Overview of MIMO systems

S-72. 333 Postgraduate Course in Radio Communications

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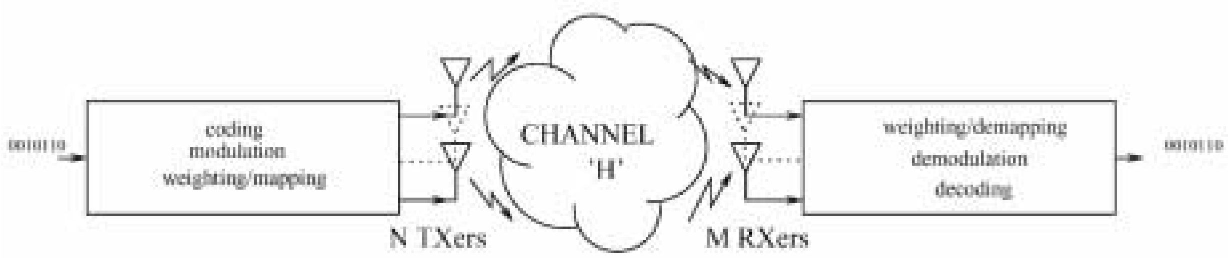
Outline

Multiple-Input Multiple-Output (MIMO) Wireless Systems

1.1 What are MIMO systems ?

- A MIMO system consists of several antenna elements, plus adaptive signal processing, at both transmitter and receiver
- First introduced at Stanford University (1994) and Lucent (1996)
- Exploit multipath instead of mitigating it



1.2 Wireless channels limitations

Wireless transmission introduces:

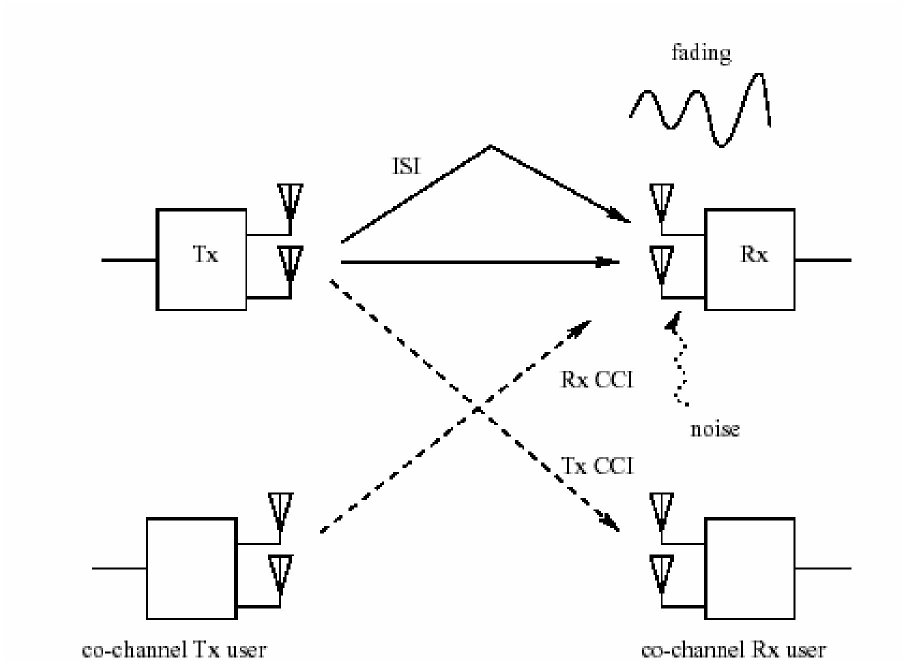
Fading: multiple paths with different phases add up at the receiver, giving a random (Rayleigh/Ricean) amplitude signal.

ISI:multiple paths come with various delays, causing intersymbol interference.

CCI: Co-channel users create interference to the target user

Noise: electronics suffer from thermal noise, limiting the SNR.

