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ARRAY PROCESSING II (2012)

-Course Notes at:

http://www.cttc.es "training" "Graduate and undergraduate lectures.

Spanish: ARRAY PROCESSING II (Chapters 0-11)

English: MIMO PROCESSING (English Version)

Recommended: ARRAY PROCESSING I (Spanish)

Name: Miguel Angel LAGUNAS

CTTC Avda. Canal Olimpic s/n

08860 Castelldefels

m.a.lagunas@cttc.es http://www.cttc.es Final Exam.

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ARRAY PROCESSING II (2012)

- March 8 NO
- Feb-March: M.A.Lagunas
- April 23: Ana Perez-Neira
- Final exam

The Centre Tecnològic de Telecomunicacions de Catalunya

A gateway to advanced communication technologies

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MIMO:INTRODUCTION

Miguel Ángel Lagunas
m.a.lagunas@cttc.es

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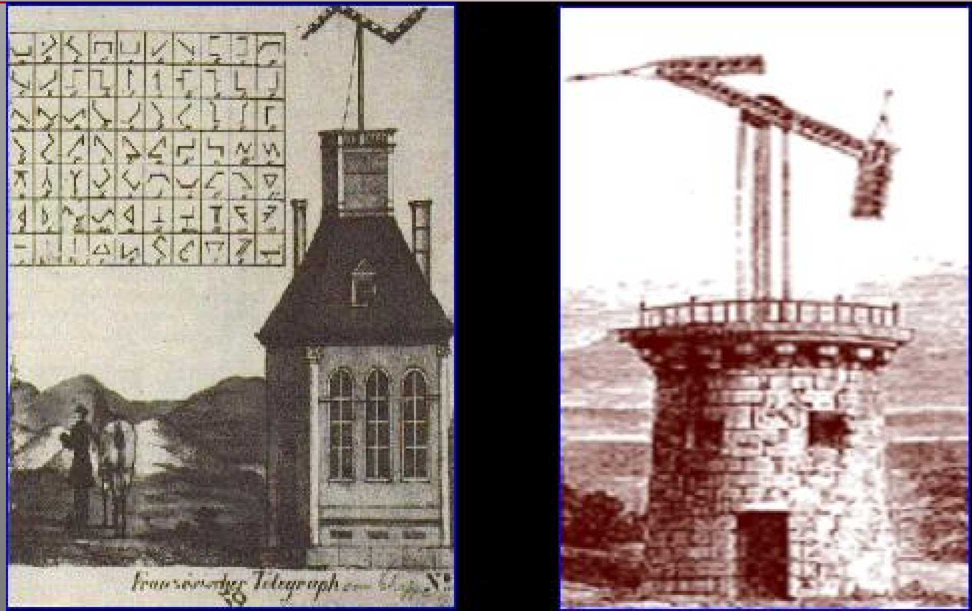
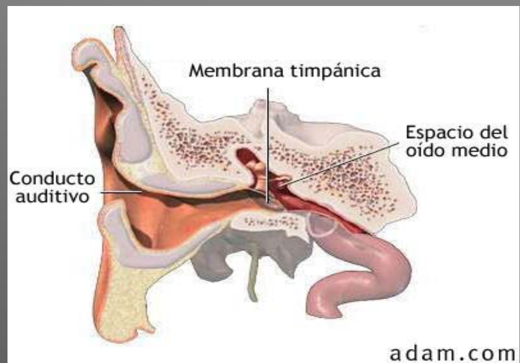
The roots of communications



0.33 bits/sec

Chapé / Betancourt

100 Kbps.



15 Mbps..

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Comm. Layers

Session

Access Layer

Physical Layer (wired, wireless, optical)

SIGNAL PROCESSING

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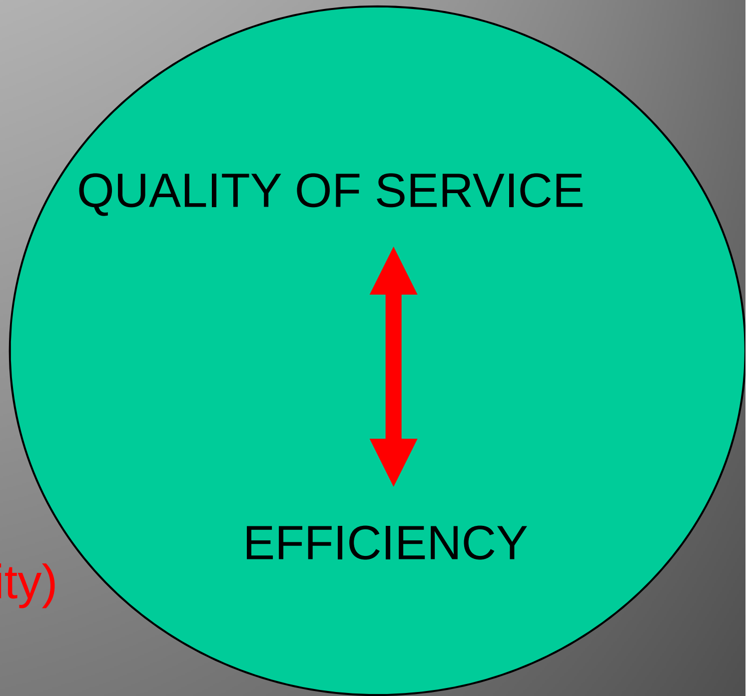
Wireless Systems

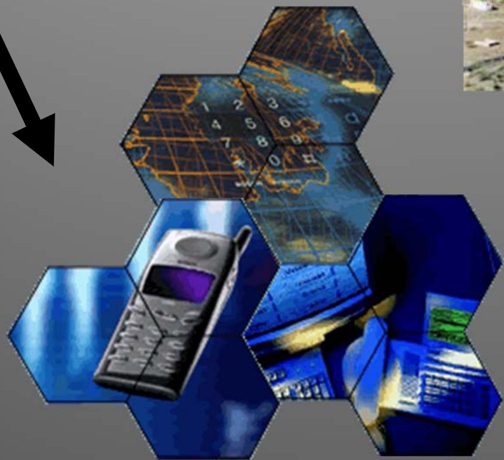
- Challenges
  - Higher data rate
  - Wider coverage
  - Energy efficient
  - Affordable
  - Reliable
- Possible solution
  - Multiple antenna systems:

  ANTENNA ARRAYS (Spatial diversity)



Combination of Wired Communications / Spatial Diversity contributions

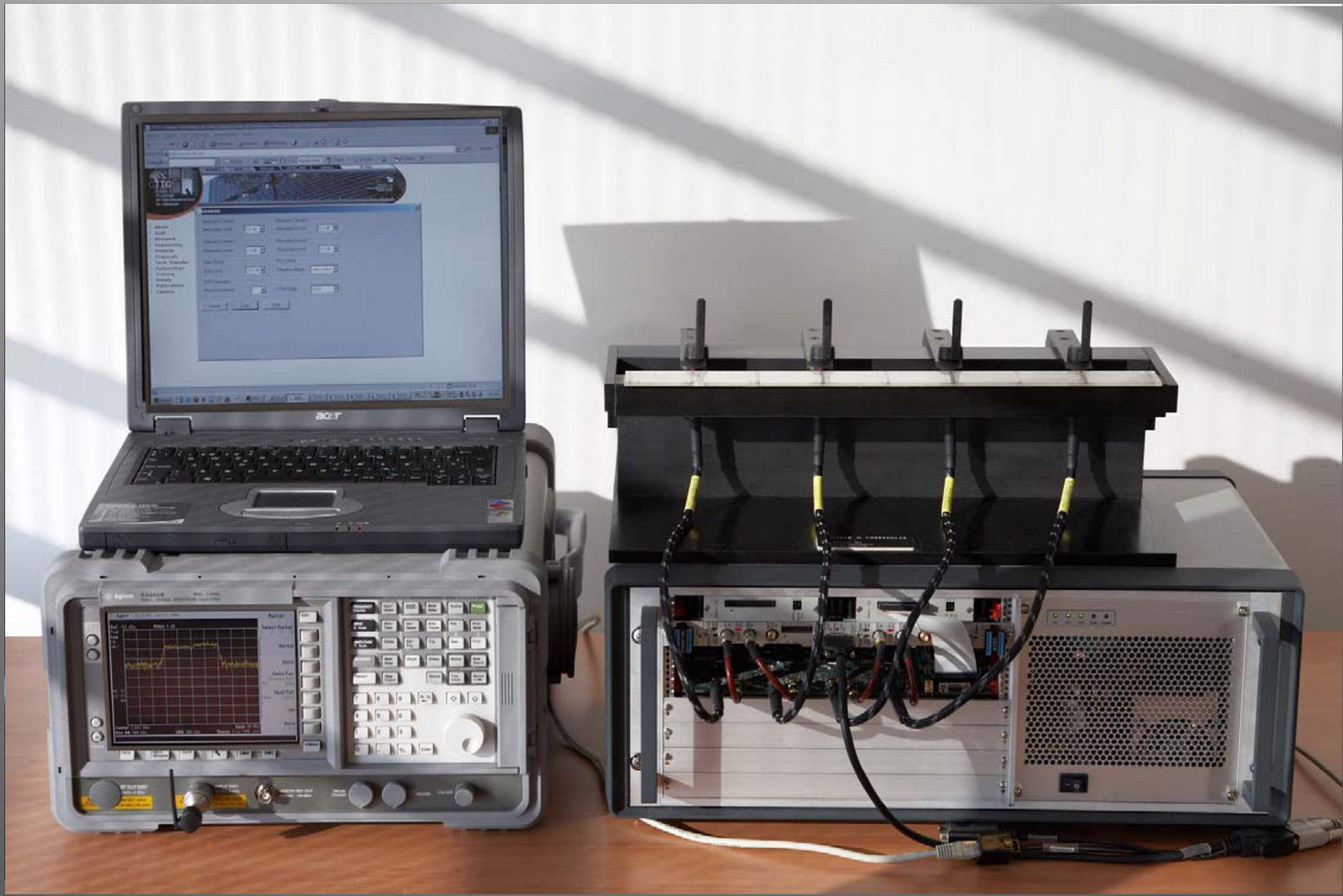
DSL Comm.



