The Centre Tecnològic de Telecomunicacions de Catalunya

A gateway to advanced communication technologies

MIMO-MAC and MIMO-BC

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Full Collaborative

Sum-rate

$$r1 + r2 = 2\log\left[\frac{E_T}{2}.\Delta^{0.5} + \frac{tr(R_H)}{2.\Delta^{0.5}}\right]$$

where

$$\Delta \rightarrow \text{determinant} = \left|\underline{h}_1\right|^2.\left|\underline{h}_2^2\right| - \left|h_{12}\right|^2$$

$$R_H = \begin{pmatrix} \left|\underline{h}_1\right|^2 & h_{12} \\ h_{12}^{*} & \left|\underline{h}_2^2\right| \end{pmatrix}$$

$$\lambda_{HAR} \rightarrow \text{harmonic mean} = \frac{2.\Delta}{tr(R_H)}$$

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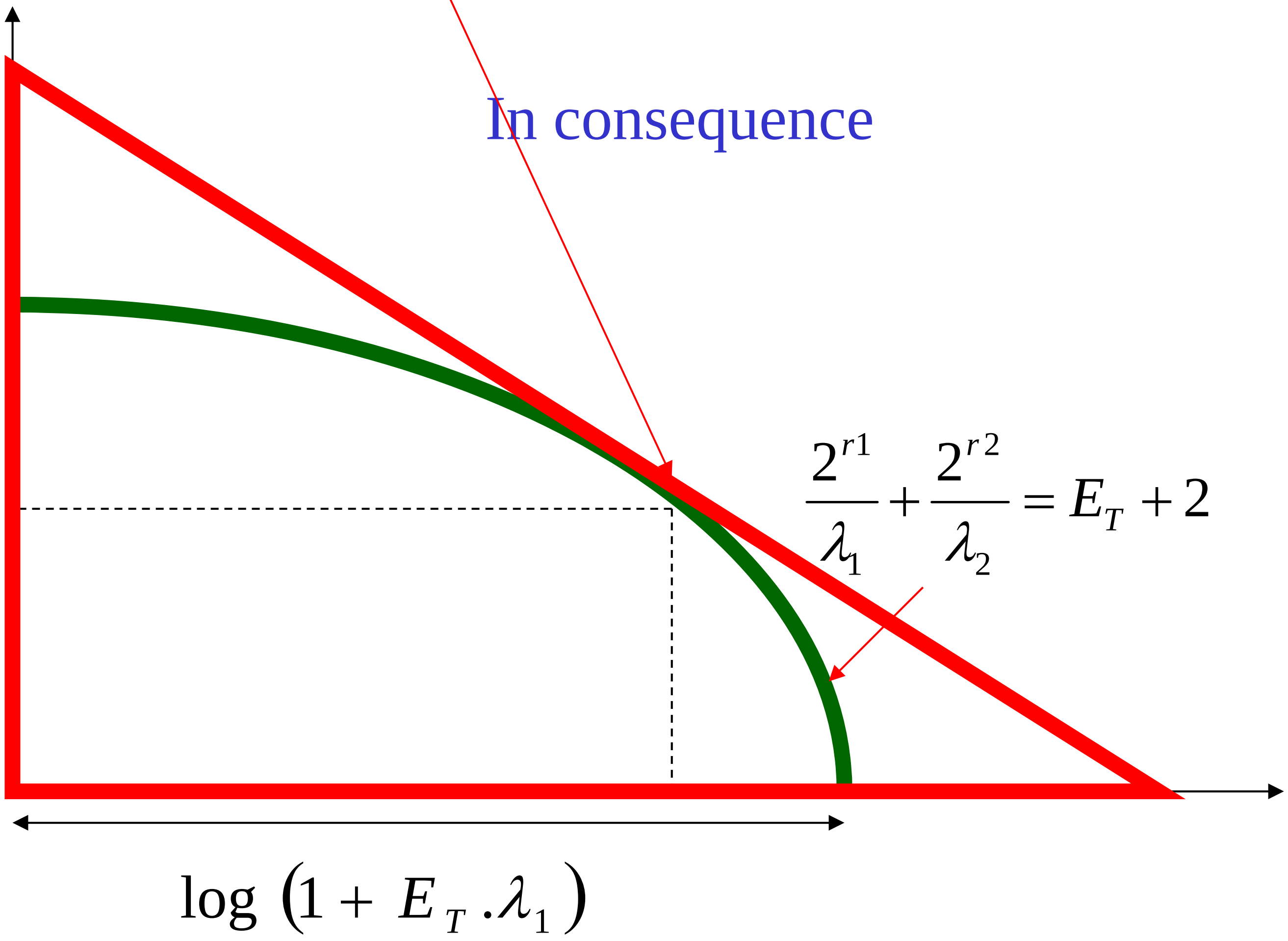
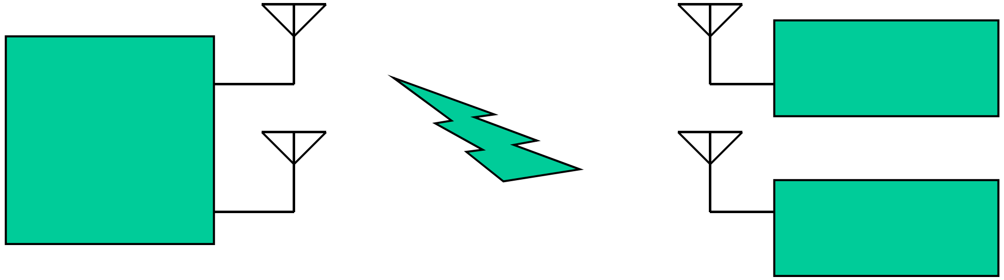
$$r1 = \log(1 + z1.\lambda 1) = \log(\mu.\lambda 1)$$