Wireless channels limitations : summary



1.3 MIMO Benefits :

• higher capacity (bits/s/Hz)

(spectrum is expensive; number of base stations limited)

• better transmission quality (BER, outage)

• Increased coverage

• Improved user position estimation

Due to :

➢ **Spatial multiplexing gain : Capacity gain at no additional power or bandwidth consumption obtained through the use of multiple antennas at both sides of a wireless radio link**

➢ **Diversity gain : Improvement in link reliability obtained by transmitting the same data on independently fading branches**

➢ **Array gain**

➢ **Interference reduction**

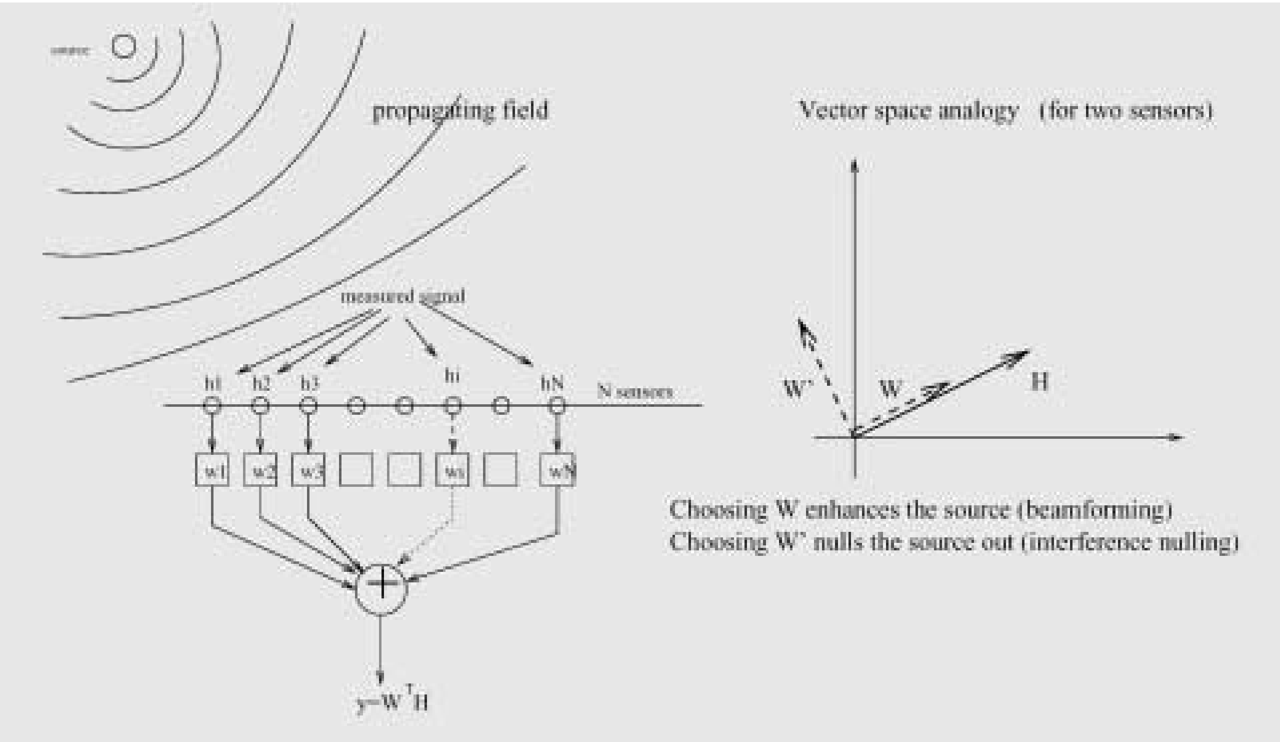
Array gain principle :

The array gain is defined by the gain in mean SNR

$$\overline{SNR} = \frac{\left(E|h_1|^2 + ... + E|h_N|^2\right)\sigma_s^2}{\sigma_n^2} = N\frac{E|h|^2\sigma_s^2}{\sigma_n^2} = N\overline{SNR}_{input}$$

↳ The output SNR is ***N*** times the input SNR

Receiving data over N antennas :



2 SISO Vs MIMO

Capacity of SISO Systems (1 by 1)

