New Paradigm of Wireless Communications – MIMO[1] Architecture

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[1]MIMO - Multiple-Input Multiple-Output, also known as BLAST - Bell Labs Layered Space-Time

Why MIMO?

- High demand for spectrum $\rightarrow$ need for **spectral efficiency**
- **Fading** is a headache of system designers
- Time and frequency domain processing are at limits, **space** one - not!

What is MIMO/BLAST?

- MIMO is an extraordinarily bandwidth-efficient approach to wireless communication
- It was originally developed in Bell Labs in 1995-1997
- It takes advantage of the spatial dimension
- The central paradigm is **exploitation** rather than mitigation of **multipath** effects

Wireless system with single antennas

- Classical Shannon's limit for channel capacity :

$$C = \log_2(1 + SNR) \qquad [bit / Hz / s]$$

- Increases as log of SNR $\rightarrow$ very slowly!

Wireless system with single antennas (cont.)

- Channel capacity is low $\rightarrow$ few bits/Hz/s
- Fading is huge $\rightarrow$ 20-40 dB
- No space domain signal processing
- Design is simple

Wireless system with multiple antennas
(phased array, diversity combining etc.)

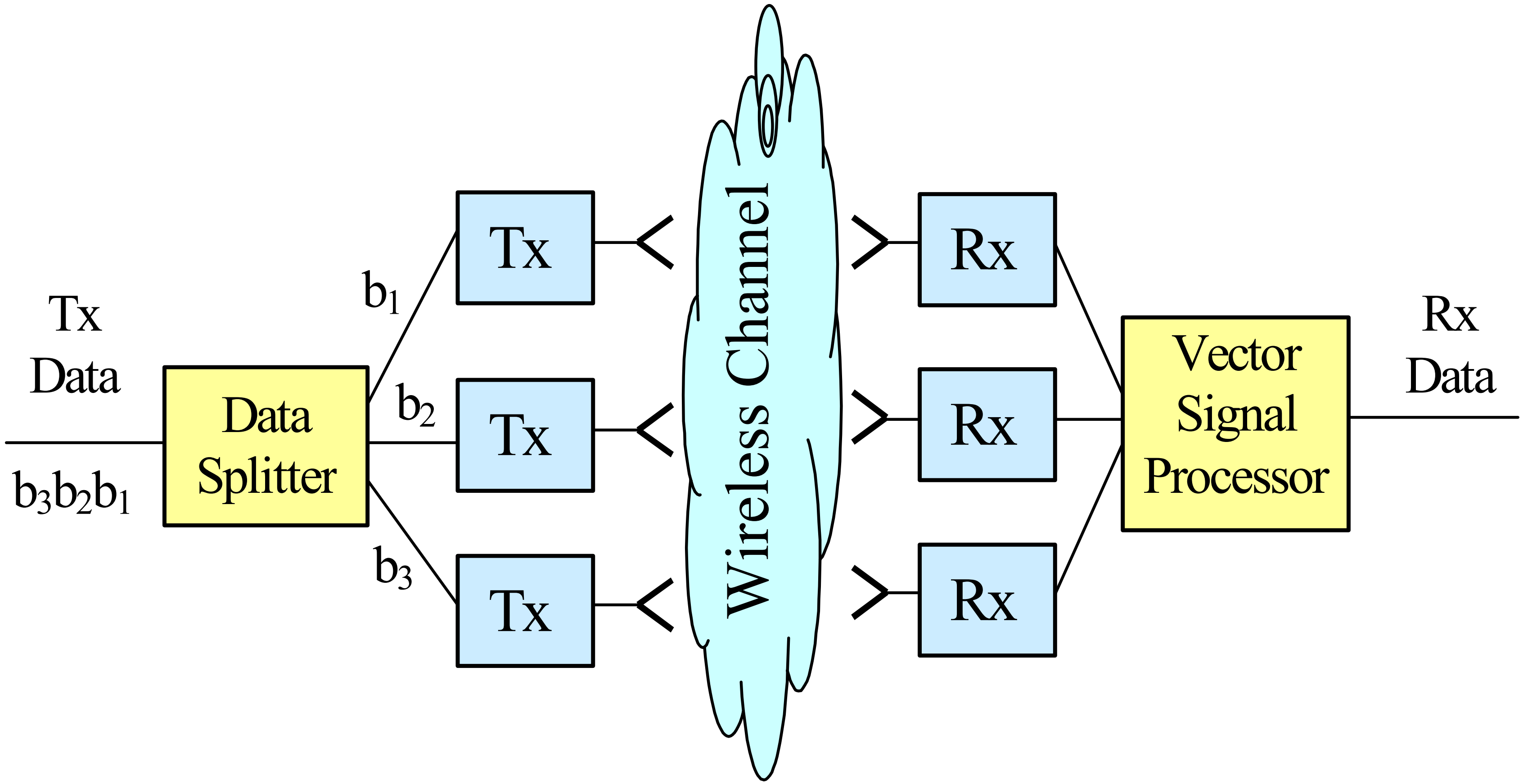
$$C = \log_2\left(1 + SNR \cdot n^2\right) \quad [bit/Hz/s]$$

- Increases as the log of n $\rightarrow$ very slowly!

Wireless system with multiple antennas (cont.)

- Channel capacity is still low (few bits/Hz/s)
- Fading is smaller but still large (10-20 dB)
- Space-domain signal processing - partially
- Complex antennas, beamforming etc.

MIMO: launch multiple bit streams!



