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Classical Diversity

Thomas Zwick, Lars Reichardt, Christian Sturm, Christian Waldschmidt, Werner Wiesbeck

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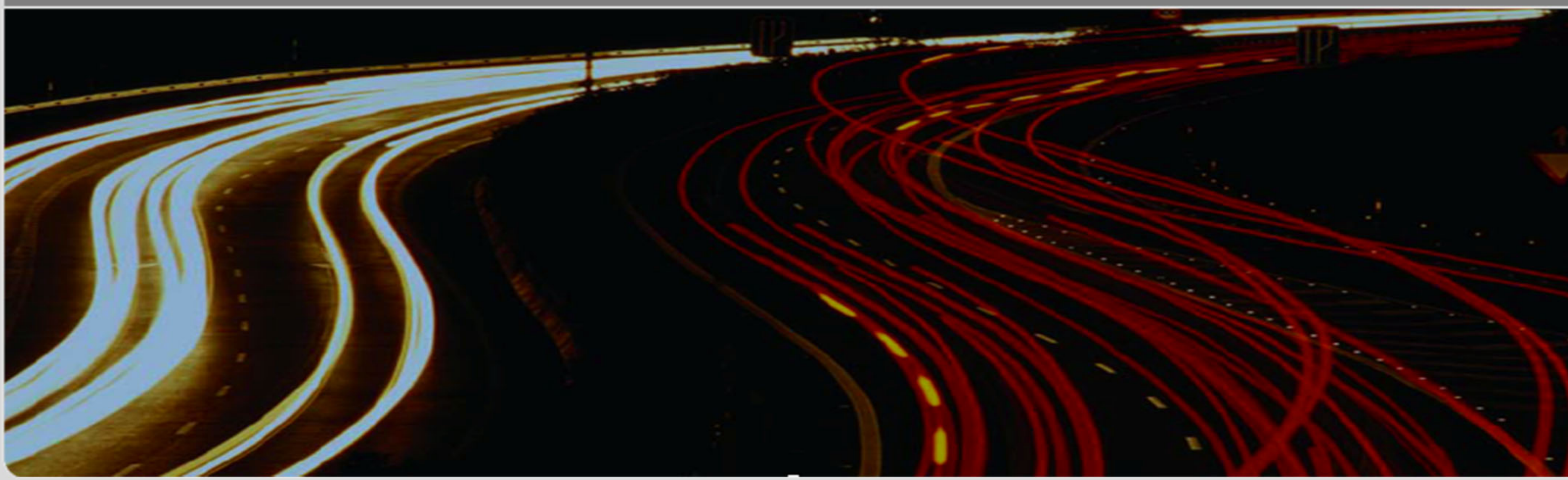

Outline

- The Problem
- Fading
- Signal Correlation
- Diversity Methods
- Diversity Combiner
- Diversity Efficiency

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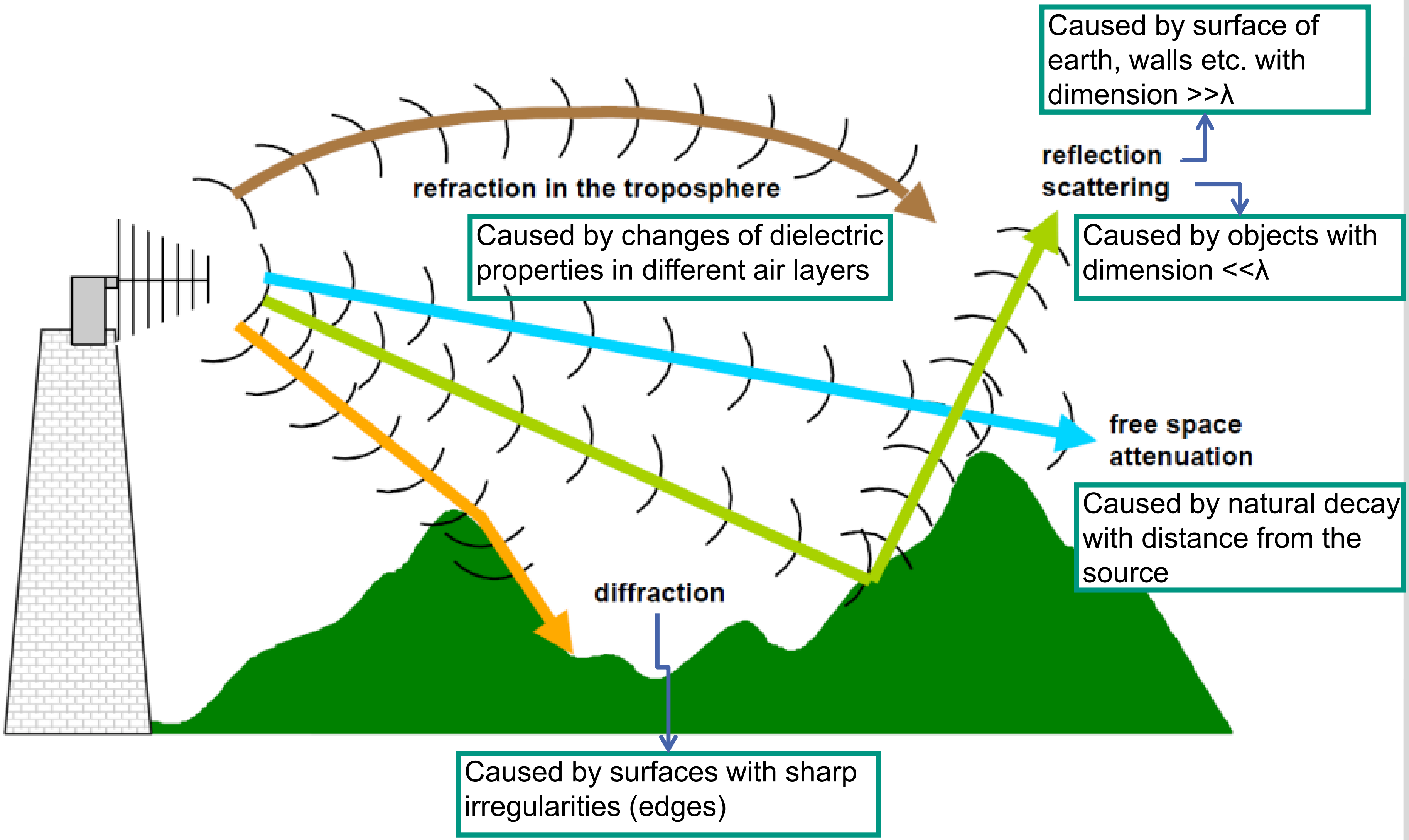
Wave Propagation Phenomena



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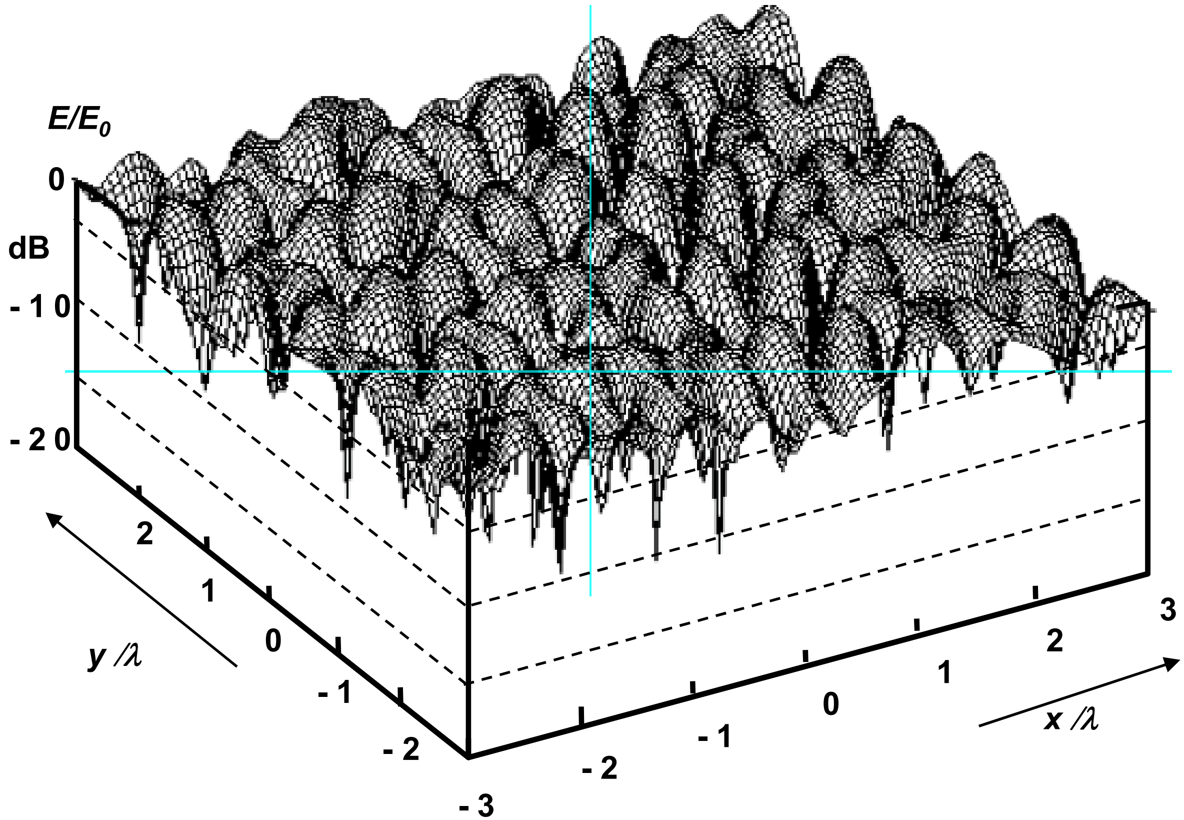
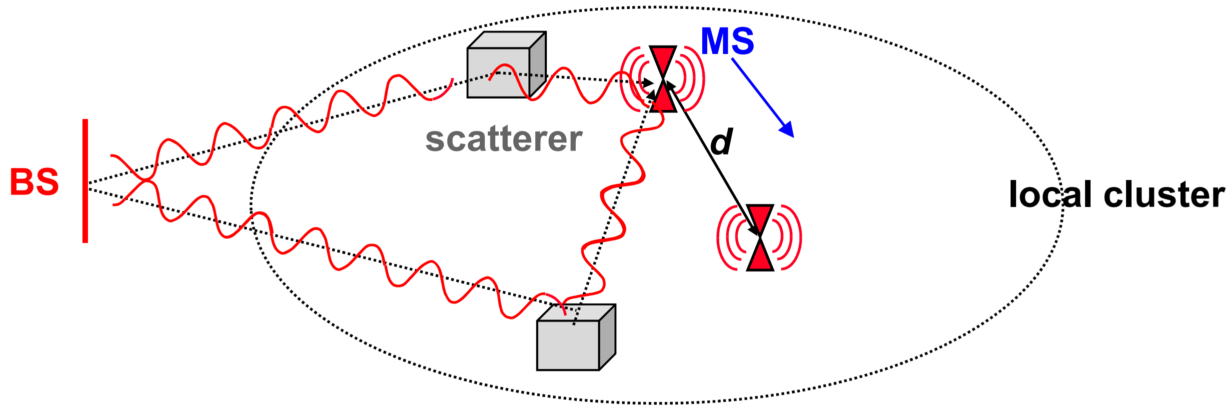
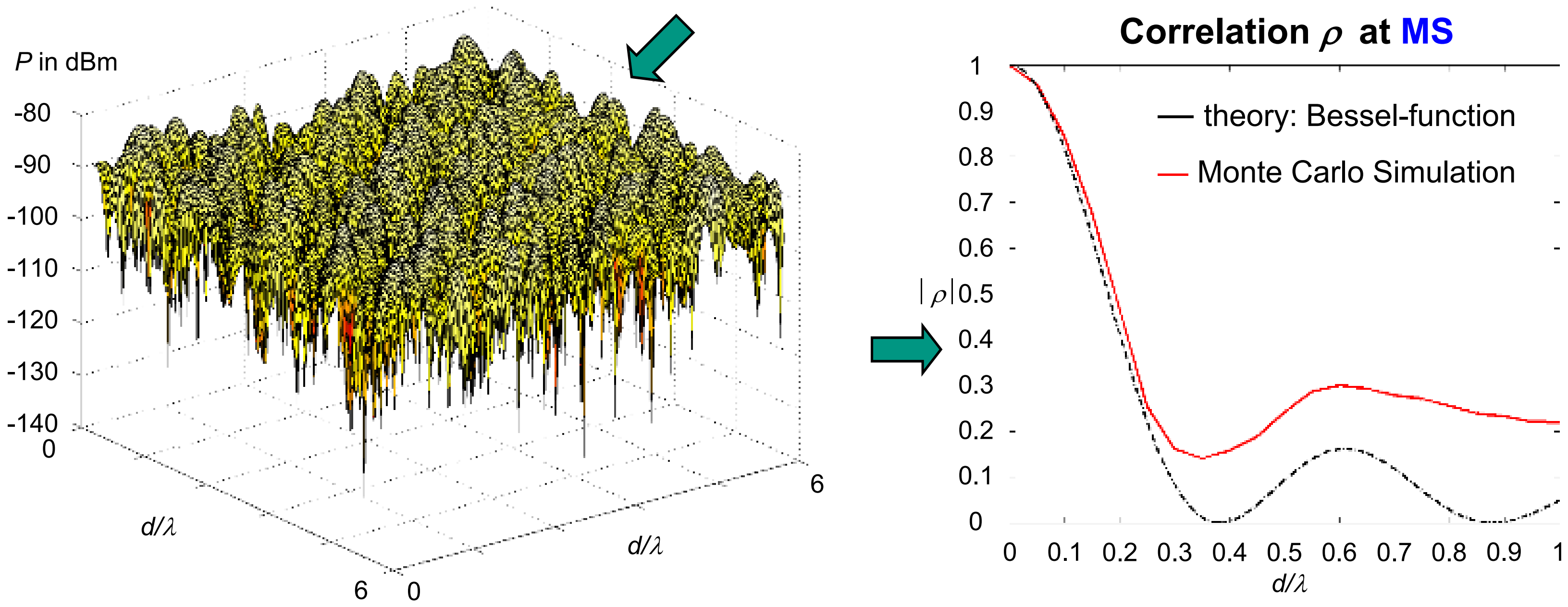
Relative Signal Strength in a Multi-Path



Relative Power in a Multi-Path Environment





What is Diversity?

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Task of Diversity:

Diversity is a means to overcome the fading problem by multiple receiving subsystems.

Principle of Diversity:

The principle of diversity is to select or combine the multiple received signals in a way that the resulting signal is always better than, or equal to, the better one of the single signals.

General Diversity Requirements and Assumptions

Requirements:

- **similar average signal strength in all channels**
- **similar average noise in all channels**
- **low correlation of the receive channels**

Assumptions:

- **signal independent additive noise**
- **uncorrelated noise**
- **signal amplitude is Rayleigh distributed**