At fixed time t, the SISO channel is an additive white Gaussian noise (AWGN) channel with capacity :

$$C(t) = \log2(1 + SNR_{siso}(t)) \text{ Bit/Sec/Hz}$$

where $SNR_{siso}(t)$ is the *received* signal to noise ratio at time t :

$$SNR_{siso}(t) = \frac{|h(t)^2| \sigma_s^2}{\sigma_n^2}$$

➡ **+3dB of extra power needed for one extra bit per transmission !**

Capacity of MIMO systems

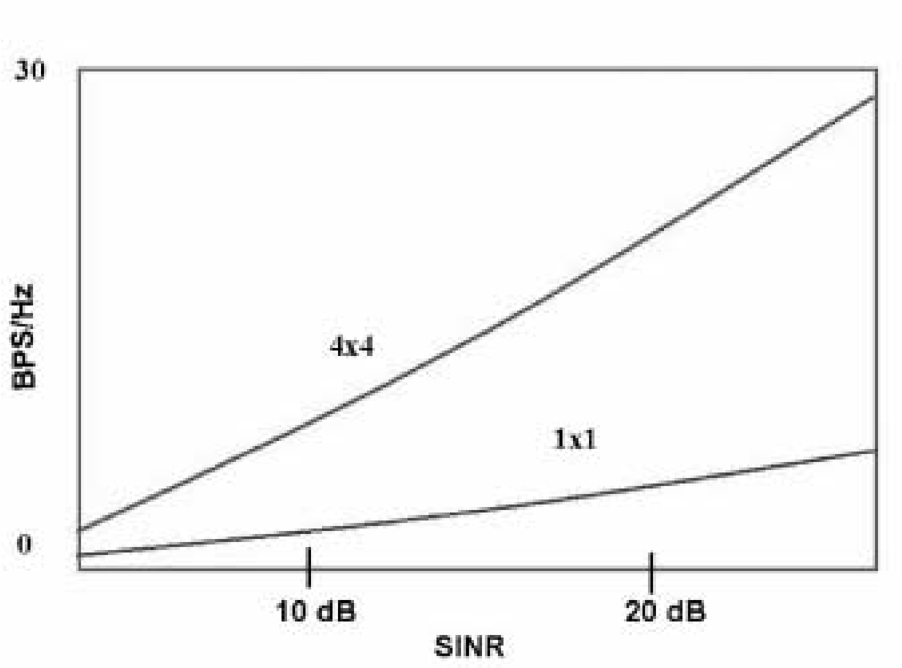
Note: we assume channel unknown at transmitter

$$C_{erg} = \varepsilon_H \left(\log_2 \left[\det \left(I_M + \frac{\rho}{N} \mathrm{HH}^* \right) \right] \right) \approx \alpha \min(M, N)$$

where $\mathbf{H}$ is the *M X N* random channel matrix and ρ is the average signal-to-noise ratio (SNR) at each receiver branch.

➡ **Capacity proportional to min of # TX and # RX antennas!**

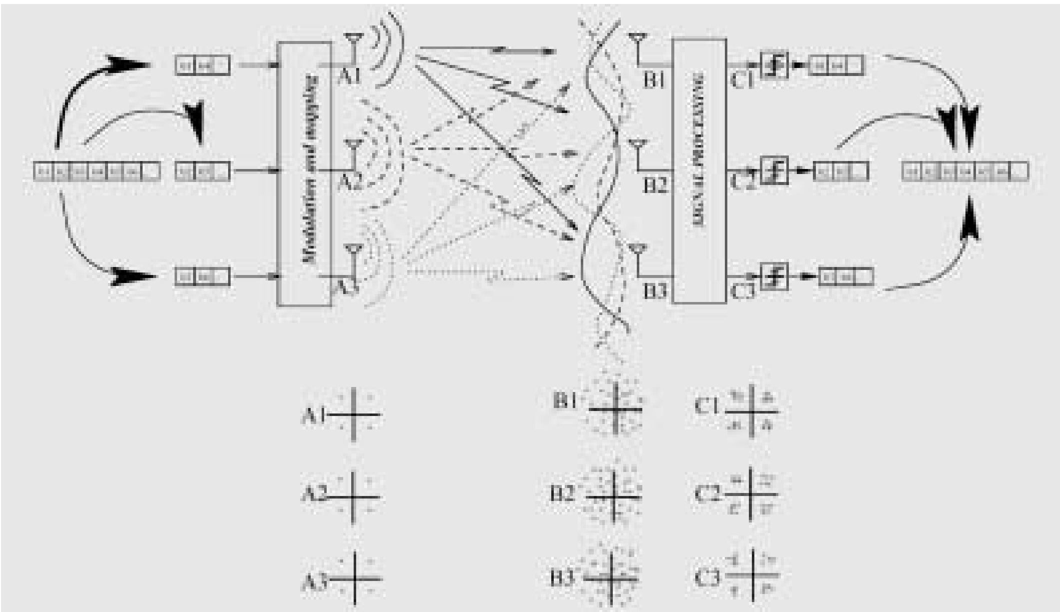
Comparison : Average capacity of ideal MIMO systems



3 Spatial multiplexing

3.1 Principle

We send multiple signals, the receiver learns the channel matrix and inverts it to separate the data.



