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

Environment and source	Mobile Orientation	χ (dB)	Frequency	Correlation ρ_{env}
Urban [1]	Vertical car antenna	4-7	920 MHz	median 0.02
Urban [2]	30° on large groundplane	7	463 MHz	-0.003
Sub-urban [2]		12		0.019
Urban & sub-urban [3]	0°	10	1790 MHz	<0.7 for 95%
	45°	4.6-6.3		<0.7 for 95%
Urban [4]	70±15° in- and outdoor	1-4	1821 MHz	<0.2 for 90%
Sub-urban [4]		2-7		<0.1 for 90%
Urban & sub-urban [5]	0°	4-7	1848 MHz	<0.5 for 93%
	45°	0		<0.5 for 93%
Urban [6]	Car mounted monopole	7.6 ± 2.1	970 MHz	0.09 ± 0.09

[1] S. Kozono, T. Tsuruhara, and M. Sakamoto, "Base station polarization diversity reception for mobile radio," *IEEE Trans. Veh. Technol.*, vol. 33, pp. 301–306, Nov. 1984.

[2] R. G. Vaughan, "Polarization diversity in mobile communications," *IEEE Trans. Veh. Technol.*, vol. 39, pp. 177–186, Aug. 1990.

[3] A. M. D. Turkmani, A. A. Arowojolu, P. A. Jefford, and C. J. Kellett, "An experimental evaluation of the performance of two branch space and polarization diversity schemes at 1800 MHz," *IEEE Trans. Veh. Technol.*, vol. 44, pp. 318–326, May 1995.

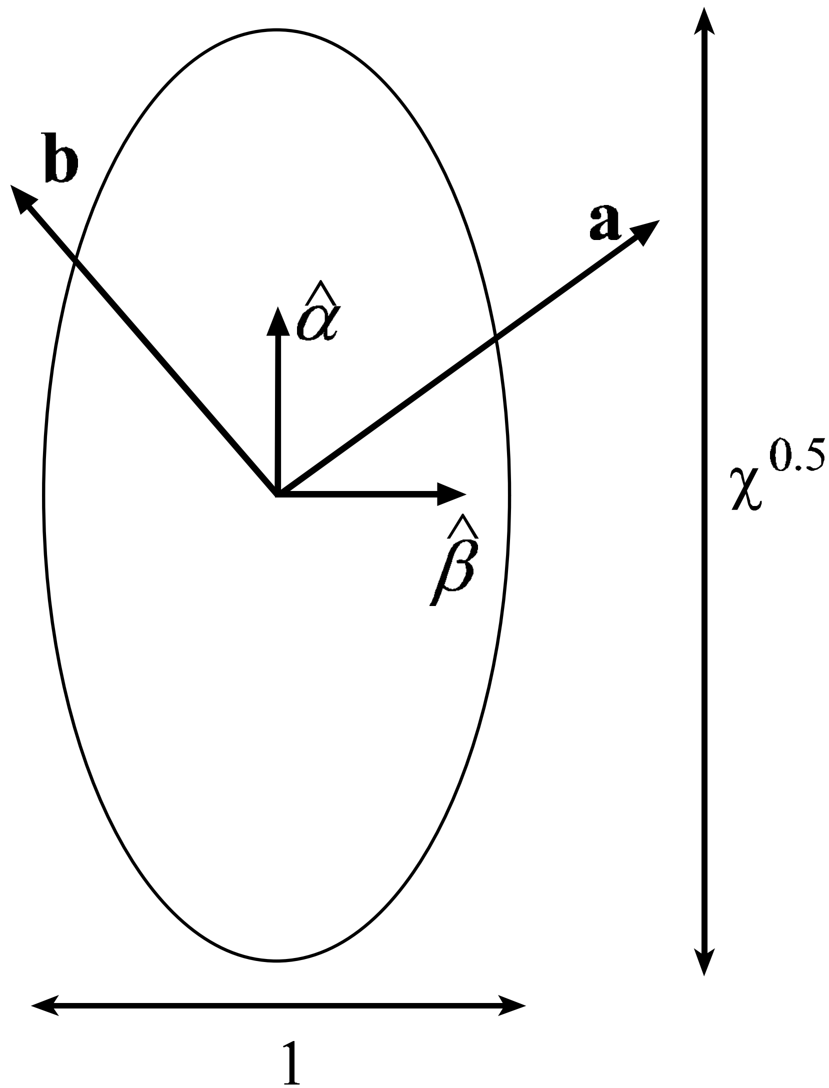
[4] F. Lotse, J.-E. Berg, U. Forssen, and P. Idahl, "Base station polarization diversity reception in macrocellular systems at 1900 MHz," in *Proc. 46th IEEE Veh. Technol. Conf.*, pp. 1643–1646, Apr. 1996.

[5] U. Wahlberg, S. Widell, and C. Beckman, "Polarization diversity antennas," in *Proc. Antenn 97, Nordic antenna symposium*, (Göteborg, Sweden), pp. 59–65, May 1997.

[6] P. C. F. Eggers, J. Toftgaard, and A. M. Oprea, "Antenna systems for base station diversity in urban small and micro cells," *IEEE J. Select. Areas Commun.*, vol. 11, pp. 1046–1057, Sept. 1983.

Antenna model

The channel vectors **a**,**b** are projected onto the polarization ellipse of axial ratio $\chi^{0.5}$



Derivation of Power Correlation from Far-field Coupling

Incident field:

$$\mathbf{E}_\alpha = E_\alpha \hat{\alpha} = r_\alpha(t) e^{-j\phi_\alpha(t)} \hat{\alpha} \qquad (1)$$

$$\mathbf{E}_\beta = E_\beta \hat{\beta} = r_\beta(t) e^{-j\phi_\beta(t)} \hat{\beta}. \qquad (2)$$

where

$$p(r) = \frac{r}{\sigma^2} e^{-r^2/2\sigma^2} \qquad (3)$$

Antenna representation by far-field vector functions:

$$\mathbf{a} = a(\theta,\phi)\hat{a}(\theta,\phi) \qquad (4)$$

$$\mathbf{b} = b(\theta,\phi)\hat{b}(\theta,\phi) \qquad (5)$$

If we define a matrix:

$$\mathbf{A} = \begin{bmatrix} a^*\langle\hat{\alpha},\hat{a}\rangle & a^*\langle\hat{\beta},\hat{a}\rangle \\ b^*\langle\hat{\alpha},\hat{b}\rangle & b^*\langle\hat{\beta},\hat{b}\rangle \end{bmatrix} \qquad (6)$$

then the output from the antenna is

$$\begin{bmatrix} V_a \\ V_b \end{bmatrix} = \mathbf{A} \begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix} \quad \text{or} \quad y = \mathbf{A}\eta. \qquad (7)$$