$$r2 = \log(1 + z2.\lambda 2) = \log(\mu.\lambda 2)$$

$$\mu = \frac{E_T}{2} + \frac{1}{\lambda_{HARM}}$$



MIMO_MAC



The Tx cannot diagonalice the channel

The capacity bounds are set independently for every transmitter

$$r1 = \log\left(1 + \left|\underline{h}_1\right|^2 E_1\right)$$

$$r2 = \log\left(1 + \left|\underline{h}_2\right|^2 E_2\right)$$

As MIMO it is a bound on the sum-rate

$$r1 + r2 = \log\left[\det\left(\underline{\underline{I}} + \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix} \begin{pmatrix} \left|\underline{h}_1\right|^2 & h_{12} \\ h_{21} & \left|\underline{h}_2\right|^2 \end{pmatrix}\right)\right] =$$

$$= \log\left[1 + \left|\underline{h}_1\right|^2 .E_1 + \left|\underline{h}_2\right|^2 .E_1 + E_1.E_2.\Delta\right]$$

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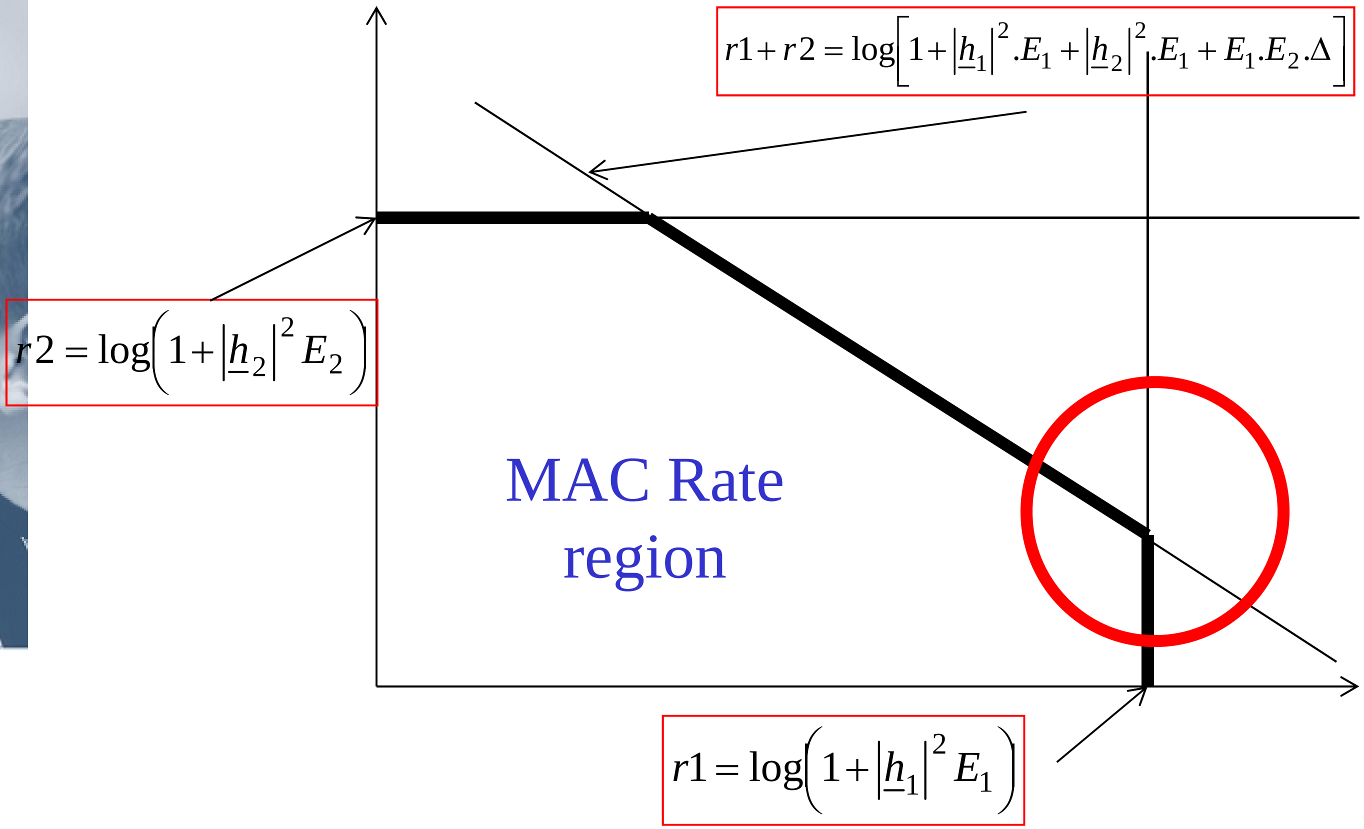

Decoding one user without interference implies that (solve for the cross point of the two lines):

$$r1B=\log(1+|\underline{h}_1|^2.E_1)$$

$$r2B=\log(1+\frac{|\underline{h}_2|^2.E_2}{1+|\underline{h}_1|^2.E_1}+\frac{E_1.E_2.\Delta}{1+|\underline{h}_1|^2.E_1})$$