Example for 3x3:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} + Noise$$

$$\begin{bmatrix} \hat{b}_1 \\ \hat{b}_2 \\ \hat{b}_3 \end{bmatrix} = \mathrm{H}^{-1} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

3.2 Impact of channel model

MIMO Performance is very sensitive to channel matrix ***invertibility.***

- **The following degrades the conditioning of the channel matrix:**

  Antenna correlation caused by:

  - Small antenna spacing, or

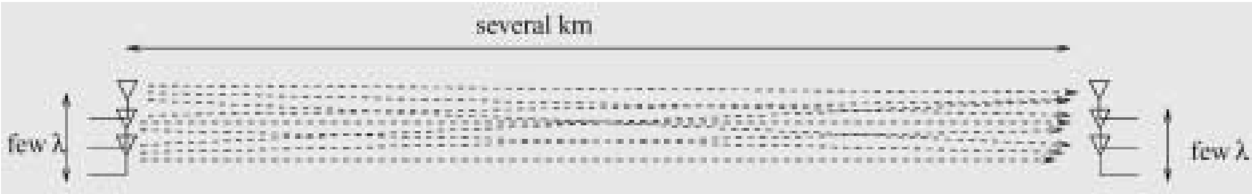
  - Small angle spread

- **Line of sight component compared with multipath fading component :**

  - Multipath fading component, close to random identical independent distribution, is well conditioned

  - Line of sight component is very poorly conditioned.

MIMO spatial multiplexing in Line-of-sight

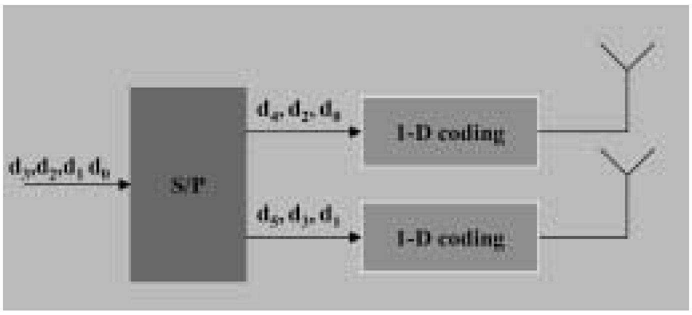


The system $$H \approx \alpha \begin{bmatrix} 111 \\ 111 \\ 111 \end{bmatrix}$$ **is near rank one (non invertible) !!**

➡ **Spatial multiplexing requires multipath to work !!**

3.3 V-BLAST/ D-BLAST Algorithms

(**B**ell-labs **LA**yered **S**pace-**T**ime architecture)
Belong to the class of **L**ayered **S**pace-**T**ime Coding



• In D-BLAST, output of coders can be applied to the transmit antennas in turn ➡ Diagonal LST coding (D-BLAST)

• In V-BLAST, output of coders operate co-channel with synchronized symbol timing ➡ Vertical LST coding (V-BLAST)

4 MIMO Receiver Design

4.1 Linear receivers for BLAST (Zero-Forcing, MMSE)

Zero-Forcing receiver

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & .. \\ h_{21} & h_{22} & .. \\ \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ \vdots \end{bmatrix} + N$$

Zero Forcing implements matrix (pseudo)-inverse (ignores noise enhancement problems) : $\hat{S} = \mathrm{H}^{\#} X$

Where : $\mathrm{H}^{\#} = \left(\mathrm{H}^{*}\mathrm{H}\right)^{-1}\mathrm{H}^{*}$

MMSE receiver

The MMSE (Minimum mean square error) receiver optimizes the following criterion:

$$\mathbf{W} = \text{argmin } \{E\,|\mathbf{W}^{*}\mathbf{x} - \mathbf{s}|^{2}\}$$

We find:

$$\hat{\mathbf{S}} = \mathbf{H}^{*}(\mathbf{H}\mathbf{H}^{*} + \mathbf{R}n)^{-1}\,\mathbf{x}$$

where $\mathbf{R}n$ is the noise/intf covariance.