The covariance matrix of the input signal is

$$\mathbf{C}_\eta = \begin{bmatrix} \mathrm{Var}\{E_\alpha\} & 0 \\ 0 & \mathrm{Var}\{E_\beta\} \end{bmatrix}. \qquad (8)$$

and the corresponding matrix for the output is thus:

$$\mathbf{C}_y = \mathbf{A}\mathbf{C}_\eta\mathbf{A}^H \qquad (9)$$

The complex normalized cross-covariance is

$$\rho_c = \frac{C_y^{(2,1)}}{\sqrt{C_y^{(1,1)} C_y^{(2,2)}}} = \frac{C_y^{(1,2)\,*}}{\sqrt{C_y^{(1,1)} C_y^{(2,2)}}} \qquad (10)$$

and for the circularly symmetric Rayleigh signals:

$$\rho_{power} = |\rho_c|^2 = \frac{|C_y^{(2,1)}|^2}{|C_y^{(1,1)} C_y^{(2,2)}|}. \qquad (11)$$

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

$$\rho_c = \langle\hat{a},\hat{b}\rangle^* e^{-j\arg\{ab^*\}}. \qquad (12)$$

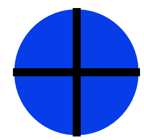
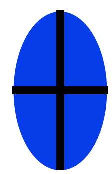
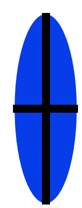
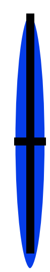
So (11) reduces to:

$$\rho_{power} = |\langle\hat{a},\hat{b}\rangle|^2. \qquad (13)$$

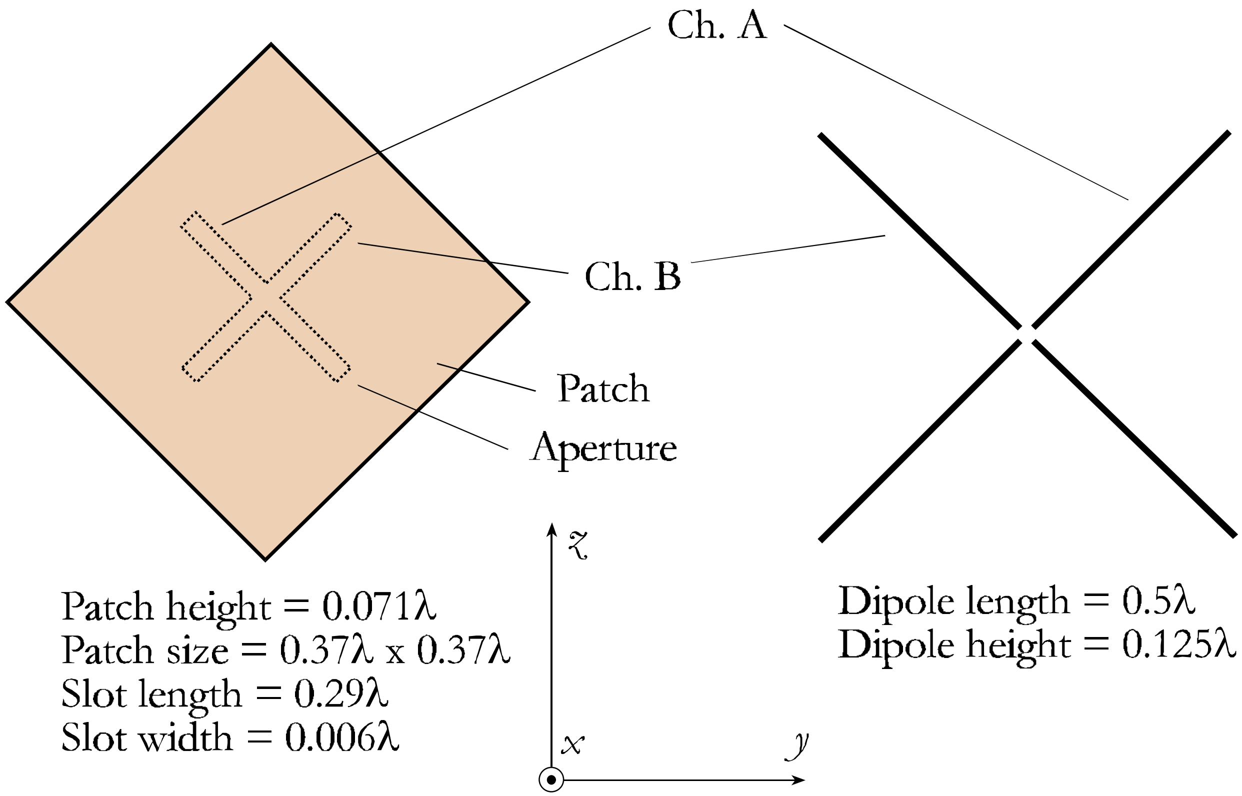
Thus, the power correlation is equal to the square of the far-field coupling.

Output Correlation

Ideal ±45^o Slanted Dual Polarized Antenna

Environment (XPD in dB)	**Received Polarization Statistical Distribution**	**Output Correlation Coefficient** (ρ_{power})
0 (indoor-microcell)		0.00
3 (urban)		0.11
6 (urban-suburban)		0.36
9 (rural)		0.77

