\alpha = E_\alpha \hat{\alpha} = r_\alpha(t) e^{-j\phi_\alpha(t)} \hat{\alpha} \]
\[ E_\beta = E_\beta \hat{\beta} = r_\beta(t) e^{-j\phi_\beta(t)} \hat{\beta}. \]

where

\[ p(r) = \frac{r}{\sigma^2} e^{-r^2/2\sigma^2} \]

Antenna representation by far-field vector functions:

\[ a = a(\theta, \phi) \hat{\alpha}(\theta, \phi) \]
\[ b = b(\theta, \phi) \hat{\beta}(\theta, \phi) \]

If we define a matrix:

\[ A = \begin{bmatrix} a^* \langle \hat{\alpha}, \hat{\alpha} \rangle & a^* \langle \hat{\beta}, \hat{\alpha} \rangle \\ b^* \langle \hat{\alpha}, \hat{\beta} \rangle & b^* \langle \hat{\beta}, \hat{\beta} \rangle \end{bmatrix} \]

then the output from the antenna is

\[ \begin{bmatrix} V_a \\ V_b \end{bmatrix} = A \begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix} \quad \text{or} \quad y = A\eta. \]

The covariance matrix of the input signal is

\[ C_\eta = \begin{bmatrix} \text{Var}\{E_\alpha\} & 0 \\ 0 & \text{Var}\{E_\beta\} \end{bmatrix}. \]

and the corresponding matrix for the output is thus:

\[ C_y = A C_\eta A^H \]

The complex normalized cross-covariance is

\[ \rho_c = \frac{C_y^{(2,1)}}{\sqrt{C_y^{(1,1)} C_y^{(2,2)}}} \]

and for the circularly symmetric Rayleigh signals:

\[ \rho_{\text{power}} = |\rho_c|^2 = \frac{|C_y^{(2,1)}|^2}{|C_y^{(1,1)} C_y^{(2,2)}|}. \]

For the un-polarized case with equal mean power in the vertical and horizontal components, (10) equals

\[ \rho_c = \langle \hat{\alpha}, \hat{\beta} \rangle^* e^{-j\text{arg}(ab^*)}. \]

So (11) reduces to:

\[ \rho_{\text{power}} = |\langle \hat{\alpha}, \hat{\beta} \rangle|^2. \]

Thus, the power correlation is equal to the square of the far-field coupling.
# Output Correlation

**Ideal ±45° Slanted Dual Polarized Antenna**

<table>
<thead>
<tr>
<th>Environment</th>
<th>Received Polarization Statistical Distribution</th>
<th>Output Correlation Coefficient ($\rho_{\text{power}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (indoor-microcell)</td>
<td><img src="image1" alt="Diagram" /></td>
<td>0.00</td>
</tr>
<tr>
<td>3 (urban)</td>
<td><img src="image2" alt="Diagram" /></td>
<td>0.11</td>
</tr>
<tr>
<td>6 (urban-suburban)</td>
<td><img src="image3" alt="Diagram" /></td>
<td>0.36</td>
</tr>
<tr>
<td>9 (rural)</td>
<td><img src="image4" alt="Diagram" /></td>
<td>0.77</td>
</tr>
</tbody>
</table>
Geometry of the simulated antennas

Aperture Coupled Patch over an infinite groundplane

Patch height = 0.071λ
Patch size = 0.37λ x 0.37λ
Slot length = 0.29λ
Slot width = 0.006λ

Slanted dipoles over an infinite groundplane

Dipole length = 0.5λ
Dipole height = 0.125λ
Simulated Patterns
(HP-Momentum and $\lambda/2$ dipole theory)

Aperture Coupled Patch over an infinite groundplane:
HBW = 72 degrees

Slanted dipoles over an infinite groundplane:
HBW = 75 degrees
Simulated Patterns, cont.
Phase between horizontal and vertical far-field components
Far-field coupling

The scalar product of the normalized far-fields of the two channels: $\langle a, b \rangle = (a, b^*)$
Calculated Output Power Correlation for Rayleigh Distributed Incident Fields

Aperture Coupled Patch over an infinite groundplane

Slanted dipoles over an infinite groundplane
Geometry of the two Measured Base Station Antennas

• Dual polarized antenna arrays of 8 elements.
  • Aperture Coupled Patch elements are symmetrical and centred
  • Dipole elements are displaced to increase isolation