This offers a compromise between residual interference between input signals and noise enhancement.

4.2 Non linear receiver (ML, SIC)

Maximum likelihood receiver:

- Optimum detection
- Exhaustive search. No iterative procedure for MIMO.
- Complexity exponential in QAM order and *N*.

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & .. \\ h_{21} & h_{22} & .. \\ \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ \vdots \end{bmatrix} + N$$

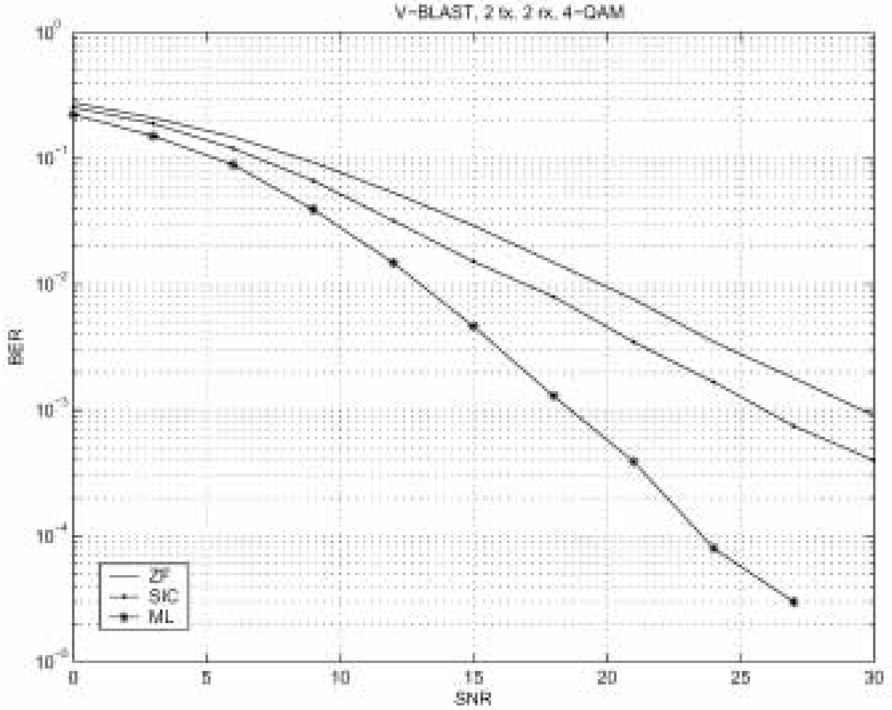
Maximum Likelihood Solution: $\hat{S} = \text{argmin} \, |x - Hs|^2$

where S is searched over the modulation alphabet (e.g. 4QAM, 16QAM..)