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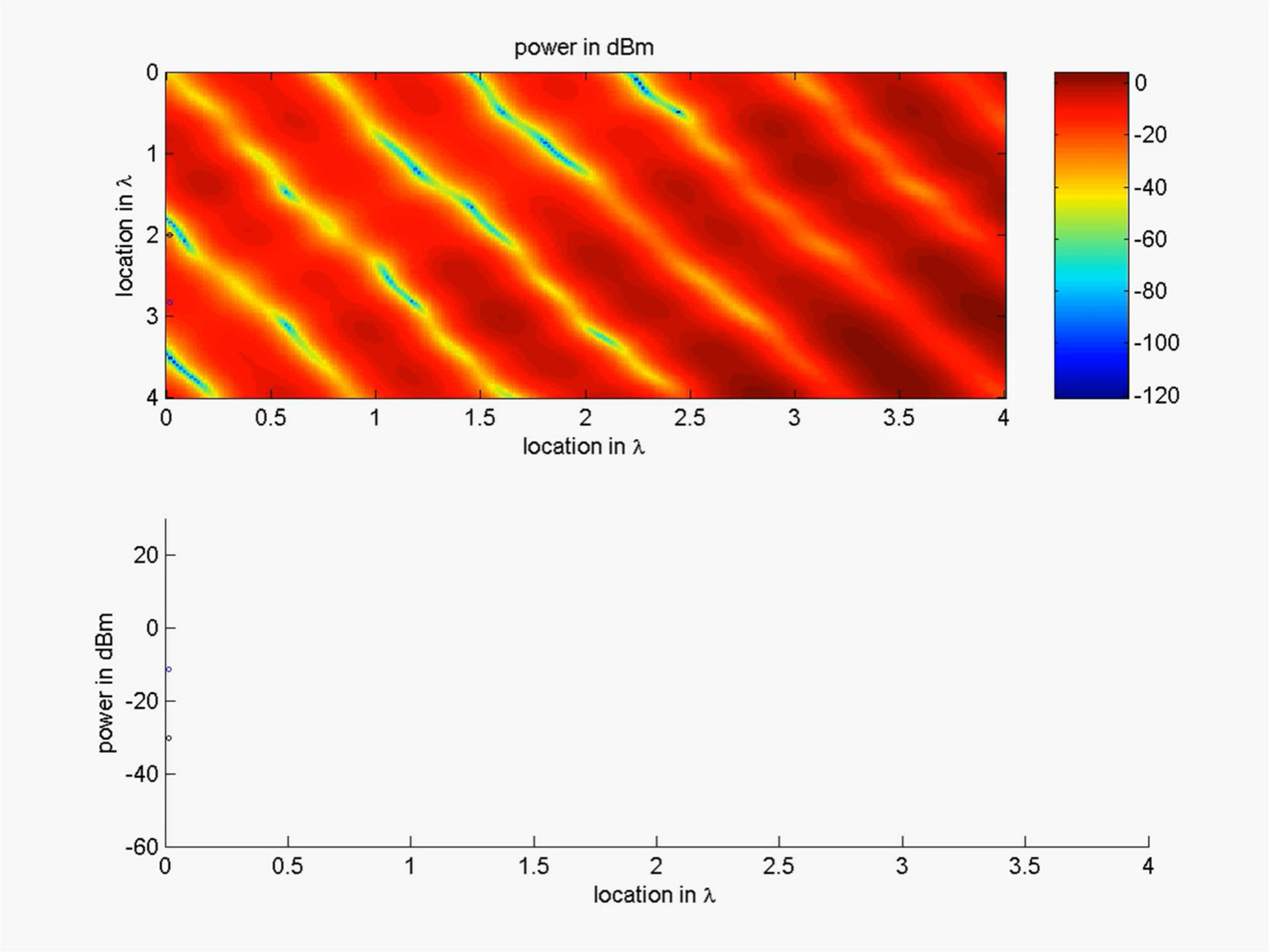
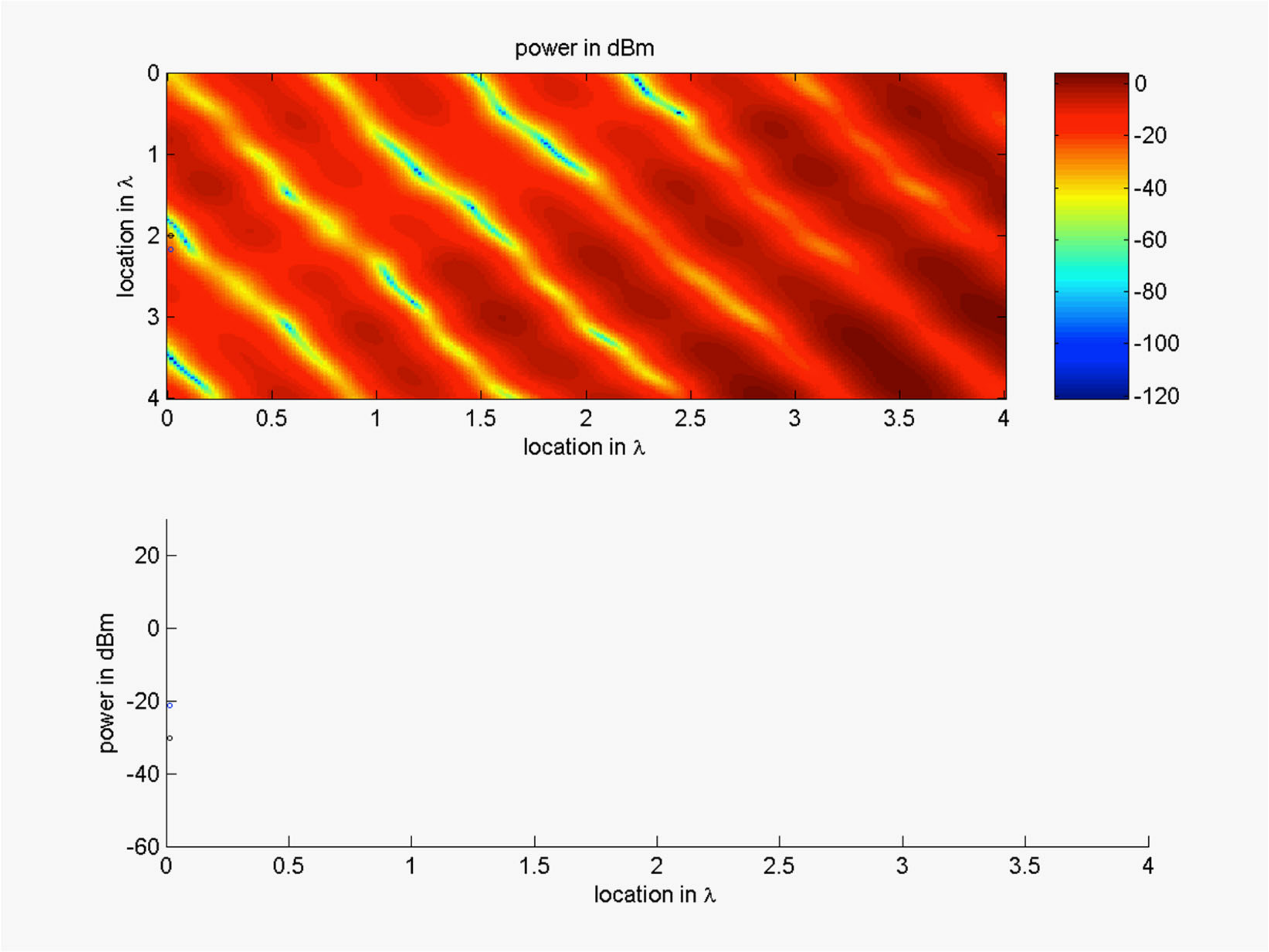
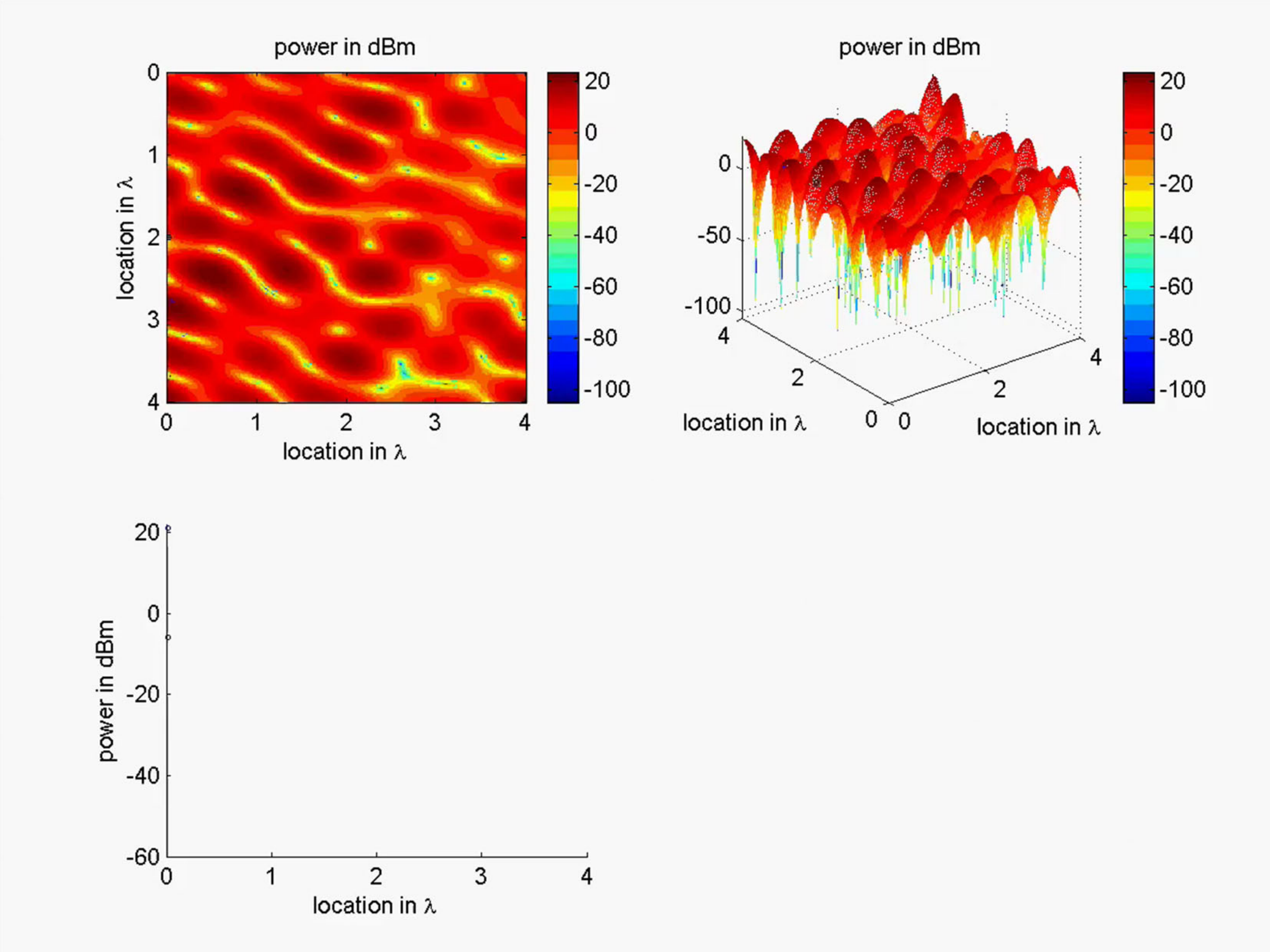
Space Diversity, Antenna Separation $d = 0.7\lambda$



Diversity with Small Antenna Separation, *d* = 0.05λ

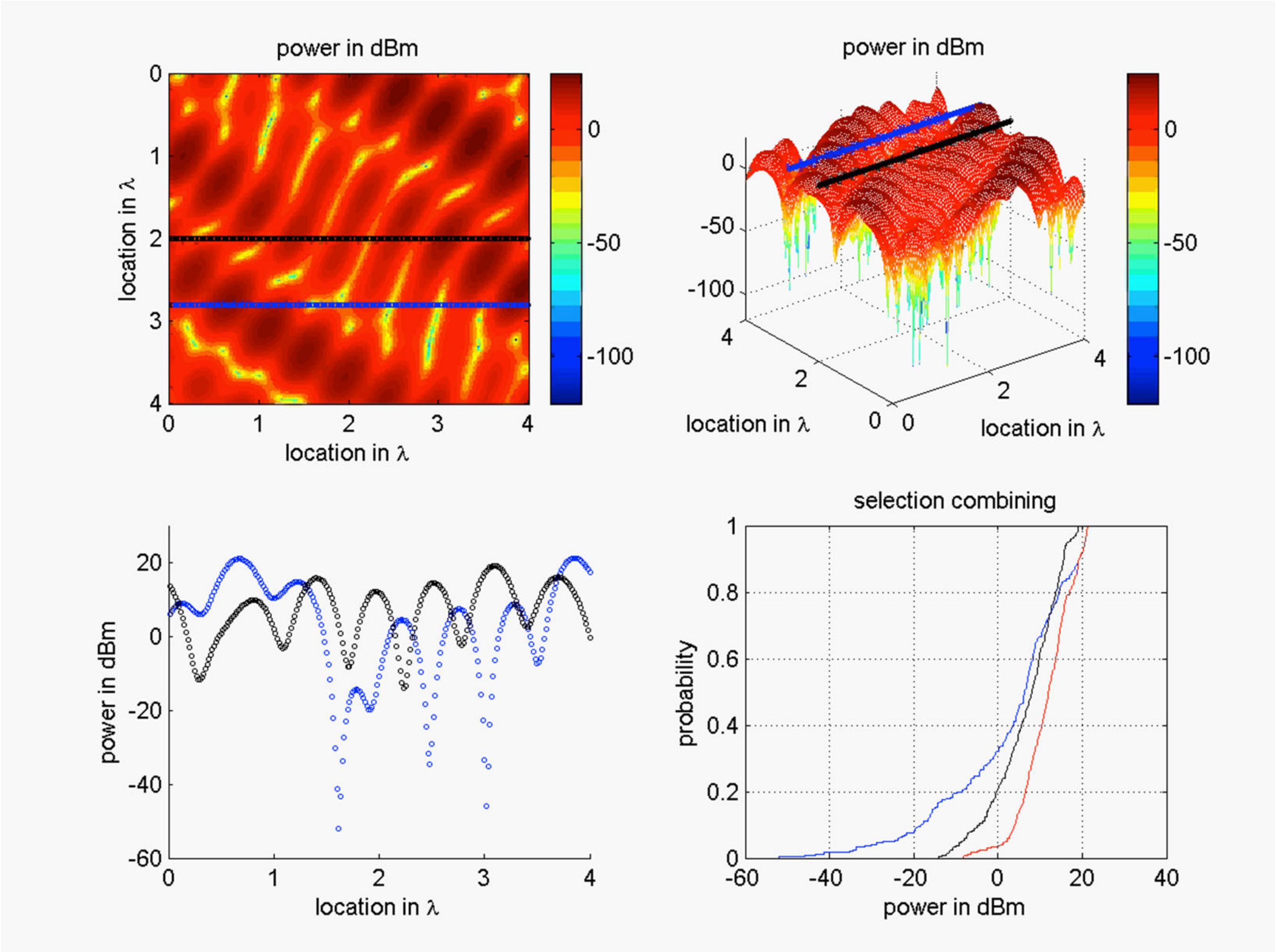


Diversity with Wide Antenna Separation, $d = 0{,}7\lambda$



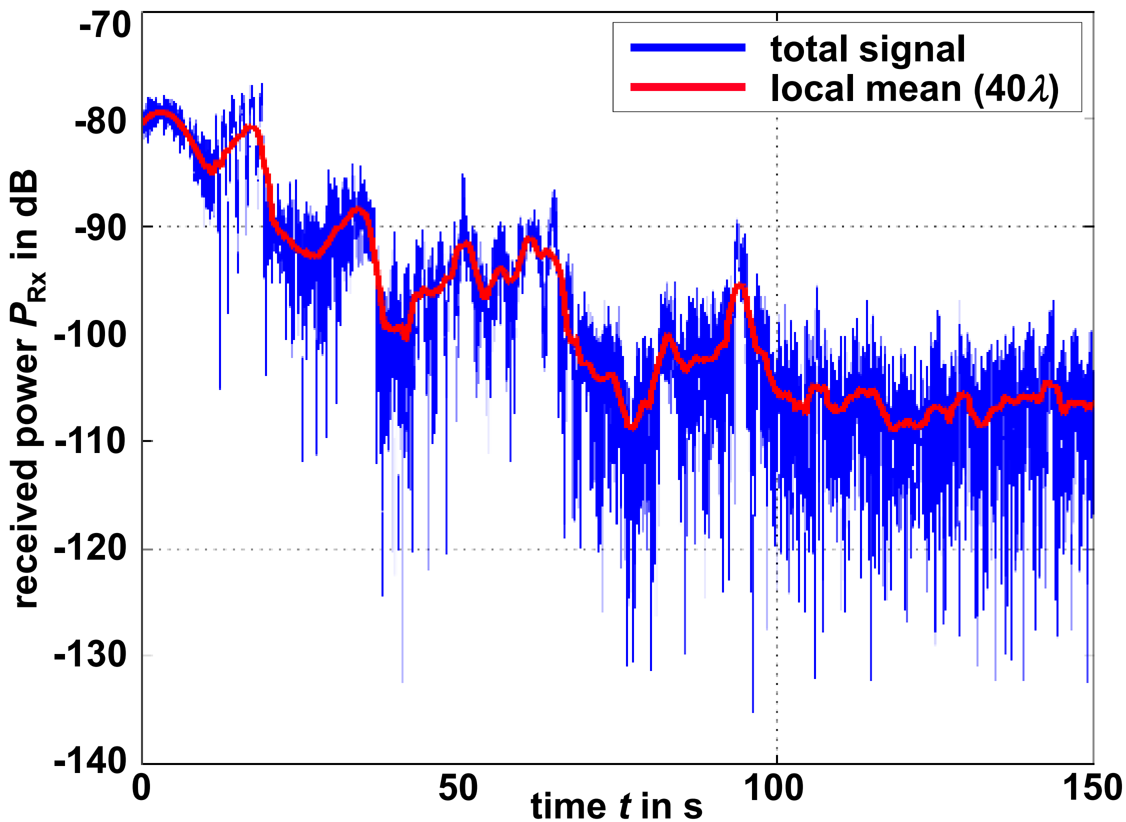
- signal no. 1
- signal no. 2
- combined signal

Diversity with Wide Antenna Separation, d = 0,7λ



- signal no. 1
- signal no. 2
- combined signal

Components of Fading (Narrow-Band Analysis)



receive signal transfer function at single carrier frequency: $\left|H^{TP}(t)\right| = l(t)\cdot s(t)$

$l(t)$: long-term fading
➢ **absolute values**

$s(t)$: short-term fading
➢ **statistical parameters**

Long-Term Fading & Short-Term Fading

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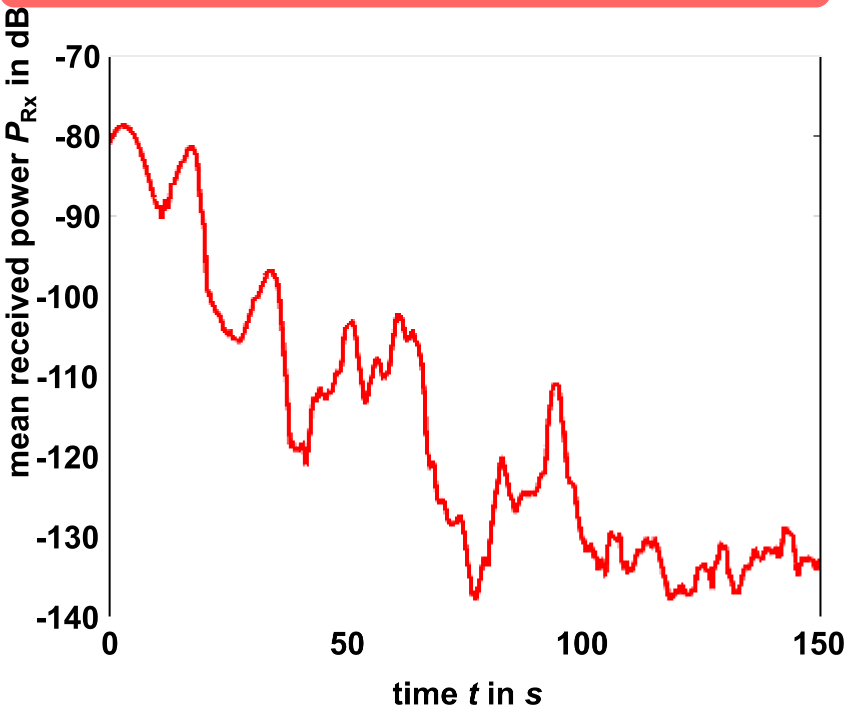
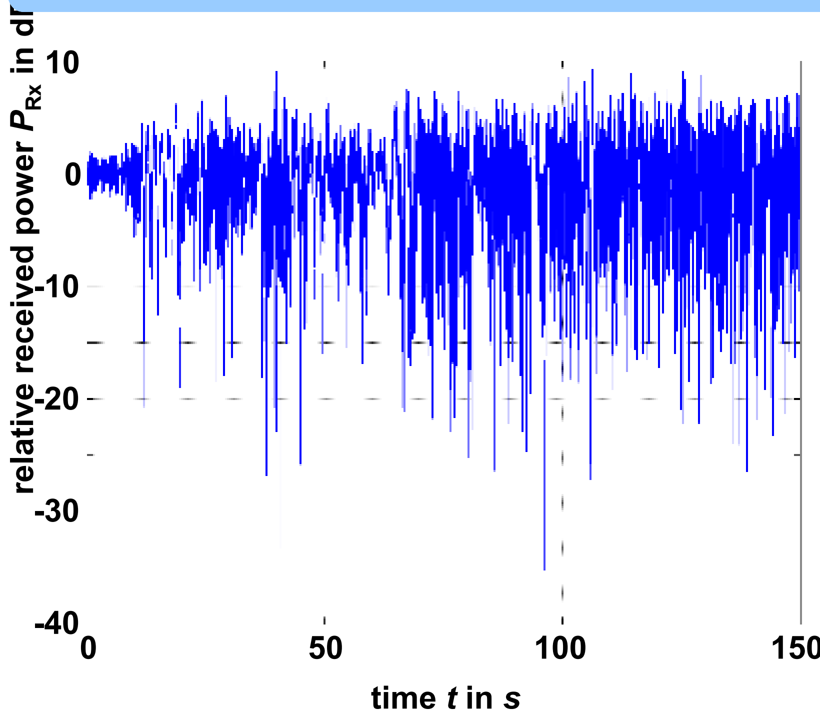
long-term fading $l(t)$



short-term fading $s(t)$



$$l(t) = \frac{1}{2w} \int_{t-w}^{t+w} \left| H^{TP}(t) \right| dt; \qquad l(t_k) = \frac{\sum_{i=t_k - w_{t_k}}^{t_k + w_{t_k}} \left| H^{TP}(i) \right|}{2 w_{t_k} + 1}$$

$$s(t) = \frac{\left| H^{TP}(t) \right|}{l(t)}; \qquad s(t) = \frac{\left| H^{TP}(t_k) \right|}{l(t_k)}$$

$$\text{window w}: \; w = \frac{w_\lambda \cdot c_0}{v \cdot f_0}; \quad \text{discret}: \; w_{t_k} = w \cdot f_{sampling}$$

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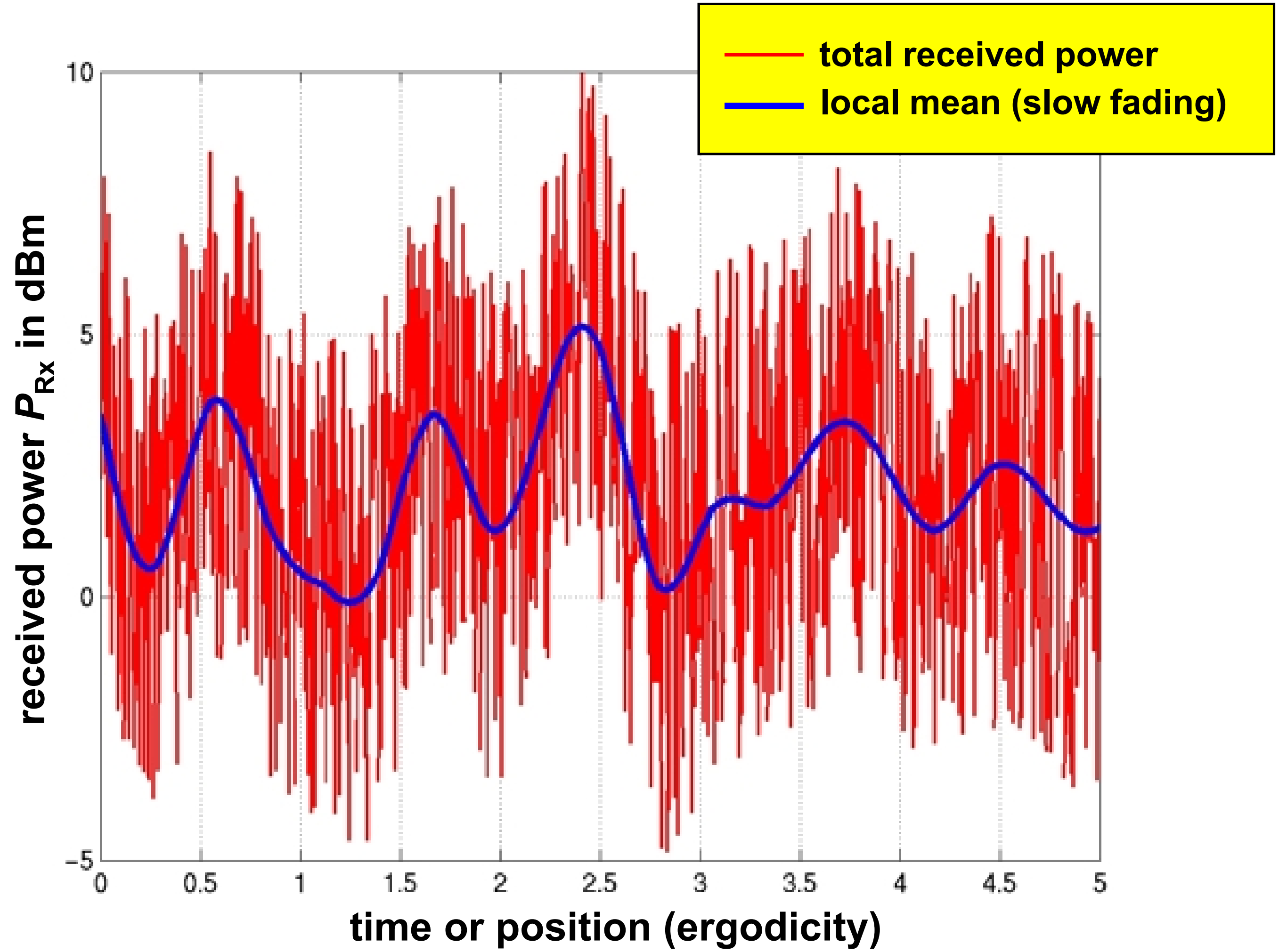
Small-Scale (Fast) & Large-Scale (Slow) Fading