Radar/Sonar

Wireless Communications

Acoustics/Sonar/Radar/Civil Eng./Wireless



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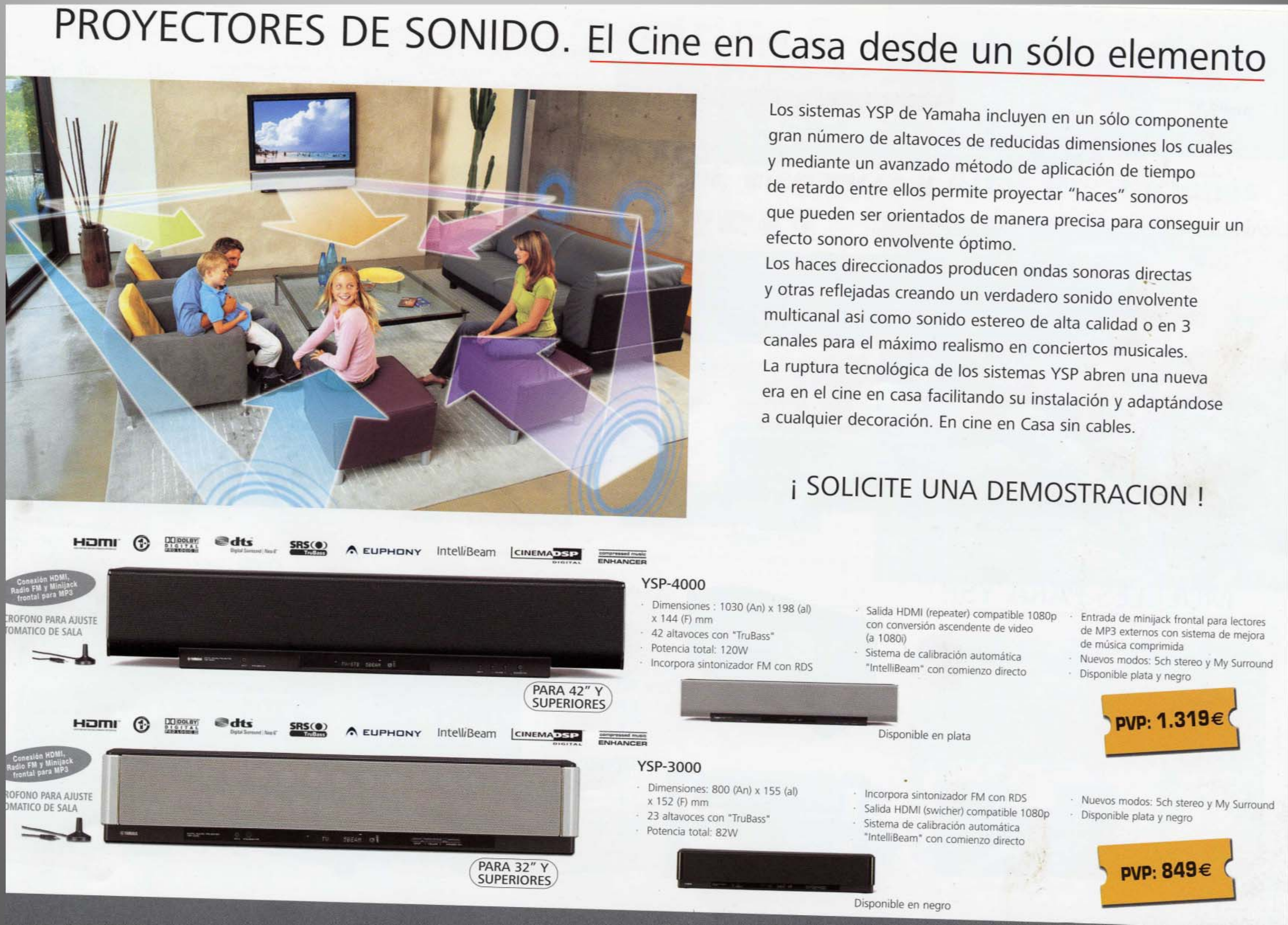

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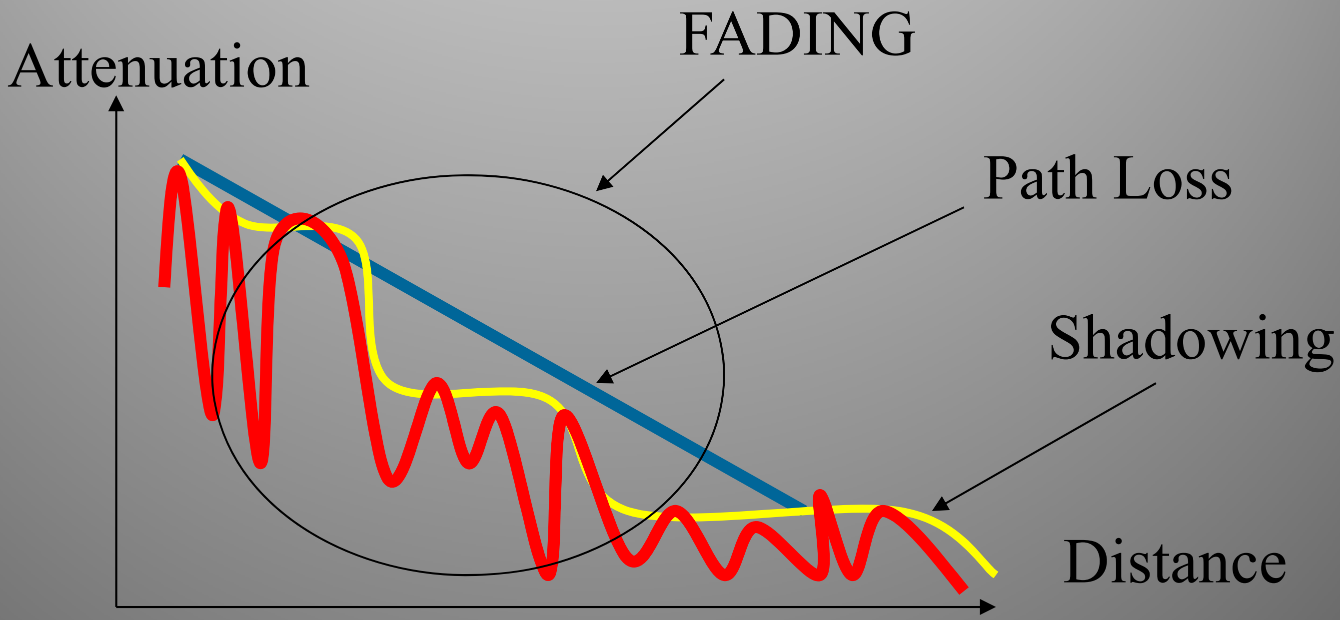
The Wireless Channel