1.3 m
Measured Radiation Patterns: Co- and Cross-Polar

ACP antenna

Slanted dipole antenna
Measured Radiation Patterns: Vertical and Horizontal Polarizations

ACP antenna

Slanted dipole antenna
Simulated Output Envelope Correlation from Measured Radiation Patterns: 10000 samples

ACP antenna:
\[ \rho_{\text{envelope}} \sim 0.3 \text{ at } -60 \text{ degrees} \]

Slanted dipole antenna:
\[ \rho_{\text{envelope}} = 0.8 \text{ at } -60 \text{ degrees} \]

Both antennas: \[ \rho_{\text{envelope}} = 0.38 \text{ at boresight due to projection onto the polarization ellipse} \]
Far-field coupling from amplitude-only radiation patterns

Project \( \mathbf{a} \) and \( \mathbf{b} \) onto the vertical and horizontal polarizations:

\[
\begin{align*}
\mathbf{a} &= a_v \hat{v} + a_h \hat{h} \quad (1) \\
\mathbf{b} &= b_v \hat{v} + b_h \hat{h}. \quad (2)
\end{align*}
\]

Now, if there is a symmetry in the radiation patterns with respect to the vertical axis, i.e:

\[
\begin{align*}
b_v &= e^{-j\theta} a_v \quad (3) \\
b_h &= -e^{-j\theta} a_h, \quad (4)
\end{align*}
\]

the Far-field coupling \( \langle \mathbf{a}, \mathbf{b} \rangle \) can be expressed as:

\[
\langle \mathbf{a}, \mathbf{b} \rangle = (\mathbf{a}, \mathbf{b}^*)
\]

\[
= (a_v \hat{v} + a_h \hat{h}) \cdot (e^{j\theta} a_v^* \hat{v} - e^{j\theta} a_h^* \hat{h})
\]

\[
= e^{j\theta} (|a_v|^2 - |a_h|^2)
\]

since \( \langle \hat{v}, \hat{h} \rangle = 0 \).

For the unpolarized case \( \rho_{power} = |\langle \mathbf{a}, \mathbf{b} \rangle|^2 \), hence the output power correlation is simply:

\[
\rho_{power} = (|a_v|^2 - |a_h|^2)^2. \quad (6)
\]
Impact of correlation on diversity gain

- Mobile at -60 degrees azimuth (cell border):
  \[ \rho_{\text{envelope}} = 0.3 \text{ for ACP and } 0.8 \text{ for slanted dipole antenna} \]
- Radio channel XPD (vert./hor. power) = 6 dB

Note: \( \rho_{\text{env}} \approx \rho_{\text{power}} = \rho^2 \) for Rayleigh signals

- a) Selection diversity
  (Schwartz, Bennett, Stein 1966)
  - Dipoles: \( \rho_{\text{power}} = 0.8 = 0.9^2 \)
  \[ \text{SNR loss } \approx 2.5 \text{ dB} \]

- b) Maximum Ratio Combining
  (Yongbing Wan, J.C. Chen 1995)
  - ACP: \( \rho_{\text{power}} = 0.3 = 0.55^2 \)
  \[ \text{SNR loss } \approx 2.8 \text{ dB} \]
Slant ±45° vs. vertical/horizontal polarization

Pre-detection combining:

• With orthogonal far-fields of the two channels, all power is received at the antenna and thus all the information in both cases
• We can change slant ±45° to vertical/horizontal using loss-less, reciprocal networks
• The eigen-values of the covariance matrix and thus the probability density function are identical in both cases

⇒ no difference between the two with optimal combining (MRC)
Conclusions

- A closed form expression for the output correlation as a function of far-field patterns has been shown.
- The output correlation is a function of the antenna far-field coupling as well as the XPD of the environment.
- For an un-polarized environment ($XPD = 0 \, \text{dB}$) the output correlation equals the square of this coupling.
- Symmetrical antenna designs with equal patterns for vertical and horizontal polarizations provide orthogonal far-fields $\iff$ low far-field coupling.
- The aperture coupled patch provides the lower output correlation in all investigated cases.
- For symmetrical radiation patterns, the far-field coupling can be calculated from amplitude-only patterns.
- A high far-field coupling, i.e. poor orthogonality, could result in a loss of 2-3 dB diversity gain for selection or MR combining.