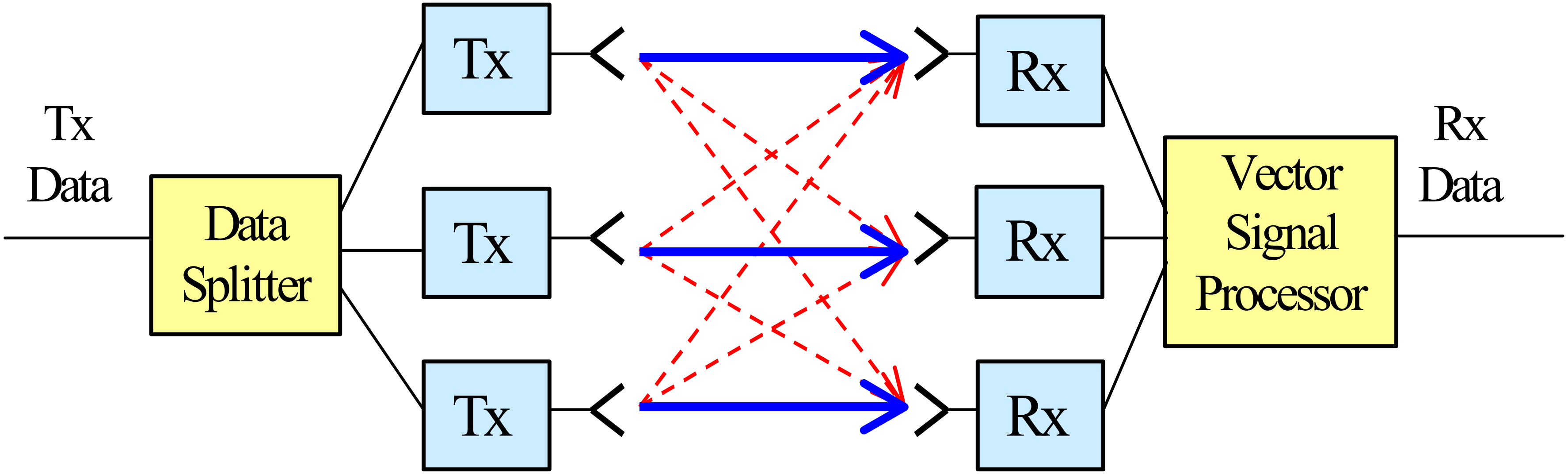
MIMO: launch multiple bit streams! (cont.)

$$C = n \cdot \log_2\left(1 + \frac{SNR}{n}\right) \quad [bit / Hz / s]$$

- Enormous channel capacity $\rightarrow$ 10 fold increase has been demonstrated
- Fading is small (1-5 dB)
- Full space-domain signal processing
- More complex design is fully compensated by huge advantages

Why and where it works ?

- Uncorrelated subchannels $\rightarrow$ parallel independent subchannels



- Mathematically,

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{32} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

$$\Downarrow$$

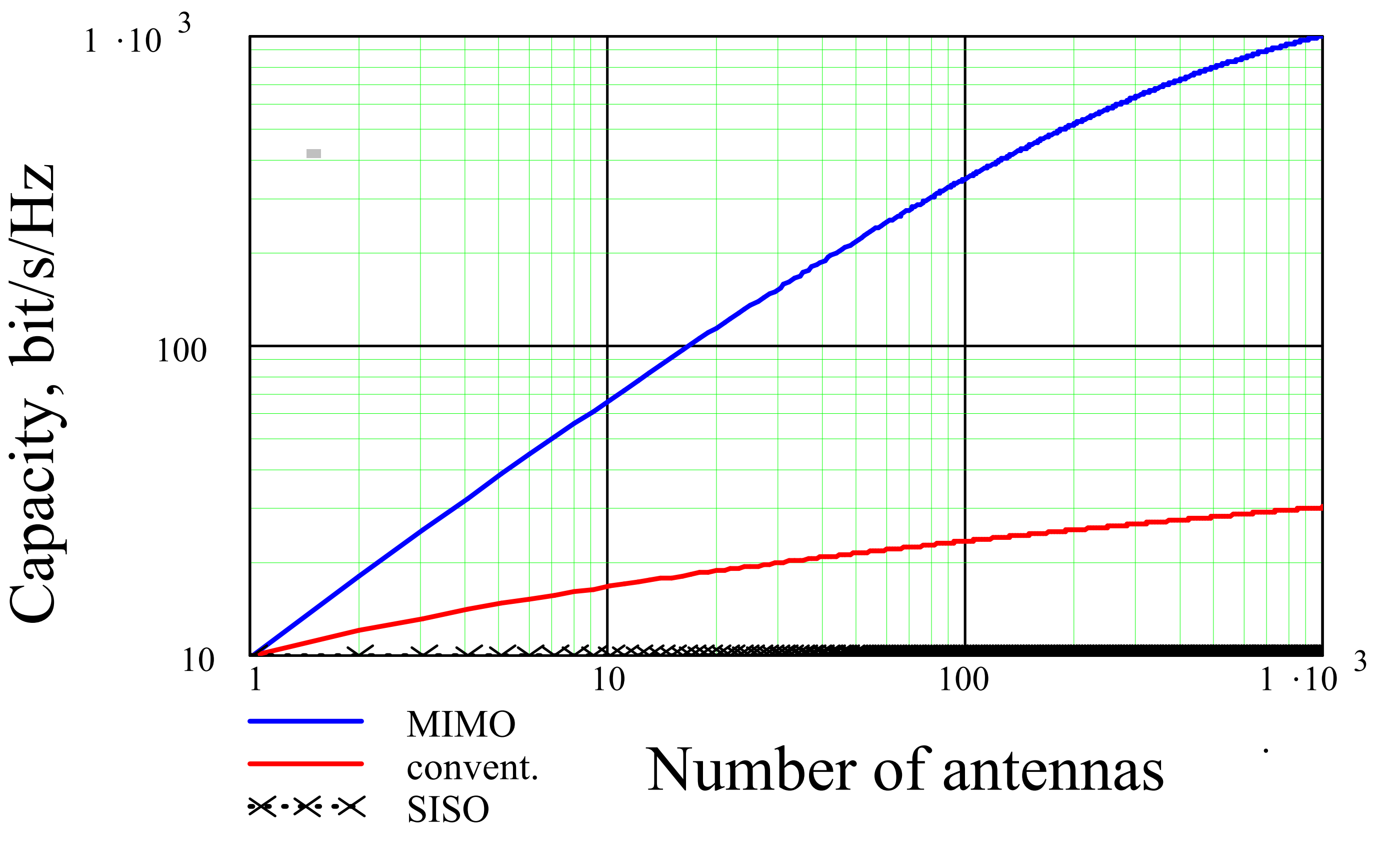
$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} h_{11} & 0 & 0 \\ 0 & h_{22} & 0 \\ 0 & 0 & h_{33} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