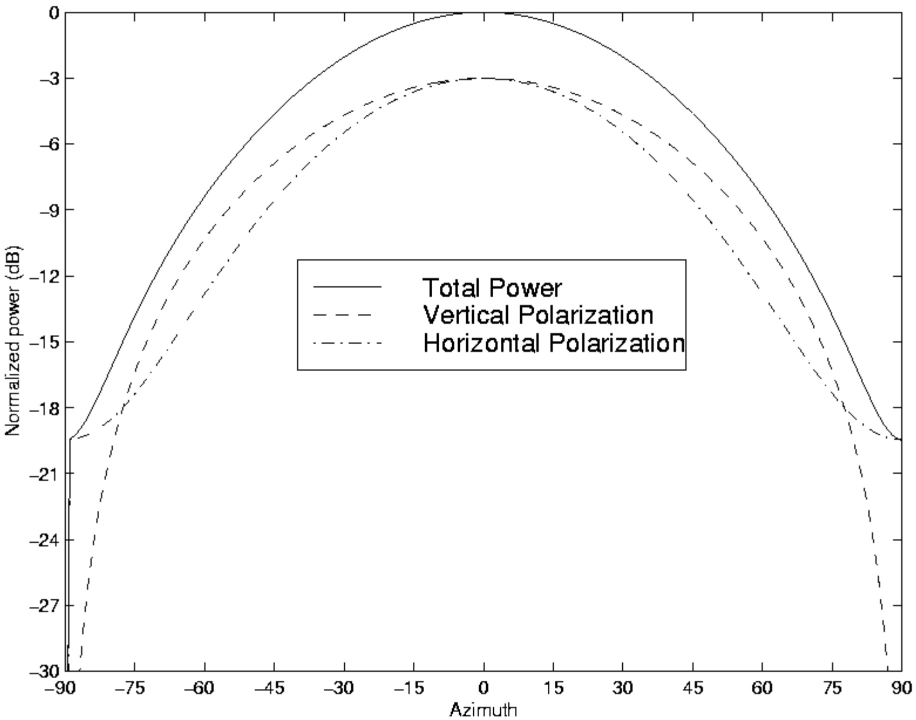
Geometry of the simulated antennas



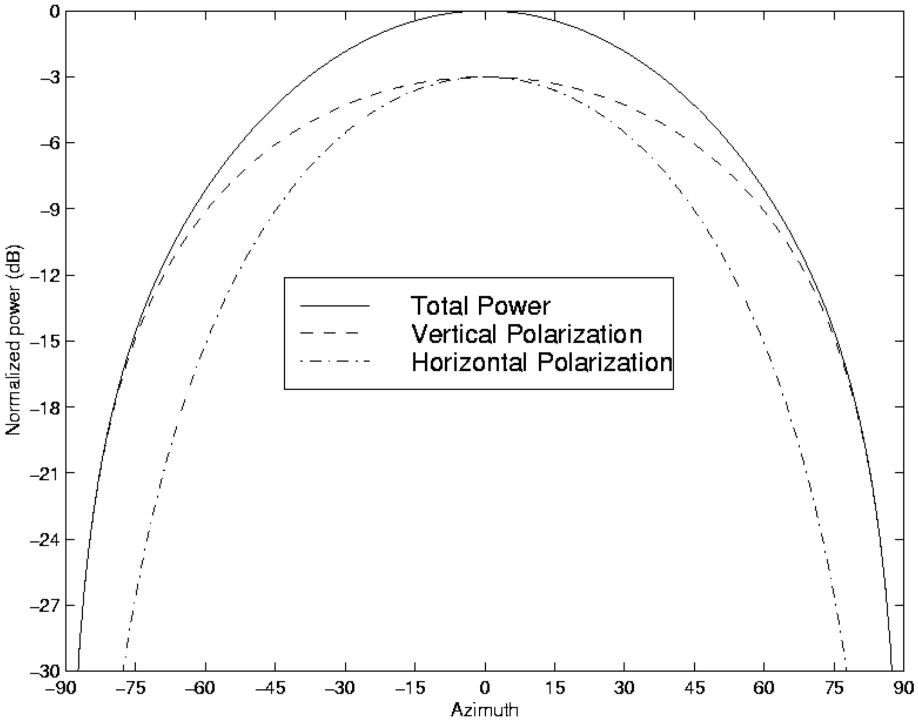
Aperture Coupled Patch over an infinite groundplane

Slanted dipoles over an infinite groundplane

Simulated Patterns
(HP-Momentum and *l* / 2 dipole theory)

