Multiple Antenna Optimization for VHF Receive

Lars Reichardt, Stefan Schulteis and Werner Wiesbeck
Test of modeled areas for material and connections f.e. by FEKO

Courtesy EMSS
Windscreen Antenna Radiation Pattern

Critical:
- material
- slots
- ground

Courtesy EMSS
Example for Car Integrated Antennas
Characteristics of Car Integrated Antennas

- mirrors (R/L)
- front window sides (R/L)
- rear window bottom (R/L)
- wires in mirrors (R/L)
- front window top (R/L)
- rear window horizontal.
- rear window vertical

(f=100MHz)
Example for Urban FM-Coverage Prediction

Urban coverage grid:
- ca. 2500 positions
- grid spacing 30 m (ca. 10\(\lambda\))
- prediction height 1 m above ground

FM-Transmitter Grünwettersbach:
Position (2000, -6000, 445)
Wave Extension from Reference Point

Plane wave to reference point

Reference point from coverage prediction

Plane wave to reference point

Plane wave to reference point
Calculation of the Antenna Output Signals

Antenna receive voltage $V_{Rx}$:

$$V_{Rx}(x) \approx C_{\nu}(\theta_i, \psi_i) \cdot E_i(x) \cdot e^{-jk_i \tilde{x}_i}$$
Calculation of the Received Power $P_{Rx_i}$

**Calculation of the complex, polarimetric incident field-strength by ray-tracing:**

**Wave:**
- phase
- polarization
- ray vector

**Rays:**
- for each ray $n$ of $N$
- for each antenna $i$
- for each car position $x$

**Known:**
- position of the BS
- position of the car
- position of antennas
- antenna characteristics

**Calculation of the total received power $P_{Rx_i}$ for each antenna $i$:**

$$P_{Rx_i, \text{coherent}} = \frac{\left| V_{Rx,i} \right|^2}{8 \text{Re} \left( \frac{Z_{ARx,i}}{Z_{ARx,i}} \right)} = \frac{\lambda^2}{\pi} \frac{1}{Z_{F0}} \sum_{n=1}^{N} C_{Rx,i}(\theta_{Rx,n}, \psi_{Rx,n}) e^{j\Delta \phi_{in}} E_{Rx,n}(\theta_{Rx,n}, \psi_{Rx,n})$$

$$P_{Rx_i, \text{incoherent}} = \frac{\left| V_{Rx,i} \right|^2}{8 \text{Re} \left( \frac{Z_{ARx,i}}{Z_{ARx,i}} \right)} = \frac{\lambda^2}{\pi} \frac{1}{Z_{F0}} \sum_{n=1}^{N} C_{Rx,i}(\theta_{Rx,n}, \psi_{Rx,n}) e^{j\Delta \phi_{in}} E_{Rx,n}(\theta_{Rx,n}, \psi_{Rx,n})$$

**Calculation of the cumulative distributive function CDF of the received power $P_{Rx_i}$**
Calculation of the Antenna Correlation Coefficients

Voltage correlation coefficient:

\[ \rho_{V,i,j} = \frac{\sigma_{V,i} \cdot \sigma_{V,j}}{\sigma_{V,i} \cdot \sigma_{V,j}} \]

\( i, j = 1...13 \)

Power correlation coefficient

\[ \rho_{P,i,j} \approx \left| \frac{\rho_{V,i,j}}{\sigma_{V,i} \cdot \sigma_{V,j}} \right|^2 \]

\( 0 \leq \rho_{P} \leq 1 \)

- \( \rho_{P} \) mirror R & mirror wire R: \( \rho_{P} \approx 1 \)
- \( \rho_{P} \) mirrors R & L: \( \rho_{P} << 1 \)

<table>
<thead>
<tr>
<th>Frequency in MHz</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.2</td>
</tr>
<tr>
<td>95</td>
<td>0.2</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>105</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- Korr-Koeff. horiz
- Korr-Koeff. vert

<table>
<thead>
<tr>
<th>Frequency in MHz</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.2</td>
</tr>
<tr>
<td>95</td>
<td>0.2</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>105</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- Korr-Koeff. horiz
- Korr-Koeff. vert

1/2: mirrors R/L
3/4: mirror wires R/L
5/6: front window sides R/L
7/8: front window top R/L
9/10: front window low R/L
11: front window center
12: rear window horizontal
13: rear window vertical
Power Correlation Coefficients $\rho_p$ of all Antennas

1/2: mirrors R/L
3/4: mirror wires R/L
5/6: front window sides R/L
7/8: front window top R/L
9/10: front window low R/L
11: front window center
12: rear window horic.
13: rear window vert.
Power Correlation Coefficients $\rho_P$ of all Antennas

1/2: mirrors R/L
3/4: mirror wires R/L
5/6: front window sides R/L
7/8: front window top R/L
9/10: front window low R/L
11: front window center
12: rear window horic.
13: rear window vert.