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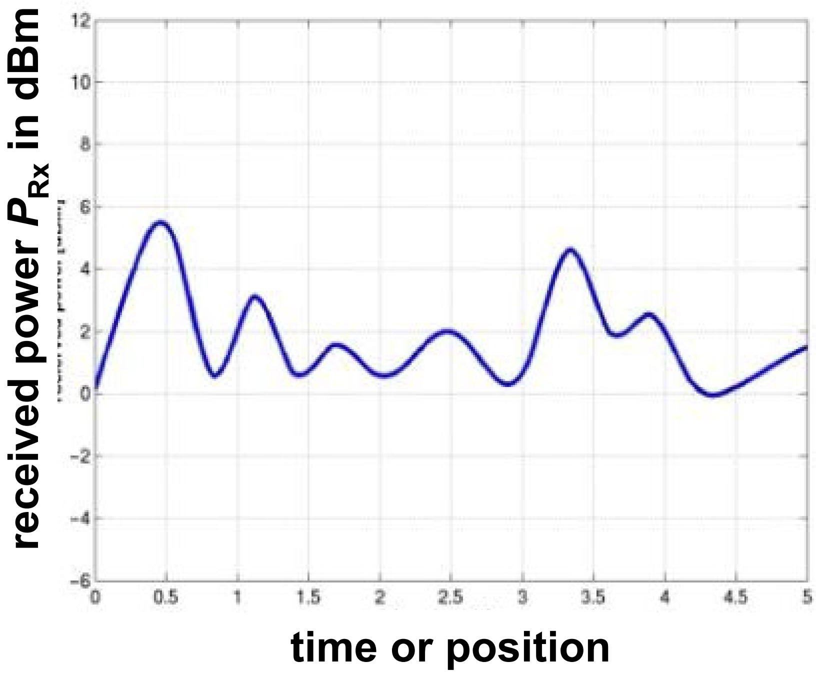
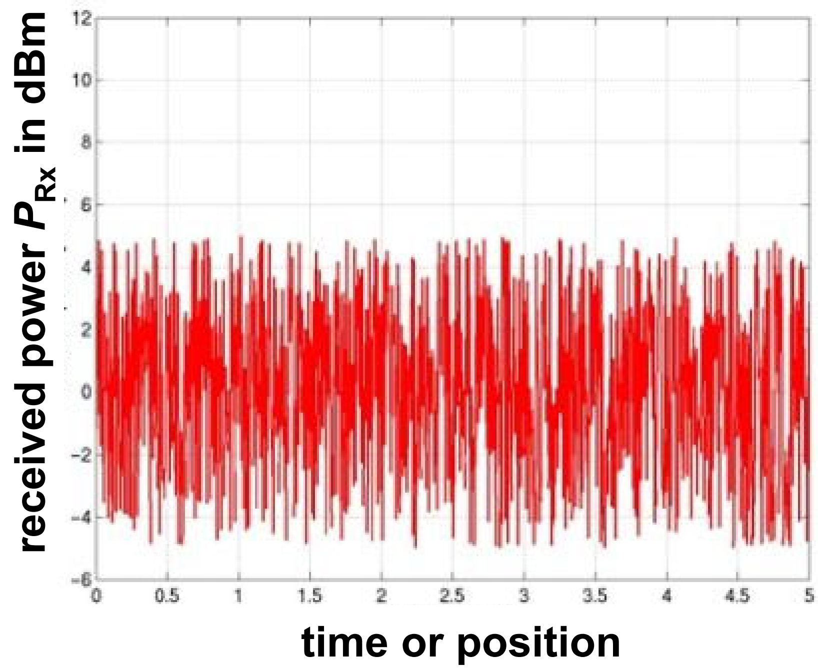
The Components of Fading

Long-term fading *l(t)*
(slow fading)



Short-term fading *s(t)*
(fast fading)



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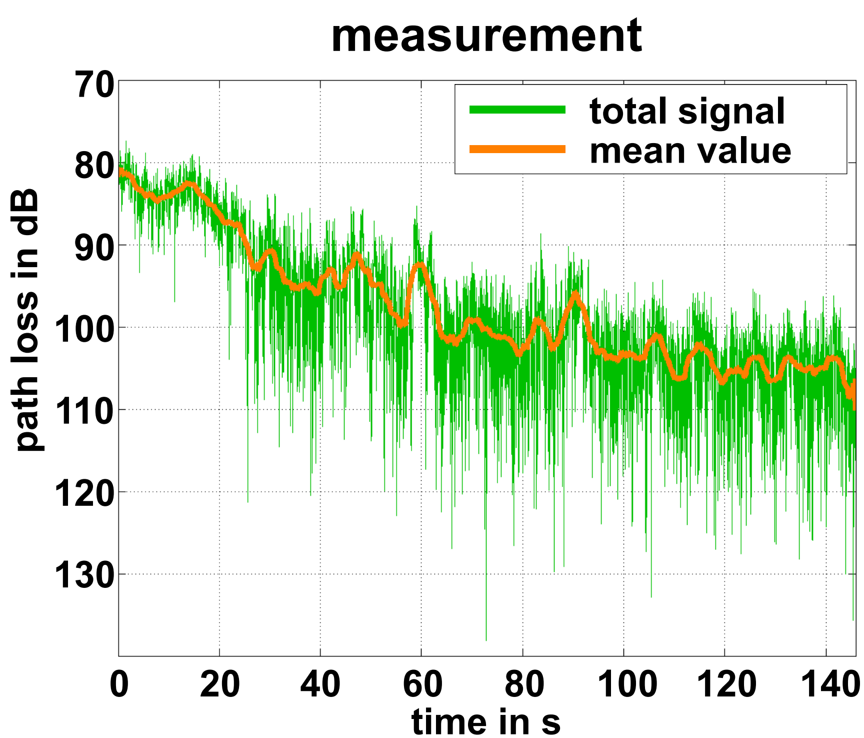
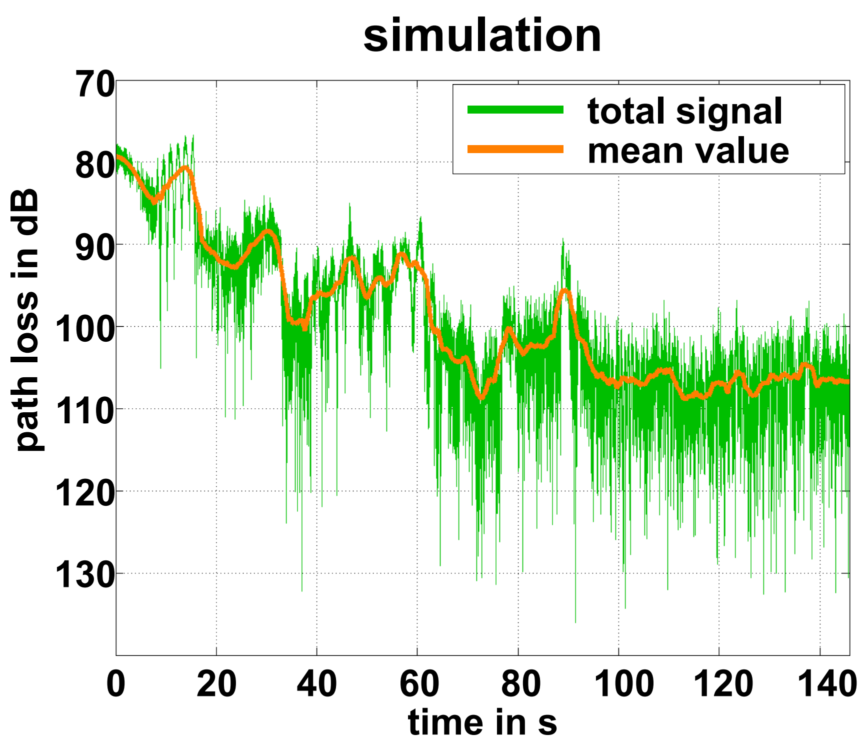
Narrow-band Analysis - Measurement-Simulation





$$s(t) = l(t) \bullet s(t)$$

l(t): **long-term fading**
→ **absolute values**

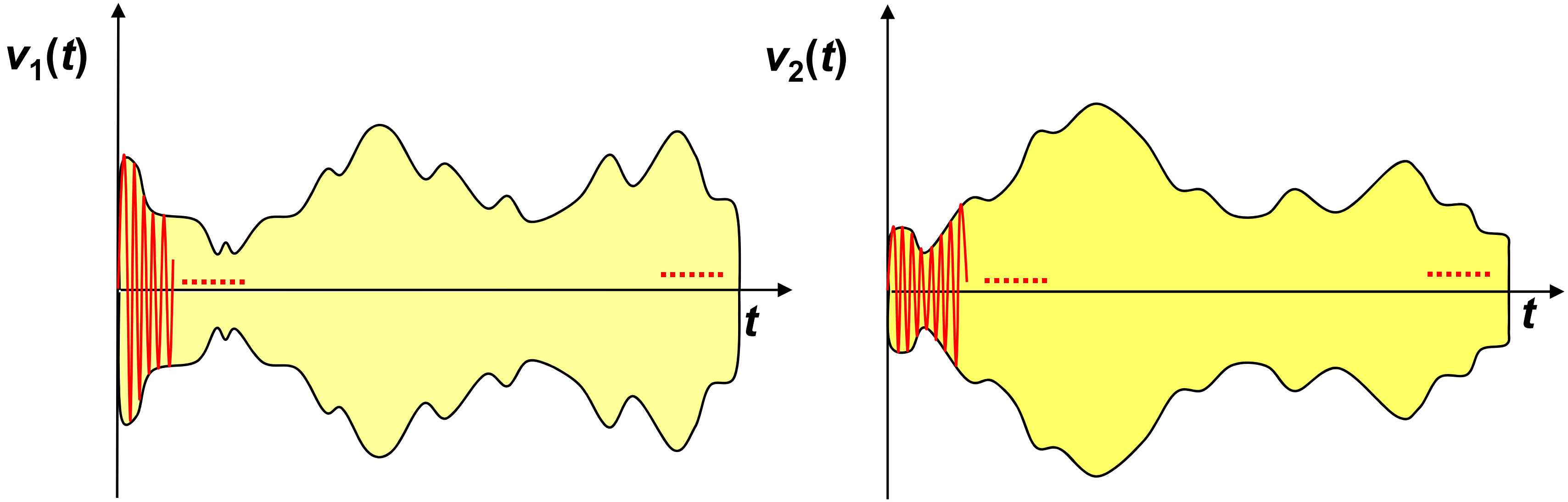
s(t): **short-term fading**
→ **statistical parameters**

Multi-path Effects

Multi-path in the radio channel creates *short-term fading* effects. This results in:

- **rapid changes in signal strength over a small travel distance or time interval**
- **frequency selectivity caused by multi-path propagation delays**
- **frequency modulation due to varying Doppler shifts on different multi-path signals**

Signals in two Diversity Receiving Channels



$$v_1(t) = a_1(t) \cdot \cos(\omega t + \varphi_1(t))$$

$$v_2(t) = a_2(t) \cdot \cos(\omega t + \varphi_2(t))$$

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Signals in two Diversity Receiving Channels

The antenna ν output voltage $\underline{V}_\nu$ results from N incident waves for a position x:

$$\underline{V}_\nu(\vec{x}) \approx \sum_{i=1}^{N} \underline{C}_\nu(\theta_i,\psi_i) \cdot \underline{\vec{E}}_i e^{-j\omega\tau_i} e^{-jk_i \vec{x}}$$

$$\underline{C}_\nu(\theta_i,\psi_i) = \underline{C}_{\theta_\nu}(\theta_i,\psi_i) \cdot \vec{e}_\theta + \underline{C}_{\psi_\nu}(\theta_i,\psi_i) \cdot \vec{e}_\psi$$

$$\underline{\vec{E}}_i = \left|\underline{\vec{E}}_{\theta i}\right| e^{-j\varphi_{\theta i}} \cdot \vec{e}_\theta + \left|\underline{\vec{E}}_{\psi i}\right| e^{-j\varphi_{\theta i}} \cdot \vec{e}_\psi$$

$$\vec{k}_i = -k\sin\theta_i \cdot \cos\psi_i \cdot \vec{e}_x - k\sin\theta_i \cdot \sin\psi_i \cdot \vec{e}_y - k\cos\theta_i \cdot \vec{e}_z$$

$C_{\theta\nu}(\theta,\psi)$ and $C_{\psi\nu}(\theta,\psi)$ define the polarization dependent complex far field antenna pattern of the receive antenna ν

For two antennas the output voltages $v_\nu(t)$ an $v_\mu(t)$ are:

$$v_\nu(t) = a_\nu(t) \cdot \cos(\omega t + \varphi_\nu(t))$$

$$v_\mu(t) = a_\mu(t) \cdot \cos(\omega t + \varphi_\mu(t))$$

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Received Signals Correlation of Diversity and MIMO Antenna Systems

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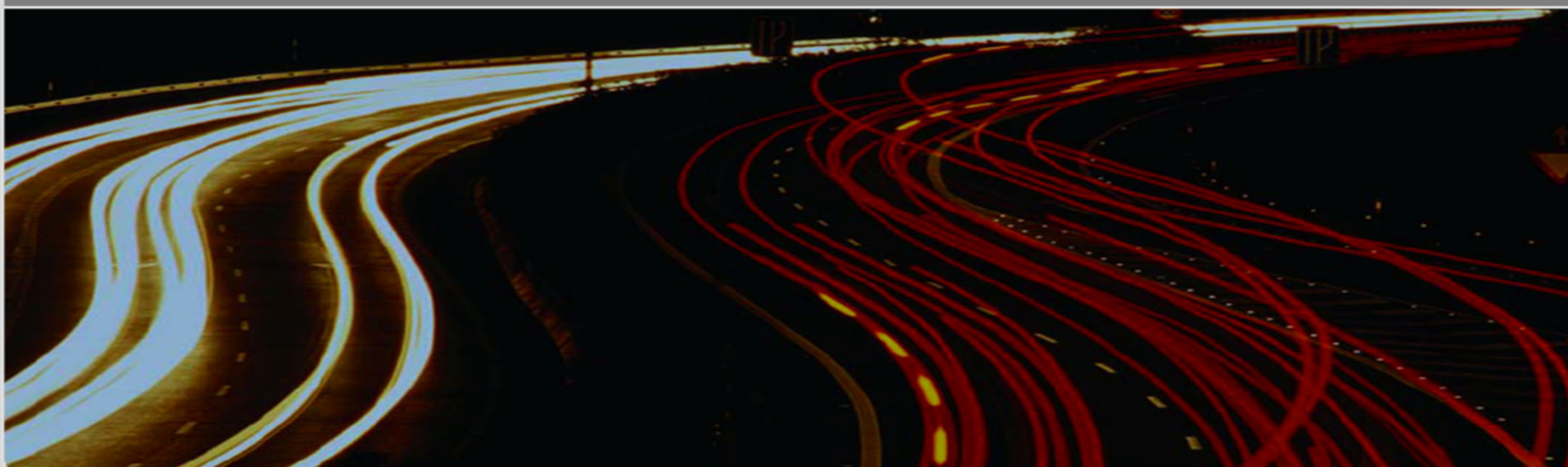

Definitions for Signal Correlation

Reveived signal amplitude *A* at antenna *i or j* : $\underline{A}_{i,j}(t)$

Reveived power *P* at antenna *i or j* : $P_{i,j}(t)$

Reveived mean signal at antenna *i or j* : $m_{i,j}$

Amplitude Standard Deviation at antenna *i or j* : $\sigma_{Ai,j}$

Power Standard Deviation at antenna *i or j* : $\sigma_{Pi,j}$

Incident field-strength: $E(\theta,\psi)$; Incident power density: $S(\theta,\psi)$

Envelope-Covariance-Coefficient ρ_{Aij}

Amplitude Cross Correlation

Normalized Amplitude-Cross-Correlation-Coefficient

$$\rho_{Aij} = \frac{R_{Aij}}{\sigma_{Ai}\sigma_{Aj}}$$

$\sqrt{\text{Variances of}}\ A_{pi,j}$

$$R_{Aij} = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T}\left(\left|\left\langle \underline{A}_i(t)\right\rangle\right| - m_i\right)\left(\left|\left\langle \underline{A}_j(t)\right\rangle\right| - m_j\right)dt$$

$$\sigma_{Ai,j} = \sqrt{\lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T}\left(\left|\left\langle \underline{A}_{i,j}(t)\right\rangle\right| - m_{i,j}\right)^2 dt}$$

$$m_{Ai,j} = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T}\left|\left\langle \underline{A}_{i,j}(t)\right\rangle\right| dt$$

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Power-Covariance-Coefficient ρ_{Pij}

Power Cross Correlation

Normalized Power-Cross-Correlation-Coefficient

$$\rho_{Pij} = \frac{R_{Pij}}{\sigma_{Pi}\sigma_{Pj}}$$

$\sqrt{\text{Variances of } P_{pi,j}}$

$$R_{Pij} = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T}\left(P_{Pi}(t) - m_{Pi}\right)\left(P_{Pj}(t) - m_{Pj}\right)dt$$

$$\sigma_{Pi,j} = \sqrt{\lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T}\left(P_{Pi,j}(t) - m_{Pi,j}\right)^2 dt}$$

$$m_{Pi,j} = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T}P_{Pi,j}(t)\,dt$$

Power-Covariance-Coefficient ρ_{Pij}

$$\rho_{Pij} \approx \left|\rho_{Aij}\right|^2 = \frac{\left|R_{ij}\right|^2}{\sigma_i \sigma_j}$$

$$R_{ij} = K \int_0^{2\pi} \int_0^{\pi} G_i \cdot \underline{C}_i(\theta,\psi) \cdot G_j \cdot \underline{C}^*_j(\theta,\psi) \cdot S(\theta,\psi) \cdot e^{jk\Delta\Phi(\theta,\psi)} \sin\theta \cdot d\theta \cdot d\psi$$

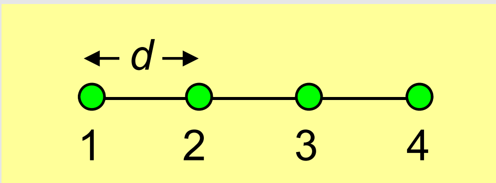
$$\sigma_{i,j} = \sqrt{K \int_0^{2\pi} \int_0^{\pi} G_{i,j} \cdot \left|C_{i,j}(\theta,\psi) \cdot G_{i,j}\right|^2 \cdot S(\theta,\psi) d\Omega}$$

For an analytical evaluation an assumption on the incoming wave front distribution has to be made:

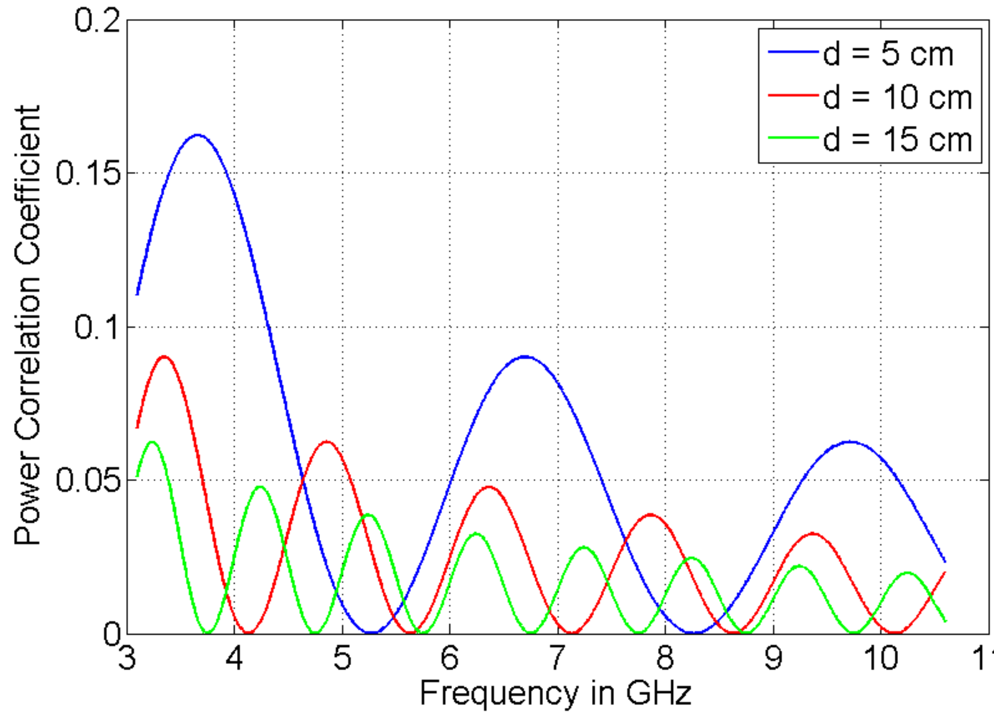
e.g. - incident waves from 360° in azimuth ψ
- incidence in elevation θ: 90° ± 10° Gauß distributed

Analytic Calculation of Correlation Coefficients I

4 element array



Isotropic elements
‚worst case ‘
same polarization



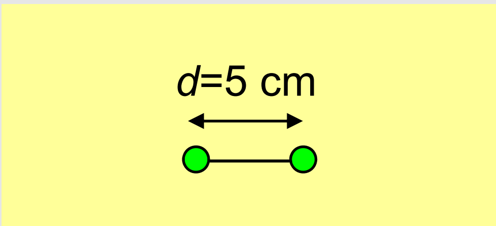
Assuming uniform 2D distribution of incoming waves:

$$\rho(d)=\int_0^{2\pi}\underbrace{C(\psi)}_{\equiv 1}\cdot\underbrace{C(\psi)}_{\equiv 1}e^{j2\pi d/\lambda\cdot\cos\psi}\,d\psi=\int_0^{2\pi}e^{j2\pi d/\lambda\cdot\cos\psi}\,d\psi=J_0(2\pi d/\lambda)$$

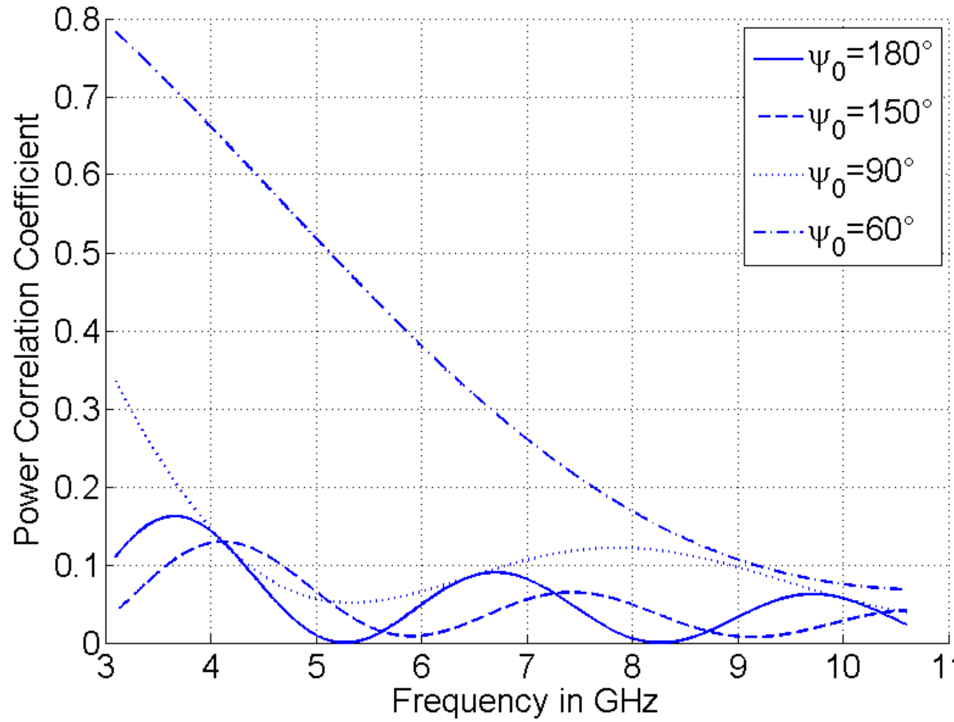
for isotropic elements

Analytic Calculation of Correlation Coefficients II

2 elements



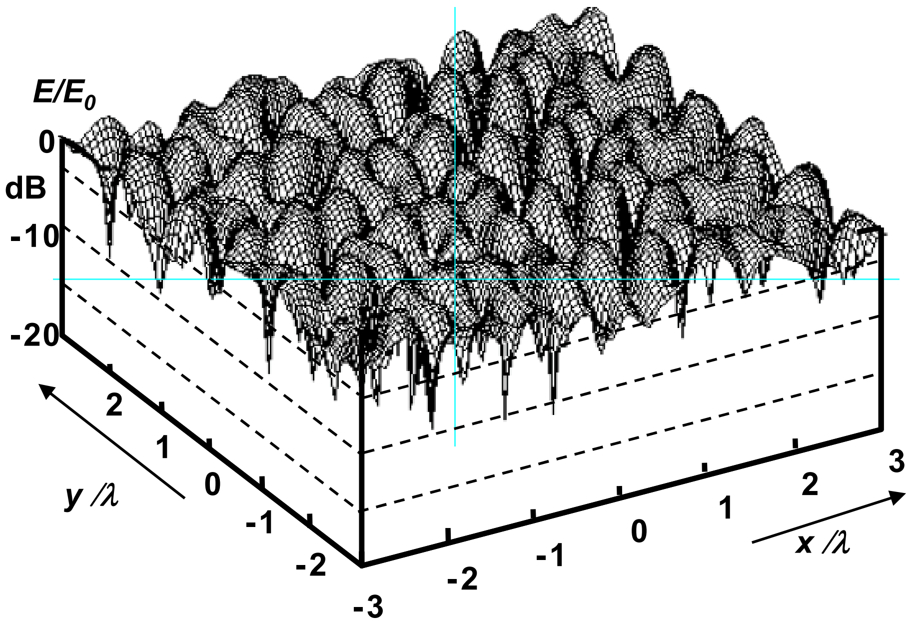
Isotropic elements
‚worst case‘
same polarization

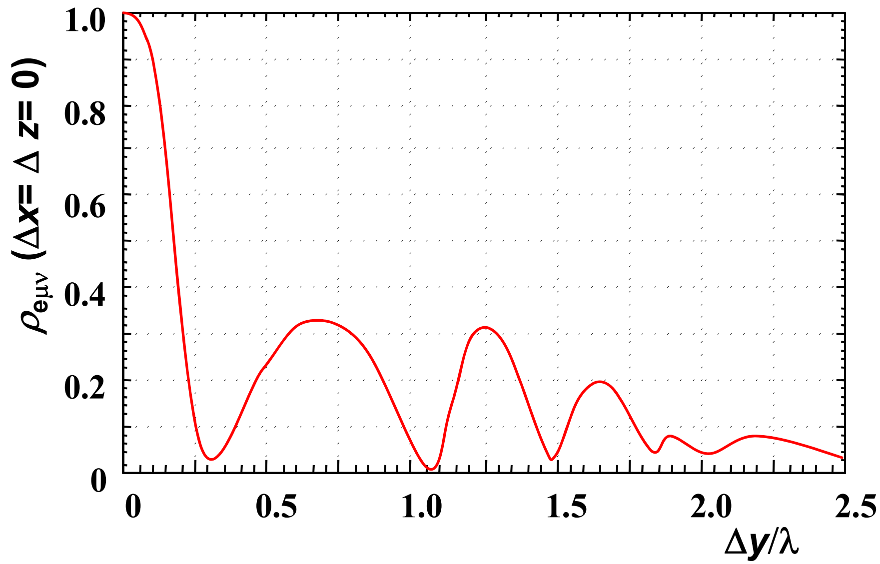


Assuming uniform 2D distribution over a limited angular sector ψ_0:

$$\rho(d,\lambda)=\frac{1}{\psi_0}\int_0^{\psi_0} e^{j2\pi d/\lambda\cdot\cos\psi}\,d\psi$$

Envelope Cross Correlation Coefficient





urban environment, $\lambda/2$-dipole, vertical polarization, f=925MHz

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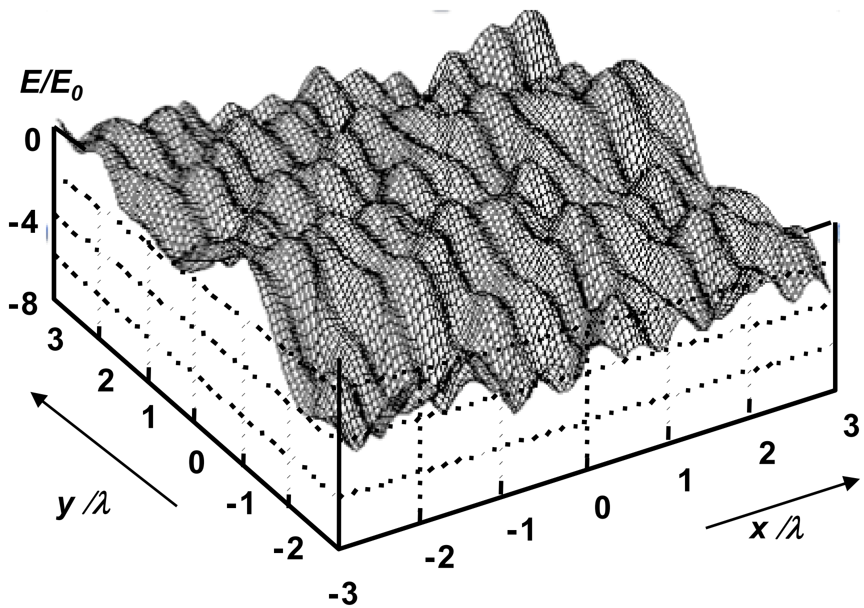
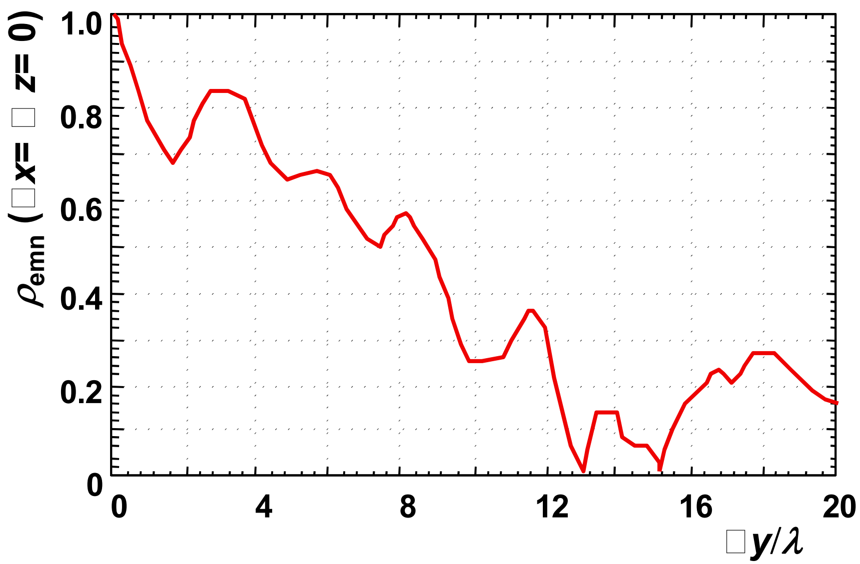
Envelope Cross Correlation Coefficient





hilly terrain, λ/2-dipole,
vertical polarization, *f*=925MHz

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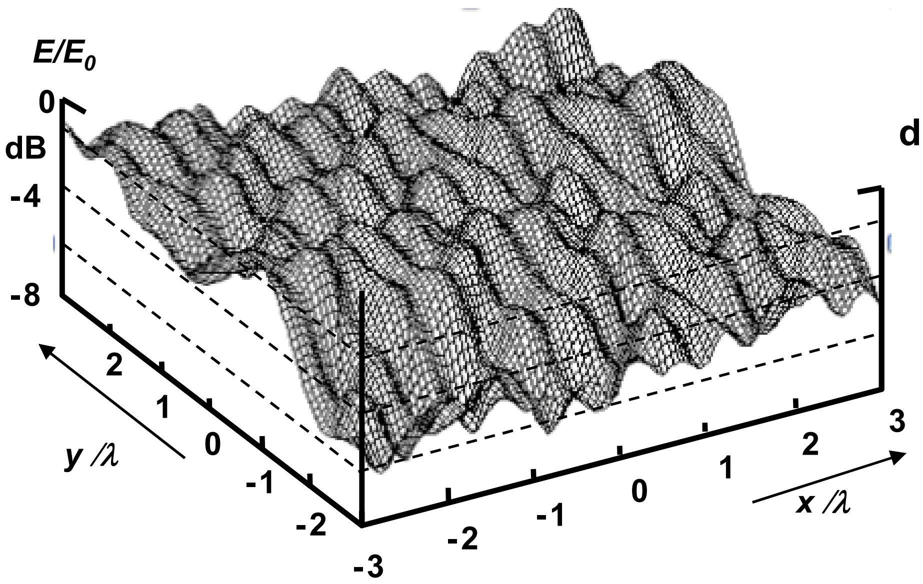
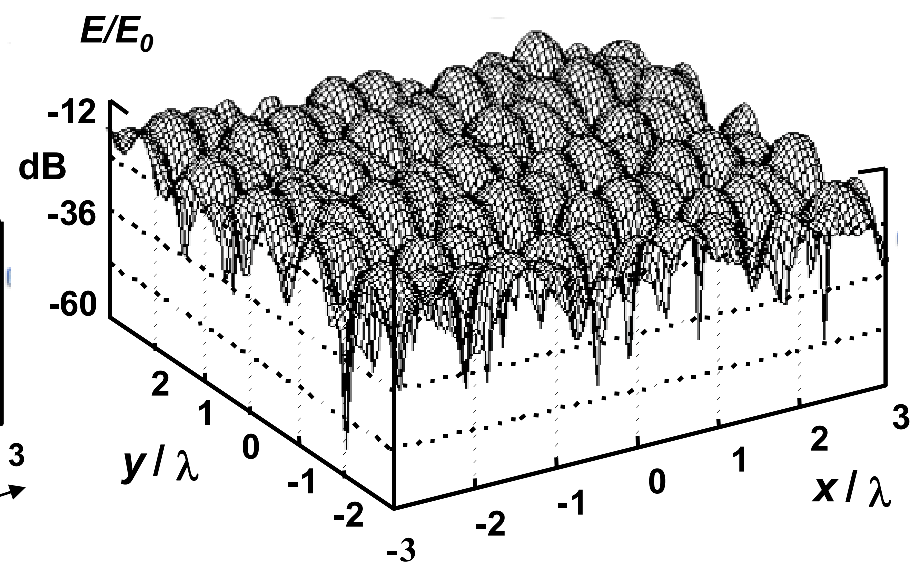
Relative Signal Strength in Multi-path Environments

Hilly terrain, λ/2-dipole



vertical polarization, f=925MHz
rel. average E/E_0 level =- 3,8dB

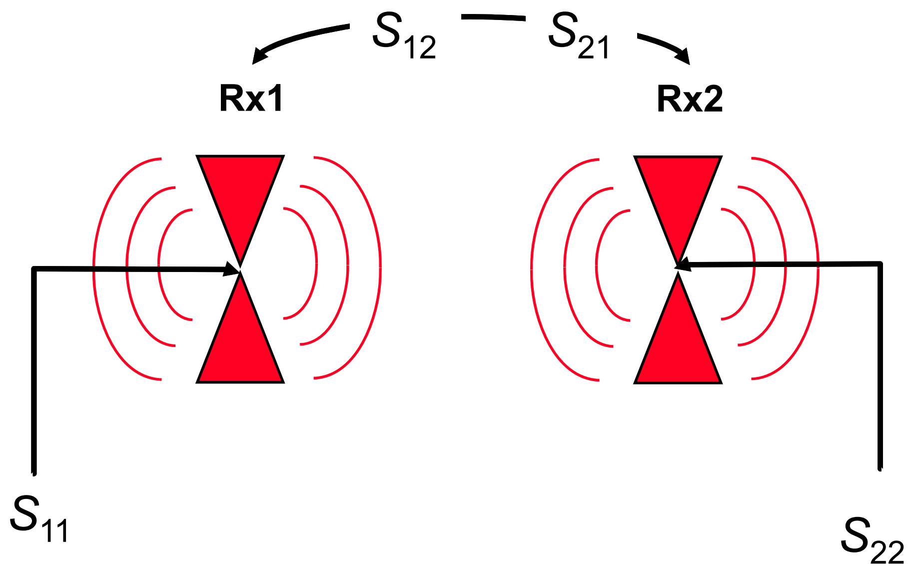
Hilly terrain, loop antenna



horizontal polarization, f=925MHz
rel. average E/E_0 level =- 27,1dB

ρ_{e12}= 0,34

Envelope Correlation Coefficient by S-Parameters



$$\rho_{1-2} = \frac{\left|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}\right|^2}{\left(1-\left(\left|S_{11}\right|^2+\left|S_{21}\right|^2\right)\right)\cdot\left(1-\left(\left|S_{22}\right|^2+\left|S_{12}\right|^2\right)\right)}$$

S. Blanch, J. Romeu, and I. Corbella, "Exact representation of antenna system diversity performance from input parameter description," *Electronics Lett.*, vol. 39, no. 9, pp. 705−707, May 2003.