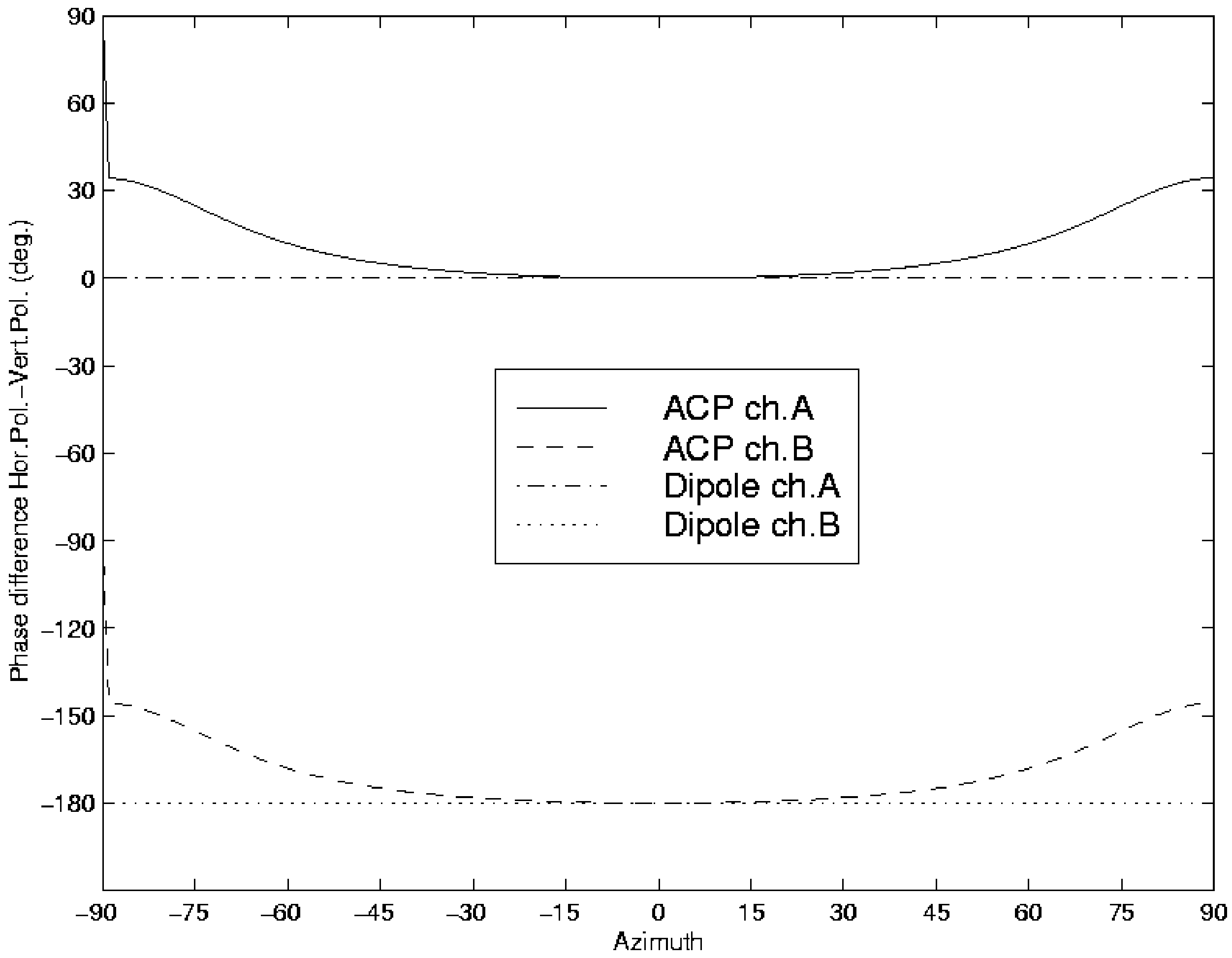


Aperture Coupled Patch over an infinite groundplane: HBW = 72 degrees

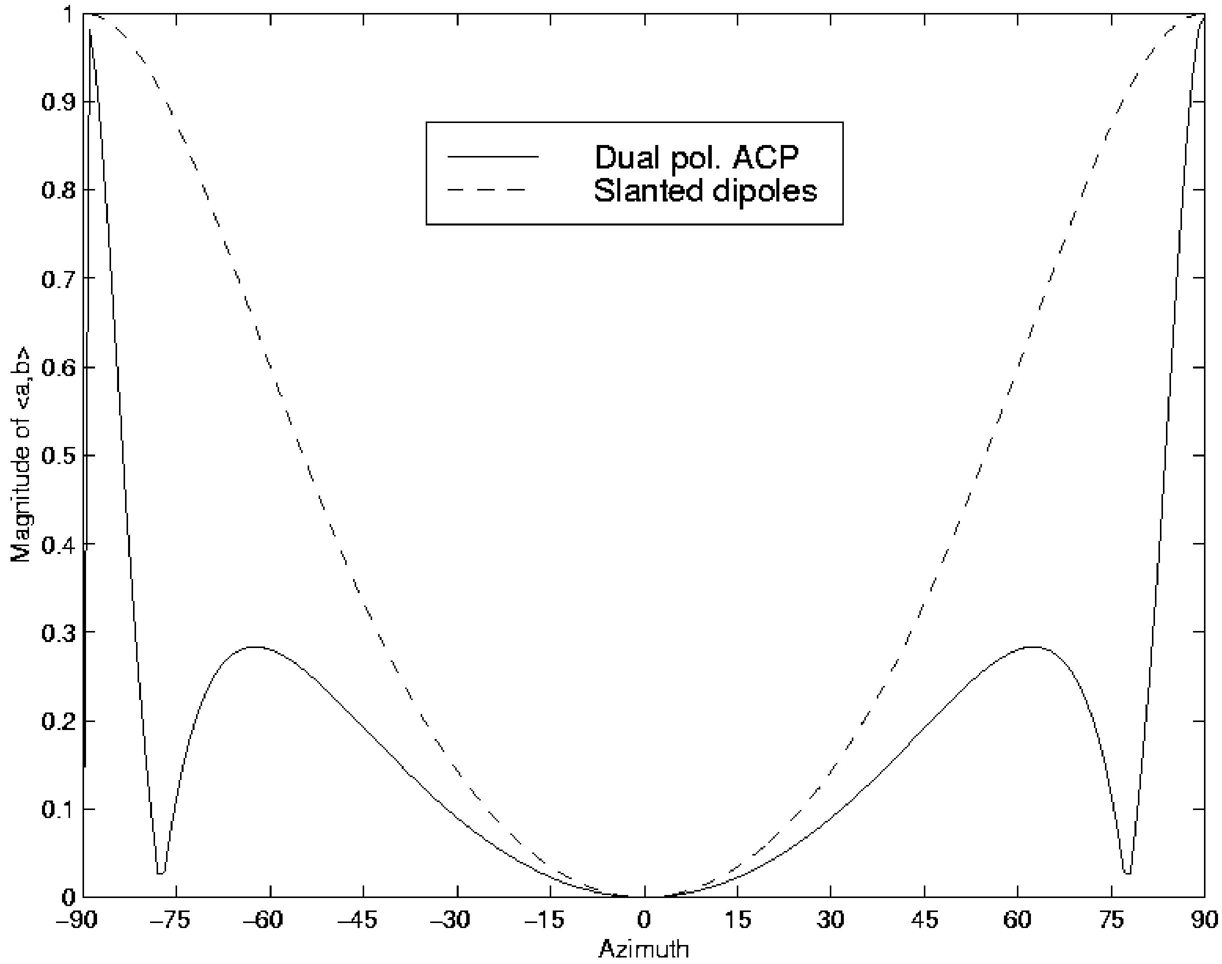


Slanted dipoles over an infinite groundplane: HBW = 75 degrees

Simulated Patterns, cont.
Phase between horizontal and vertical far-field components