Frequency Selective

$$h(t) = \alpha . g(t)$$

Flat Fading

$$h(t) = \alpha$$

Multicarrier Systems-> OFDM, Poly-Phase Filter Bank

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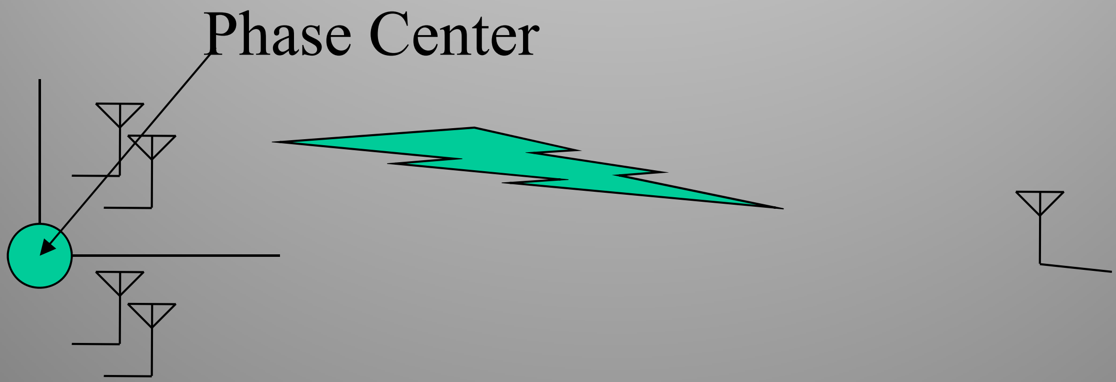
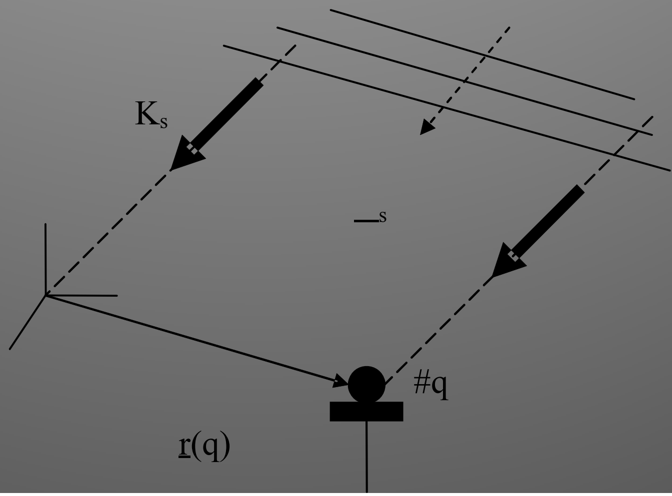
THE SPATIAL CHANNEL (LOS)



LOS: Line of Sigth

$$e^{w_0.t} \longrightarrow e^{jw_o.t}.e^{j.K_s.r_q}$$



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$$\underline{K}_s = \frac{2\pi}{\lambda}\left(\mathrm{sen}(\theta_s).\cos(\varphi_s), \mathrm{sen}(\theta_s).\mathrm{sen}(\varphi_s), \cos(\theta_s)\right)$$

$$\underline{r}_q = d_q\left(\cos(\varphi_q), \mathrm{sen}(\varphi_q), 0\right)$$

Wideband-Narrowband→Small group delay

$$x_q(t) = x_s(t-\tau_{qs}) \cong a_s(t).\exp(-j2\pi f_o t).\exp(j\varsigma_{qs});$$

$$\varsigma_{qs} = 2\pi f_o.\tau_{qs} = \frac{2\pi f_o}{c}.d_q.\mathrm{sen}(\theta_s).\cos(\varphi_s - \varphi_q)$$

$$\underline{h} = \alpha.\underline{S}_s$$ Flat-Fading, LOS STEERING VECTOR

Source Signal $$x_r(t) = s(t).\alpha.\underline{S}_s + \underline{w}(t)$$

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The path loss is almost deterministic in the LOS scenario for frames of continuous per channel uses of the link.

The receiving aperture captures all the symbol information of the source in a single snapshot

$$\underline{Y}_n = s(n).\alpha \underline{S}_s + \underline{w}_n$$

Snapshot

Steering vector of the source

Noise and interference

This requires "small" size apertures

$$\frac{D}{\lambda_c} < \frac{f_c}{B}$$

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When multipath do not produces ISI the model is still valid but the steering vector multiplied by the path loss pass to be the "Spatial signature" of the source.

$$\underline{Y}_n = s(n).\underline{b}_s + \underline{w}_n$$

$$where$$

$$\underline{b}_s = \sum_{1}^{\#ofpaths} \alpha_s \underline{S}_s$$

Note that the received vector due to the source still preserves the rank one structure. When the group delay in the multiple paths cannot be neglected, the received vector increases its rank

$$\underline{Y}_t = \sum_{1}^{\#ofpaths} s(t-\tau_s)\alpha_s \underline{S}_s + \underline{w}_t$$

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When the group delay is not small across the aperture (i.e. the spatial dimension of the aperture is high), the receiver suffers ISI.

The receiver, in order to capture the information of a given transmitted symbol needs to redefine a new snapshot including time-diversity.

$$\underline{\underline{Y}}_n = \left[\underline{Y}_n \quad \underline{Y}_{n-1} \quad \underline{Y}_{n-2} \quad \cdots \quad \underline{Y}_{n-L}\right]$$

Where L (LT seconds) is the time that is between the signal arrives to the first antenna and fully appears in the last antenna due to the propagation across the aperture.

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The NLOS contribution

Most of the wireless systems work under only NLOS channel conditions

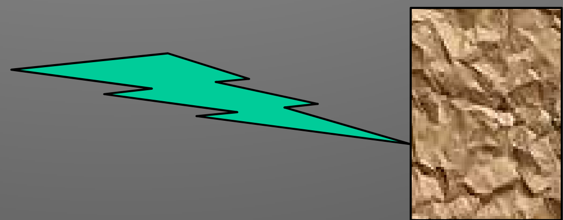
$$\underline{h} = \underline{\bar{h}} + \underline{h}_{NLOS}$$

Channel Mean LOS

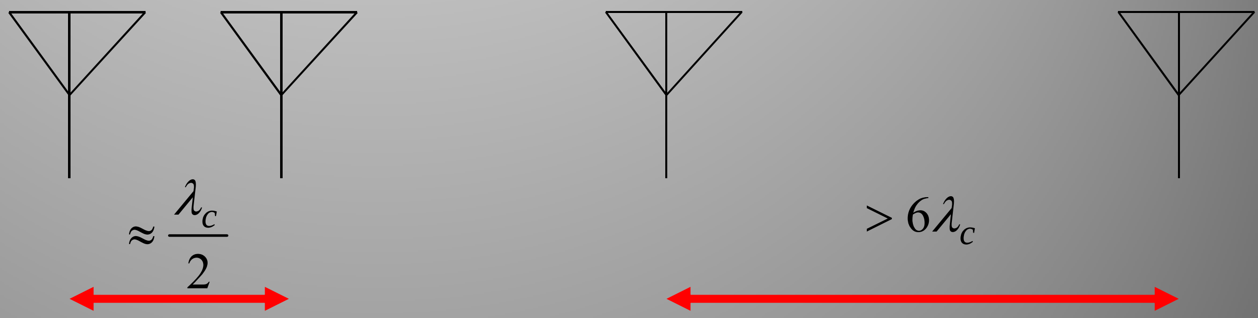
Rayleigh component NLOS

$$\underline{h} = G\left(\underline{\bar{h}}, \underline{\underline{\Sigma}}\right)$$

- Steering and/or Scattering cluster



Remember



- Full coherent receiver aperture
- $h_{NLOS/LOS}$ almost the same for all antennas
- Aiming high QoS
- Low BER and high SNR

- Channels uncorrelated, i.e. covariance of the channel matrix diagonal
- Aiming Capacity
- MULTIPLEXING capabilities

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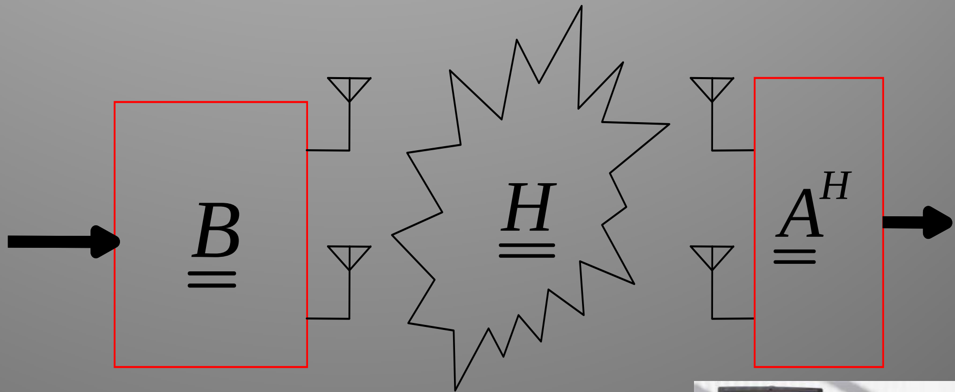
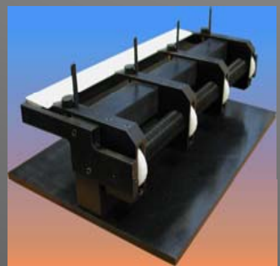
Multi-Antenna Tx/Rx (MIMO)