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Diversity Principles

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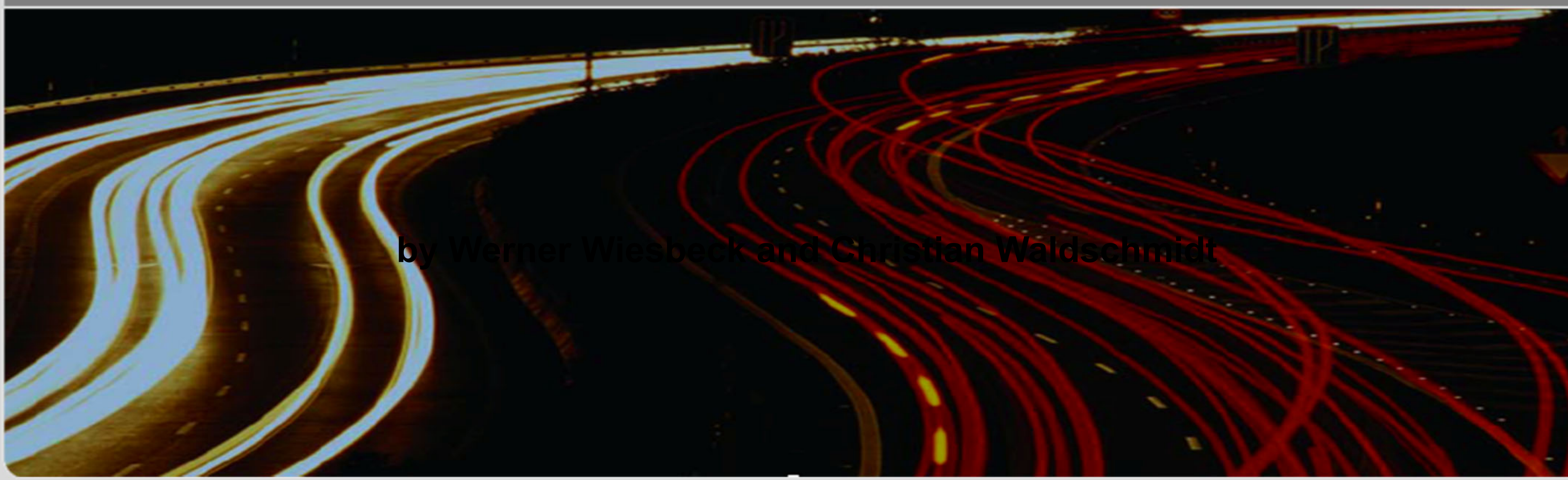
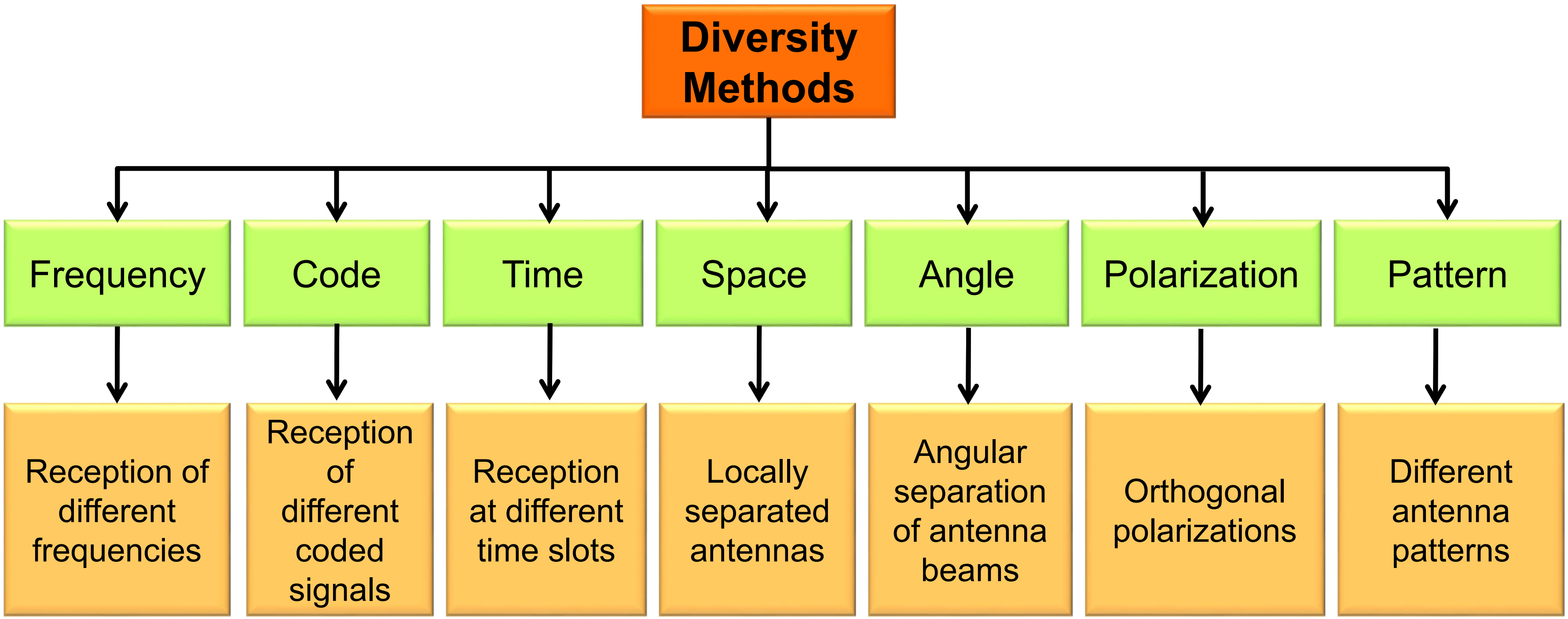


by Werner Wiesbeck and Christian Waldschmidt

Diversity Methods



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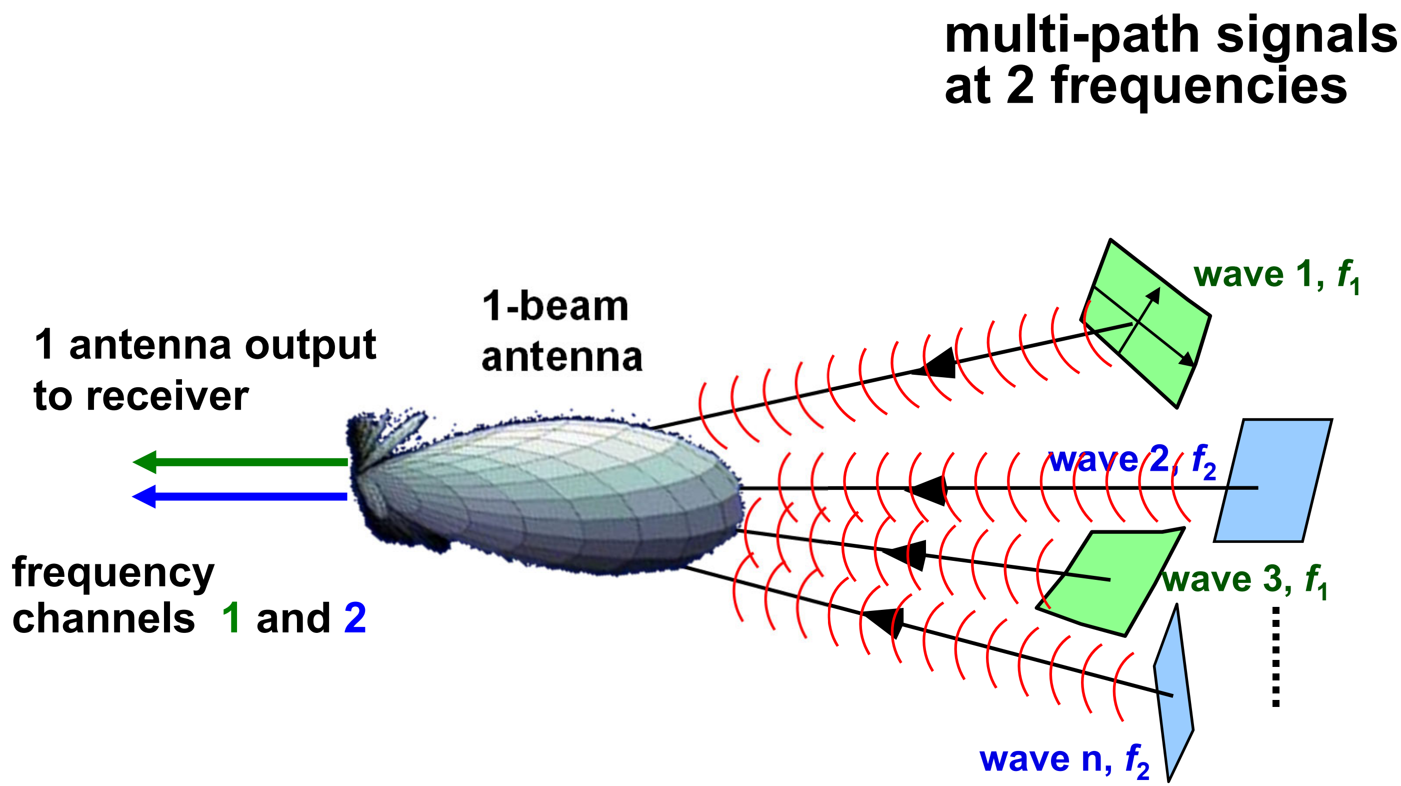
Frequency-Diversity

2 frequencies from one receiving antenna



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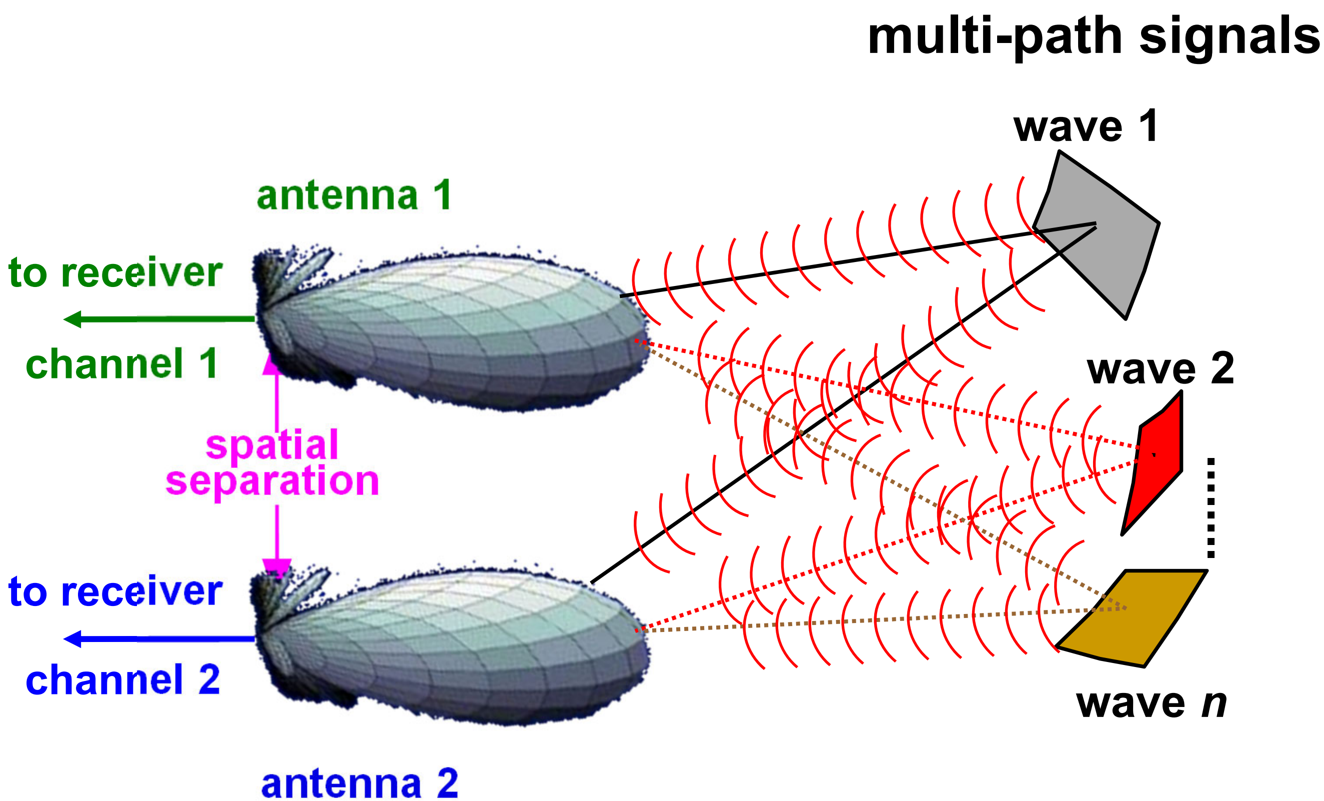
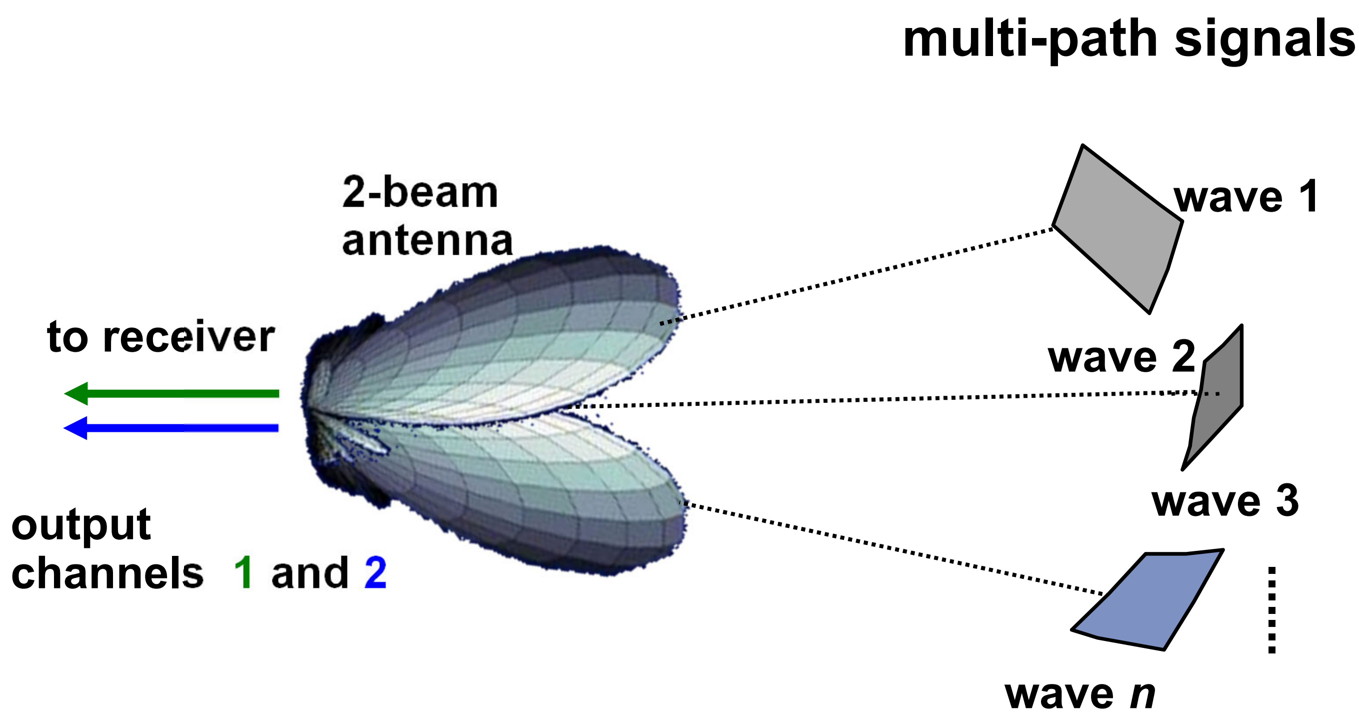
Space-Diversity

2 locally separated antennas



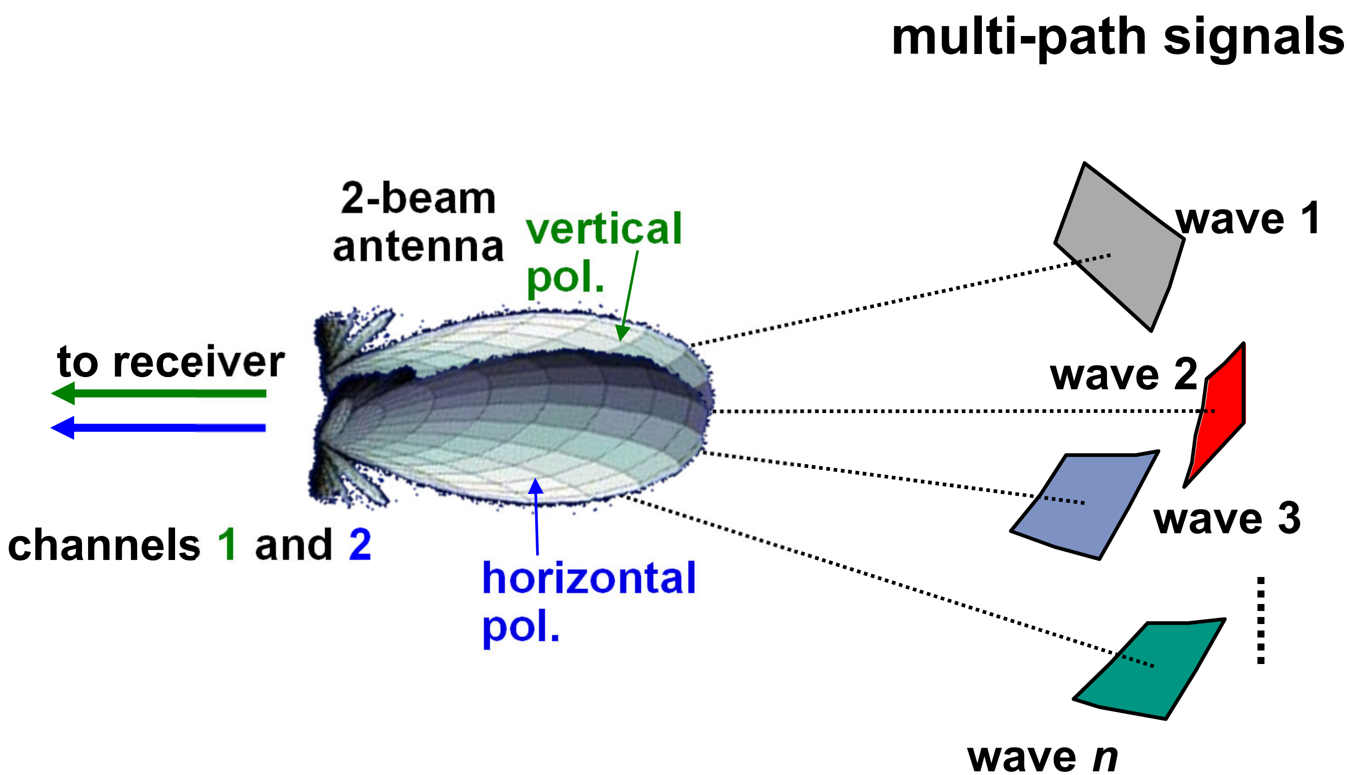
Angular-Diversity

2 medium gain antennas, angular separation of app. 30°



Polarization Diversity

2 linear orthogonal polarized antennas



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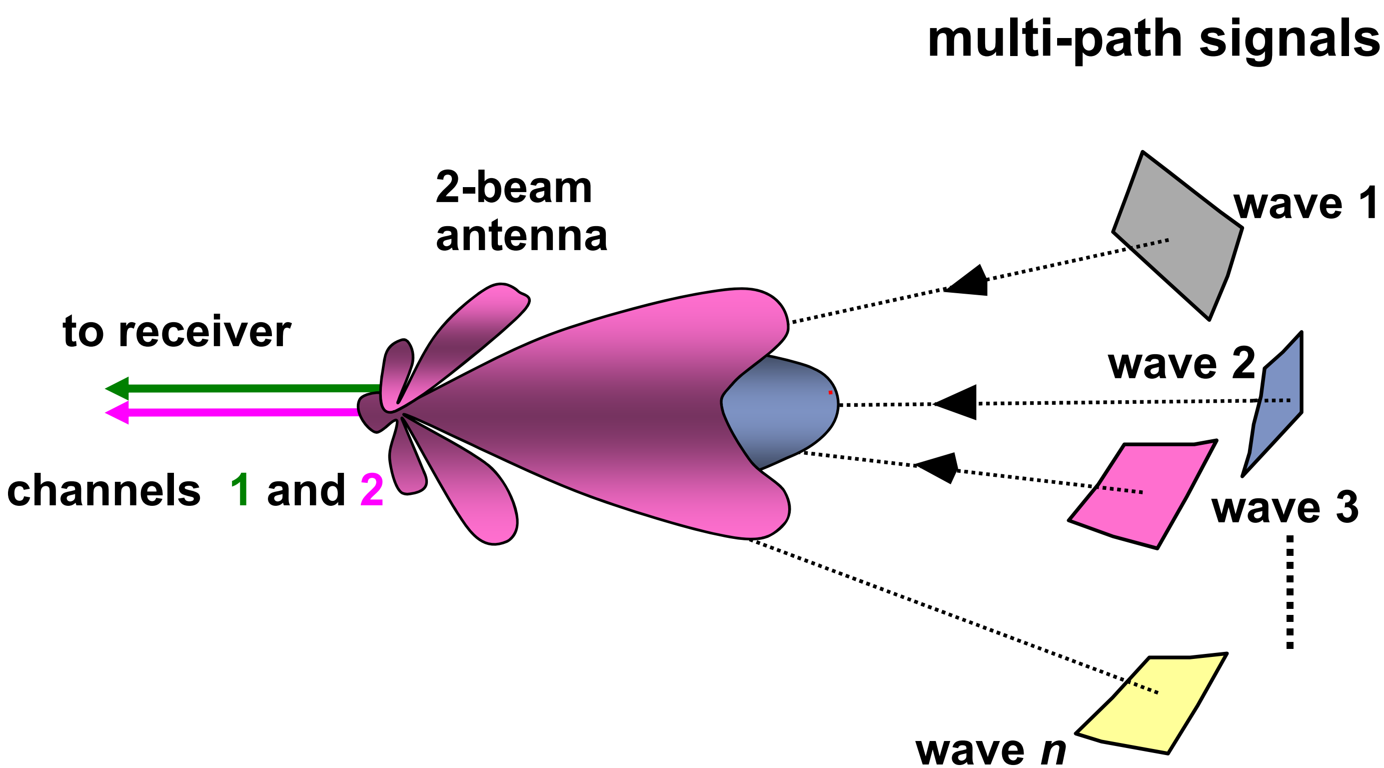
Pattern Diversity