- Channel matrix diagonalization is a key operation for MIMO
- Signal processing at the receiver must do this job
- Correlated subchannels $\rightarrow$ complete diagonalization is not possible $\rightarrow$ increase in fading and decrease in channel capacity

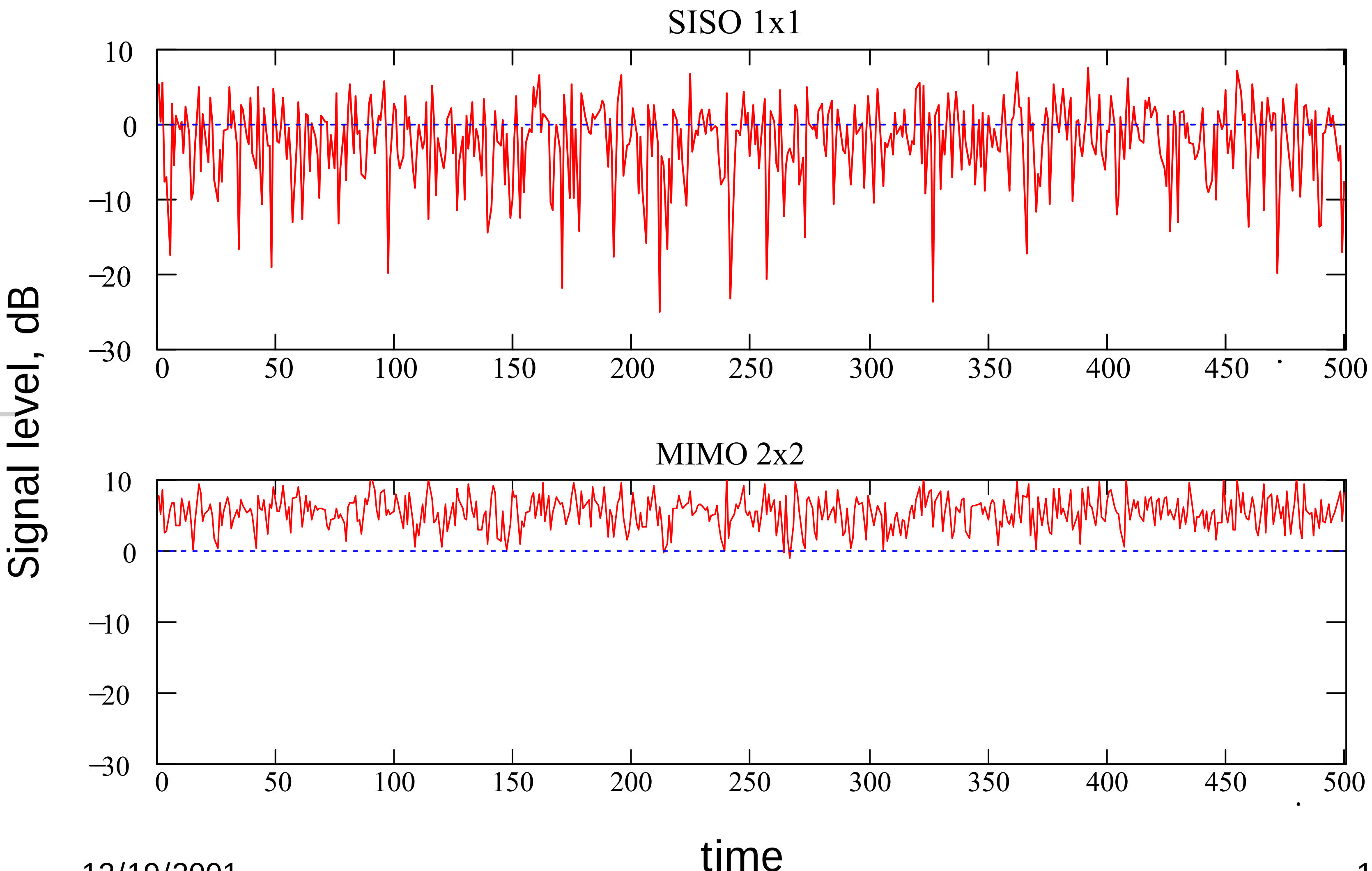
MIMO Key Advantages

- Extraordinary high spectral efficiency (from 30-40 bit/s/Hz)
- Large fade level reduction (10-30 dB)
- Co-channel interference reduction (5-15 dB)
- Multipath is not enemy, but ally !
- Flexible architecture through DSP