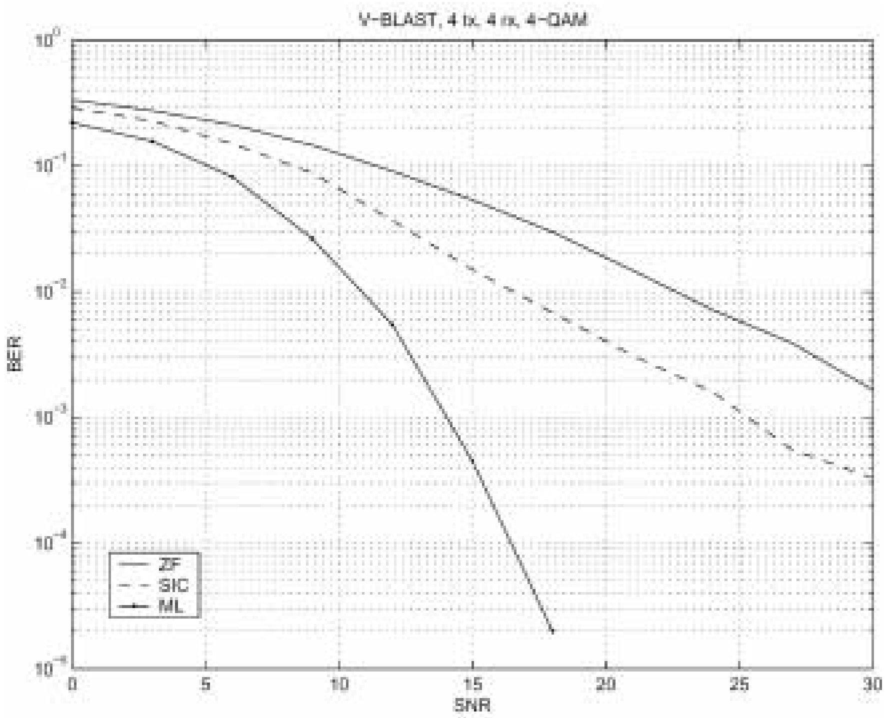
SIC : Successive Interference Canceling

4.3 Performance comparison

BLAST zero-forcing vs. V-BLAST (SIC) vs BLAST-ML (2x2)



BLAST zero-forcing vs. V-BLAST (SIC) vs BLAST-ML (4x4)



5 Space-Time Coding (Transmit/Receive Diversity)

Uses Transmission diversity to combat the detrimental effects in wireless fading channels.

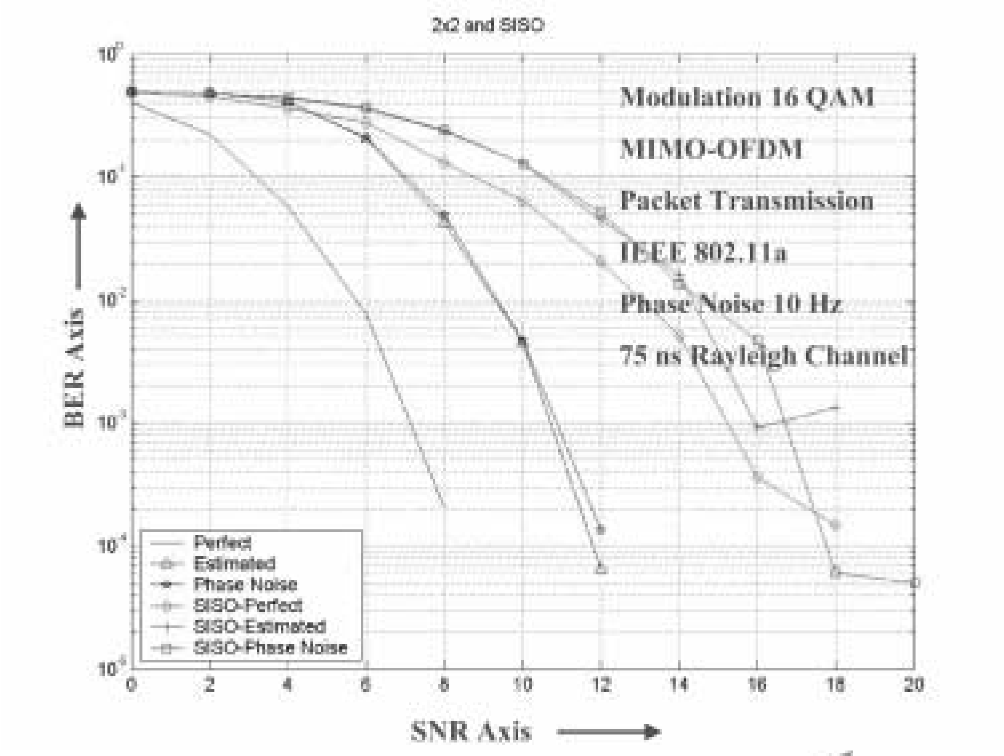
Three types:

•Trellis space time codes : complex but best performance in slow fading environment (indoors).