2 different antenna patterns from one antenna



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Diversity Methods for the GSM System

Diversity method	Technical possibility	Signal improve-ment	Size	Cost	Recommen-dation
Frequency diversity	--	++	+	-	--
Code diversity	--	++	+	-	--
Time diversity	--	++	+	-	--
Space diversity	+	+	0	-	+
Angle diversity	+	+	0	0	+
Polarization diversity	+	+	+	+	++
Pattern diversity	+	0	+	+	+

-- not possible; - bad; 0 medium; + good;

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Diversity Methods for the Automotive DAB Radio

Diversity method	Technical possibility	Signal improve-ment	Size	Cost	Recommen-dation
Frequency diversity	+	++	+	+	++
Code diversity	--	++	+	--	--
Time diversity	--	++	+	--	--
Space diversity	+	++	0	0	+
Angle diversity	+	++	0	0	+
Polarization diversity	+	+	+	+	++
Pattern diversity	+	++	0	+	+

-- not possible; - bad; 0 medium; + good;

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Diversity Combiner Principles

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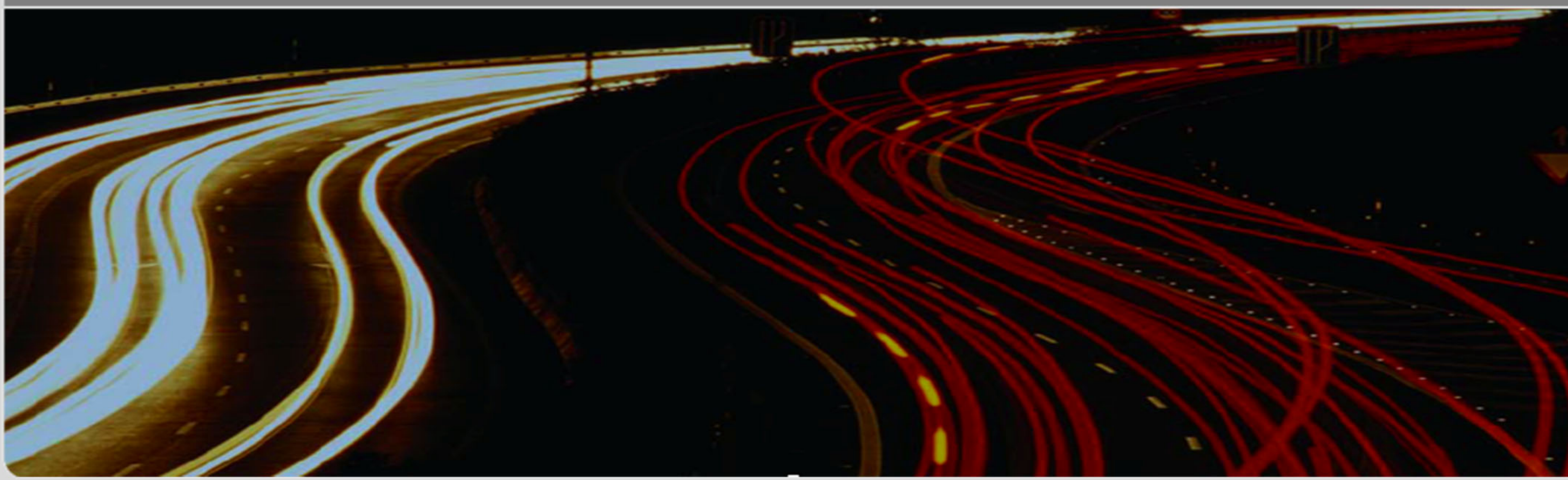
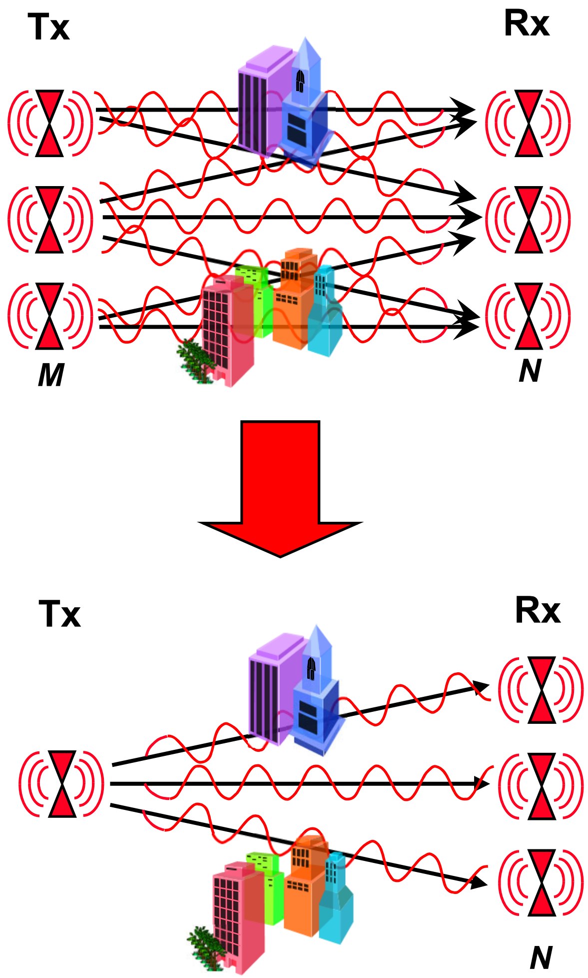


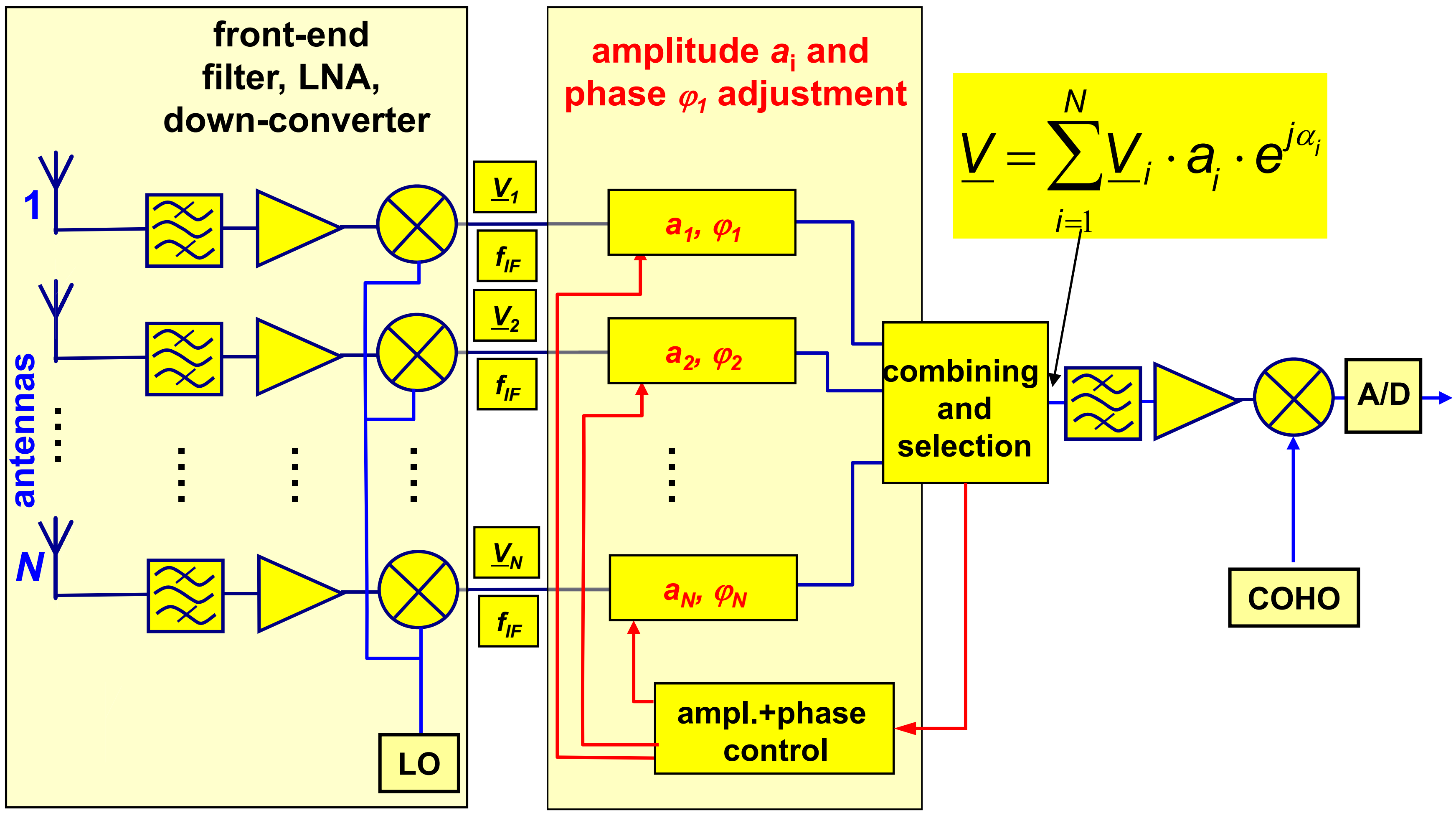
Single Tx, N Rx: Classical Diversity



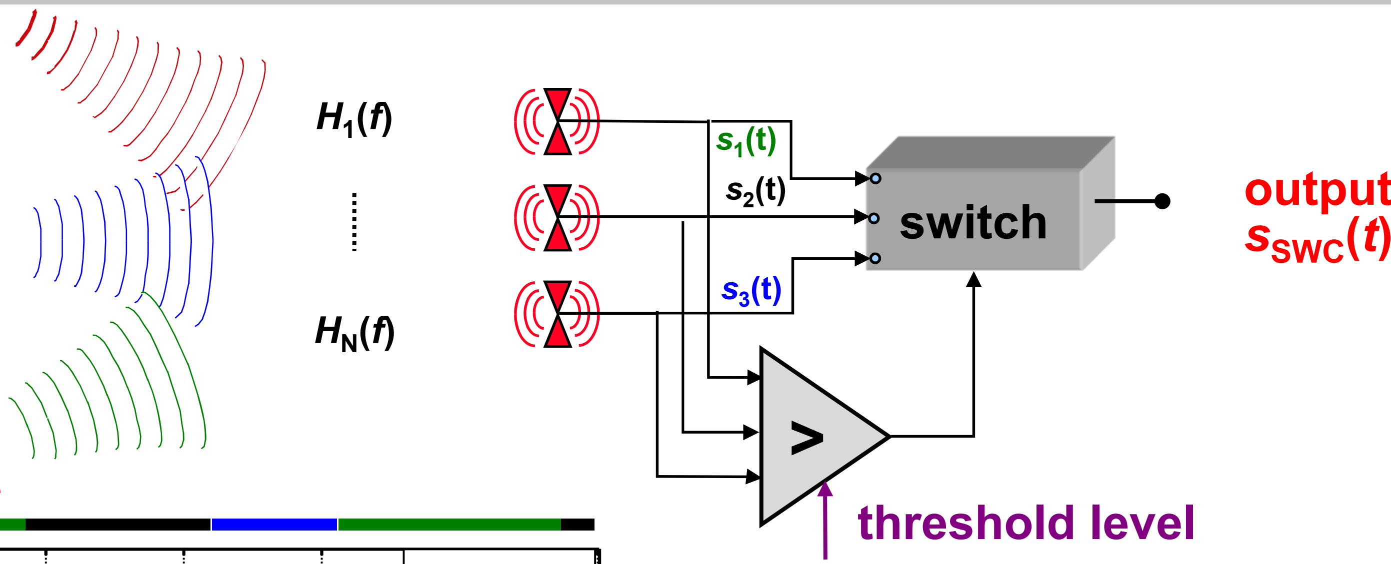
$$\mathbf{H} = \begin{pmatrix} H_{11} & H_{12} & \cdots & H_{1M} \\ H_{21} & H_{22} & \cdots & H_{2M} \\ \vdots & & \ddots & \vdots \\ H_{N1} & \cdots & & H_{NM} \end{pmatrix}$$

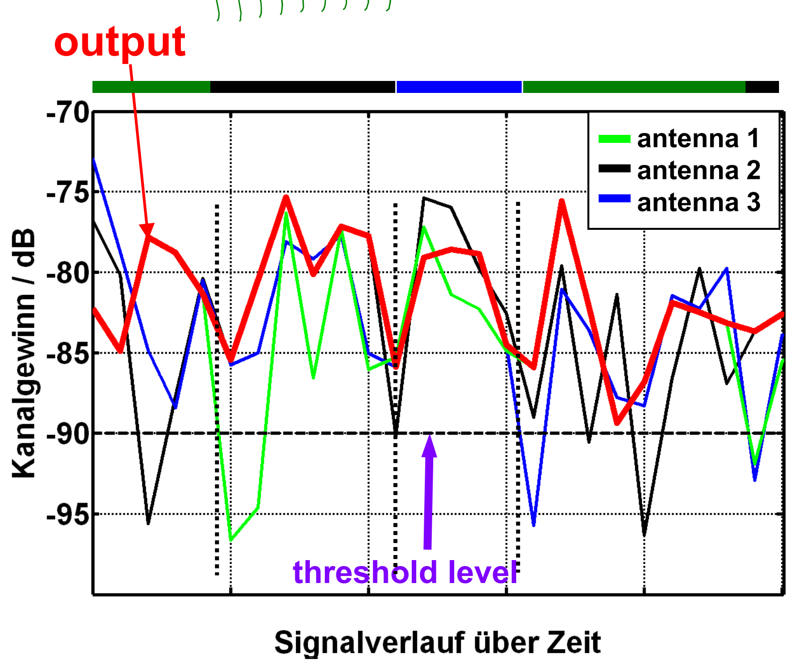
$$\mathbf{H} = \begin{pmatrix} H_{1} \\ H_{2} \\ \vdots \\ H_{N} \end{pmatrix}$$

Generic Block Diagram of a Diversity Receiver



Switched (Selection) Combining (SWC)





- easy to realize
- switching when level is crossed
- similar antenna output levels required

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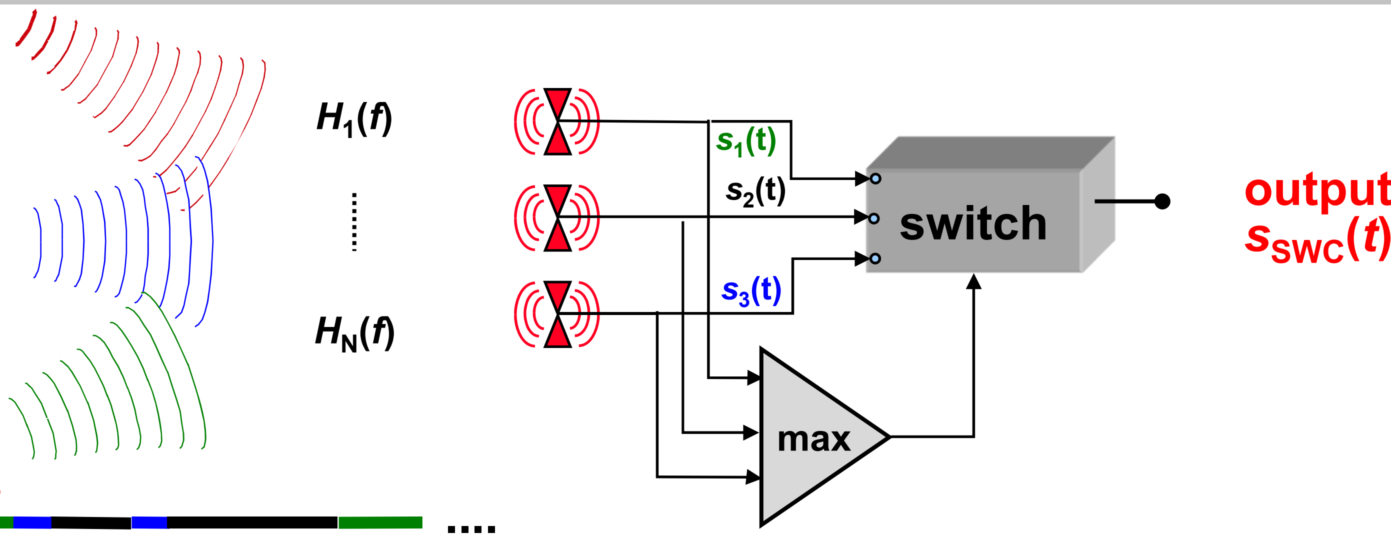
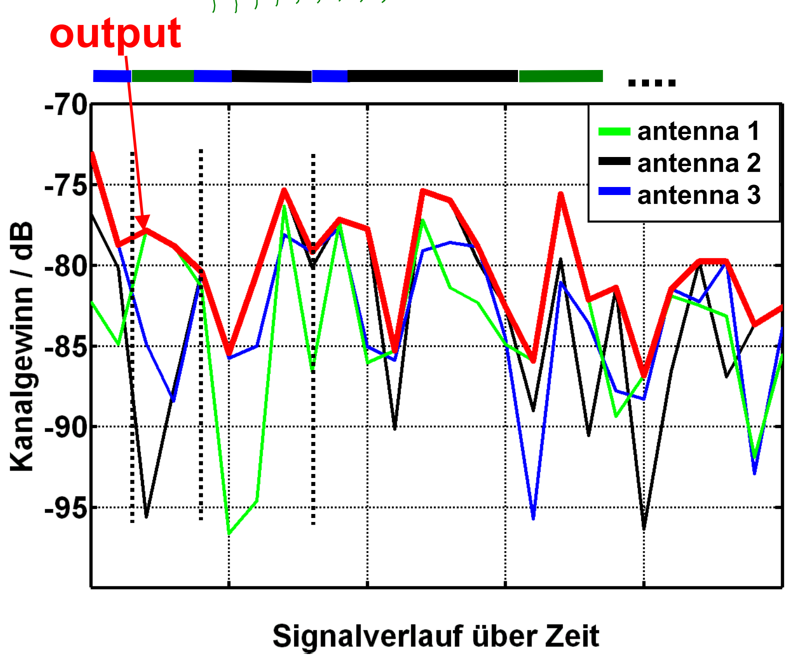
Selection Combining (SEC)