- INCREASE SPECTRAL EFFICICIENCY -> RATE
- 4x4 -> 16 Channels (???) RELIABILITY

QUALITY/RATE trade-off





The MI… and RF effects

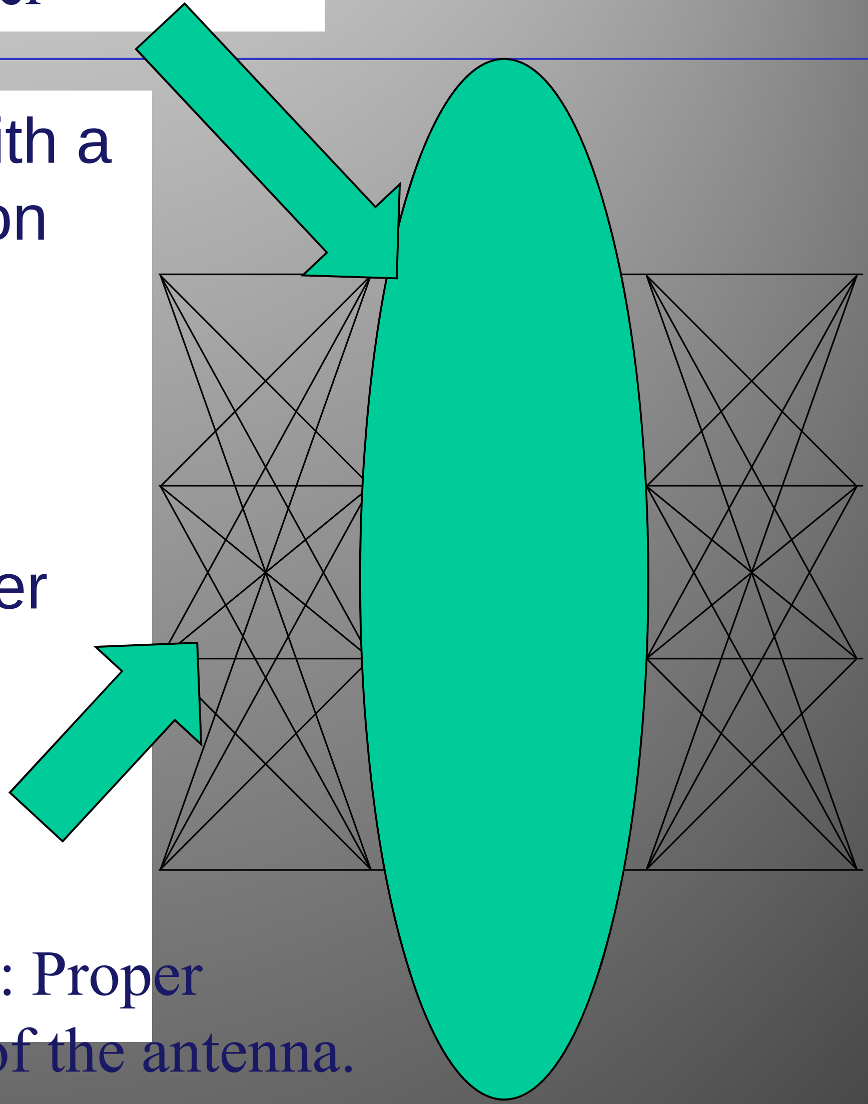
The radiated power differs substantially from the used power

- $\mathbf{H}$ is modeled statistically with a general Gaussian distribution

$$\mathbf{H} = \bar{\mathbf{H}} + \mathbf{R}_R^{1/2}\mathbf{G}\mathbf{R}_T^{T/2}$$

- Also known as the Kronecker model model

$$\mathbf{H} \sim \mathcal{CN}\left(\bar{\mathbf{H}}, \mathbf{R}_T \otimes \mathbf{R}_R\right)$$



RF Effects: Proper matching of the antenna. Mutual coupling, etc.

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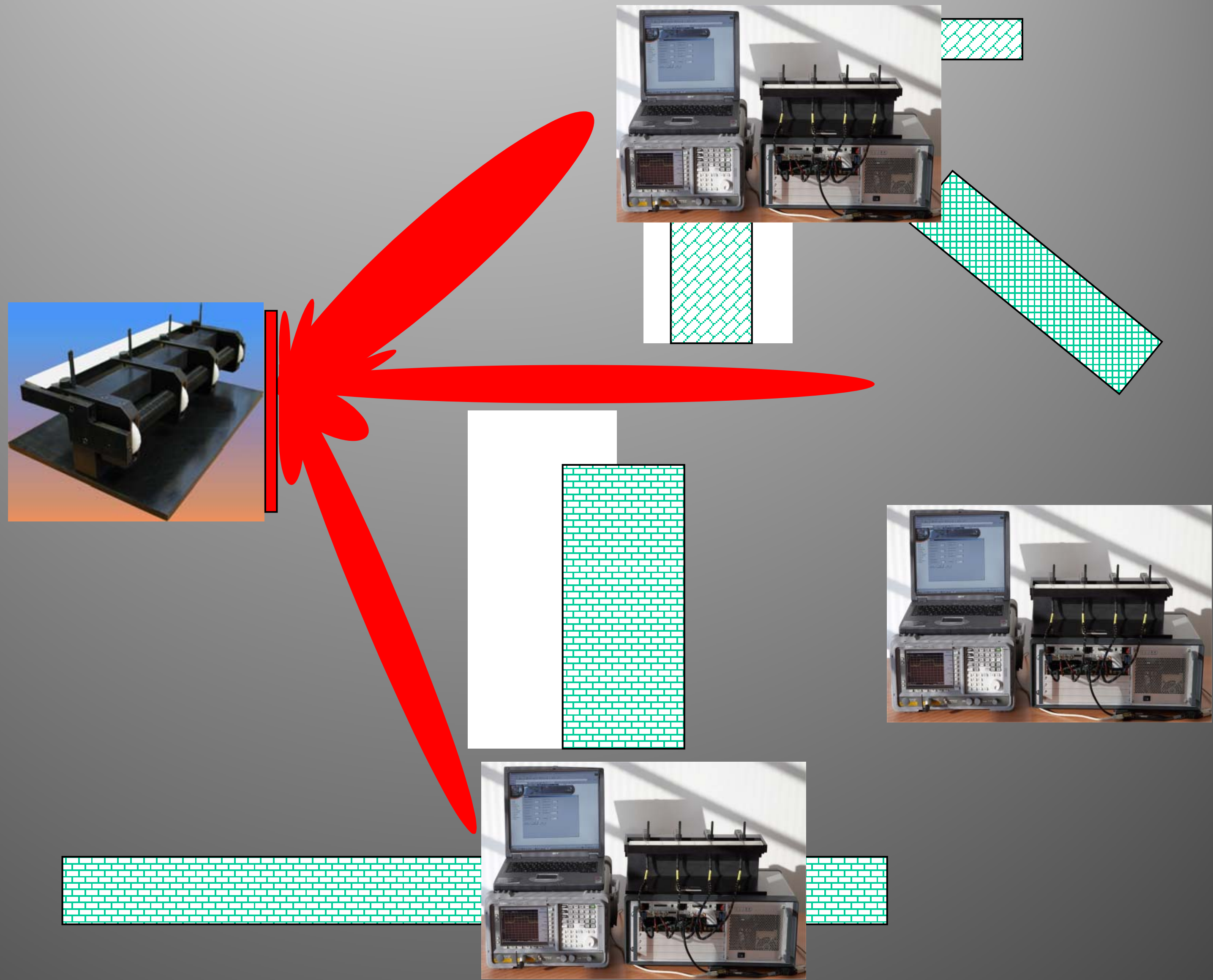
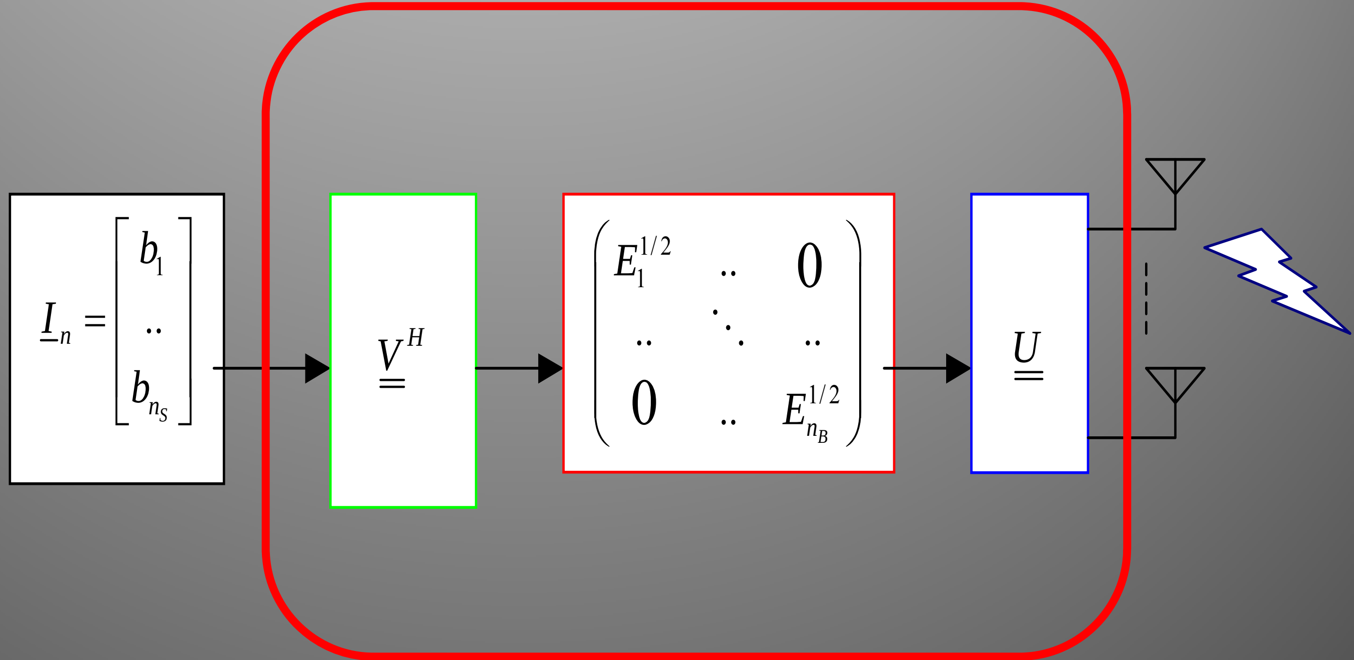
Spatial Diversity