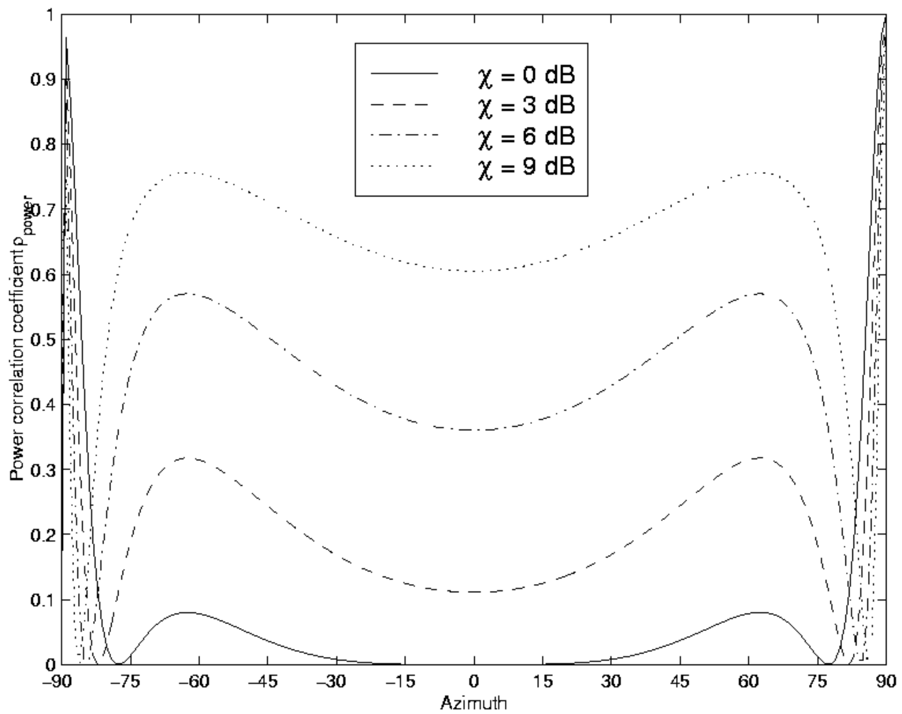


Far-field coupling

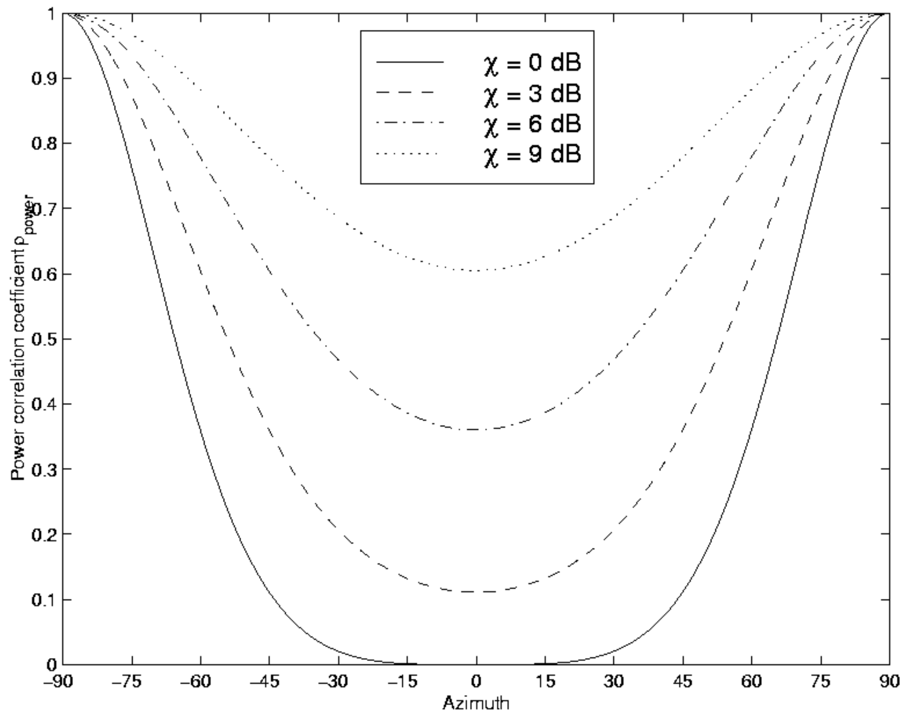


The scalar product of the normalized far-fields of the two channels: <a,b> = (a,b*)

Calculated Output Power Correlation for Rayleigh Distributed Incident Fields



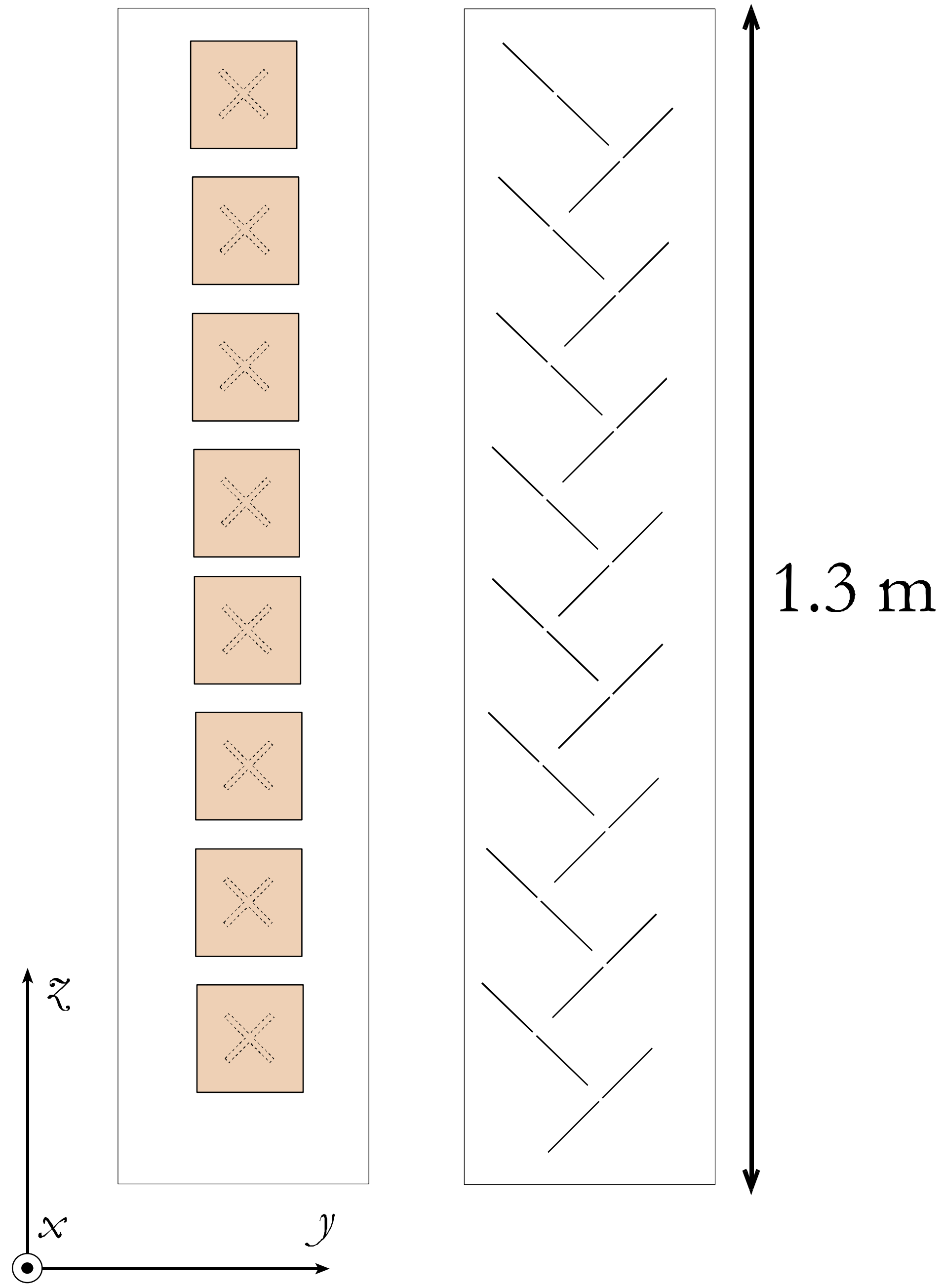
Aperture Coupled Patch over an infinite groundplane