Spectral Efficiency



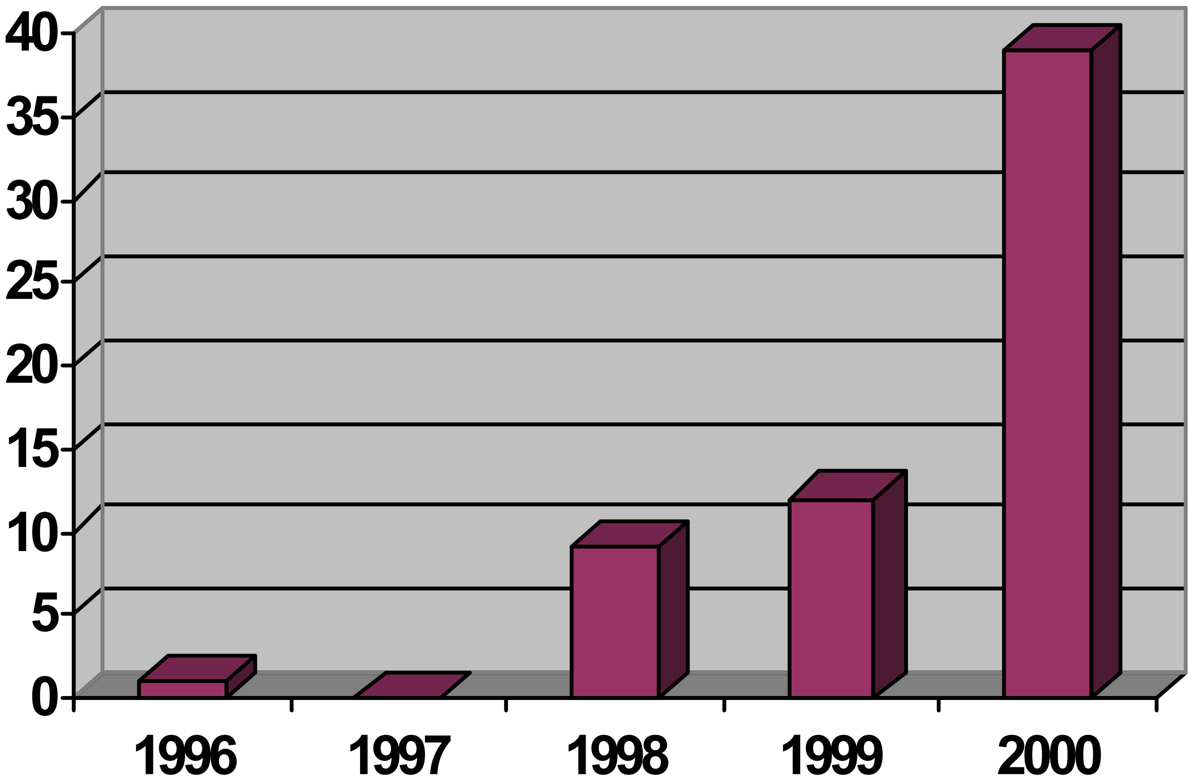
Fading Reduction



Fading Reduction

- Diversity order (DO) for MIMO $\propto n^2$ and for SIMO $\propto n$
- MIMO efficiently exploits diversity at **both** Tx and Rx sites!
- Example: correlated fading at Rx $\rightarrow$ no SIMO diversity, but MIMO works!
- Consequence: 2-fold higher system availability for MIMO than for SIMO

Number of MIMO publications



Key Players

- Lucent
- AT&T
- Nokia
- Nortel
- Motorola
- Ericsson

Current R&D

- Matrix channel modeling, simulation, characterization & measurement
- Basic system architecture development
- Space-time coding/decoding & modulation/demodulation, and performance evaluation
- Elements of system-level simulation
- Prototyping
- Application areas (indoor, cellular, LMDS etc.)

Future R&D

- Matrix channel will be still a problem
- Space-time codes into design!
- Adaptive MIMO architecture
- Nonlinear effects in Tx/Rx branches
- Full-scale system-level simulation
- First products on the market

Selected References (Non-Experts)

- http://www.bell-labs.com/project/blast/

Selected References (Experts)

- Foschini, G.J., Gans M.J.: ‘On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas’, Wireless Personal Communications, vol. 6, No. 3, pp. 311-335, March 1998.
- I.E. Telatar, "Capacity of Multi-Antenna Gaussian Channels," AT&T Bell Lab. Internal Tech. Memo., June 1995. (European Trans. Telecom., v.10, N.6, Dec.1999)
- Rayleigh, G.G., Cioffi, J.M.: "Spatio-Temporal Coding for Wireless Communications," IEEE Trans. Commun., v.46, N.3, pp. 357-366, 1998.
- http://www.bell-labs.com/project/blast/

Matrix channel correlation is the main limitation to MIMO!

MIMO Channel Capacity

$$\boxed{C = \log_2 \det\left(\mathbf{I} + \frac{\rho}{n}\mathbf{H}\cdot\mathbf{H}^{+}\right)}$$

Correlation matrix approach

$$\mathbf{R} = \mathbf{H}\cdot\mathbf{H}^{+}$$

Eigenvalue (SVD) approach

$$\mathbf{H} = \mathbf{U}\cdot\mathbf{D}\cdot\mathbf{V}^{+}$$

- Correlation matrix approach:

$$C = \log_2 \det\left(\mathbf{I} + \frac{\rho}{n} \mathbf{R} \right)$$

employed below

- Eigenvalue (SVD) approach:

$$C = \sum_i \log_2 \left(1 + \rho_i \lambda_i^2 \right)$$

Universal Upper Bound[1]

Random channel $\rightarrow$ mean (ergodic) capacity:

$$\langle C \rangle = \left\langle \log_2 \det\left[\mathbf{I} + \frac{\rho}{n} \cdot \mathbf{R}\right] \right\rangle$$

Jensen Inequality, F - concave:

$$\langle F(x) \rangle \le F(\langle x \rangle)$$

[1]S. Loyka, A. Kouki, New Compound Upper Bound on MIMO Channel Capacity, IEEE Comm. Letters, 2001, submitted

Receive bound (!!!):

$$\langle C \rangle \le \overline{C_{Rx}} = \log_2 \det\left[\mathbf{I} + \frac{\rho}{n} \cdot \langle \mathbf{R} \rangle\right]$$

$$\langle r_{ij} \rangle = \sum_k \langle h_{ik} h_{jk}{}^* \rangle$$

Captures Rx correlation only !

transmit index

Key observation: transpose does not impact *C* !

$$\boxed{\mathbf{H} \Rightarrow \mathbf{H}^{\mathrm{T}}} \quad \Rightarrow \quad \boxed{\det\left(\mathbf{I} + \frac{\rho}{n}\mathbf{H}\cdot\mathbf{H}^{+}\right) = const}$$

Transmit bound:

$$\langle C \rangle \le \overline{C_{Tx}} = \log_2 \det\left[\mathbf{I} + \frac{\rho}{n} \cdot \left\langle \mathbf{R}^{\mathrm{Tx}} \right\rangle \right]$$

$$\left\langle r_{ij}^{\mathrm{Tx}} \right\rangle = \sum_k \left\langle h_{ki} h_{kj} * \right\rangle$$

Captures Tx correlation only !