Tx Architecture

The Tx pre-coder matrix B is always formed by 3 blocks (mathematically speaking is the SVD on any matrix)



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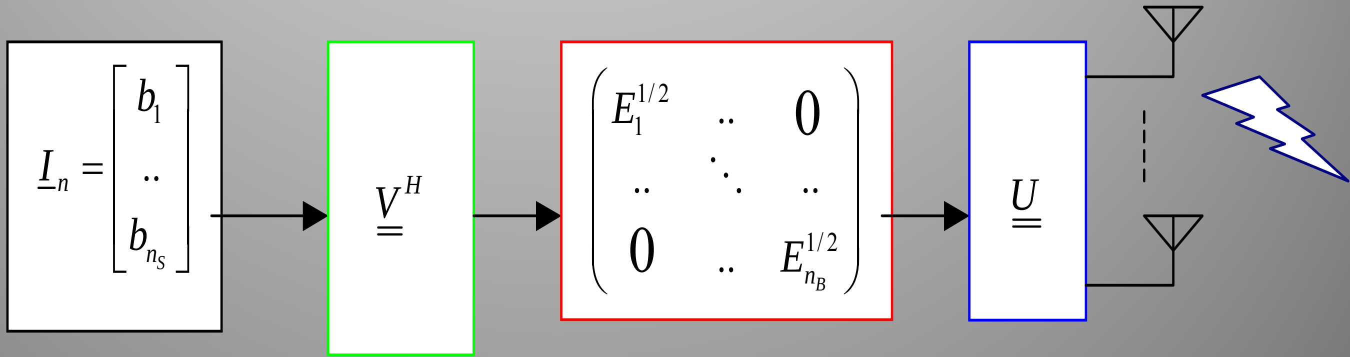
Tx Architecture: Packing in Channel Symbols (1/3)



The first matrix packs bits/symbols in channel symbols

$$\underline{I}_n = [b(1) \quad b(2) \quad .. \quad b(n_S)] \quad con \quad b(i) = \{+1, -1\} \; \forall i = 1, n_S$$

$$\underline{S}_n = \underline{\underline{V}}^H . \underline{I}_n$$

Linear/Non-Linear

Code - Constellation

$$\underline{\underline{V}}^H = \begin{bmatrix} 1 & j & 0 & 0 \\ 0 & 0 & 1 & j \end{bmatrix} \qquad \underline{\underline{V}}^H = [1 \quad 3 \quad j \quad 3j]$$

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We will use this matrix to pack a given set of symbols in order to accommodate the number of symbols transmitted to the number of channels available.

Other examples:

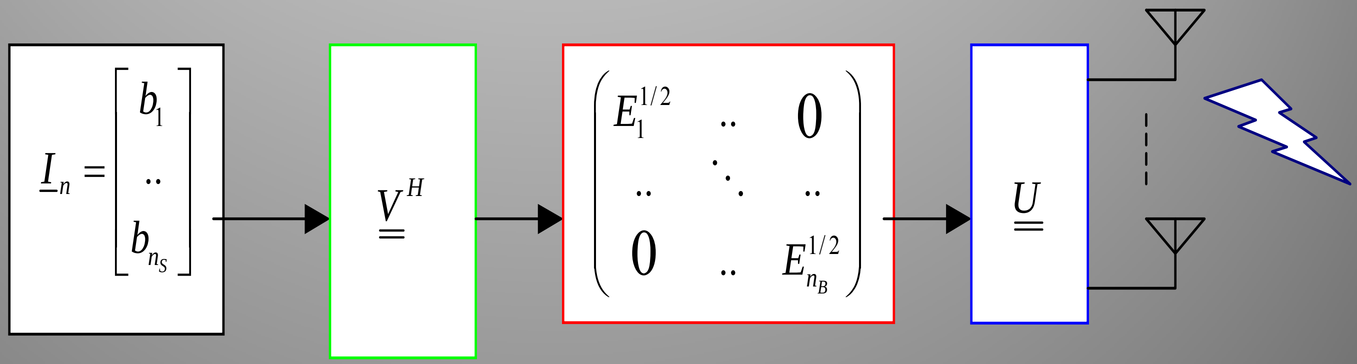
DFT transform

$$\underline{\underline{V}}^H = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & j & -1 & -j \\ 1 & -1 & 1 & -1 \\ 1 & -j & -1 & j \end{pmatrix}$$

Real entries

$$\underline{\underline{V}}^H = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{pmatrix}$$

Tx Architecture: Power allocation to every channel symbol (2/3)

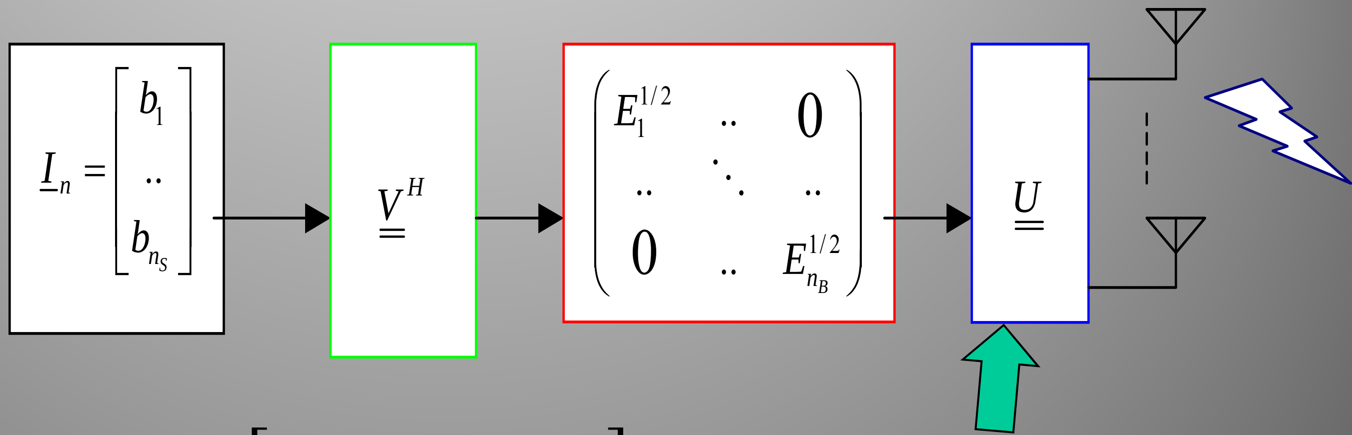


$$\underline{I}_n = \left[b(1) \quad b(2) \quad .. \quad b(n_S) \right] \quad con \quad b(i) = \{+1,-1\} \ \forall i = 1, n_S$$

Power allocation to each symbol (n_B symbols)

$$\underline{\theta}_n = diag\left[E_1^{1/2},..,E_{n_B}^{1/2} \right] \underline{\underline{V}}^H . \underline{I}_n = \underline{\underline{P}} . \underline{\underline{V}}^H . \underline{I}_n$$

Tx architecture: Beamforming 3/3



$$\underline{\underline{U}} = \left[\underline{b}_1 \quad .... \quad \underline{b}_L\right]$$