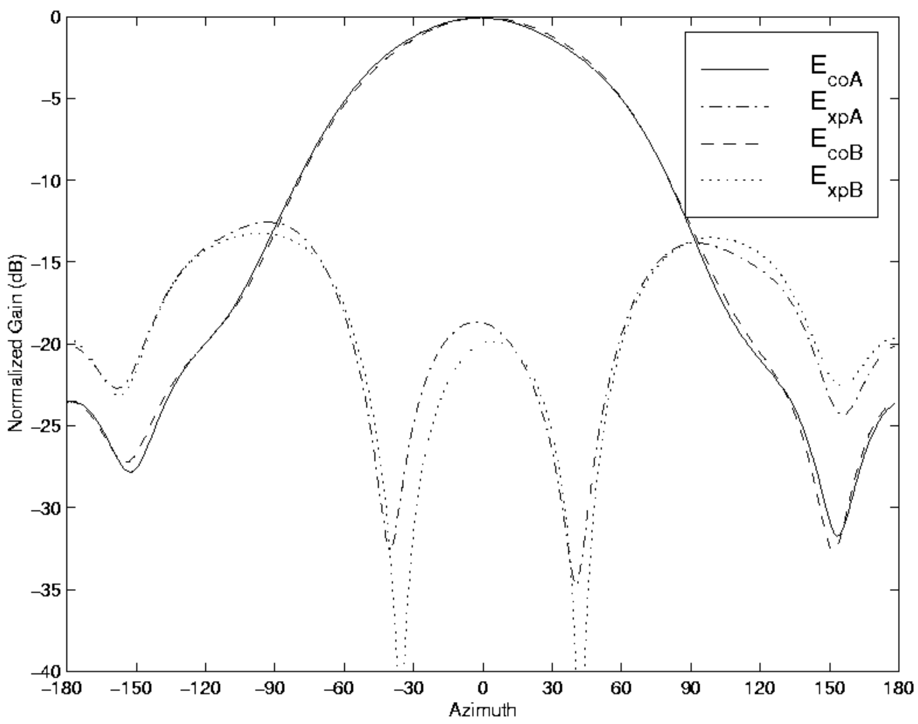
Slanted dipoles over an infinite groundplane

Geometry of the two Measured Base Station Antennas

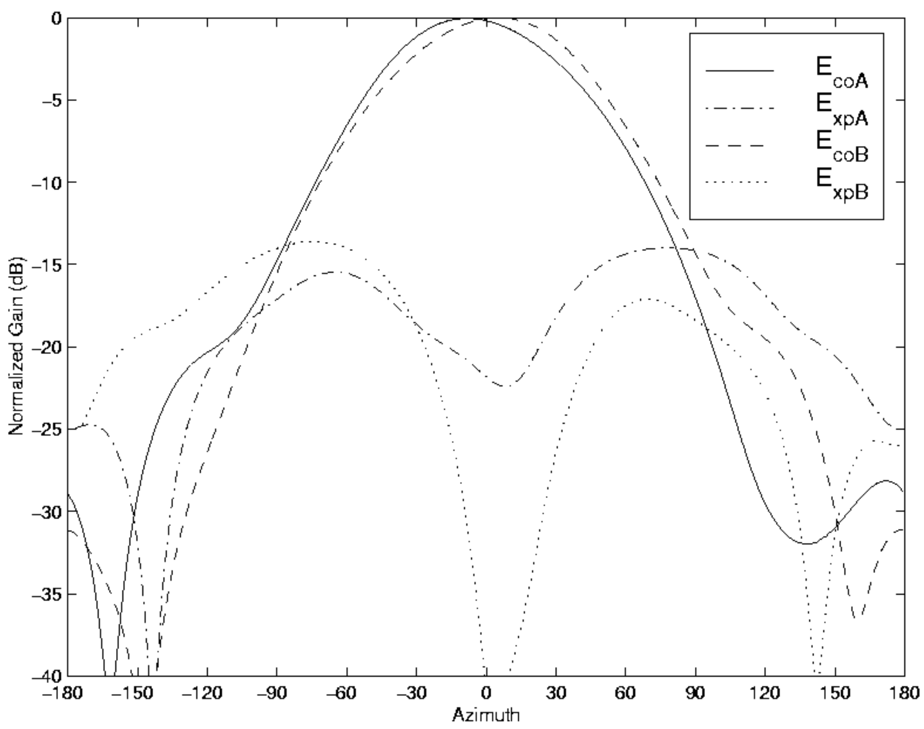
- Dual polarized antenna arrays of 8 elements.
- Aperture Coupled Patch elements are symmetrical and centred
- Dipole elements are displaced to increase isolation