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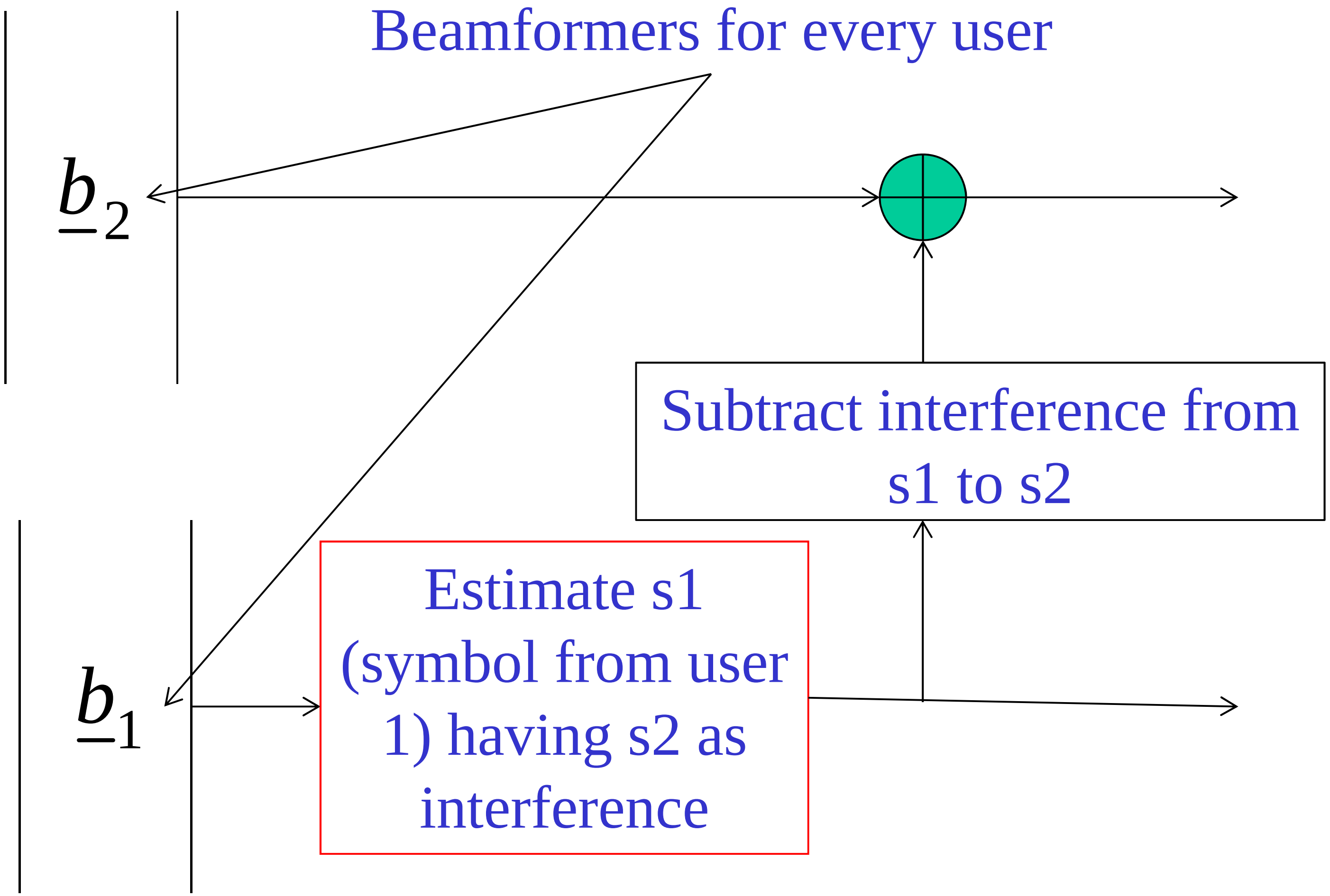
Guideline: Estimate the strongest symbol and subtract interference.



Zero-Forcing Beamformer

$$\underline{\underline{B}} = \left(\left[\underline{\underline{I}} - \frac{\underline{h}_2 \underline{h}_2^H}{\left|\underline{h}_2\right|^2} \right] \frac{\underline{h}_1}{(1-\phi)^{1/2} \cdot \left|\underline{h}_1\right|} \quad \left[\underline{\underline{I}} - \frac{\underline{h}_1 \underline{h}_1^H}{\left|\underline{h}_1\right|^2} \right] \frac{\underline{h}_2}{(1-\phi)^{1/2} \cdot \left|\underline{h}_2\right|} \right)$$

$$\underline{\underline{B}}^H \left[\underline{h}_1 \quad \underline{h}_2 \right] = \begin{pmatrix} (1-\phi)^{1/2} \left|\underline{h}_1\right| & 0 \\ 0 & (1-\phi)^{1/2} \left|\underline{h}_2\right| \end{pmatrix}$$