L beamformers for multiplexing transmitted energy across space

Beamforming

$$\underline{X}_{T,n} = \underline{\underline{U}}.\underline{\underline{P}}.\underline{\theta}_n = \underline{\underline{U}}.\underline{\underline{P}}.\underline{\underline{V}}^H.\underline{I}_n$$

$$\underline{\underline{B}}$$

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Tx Architecture: Power at Tx

$$\underline{\underline{Q}} = E\left(\underline{X}_{T,n} . \underline{X}_{T,n}^{H}\right) = \underline{\underline{U}}.\underline{\underline{P}}.\underline{\underline{V}}^{H} E\left(\underline{I}_{n} . \underline{I}_{n}^{T}\right) \underline{\underline{V}}.\underline{\underline{P}}.\underline{\underline{U}}^{H} = \underline{\underline{U}}.\underline{\underline{P}}.\underline{\underline{V}}^{H} . \underline{\underline{V}}.\underline{\underline{P}}.\underline{\underline{U}}^{H}$$

With $\underline{\underline{U}}^{H} . \underline{\underline{U}} = \underline{\underline{I}}_{ns}$ $\quad \underline{\underline{V}}^{H} . \underline{\underline{V}} = \underline{\underline{I}}_{ns}$

$$\underline{\underline{Q}} = \underline{\underline{U}}_{B} . \underline{\underline{P}}^{2} . \underline{\underline{U}}_{B}^{H} = \underline{\underline{U}}_{B} . \underline{\underline{Z}} . \underline{\underline{U}}_{B}^{H} \qquad E_{T} = Trace\left(\underline{\underline{Q}}\right) = Trace\left(\underline{\underline{Z}}\right)$$

Power budget or total energy available at Tx

Alternatives more practical and complex to manage

- Peak power per RF chain
- Radiated power (regulation)
- …..

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MIMO Scenarios depending on Coordination (Joint processing)

Tx	Rx	Description
YES	YES	MIMO PTP Point to Point
YES	NO	Broadcast MIMO
NO	YES	Access MIMO
NO	NO	Interference channel

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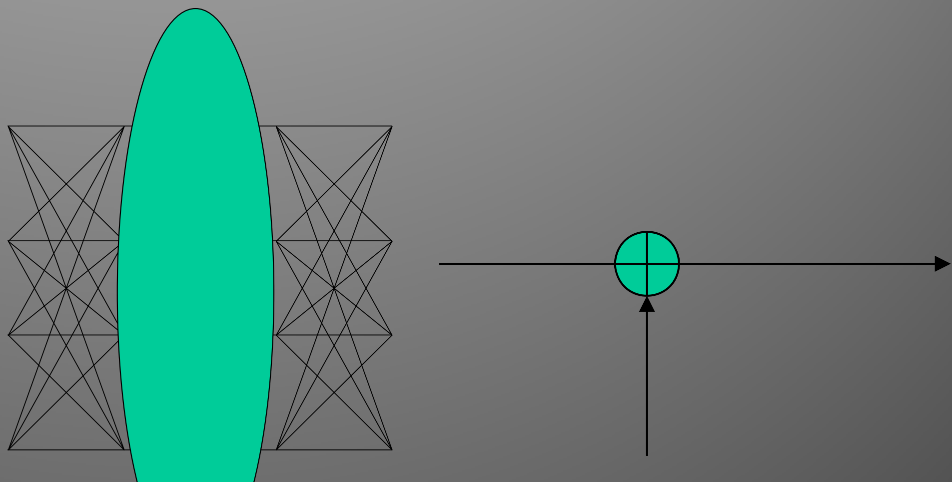
The channel architecture

$$\underline{\underline{H}} = \underline{\underline{V}}_h . \underline{\underline{\Gamma}}_h . \underline{\underline{U}}_h^H \quad con \quad \underline{\underline{\Gamma}} = diag\left[\gamma_{H1} \quad .. \quad \gamma_{H\min(n_T,n_R)}\right]$$

$$\underline{\underline{H}}^H . \underline{\underline{H}} = \sum_{q=1}^{n_R} \underline{h}_q . \underline{h}_q^H = \underline{\underline{U}}_h . \underline{\underline{\Sigma}}_h . \underline{\underline{U}}_h^H \quad con \quad \underline{\underline{\Sigma}}_h = \left[\lambda_{H1} \quad \lambda_{H2} \quad .. \quad \lambda_{H\min(n_T,n_R)}\right]$$



$$\underline{\underline{R}}_0 = N_0 . \underline{\underline{I}}_{n_R} + \underline{\underline{R}}_{oo}$$

CSI Channel State Information

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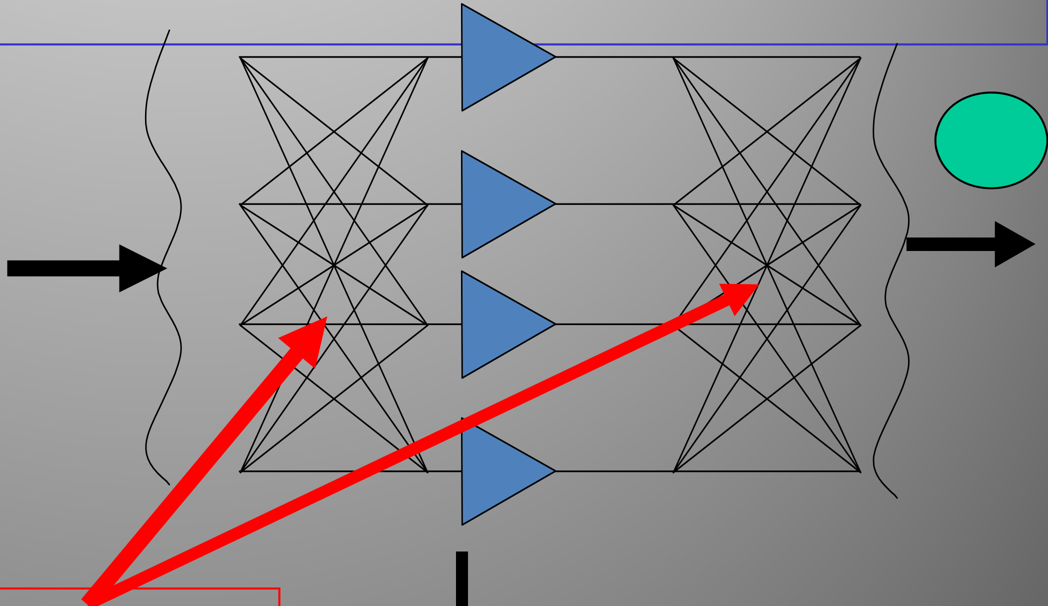
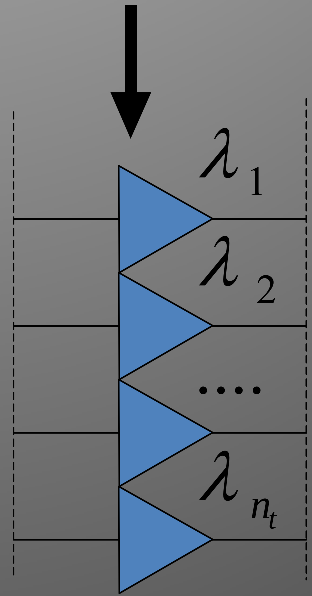
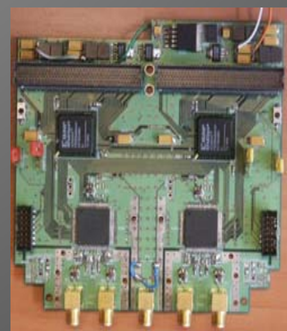


CSI: Channel State Information





Hard to afford perfect CSI, especially CSIT

MIMO Scenarios by CSI

Tx	Rx	Description
YES	YES	Full CSI (CSIT and CSIR)
NO	YES	Partial CSI (CSIR only)
NO	NO	No CSI