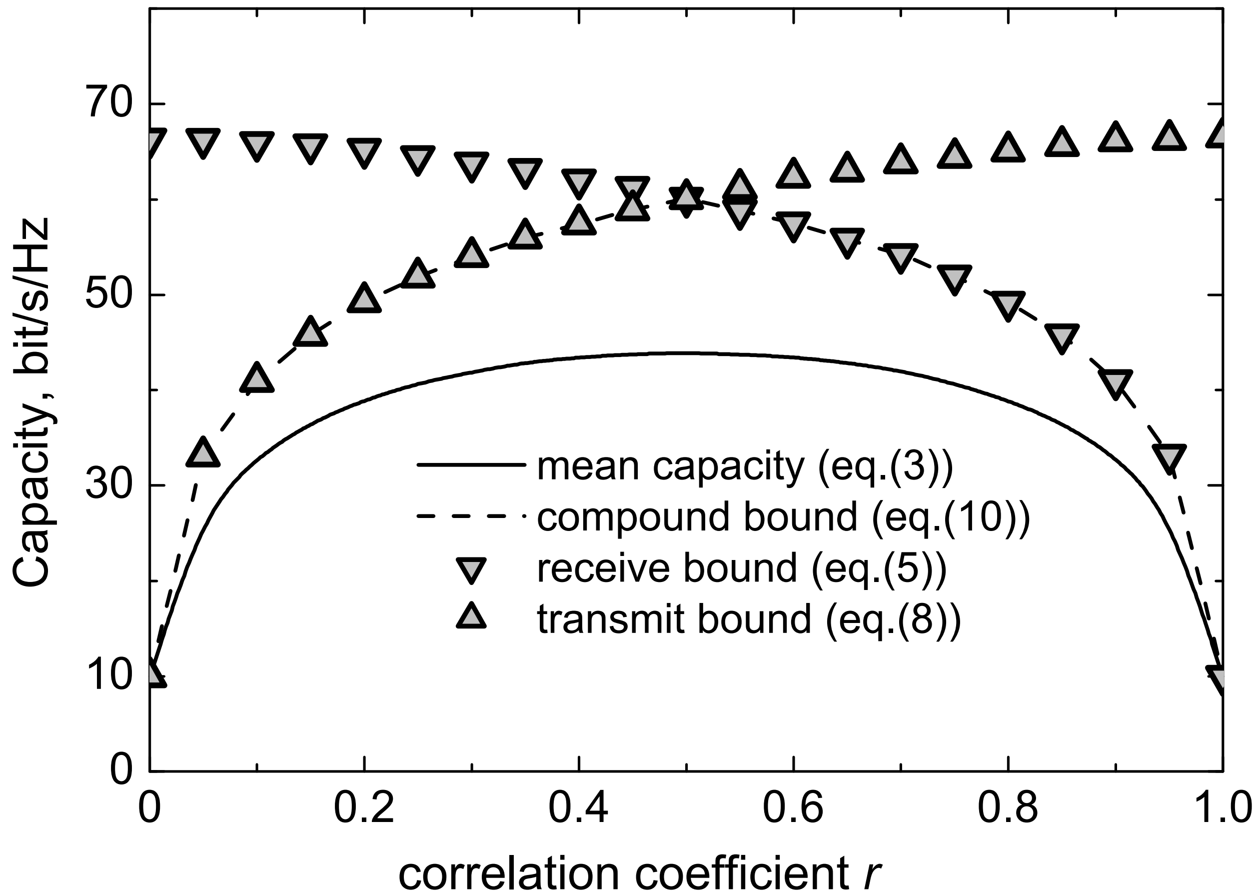
receive index

Universal bound:

$$\langle C \rangle \le \overline{C} = \min\left[\overline{C_{Rx}}, \quad \overline{C_{Tx}}\right]$$

captures both Tx & Rx correlation

$$R_{ij,km} = R_{ij}^{Rx} \cdot R_{km}^{Tx}, \quad R_{ij}^{Rx} = r, \quad R_{ij}^{Tx} = 1 - r, \quad i \neq j$$



Simple Analytical Estimations

Uniform correlation matrix model[2]:

$$R_{ij} = r, \quad i \neq j$$

Capacity $(0 \leq r < 1, \quad \rho/n >> 1)$:

r=0.5 $\rightarrow$ 3dB loss in SNR

$$C \approx n \cdot \log_2\left(1 + \frac{\rho}{n}(1-r)\right)$$

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[2]S.L. Loyka, J.R. Mosig, Channel Capacity of N-Antenna BLAST Architecture, Electronics Letters, vol. 36, No.7, pp. 660-661, Mar. 2000.

Exponential correlation matrix model[3]:

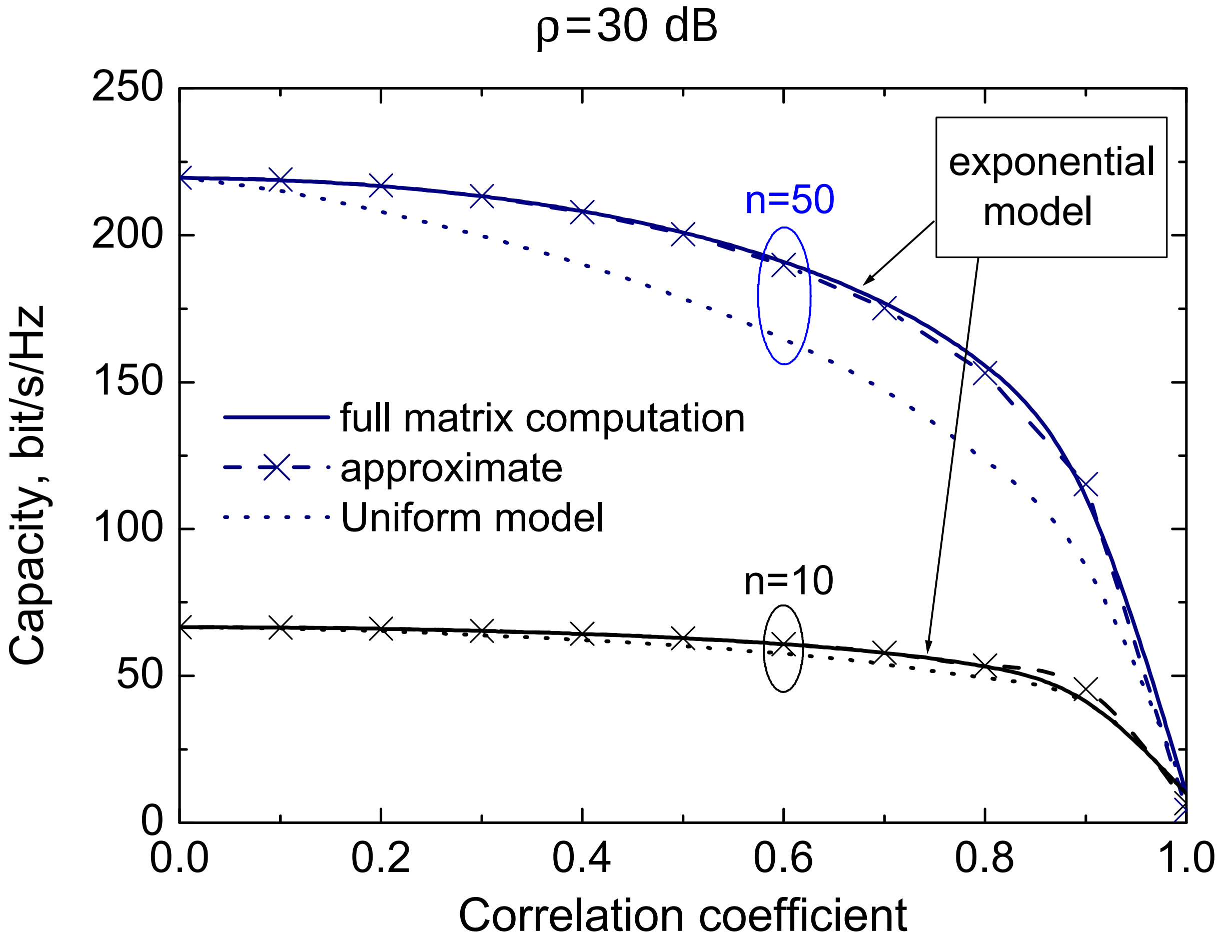
$$R_{ij} = r^{|i-j|}, \quad |r| \le 1$$

Capacity $(|r| < 1, \quad \rho/n >> 1, \quad n >> 1):$

$$C \approx n \cdot \log_2 \left(1 + \frac{\rho}{n} \left(1 - |r|^2 \right) \right)$$

r=0.7 $\rightarrow$ 3dB loss in SNR

[3]S.L. Loyka, Channel Capacity of MIMO Architecture Using the Exponential Correlation Matrix, IEEE Comm. Letters, v.5, N. 9, pp. 369 –371, Sep 2001.



ρ=30 dB
Capacity, bit/s/Hz
Correlation coefficient
0
50
100
150
200
250
0.0
0.2
0.4
0.6
0.8
1.0
full matrix computation
approximate
Uniform model
n=50
n=10
exponential model

MIMO Dimensionality Reduction

Block model of correlation matrix:

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_k & \mathbf{0} \\ \mathbf{0} & \mathbf{I}_{n-k} \end{bmatrix}$$

k correlated branches

n-k uncorrelated branches

Capacity:

$$C \approx (n-k) \cdot \log_2\left(1 + \frac{\rho}{n}\right) + k \cdot \log_2\left(1 + \frac{\rho}{n}(1-r)\right)$$

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[4] S. Loyka, A. Kouki, Correlation and MIMO Communication Architecture (Invited), 8th Int. Symp. on Microwave and Optical Technology, Montreal, June 19-23, 2001.

High correlation $(\rho/n >> 1)$: $\boxed{|r| \geq 1 - n/(2\rho)}$

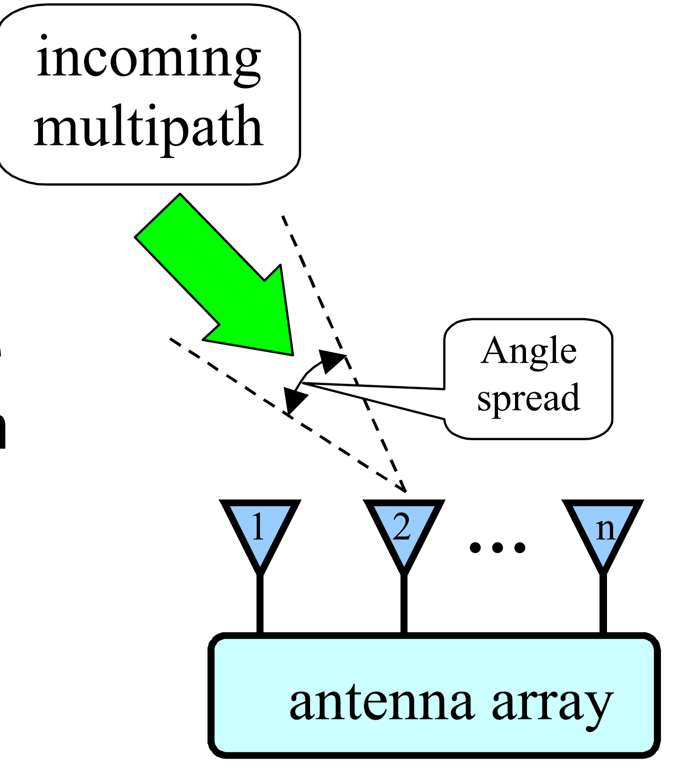
Effective dimensionality: $\boxed{n_e \approx n - k + 1}$