- only strongest signal is used
- easy to realize
- high switching sequences

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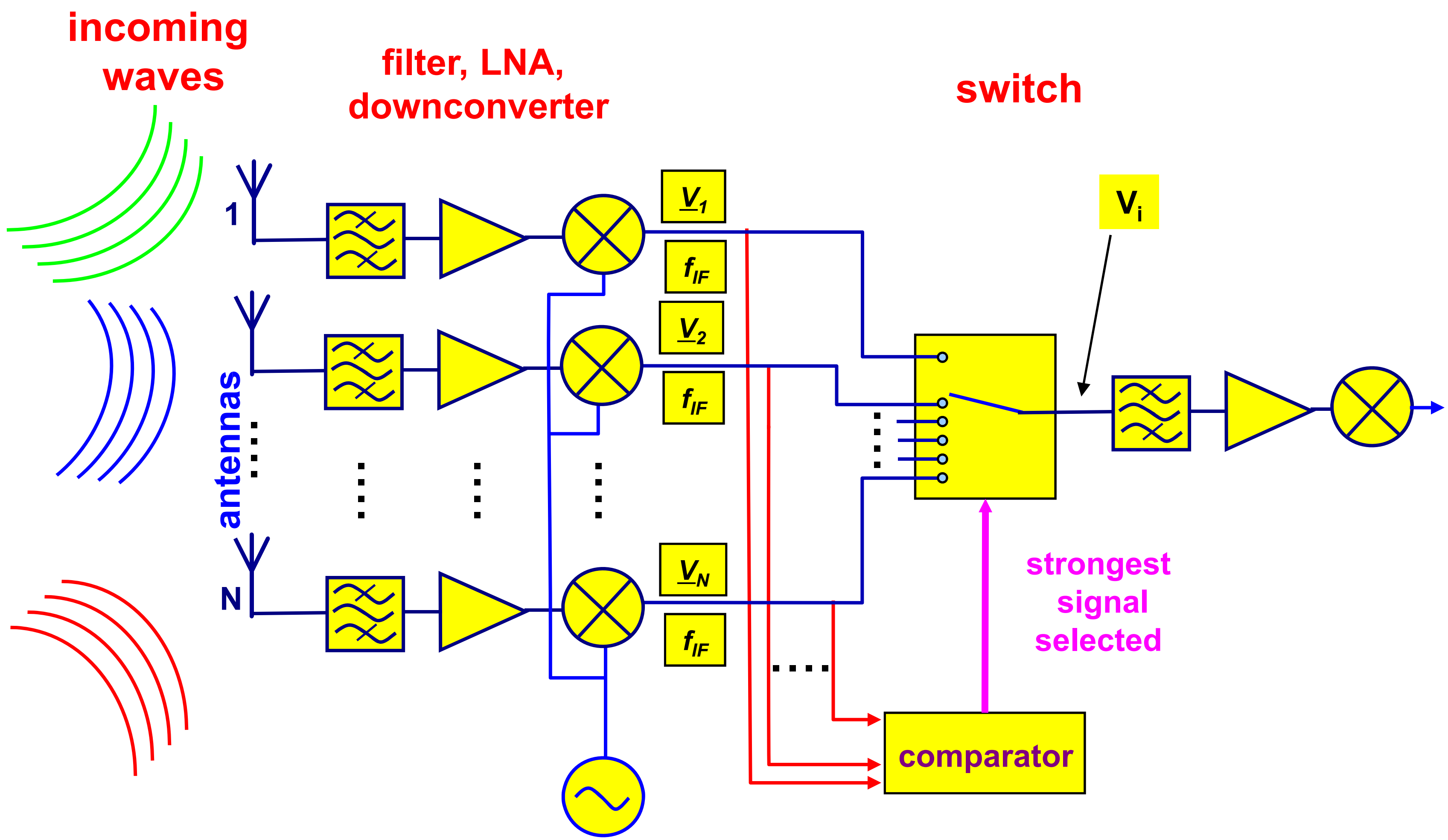
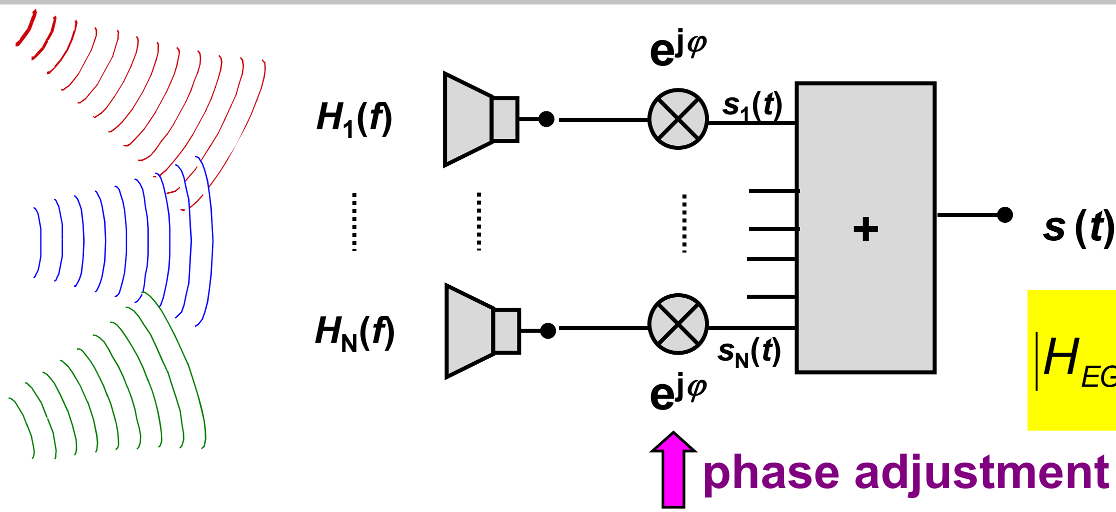
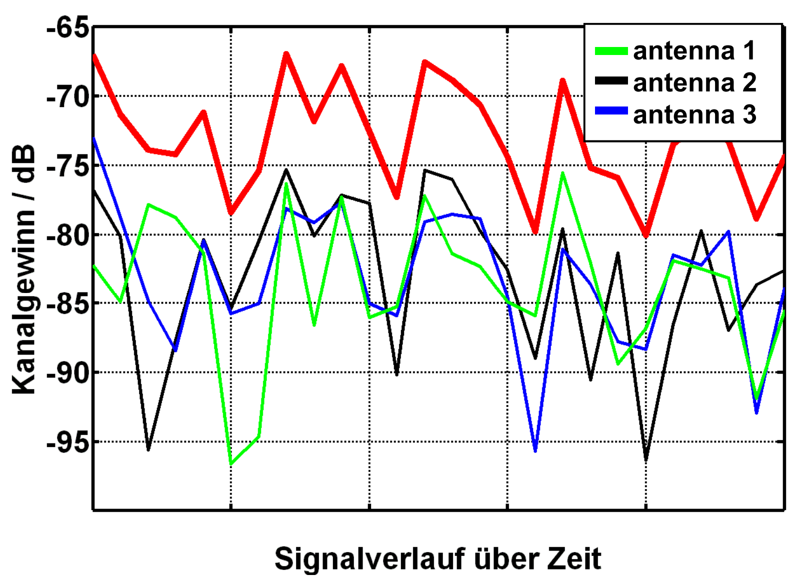
Selection Combining (SEC) Block Diagram



Equal Gain Combining (EGC)

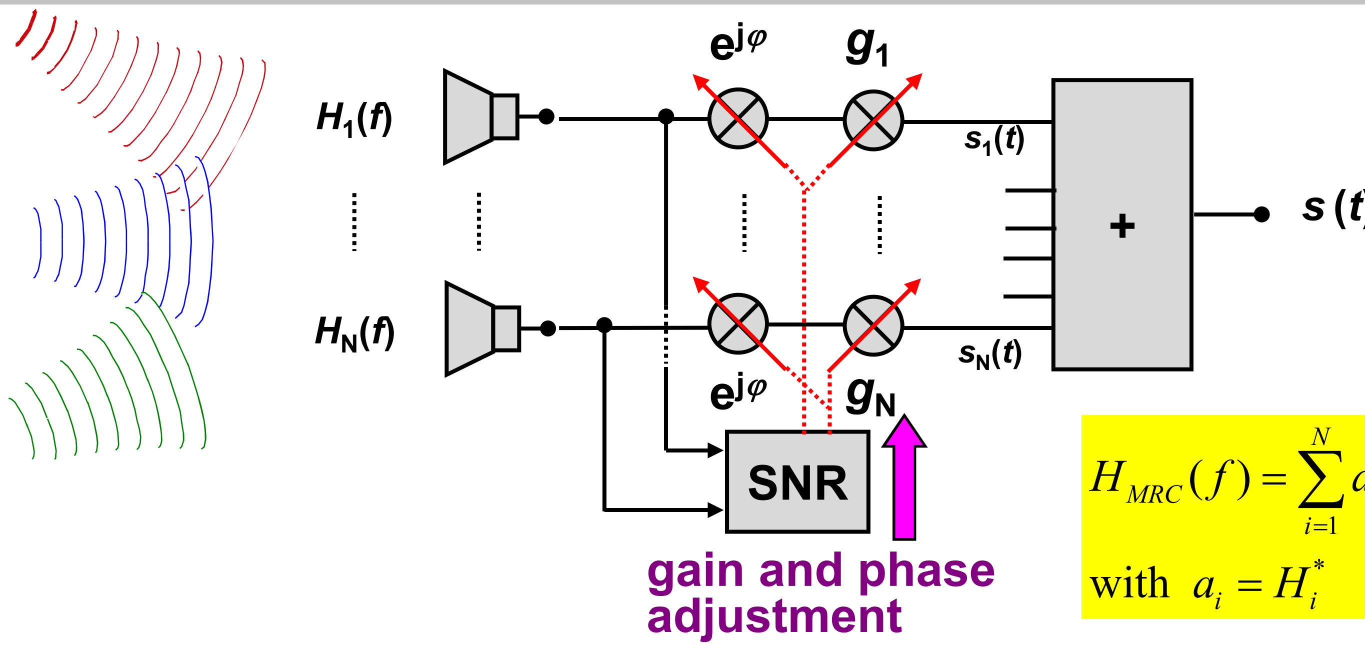


$$|H_{EGC}(f)| = \sum_{i=1}^{N} |H_i(f)|$$



- medium complexity
  - phase shifters required
- all antenna signals identically weighted
  - problem: noise summation

Maximum Ratio Combining (MRC)



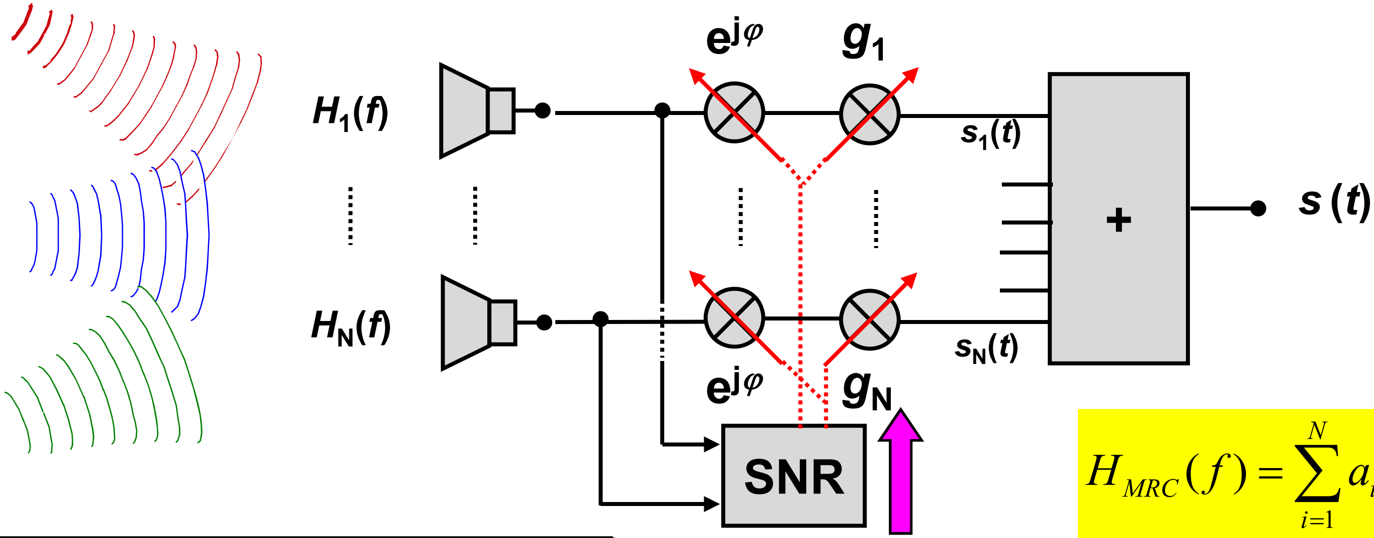
$$H_{MRC}(f) = \sum_{i=1}^{N} a_i H_i(f)$$

with $a_i = H_i^*$

$$SNR_i = \frac{|H_i|^2}{\sigma_n^2} \qquad SNR_{MRC} = \frac{\left|\sum_{i=1}^{N} H_i a_i\right|^2}{\sigma_n^2 \sum_{i=1}^{N} |a_i|^2} = \frac{1}{\sigma_n^2} \sum_{i=1}^{N} |H_i|^2 \frac{\left|\sum_{i=1}^{N} H_i a_i\right|^2}{\sum_{i=1}^{N} |H_i|^2 \sum_{i=1}^{N} |a_i|^2}$$

Cauchy-Schwartz: $\left|\sum_{i=1}^{N} H_i a_i\right|^2 \leq \sum_{i=1}^{N} |H_i|^2 \sum_{i=1}^{N} |a_i|^2$ equal for $a_i = H_i^*$ $\Rightarrow SNR_{MRC} = \sum_{i=1}^{N} SNR_i$

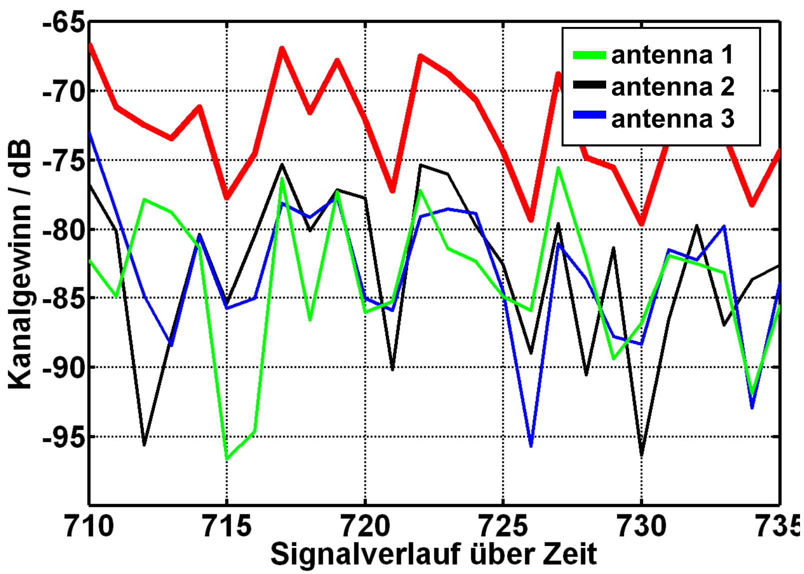
Maximum Ratio Combining (MRC)



gain and phase adjustment

$$H_{MRC}(f) = \sum_{i=1}^{N} a_i H_i(f)$$

with $a_i = H_i^*$



- high complexity
  - phase shifters
  - controlled amplifiers
- signals of all antennas weighted according to their *SNR*

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Diversity Systems Comparison

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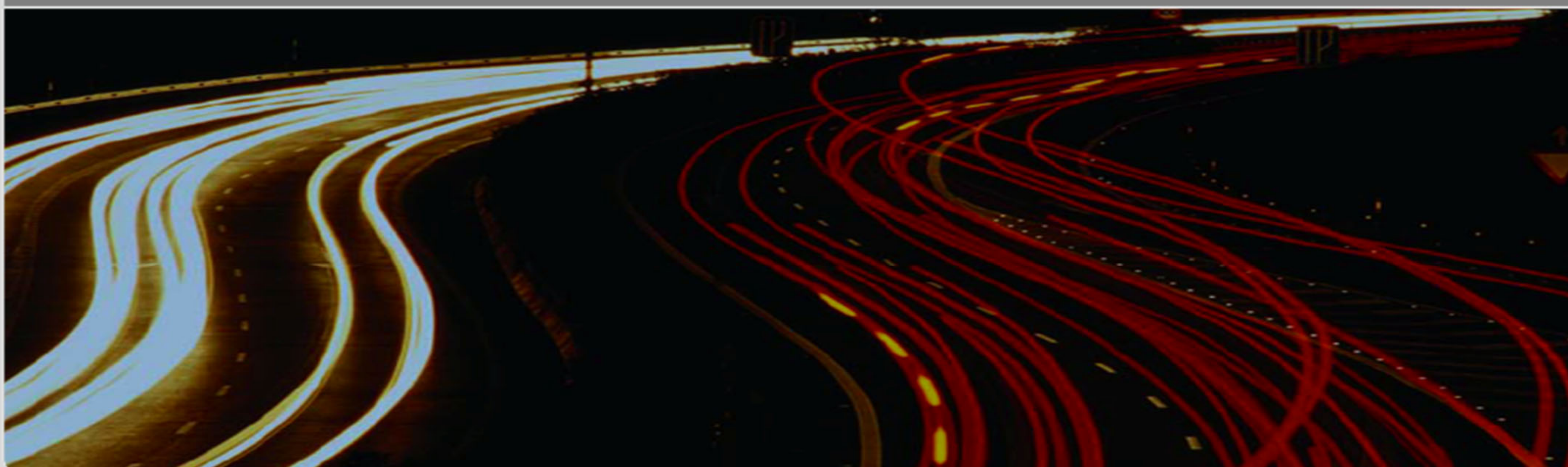
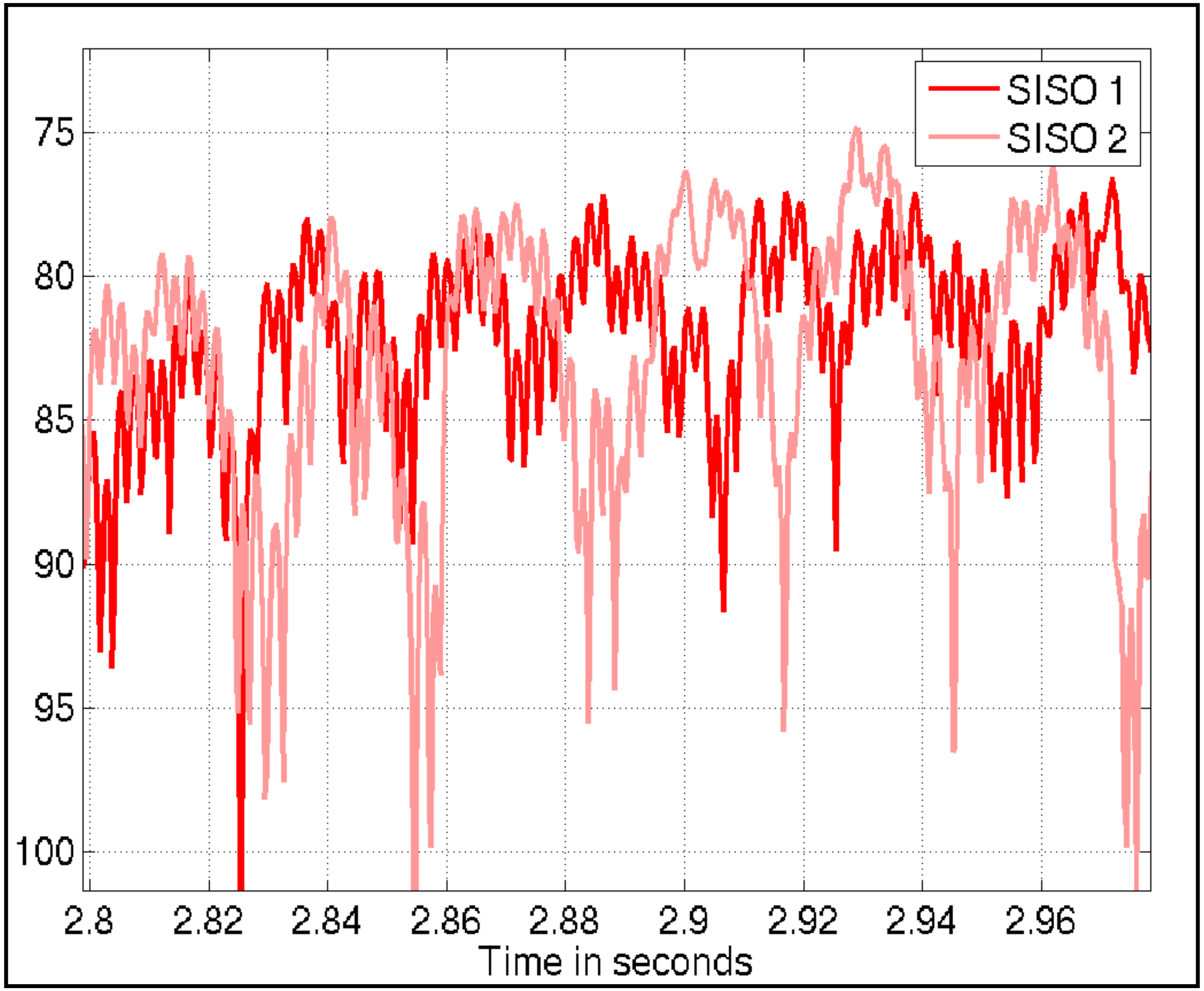
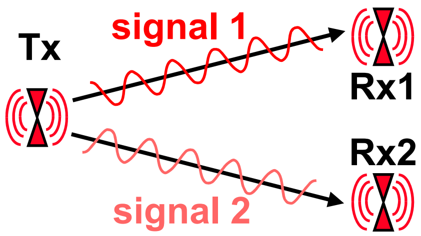
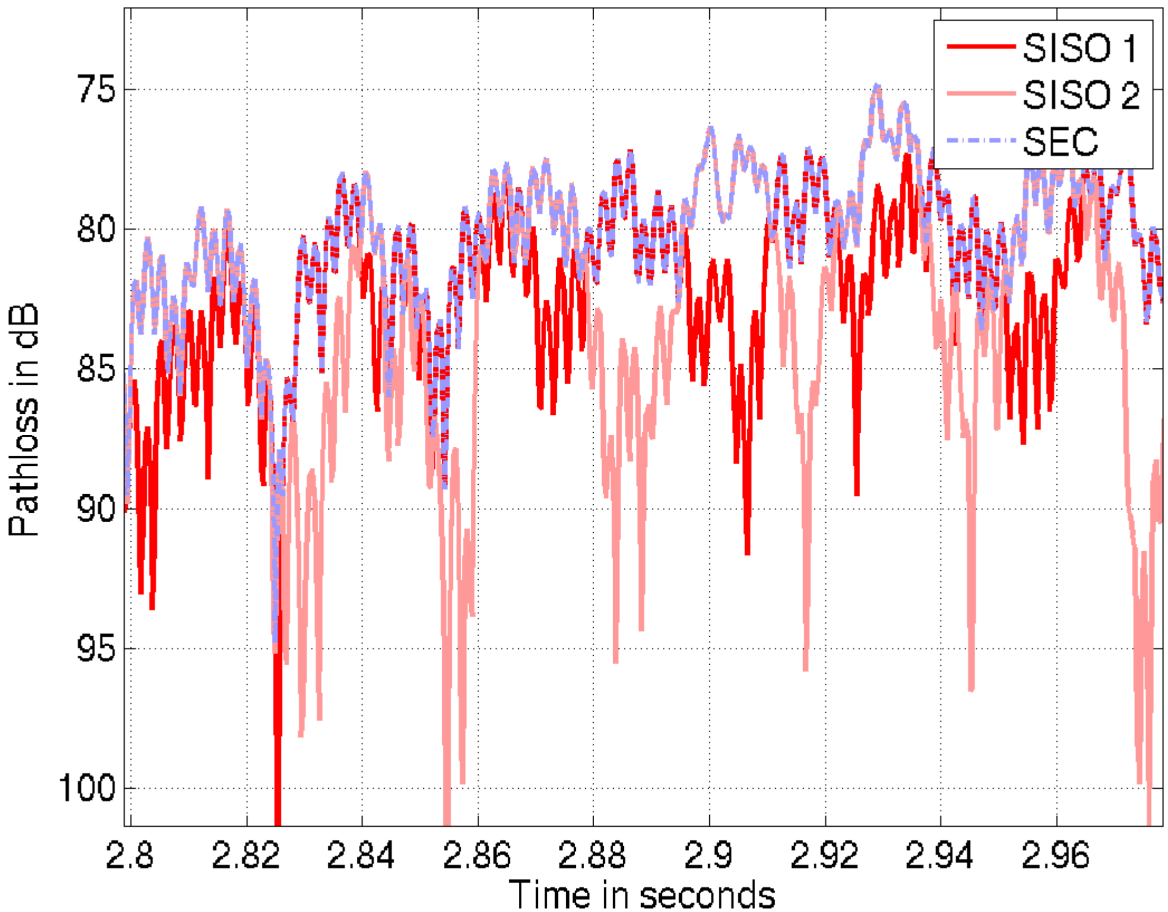