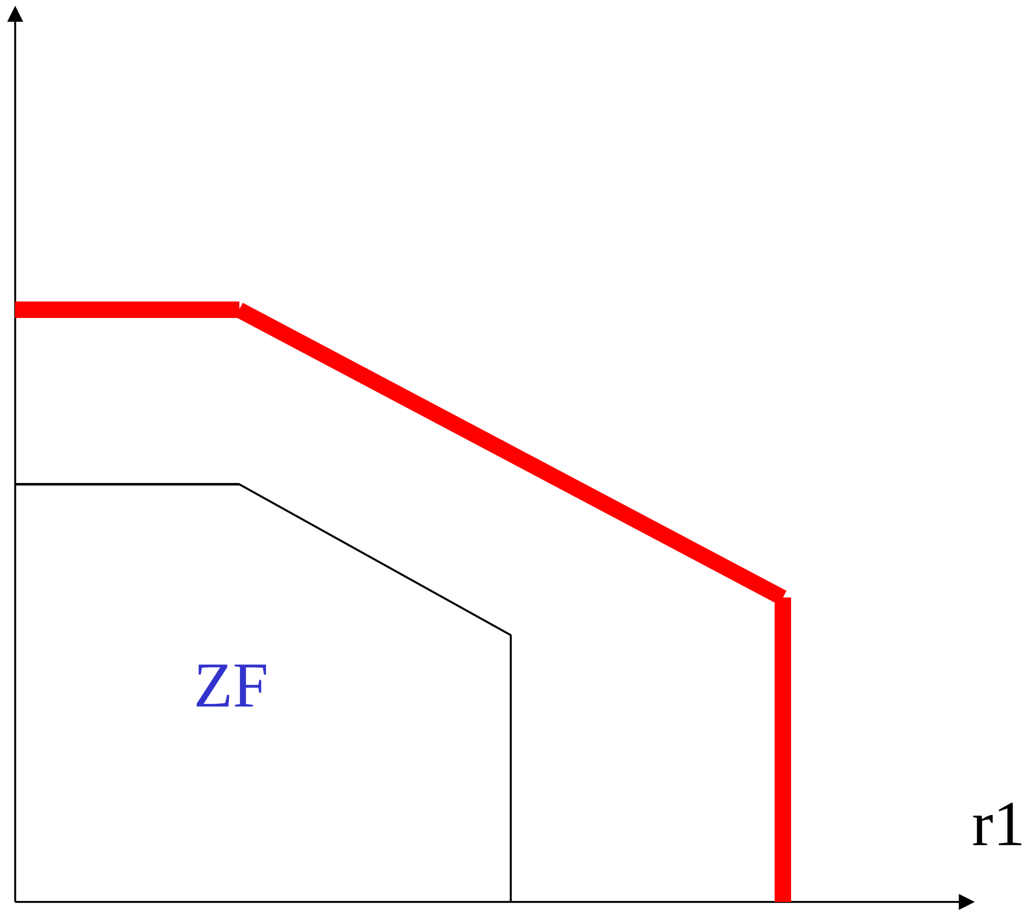
where $\phi = \frac{\left|h_{12}\right|^2}{\left|h_1\right|^2 \left|h_2\right|^2}$

In consequence, both sum-rate and single rates experience losses

$$r1 = \log\left[1 + (1-\phi)\left|\underline{h}_1\right|^2 E_1 \right]$$

$$r2 = \log\left[1 + (1-\phi)\left|\underline{h}_2\right|^2 E_2 \right]$$

ZF Region in the MAC Region



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QR Decomposition and SIC

$$\underline{\underline{B}} = \left(\frac{\underline{h}_1}{\left|\underline{h}_1\right|} \quad \left[\underline{\underline{I}} - \frac{\underline{h}_1 \underline{h}_1^H}{\left|\underline{h}_1\right|^2} \right] \frac{\underline{h}_2}{(1-\phi)^{1/2} . \left|\underline{h}_2\right|} \right)$$

$$\underline{\underline{B}}^H \left[\underline{h}_1 \quad \underline{h}_2 \right] = \begin{pmatrix} \left|\underline{h}_1\right| & h_{12} \\ 0 & (1-\phi)^{1/2} \left|\underline{h}_2\right| \end{pmatrix}$$