Example: n=10, ρ=30 dB $\Rightarrow$ $|r| \geq 0.995$

MIMO Capacity in Realistic Environment[5]

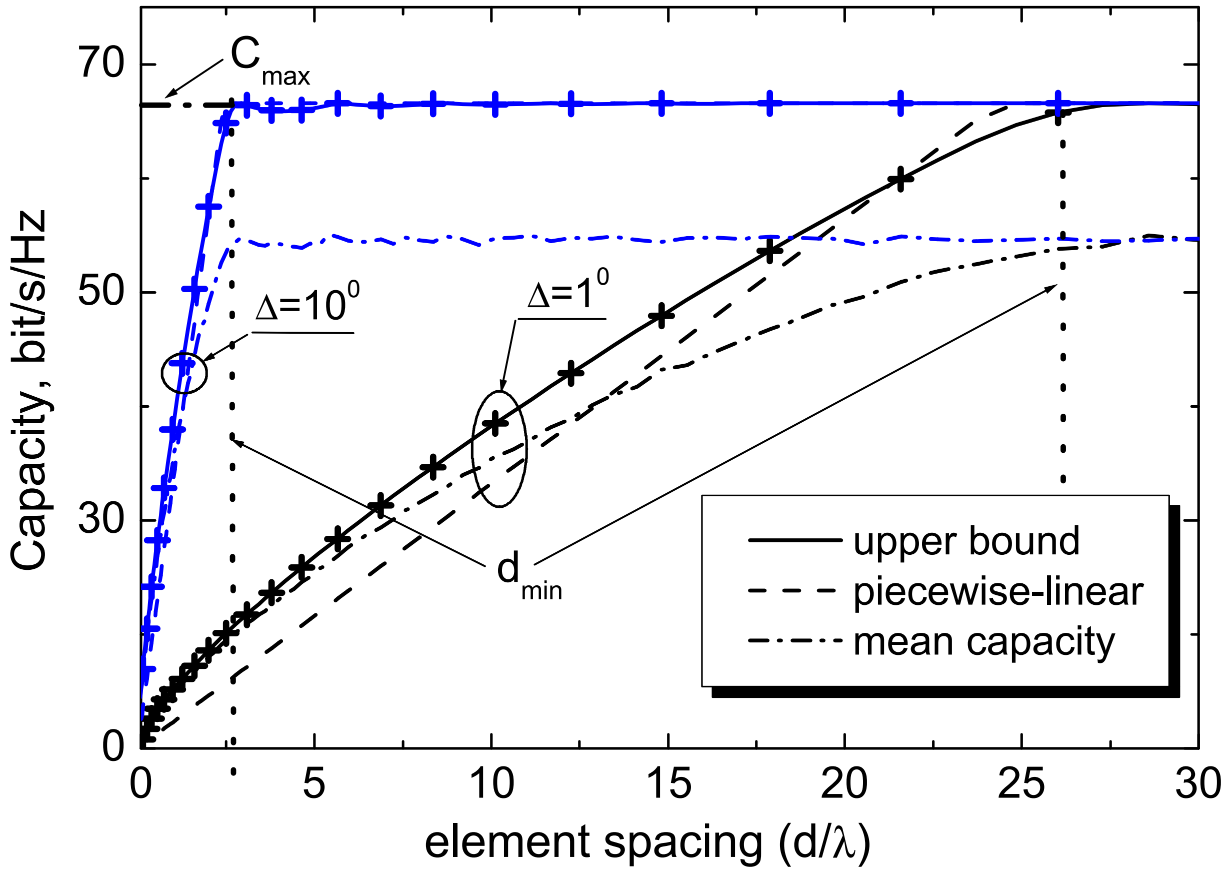
Salz-Winters Model:

Incoming multipath signals arrive to the linear antenna array within some angle spread (±Δ)



[5] S. Loyka, G. Tsoulos, Estimating MIMO System Performance Using the Correlation Matrix Approach, IEEE Comm. Letters, 2001, accepted

MIMO Capacity in Realistic Environment (cont.)



Some observations:

Capacity of n parallel channels

$$\boxed{d > d_{\min}} \Rightarrow \boxed{C = C_{\max} = n \cdot \log_2\left(1 + \frac{\rho}{n}\right)}$$

$$\boxed{d_{\min} = \frac{\lambda}{2\Delta\cos\varphi}}$$

the same as for space diversity combining!

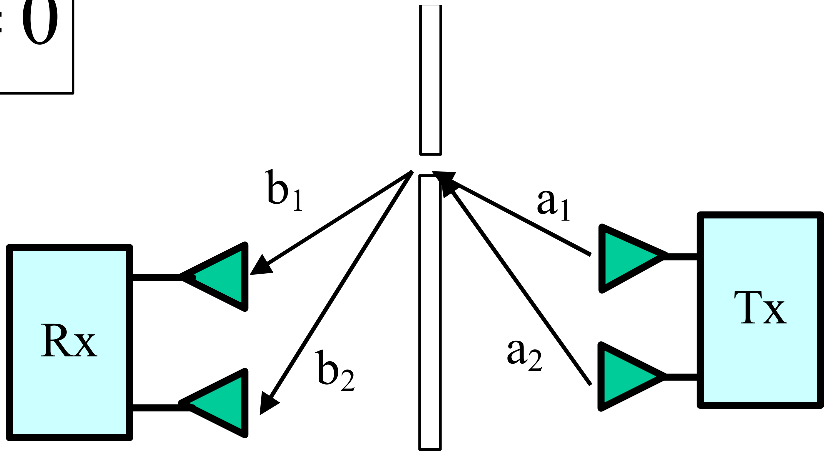
2Δ - angle spread

φ - average angle of arrival

Paradox of Zero Correlation

Keyhole: zero correlation but low capacity!