Measured Radiation Patterns: Co- and Cross-Polar

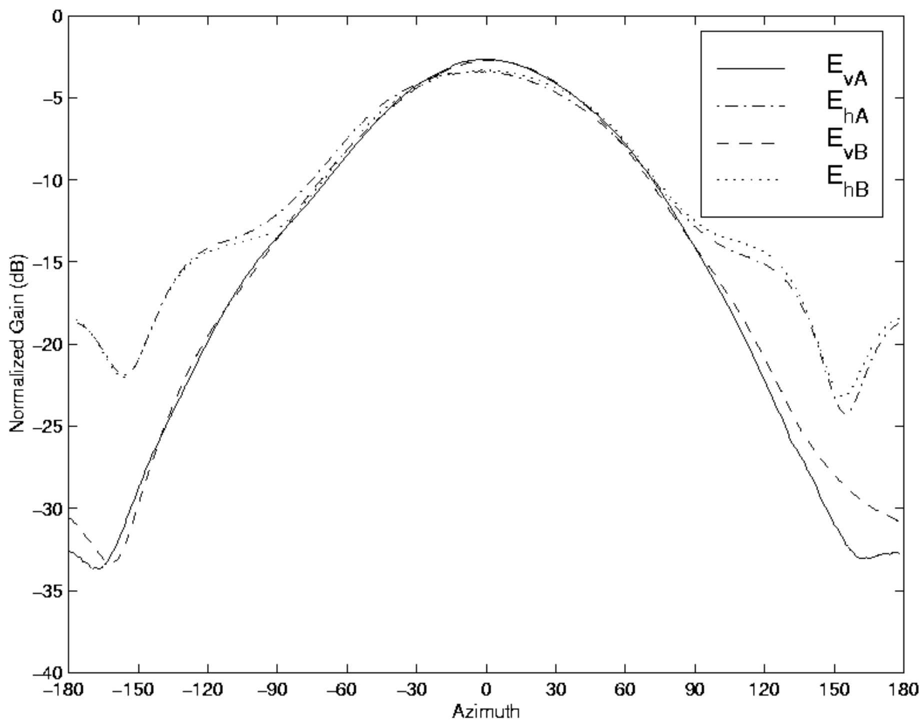


ACP antenna

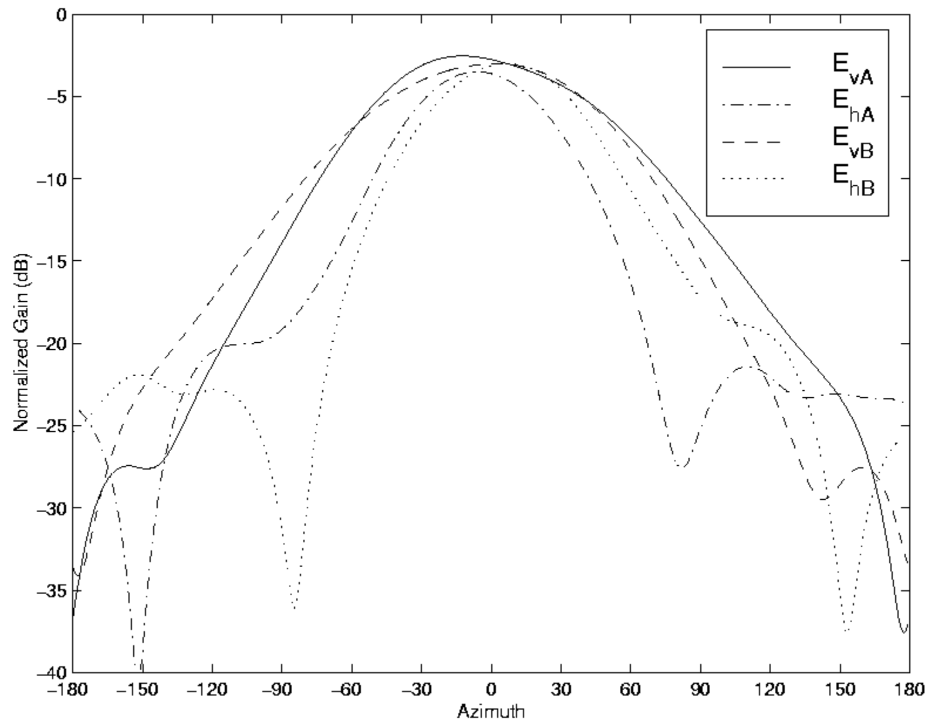


Slanted dipole antenna

Measured Radiation Patterns: Vertical and Horizontal Polarizations

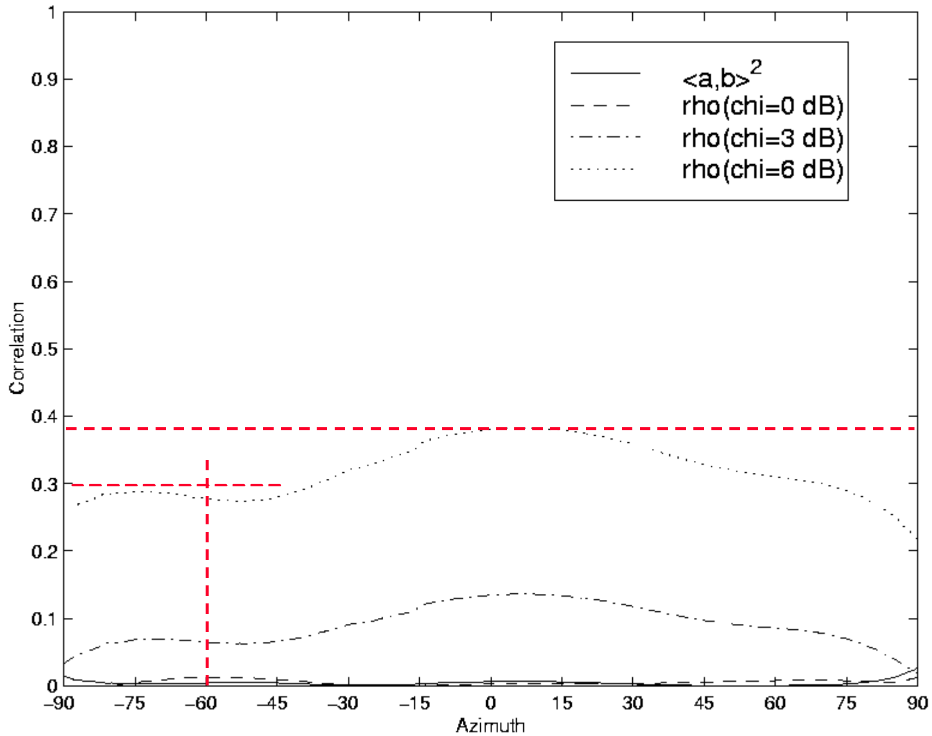


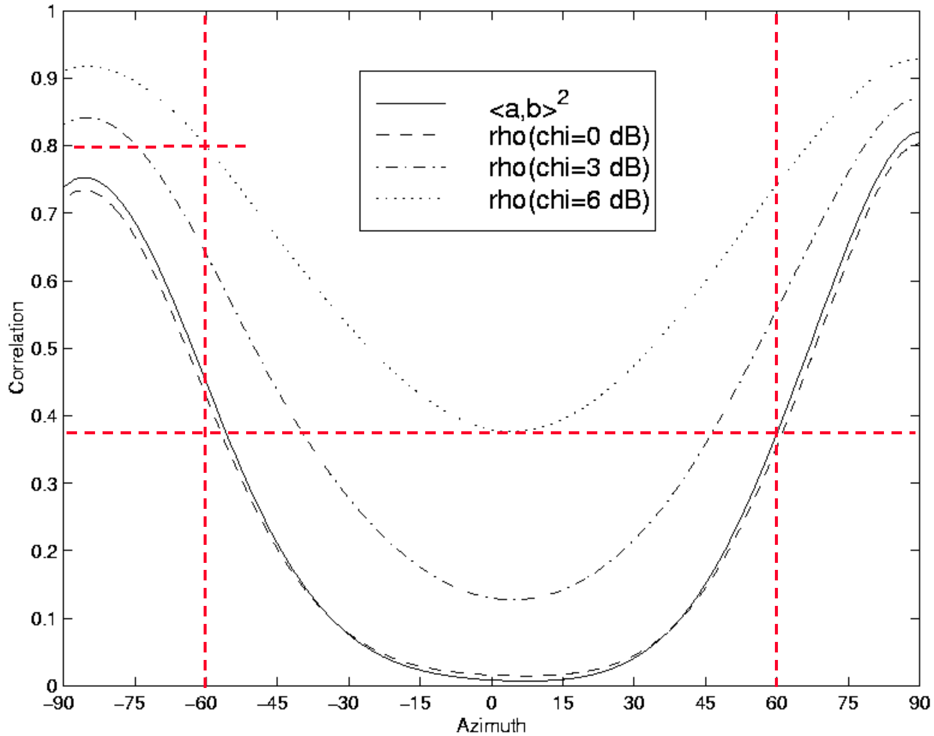
ACP antenna



Slanted dipole antenna

Simulated Output Envelope Correlation from Measured Radiation Patterns: 10000 samples





ACP antenna:

r_{envelope} ~= 0.3 at -60 degrees

Slanted dipole antenna:

r_{envelope} = 0.8 at -60 degrees

Both antennas: r_{envelope} = 0.38 at boresight due to projection onto the polarization ellipse