We get s2 free of interference

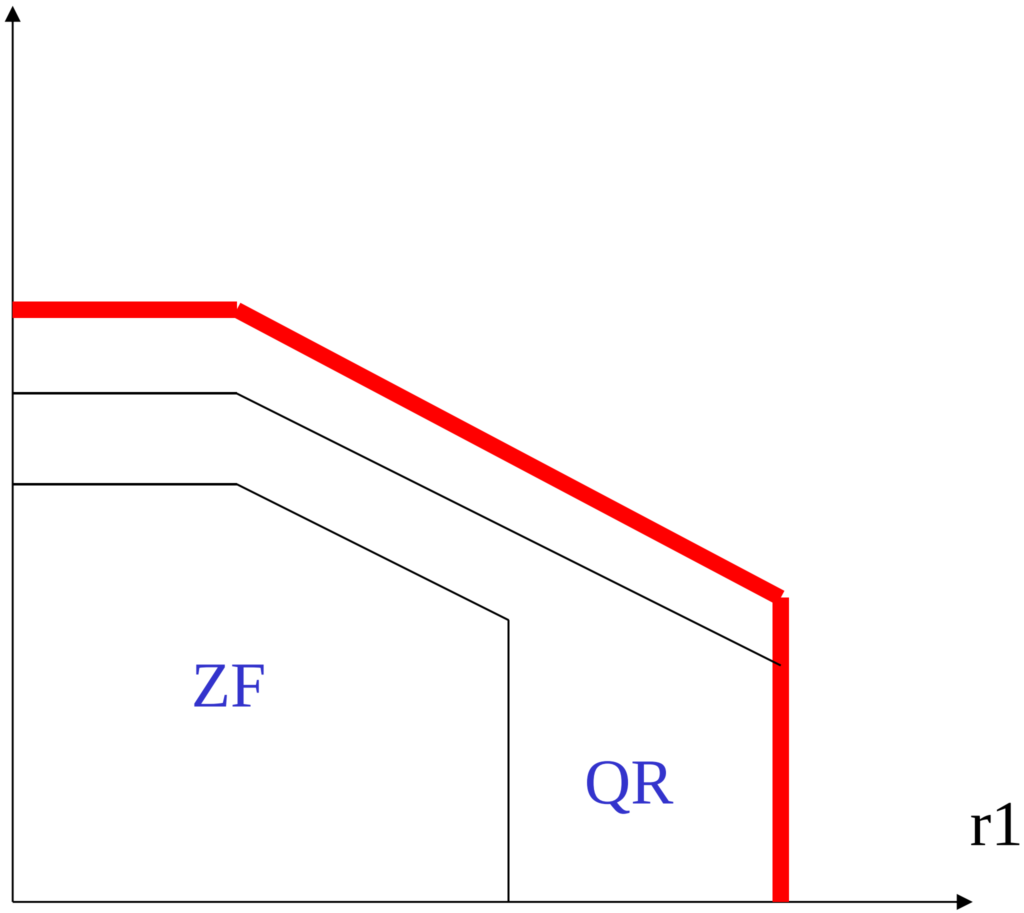
Thus, we can detect s2 and then subtract the interference to s1

Does not achieves the sum rate but r1 is detected at full-rate

$$r1 = \log\left[1 + \left|\underline{h}_1\right|^2 E_1 \right]$$

$$r2 = \log\left[1 + (1-\phi)\left|\underline{h}_2\right|^2 E_2 \right]$$

QR Region in the MAC Region



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SIC: A DSP Formulation

From the likelihood, we can define the following error

$$\underline{\underline{R}}_0^{-0.5}\left(\underline{X}_{Rn} - \underline{\underline{H}}\,\underline{\underline{P}}^{0.5}\underline{s}_n\right) \Rightarrow \left|\underline{\varepsilon}_n\right|^2 = \left|\underline{\underline{R}}_0^{-0.5}\underline{X}_{Rn} - \underline{\underline{R}}_0^{-0.5}\underline{\underline{H}}\,\underline{\underline{P}}^{0.5}\underline{s}_n\right|^2$$

Now, suing the QR decomposition for the global channel

$$\underline{\underline{R}}_0^{-0.5}\underline{\underline{H}} = \underline{\underline{Q}}\,\underline{\underline{R}}$$

Then, using a beamforming matrix B, at the receiver equal to Q, we have:

$$\underline{\underline{B}} = \underline{\underline{Q}}\left(diag(diag(\underline{\underline{R}}))\right)^{-1} \qquad \underline{\varepsilon}_n = \underline{Y}_n - \underline{\underline{R}}_a\underline{s}_n \quad where \quad \underline{Y}_n = \underline{\underline{B}}^H\underline{X}_{Rn}$$

Now…..

$$with \quad \underline{\underline{R}}^H = diag\left(diag\left(\underline{\underline{R}}^H\right)\right)\underline{\underline{R}}_a$$

$$\text{being } \; \text{diag}\left(\text{diag}\left(\underline{\underline{\text{R}}}_{\text{a}}\right)\right) \text{ is the identity matrix}$$