CSIR only requires space time codes

No CSI requires differential space time codes

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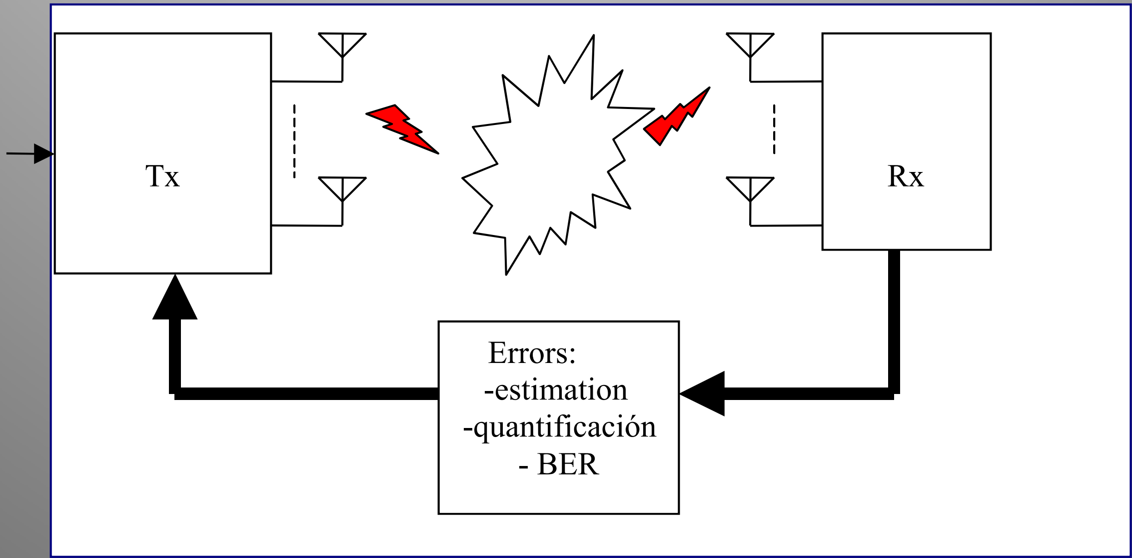
CSIT (Complexity)



- Capacity of the feedback channel

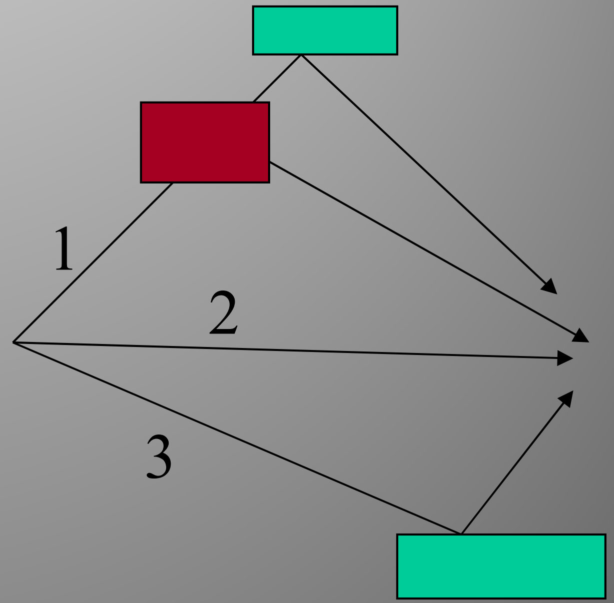
- Not accurate

-User Mobility, FDMA, TDMA

Remember: The LOS MIMO Channel

$$\underline{\underline{H}} = \left[\underline{S}_{T1}\ \underline{S}_{T2}\ \underline{S}_{T3}\right]$$

$$\underline{\underline{H}}^{H} = \left[\underline{S}_{R1}\ \underline{S}_{R2}\ \underline{S}_{R3}\right]$$



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Use the best channel (#2) or all the available paths?

Comment on the Eigenvectors and the steering vectors relationship

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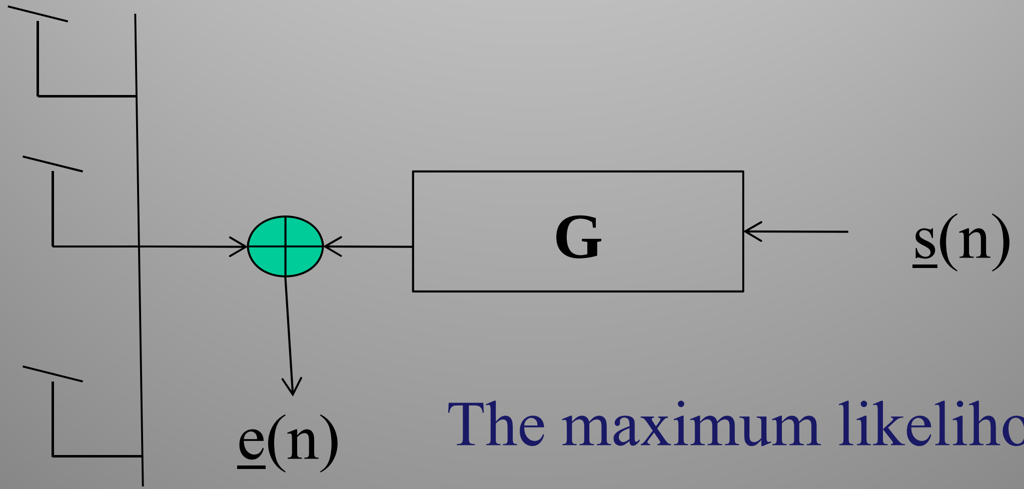
The Optimum Receiver



The maximum likelihood receiver:

$$\hat{\underline{s}}_n = \min_{\underline{s}_n \in Constellation} trace\left\{\left(\underline{X}_n - \underline{\underline{G}}.\underline{s}_n\right)\underline{\underline{R}}_0^{-1}\left(\underline{X}_n - \underline{\underline{G}}.\underline{s}_n\right)^H\right\}$$

-**G**=E($\underline{X}$n.$\underline{s}$(n)^H) is the so-called DIR of the receiver
- For white noise /$\underline{e}$(n)/^{2} minimum over $\underline{s}$(n) ЄTx Alphabet
- Scenario free of interference

COMPLEXITY/INTERFERENCE

Suboptimum Receiver: Interference as noise

When interference is present, the ML forces to detect also the interference.

$$\hat{\underline{s}}_n = \min_{\underline{s}_n \in Constellation} trace\left\{ \left(\underline{X}_n - \underline{\underline{G}}.\underline{s}_n - \underline{\underline{F}}\,\underline{j}_n \right) \left(\underline{X}_n - \underline{\underline{G}}.\underline{s}_n - \underline{\underline{F}}\,\underline{j}_n \right)^H \right\}$$

The advantage is that the front-end noise is white, but imposes to detect the interference and its channel to the receiver.

The suboptimum approach is to include the interference (not Gaussian in general in the noise matrix)

$$\hat{\underline{s}}_n = \min_{\underline{s}_n \in Constellation} trace\left\{ \left(\underline{X}_n - \underline{\underline{G}}.\underline{s}_n \right) \underline{\underline{R}}_0^{-1} \left(\underline{X}_n - \underline{\underline{G}}.\underline{s}_n \right)^H \right\}$$

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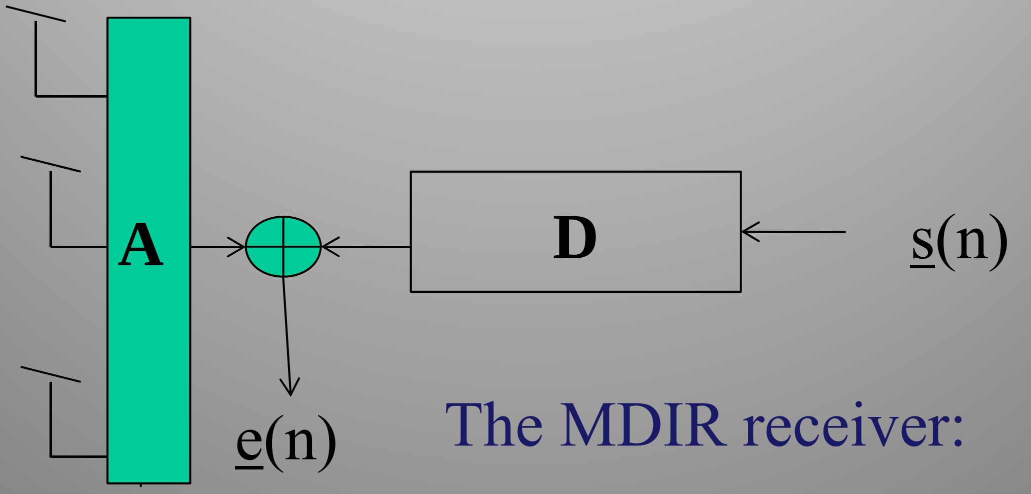
Suboptimum receiver: Include beamforming to remove interference, the MDIR receiver

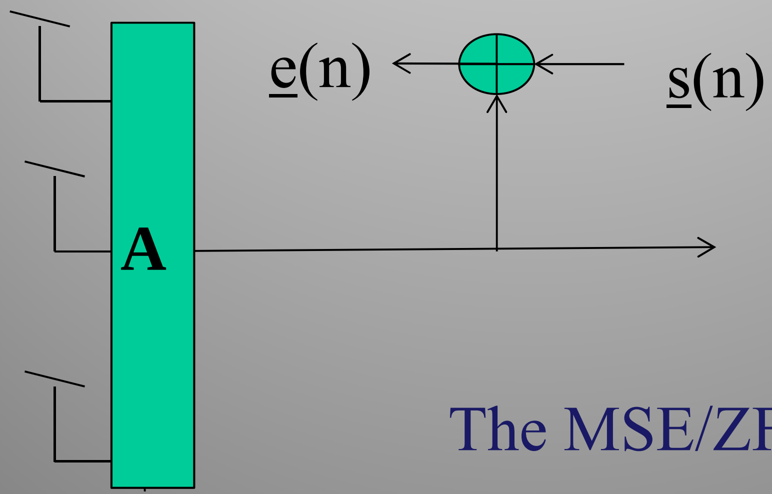


The MDIR receiver:

$$\hat{\underline{s}}_n = \min_{\underline{s}_n \in Constellation} trace\left\{\left(\underline{\underline{A}}^H \underline{X}_n - \underline{\underline{D}}.\underline{s}_n\right)\left(\underline{\underline{A}}^H \underline{X}_n - \underline{\underline{D}}.\underline{s}_n\right)^H\right\}$$

- Forward and backward processing architecture
- Noise matrix depends on the forward (beamforming stage
- Not instantaneous detection of the stream's vector.