$$\boxed{R = e^{j(\varphi_1 - \varphi_2)}} \Rightarrow \boxed{\langle R \rangle = 0}$$



$$\varphi_1 = \arg(b_1), \quad \varphi_2 = \arg(b_2)$$

a_1 , a_2 , b_1 , b_2 - i.i.d. complex gaussian

Solution to the paradox: distinguish between average (conventional) and instantaneous capacity[6] !

$$\lambda^2 - (r_{11} + r_{22})\lambda + r_{11} r_{22}\left(1 - |R|^2\right) = 0$$

$\boxed{R = e^{j(\varphi_1 - \varphi_2)}}$ ⇒ $\boxed{|R| = 1}$ ⇒ One non-zero eigenvalue

r_{11} , r_{22} - received powers, λ - eigenvalue

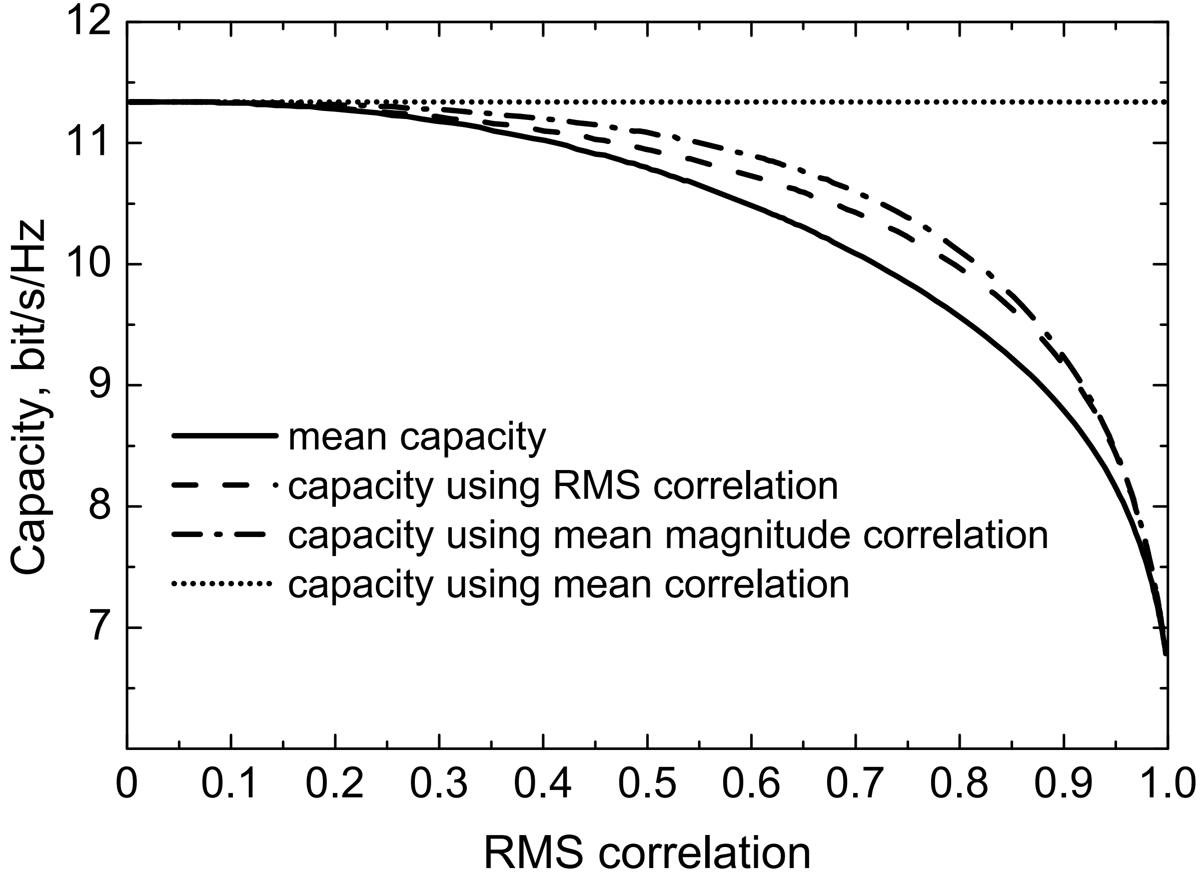
[6] S. Loyka, A. Kouki, On MIMO Channel Capacity, Correlations and Keyholes, IEEE Trans. Comm., 2001, submitted

Some observations:

- average (conventional) correlation is not a reliable tool for estimating MIMO capacity
- $\langle R \rangle = 0$ is necessary but not sufficient
- $|R| = 0$ is sufficient
- mean magnitude correlation gives an accurate estimation

Paradox of Zero Correlation (cont.)

Example: $$f(R) = c \cdot \exp\left(\frac{|R|}{\alpha}\right), \quad -1 \le R \le 1 \quad \Rightarrow \quad \boxed{\langle R \rangle = 0}$$



Measurement Issues

- Wireless channel is the most critical MIMO component
- Lack of measured data (validate theory, estimate performance in realistic scenarios etc.)
- Consequence: MIMO channel measurement is a key to future success

What to Measure?

- Channel matrix statistics
- Key channel parameters: angular & delay spread, number of multipath components, correlation
- Polarization diversity

How to Measure?

- Full-scale MIMO measurements: complexity ~ n^2
- Reduced-complexity SIMO measurements ~ n
- After-measurement DSP: adaptive array algorithms
- Indoor versus outdoor

Conclusion

- MIMO architecture is the first breakthrough in communication theory for last 50 years
- Order-of-magnitude improvement in performance
- Numerous potential applications (WLAN, LMDS, cellular etc.)
- Three-fold potential of MIMO:
    1. Research (scientific)
    2. Applications (industrial)
    3. Education

The Future of Wireless is MIMO!