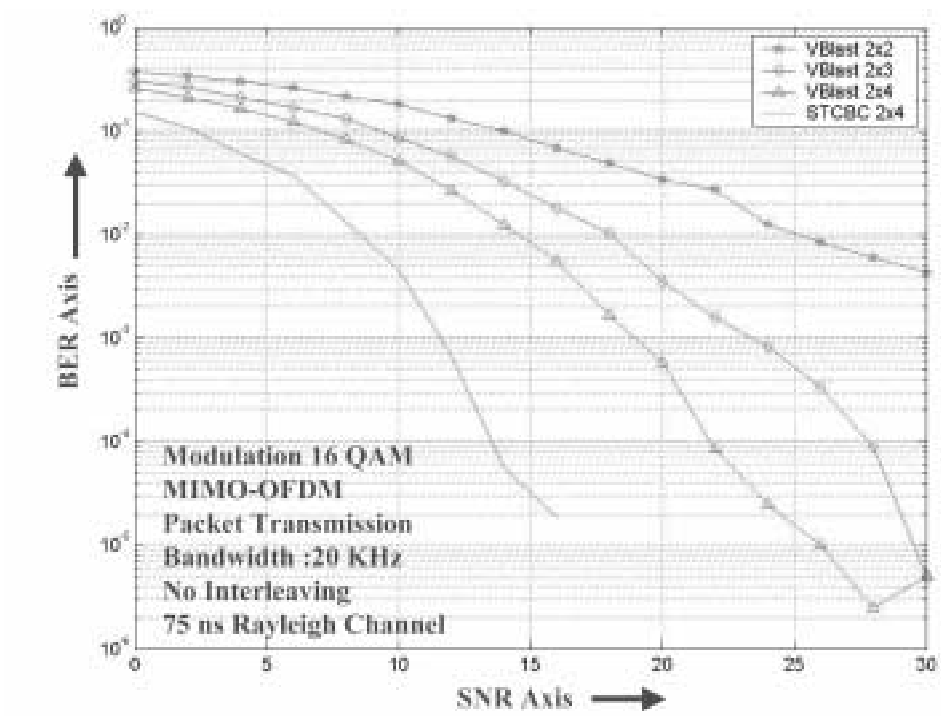
•Layered space time codes : easy to implement but not accurate due to error propagation effect.

•**Block space time codes :** best trade-off of performance vs complexity.

Comparison of Performance: 2x2 STCBC and SISO



Comparison of Performance: V-BLAST & STCBC in MIMO-OFDM



Summary : Space-Time Coding & V-BLAST

Space-Time Coding

- Space-time codes provide spatial diversity gain without requiring channel knowledge in the transmitter
- Space-time codes do not provide array gain (due to lack of channel knowledge in the transmitter)
- Orthogonal space-time codes decouple the vector detection problem into scalar detection problems -> drastically simplified algorithms

V-BLAST

- Performs well when channel estimates are good
- Degradation due to channel estimation errors is fairly high
- Successive Interference Cancellation (SIC) makes for low complexity
- Danger of error propagation that is inherent of a SIC scheme
- Inferior to STBC due to lack of diversity gain at the transmitter

6 Conclusion

MIMO extremely promising but more validation work are needed :

Algorithms:

- Unifying diversity and multiplexing approaches
- Optimum loading

Low complexity receivers

- Optimum receivers (ML) are too complex
- Simple receivers (linear) give unacceptable performance at high MIMO loading

System gain evaluation

- Real gains depend on deployment scenario
- Beamforming and MIMO needs to be compared on a system level basis

References

- “On the Capacity of OFDM-Based Spatial Multiplexing Systems”, Helmut Bolcskei, David Gesbert and Arogyaswami J. Paulraj, *IEEE Trans. Communications, Oct. 2001*

- “An Overview of MIMO Communications- A Key to Gigabit Wireless”, *A. J. Paulraj, D. Gore, R. U. Nabar, and H. B®olcskei*

- '' From theory to practice: An overview of space-time coded MIMO wireless systems '' D. Gesbert, M. Shafi, D. Shiu, P. Smith,, *IEEE Journal on Selected Areas on Communications* (JSAC). April 2003, special issue on MIMO systems. (Recipient of the 2004 IEEE Best Tutorial Paper Award by IEEE Comm. Society).

- “Implementation of a MIMO OFDM-Based Wireless LAN System”, Allert van Zelst*, Student Member, IEEE,* and Tim C. W. Schenk*, Student Member, IEEE*

- “MIMO Systems With Antenna Selection”, Andreas F.Molish, Moe Z.Win

Homework

1. Explain the principle of spatial multiplexing.

2. Describe briefly what happens in MIMO spatial multiplexing if there is just line of sight without multipath ?