Suboptimum receiver: Instantaneous detection. MSE/ZF receivers



The MSE/ZF: $\underline{\hat{s}}_n = \underline{\underline{A}}^H \underline{X}_n$

- Multichannel processing for multiple streams
- Not easy to define a function of the vector error
- Single symbol much more easier that the multiple symbols problem

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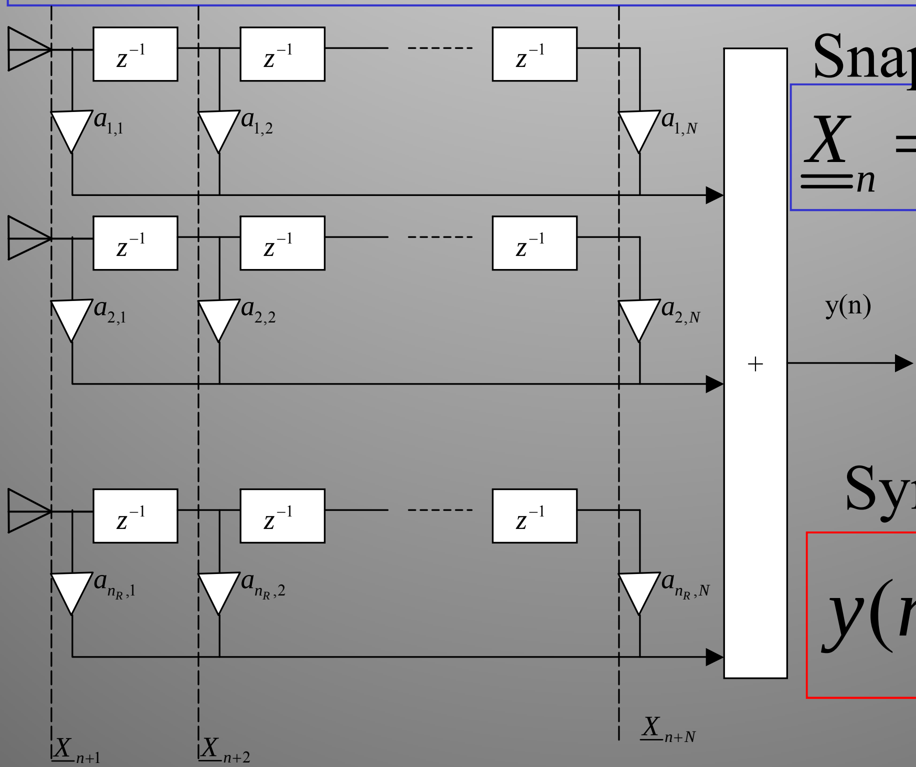
Single symbol beamforming processing



Snapshot

$$\underline{\underline{X}}_n = \left[\underline{X}_{n+1} \quad \underline{X}_{n+2} \quad \cdots \quad \underline{X}_{n+N} \right]$$

Symbol output

$$y(n) = traza\left(\underline{\underline{A}}^H . \underline{\underline{X}}_n \right)$$

$$\underline{\underline{A}} = \left[\underline{a}_1 \quad \underline{a}_2 \quad \cdots \quad \underline{a}_N \right] = \begin{bmatrix} a_{1,1} & a_{1,2} & .. & a_{1,N} \\ a_{2,1} & a_{2,2} & .. & a_{2,N} \\ .. & .. & .. & .. \\ a_{n_R,1} & a_{n_R,2} & .. & a_{n_R,N} \end{bmatrix}$$

Receiver Matrix

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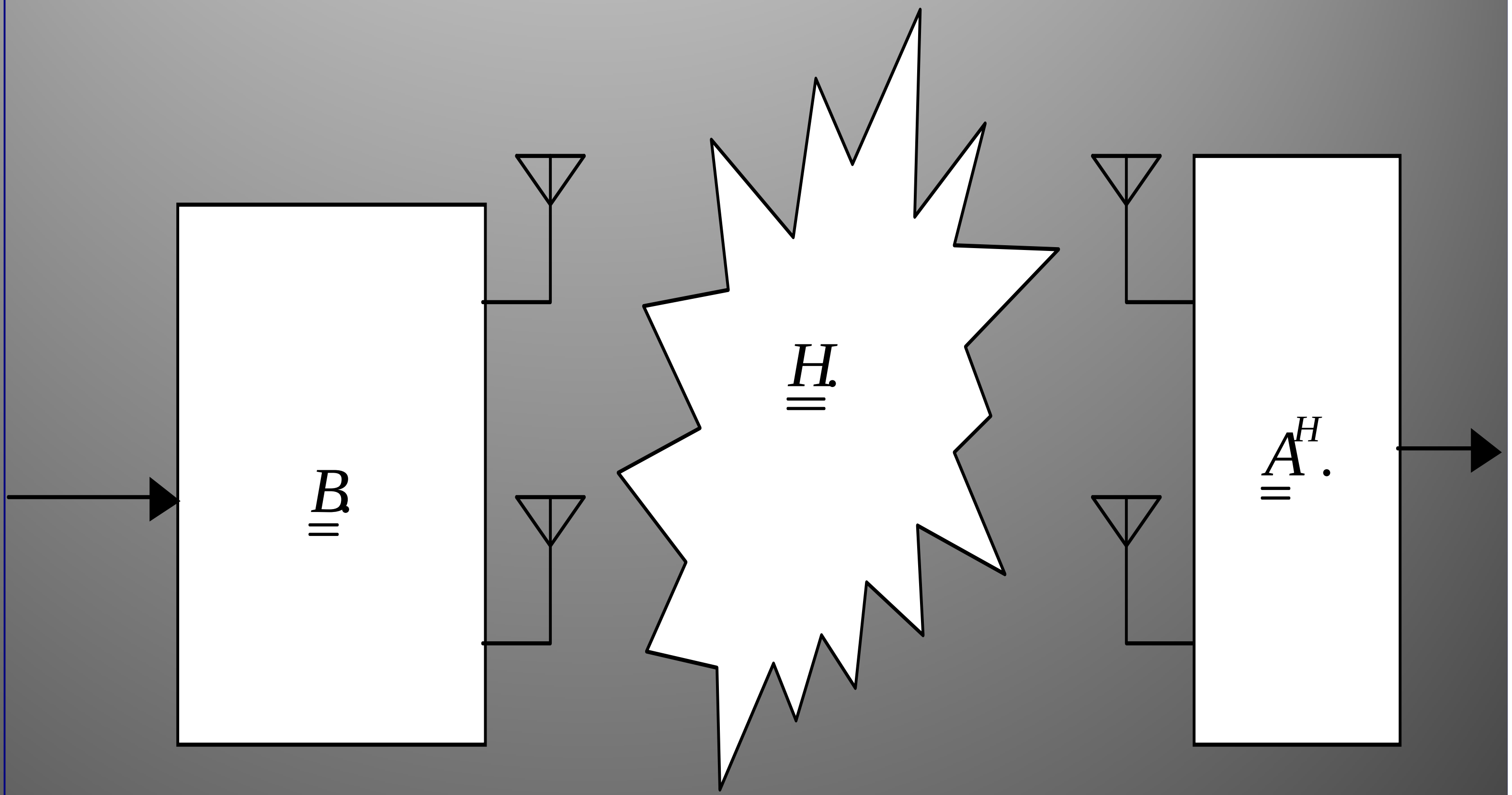
SUMMARY



Flat Fading, CSIT and CSIR, Single Symbol

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innovating communications

The Centre Tecnològic de Telecomunicacions de Catalunya

A gateway to advanced communication technologies

AENOR ER Gestión I+D+i UNE 166002

Centre Tecnològic de Telecomunicacions de Catalunya

Parc Mediterrani de la Tecnologia (PMT)

Av. Canal Olímpic S/N 08860 – Castelldefels Barcelona (Spain)

Voice: +34 93 645 29 00 :: Fax: +34 93 645 29 01

E-mail: info@cttc.es :: Web: http://www.cttc.es