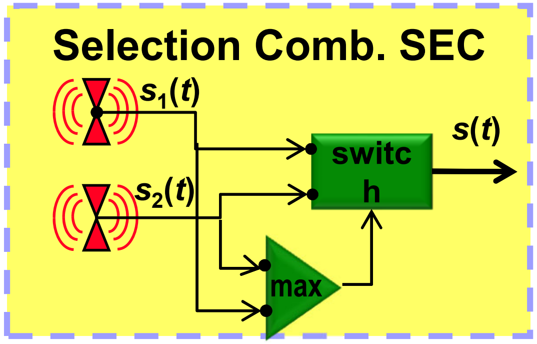
Use of Multiple Antenna Systems



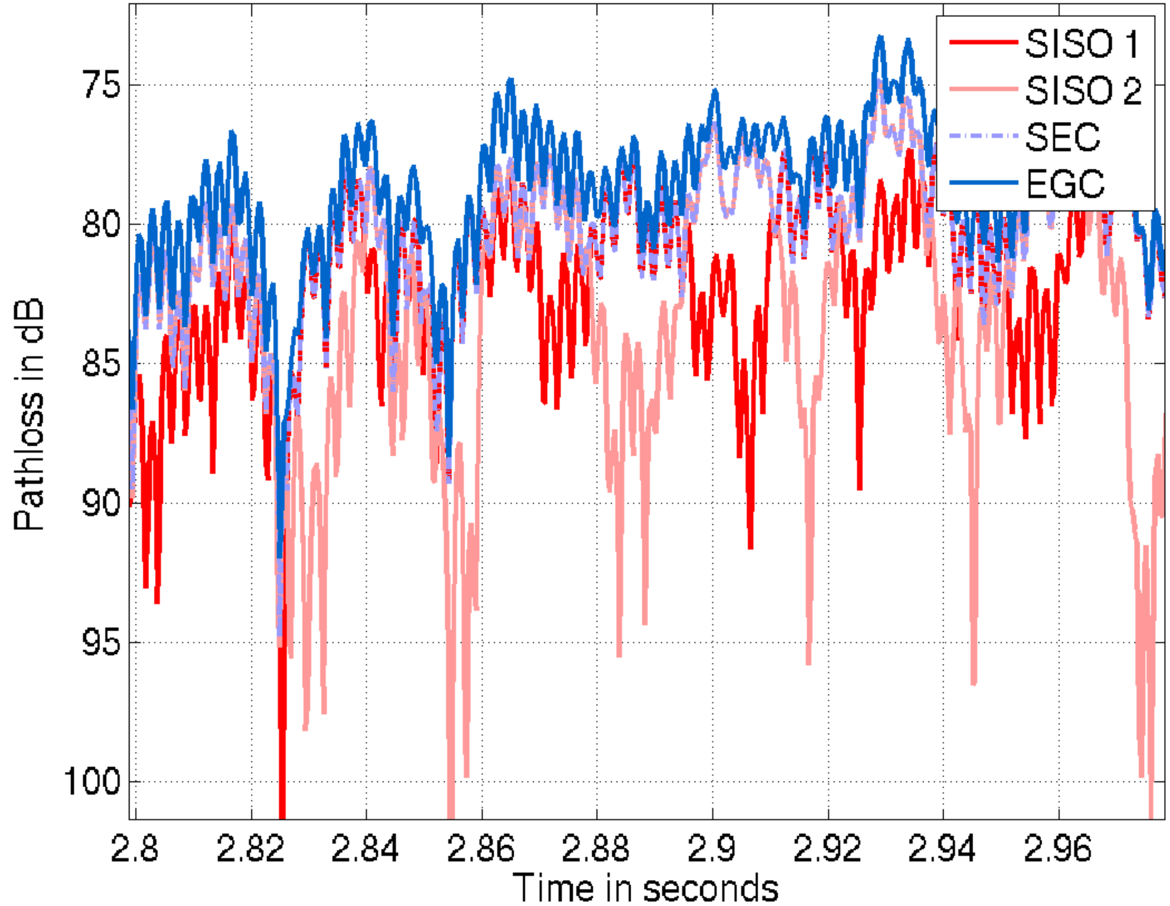


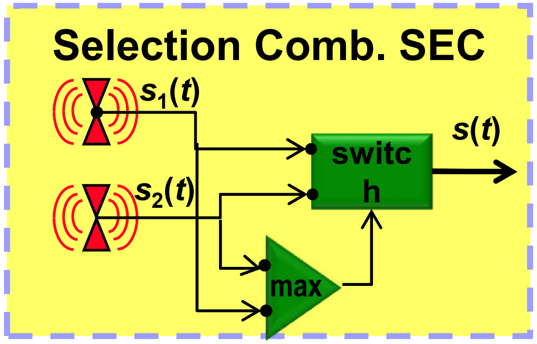
Diversity- Selection Combining (SEC)

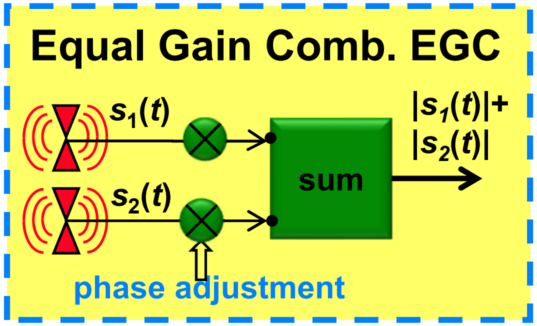




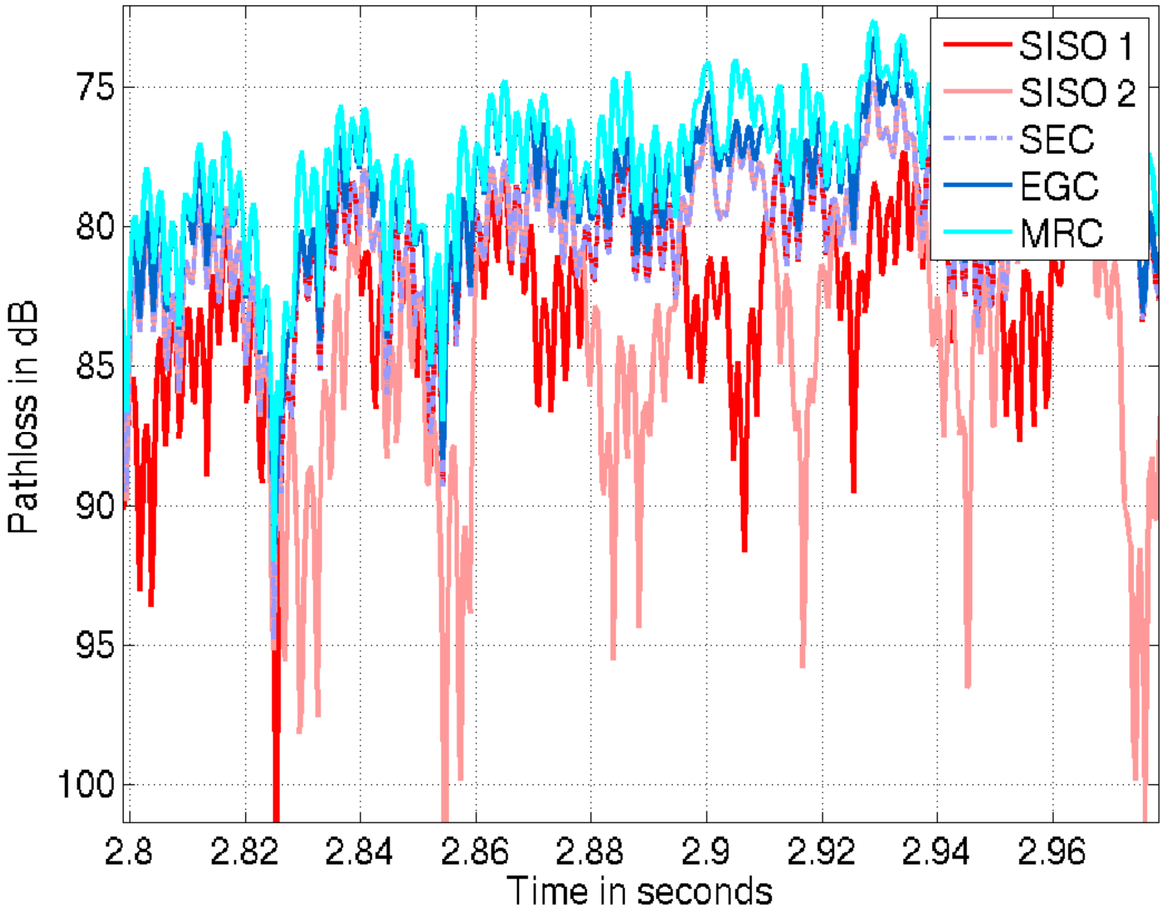
Diversity Comparison: Selection-Equal Gain

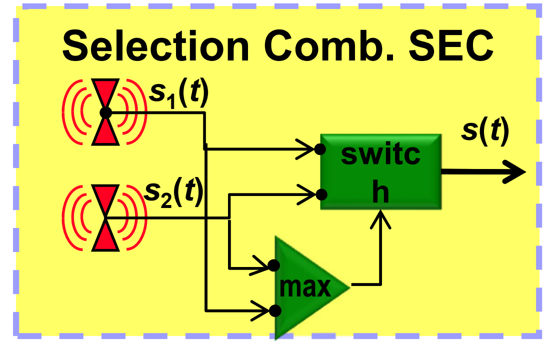


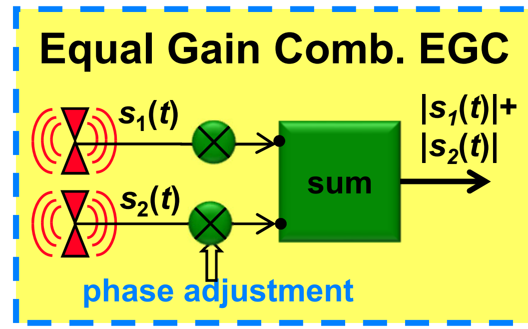


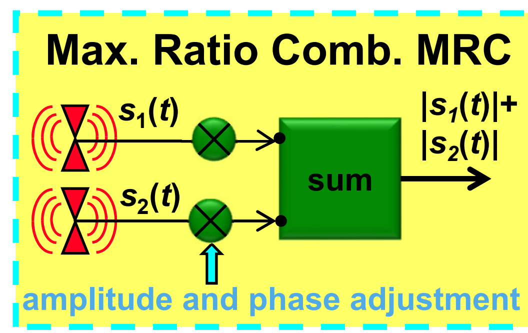


Diversity Comparison: Selection-Equal-Gain- Max Ratio









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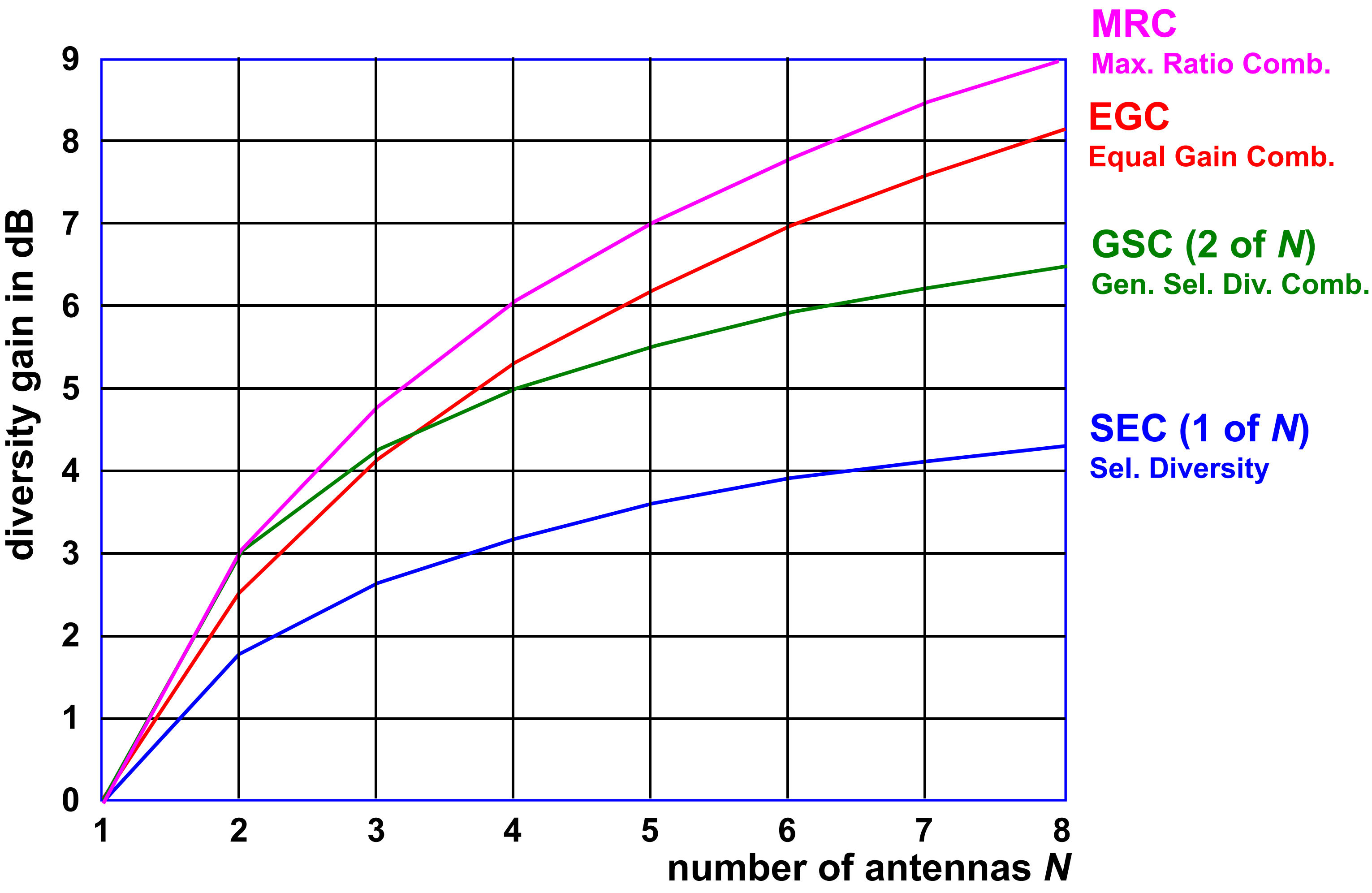
Upper SNR-Bound for Diversity Schemes



Channel: Nakagami fading channels

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Patents

- Patent: DE 102005061723.9 Verfahren zum Empfang von Antennensignalen mindestens zweier Empfangsantennen eines Antennensystems und Antennensystem
- DE 38 36 046 C2
- EP 1 126 631 B1
- DE 101 16 964 A1
- DE 38 02 130 2.1
- DE 38 02 131 2.1

Literature

(1) C. Waldschmidt, J. von Hagen und W. Wiesbeck, Influence of Power Azimuth Spectrum and Mutual Coupling on Correlations in Smart Antenna Diversity Systems. URSI Open Symposiumon Propagation and Remote Sensing, 1, CD-R OM, 2002 .

(2) A.F. Molisch, M.Z. Win, and J.H. Winters, “Performance of reduced-complexity transmit/receive-diversity systems,” in *Proc. Wireless Personal Multimedia Conf. 2002*, 2002, pp. 738–742.

(3) D.M. Novakovic, M.J. Juntti, and M.L. Dukic, “Generalised full/partial closed loop transmit diversity,” *Electron. Lett.*, vol. 38, no. 24, pp. 1588–1589, 2002.

(4) S.A. Bergmann und H.W. Arnold, Polarisation diversity in portable communications environment. IEE Eletronics Letters, 22 (11): 609-610, 1986 .

(5) J.R. Pierce und S. Stein, „Multiple Diversity with Nonindependent Fading,“ Proceedings IRE, 48, pp. 89-104, 1960 .

(6) R.G. Vaughan and J. Bach Andersen, Antenna Diversity in Mobile Communications. IEEE Transactions on Vehicular Technology , 36 (4), pp. 149-172, 1987 .

(7) R.W. Heath, A. Paulraj, and S. Sandhu, “Antenna selection for spatial multiplexing systems with linear receivers,” *IEEE Commun. Lett.*, vol. 5, pp. 142–144, Apr. 2001.

(8) D. Chizhik, G.J. Foschini, and R.A. Valenzuela, “Capacities of multi-element transmit and receive antennas: Correlations and keyholes,” *Electron. Lett.*, vol. 36, no. 13, pp. 1099–1100, 2000.

(9) A.F. Molisch, M.Z. Win, and J.H. Winters, “Reduced-complexity transmit/receive diversity systems,” *IEEE Trans. Signal Processing*, vol. 51, pp. 2729–2738, Nov. 2003.

(10) N. Kong and L.B. Milstein, “Average SNR of a generalized diversity selection combining scheme,” *IEEE Commun. Lett.*, vol. 3, pp. 57–59, Mar. 1999.

(11) M.Z. Win and J.H. Winters, “Analysis of hybrid selection/maximal- ratio combining of diversity branches with unequal SNR in Rayleigh fading,” in *Proc. 49th Annual Int. Veh. Technol. Conf.*, Houston, TX, May 1999, vol. 1, pp. 215–220.