Far-field coupling from amplitude-only radiation patterns

Project **a** and **b** onto the vertical and horizontal polarizations:

$$\mathbf{a} = a_v\hat{v} + a_h\hat{h} \quad (1)$$
$$\mathbf{b} = b_v\hat{v} + b_h\hat{h}. \quad (2)$$

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

$$b_v = e^{-j\theta}a_v \quad (3)$$
$$b_h = -e^{-j\theta}a_h, \quad (4)$$

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

$$\begin{aligned}\langle \mathbf{a}, \mathbf{b} \rangle &= (\mathbf{a}, \mathbf{b}^*) \\ &= (a_v\hat{v} + a_h\hat{h}) \cdot (e^{j\theta}a_v^*\hat{v} - e^{j\theta}a_h^*\hat{h}) \\ &= e^{j\theta}(|a_v|^2 - |a_h|^2)\end{aligned} \quad (5)$$

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

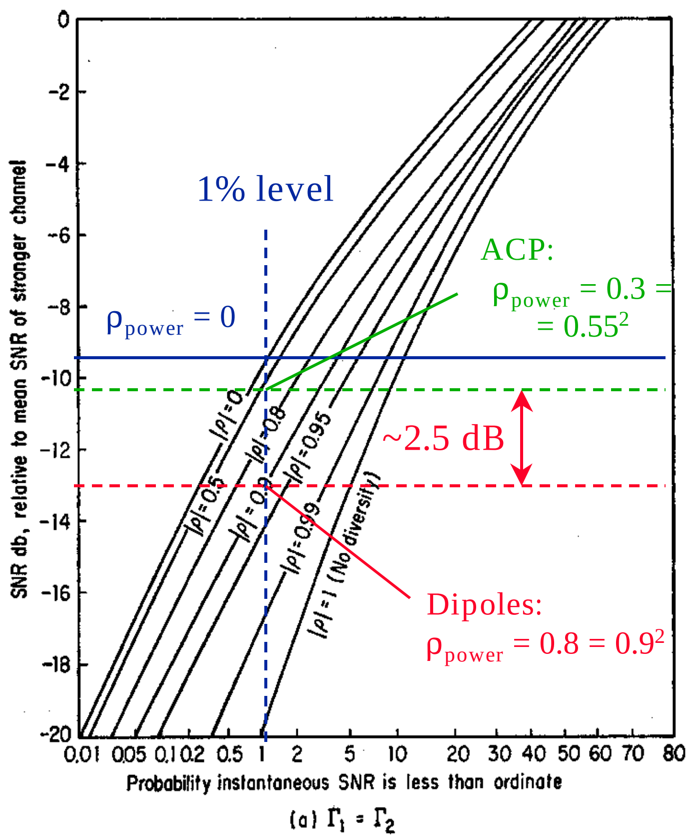
For the unpolarized case $\rho_{power} = |\langle \mathbf{a}, \mathbf{b} \rangle|^2$, hence the output power correlation is simply:

$$\rho_{power} = (|a_v|^2 - |a_h|^2)^2. \quad (6)$$

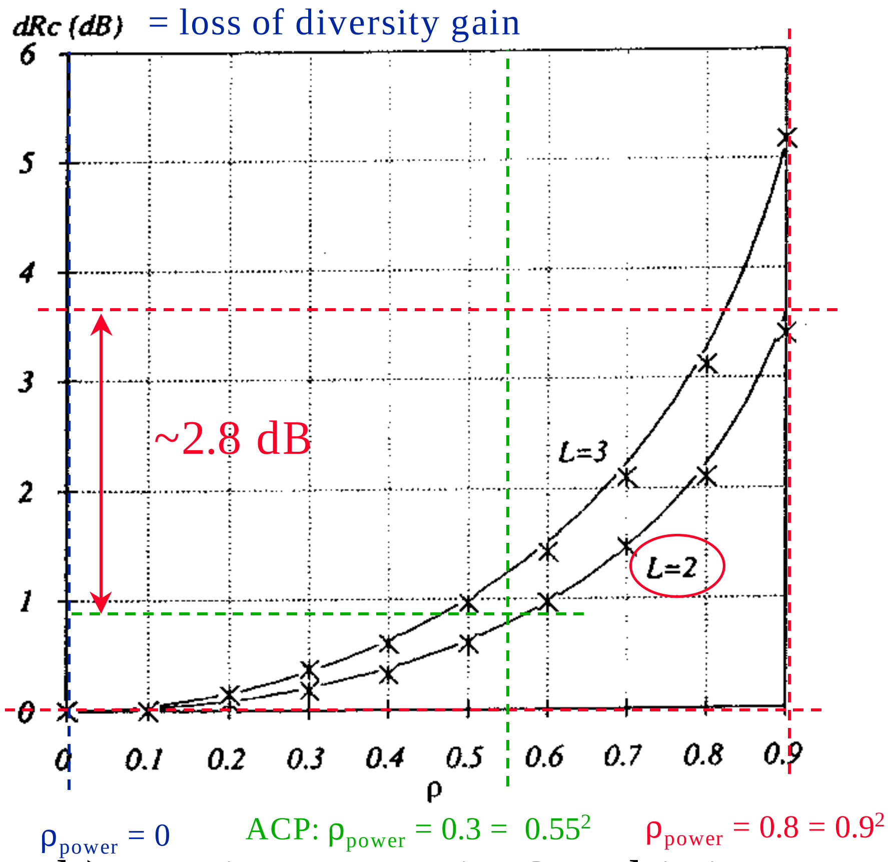
Impact of correlation on diversity gain

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

Note: $\rho_{env} \sim= \rho_{power} = \rho^2$ for Rayleigh signals

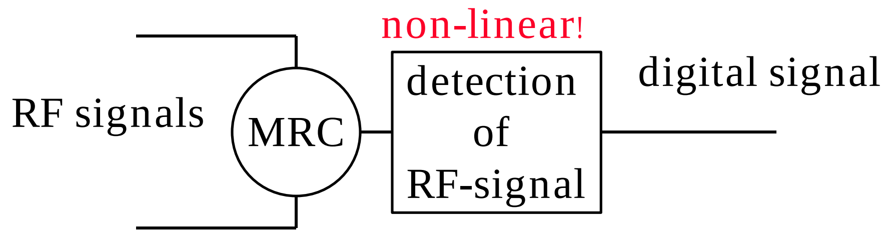


a) Selection diversity
(Schwartz, Bennett, Stein 1966)



b) Maximum Ratio Combining
(Yongbing Wan, J.C. Chen 1995)

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

$\Rightarrow$

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 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 <=> 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.