**Hor. polarization**

- 1/2: mirrors R/L
- 3/4: mirror wires R/L
- 5/6: front window sides R/L
- 7/8: front window top R/L
- 9/10: front window low R/L
- 11: front window center
- 12: rear window horic.
- 13: rear window vert.

**Vert. polarization**

- 1/2: mirrors R/L
- 3/4: mirror wires R/L
- 5/6: front window sides R/L
- 7/8: front window top R/L
- 9/10: front window low R/L
- 11: front window center
- 12: rear window horic.
- 13: rear window vert.

**Not suited:**
- $\times$ Same side mirror and wire 2
- $\times$ front window antennas co-pol

**Suited:**
- $\checkmark$ Mirror R & L
- $\checkmark$ Mirror wire R & L
- $\checkmark$ Rear window antenna & each other antenna
CDF of the Received Power $P_{Rx_i}$

- Transmitter: omni antenna, transmit power $P_{Tx} = 60 \text{ dBm}$
- no attenuation by trees, people, cars etc.
- $f = 100 \text{ MHz}$, polarization horizontal

Antennas:
1/2: mirrors R/L
3/4: mirror wires R/L
5/6: front window sides R/L
7/8: front window top R/L
9/10: front window low R/L
11: front window center
12: rear window horizontal
13: rear window vertical

mirrors R/L and mirror wires R/L are best
rear, vertical window antenna is worst
Diversity for Combination of Antennas

**Selection Combining:**

- Only 1 signal used

**Maximum Ratio Combining:**

- Good antennas are better weighted

**Monitor** $P_{Rx}$

- Select max

**Weights**

- $W_1$
- $W_2$
- $W_n$

**Receiver**
Comparison of 4 Antenna Groups, 3 Ant. Each

Selection Combining Sel.; Max. Ratio Combining Max. (all weights 1 (Equal Gain Combining))

Group 1: mirrors L, R & rear ant. horizontal

Group 2: Mirror wires L, R & rear antenna horizontal

Group 3: Front antennas side R, top R & low R

Group 4: Front antennas low L, sides R/L & center

Graph showing PRx distribution with different groups and their corresponding performance metrics.
**SNR - Comparison of the Antennas**

\[
[SNR]_{dB} = [P_{Rx}]_{dBm} - [P_N]_{dBm}
\]

- **SNR**: Signal-to-Noise-Ratio
- **\( P_N \)**: Noise power

**Assumption:**
no motor or vehicle noise

**Reference from measurements:**
- front window ant.: \( SNR_{mean} = 28 \text{dB} \)
- all others: \( SNR_{mean} = 34 \text{dB} \)

**Antennas:**
- 1/2: mirrors R/L
- 3/4: mirror wires R/L
- 5/6: front window sides R/L
- 7/8: front window top R/L
- 9/10: front window low R/L
- 11: front window center
- 12: rear window horizontal
- 13: rear window vertical
SNR - Comparison of the 4 Antenna Groups

Requirement for Maximum Ratio Combining: uncorrelated noise not satisfied → Sel. Combining

Group 1: mirrors R, L & rear ant. horizontal

Group 2: Mirror wires R, L & rear antenna horizontal

Group 3: Front antennas side R, top R & low R

Group 4: Front antennas low L, sides R/L & center
Best antenna combination with 3 elements:

- Pattern suited for terr. transmission
- All correlation coefficients below 0.2
- Receives more power than all others
- High SNR

Group 2:
Mirror wires R, L & rear antenna horizontal
Summary Virtual Drive

All tools are available for Virtual Drive

Vehicle EM-modeling → Coverage prediction

During the vehicle R&D phase the antennas and antenna positions can be optimized as soon as the shape and materials are known

Enormous advantages:
- Optimization of Diversity and MIMO systems
- Significant cost reduction
- Significant time savings