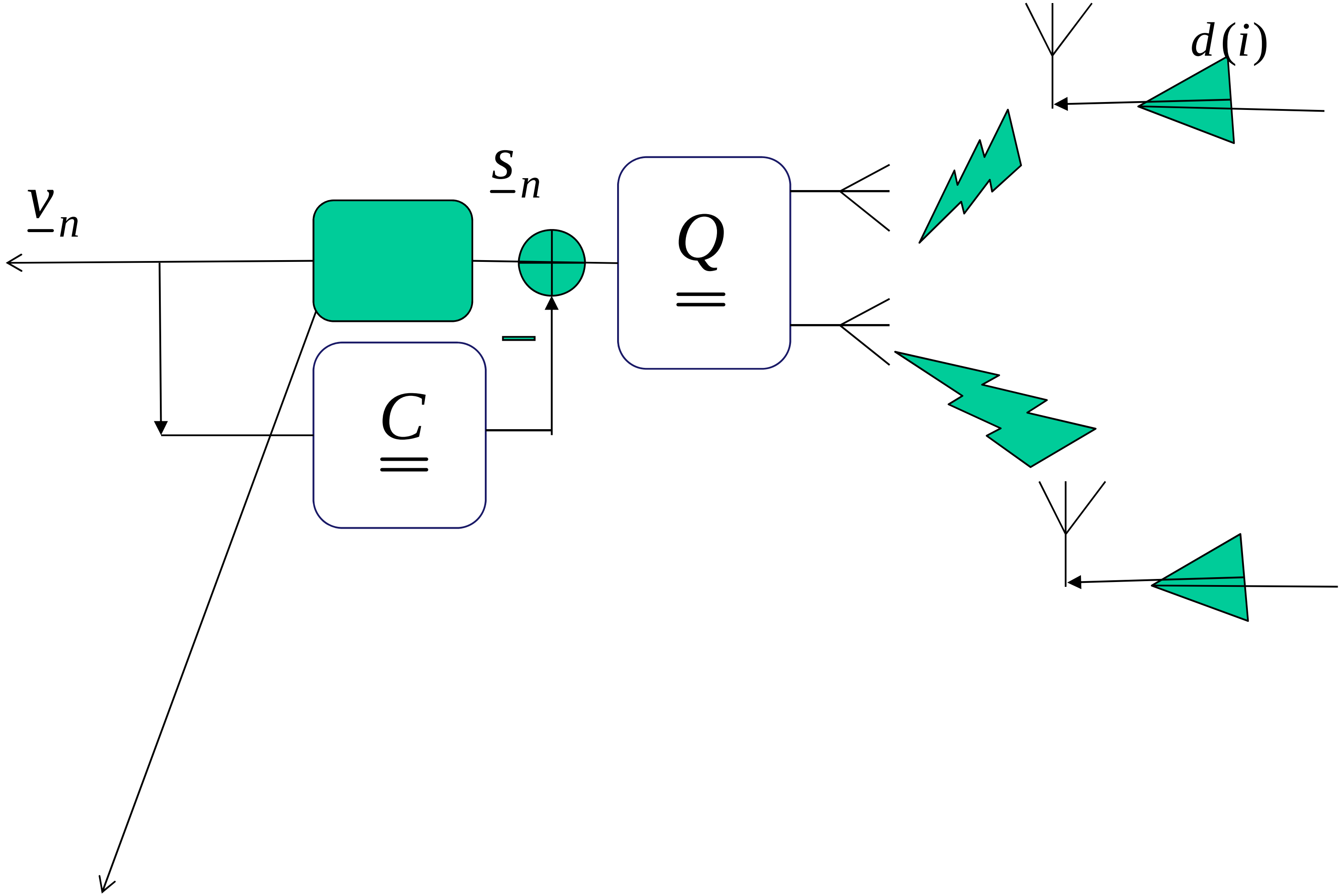
We have

$$\underline{\underline{R}}_a \underline{s}_n = \left(\underline{\underline{I}} + \underline{\underline{C}}\right)\underline{s}_n$$

$$\underline{\varepsilon}_n + \underline{s}_n = \underline{Y}_n - \underline{\underline{C}}\,\underline{s}_n$$

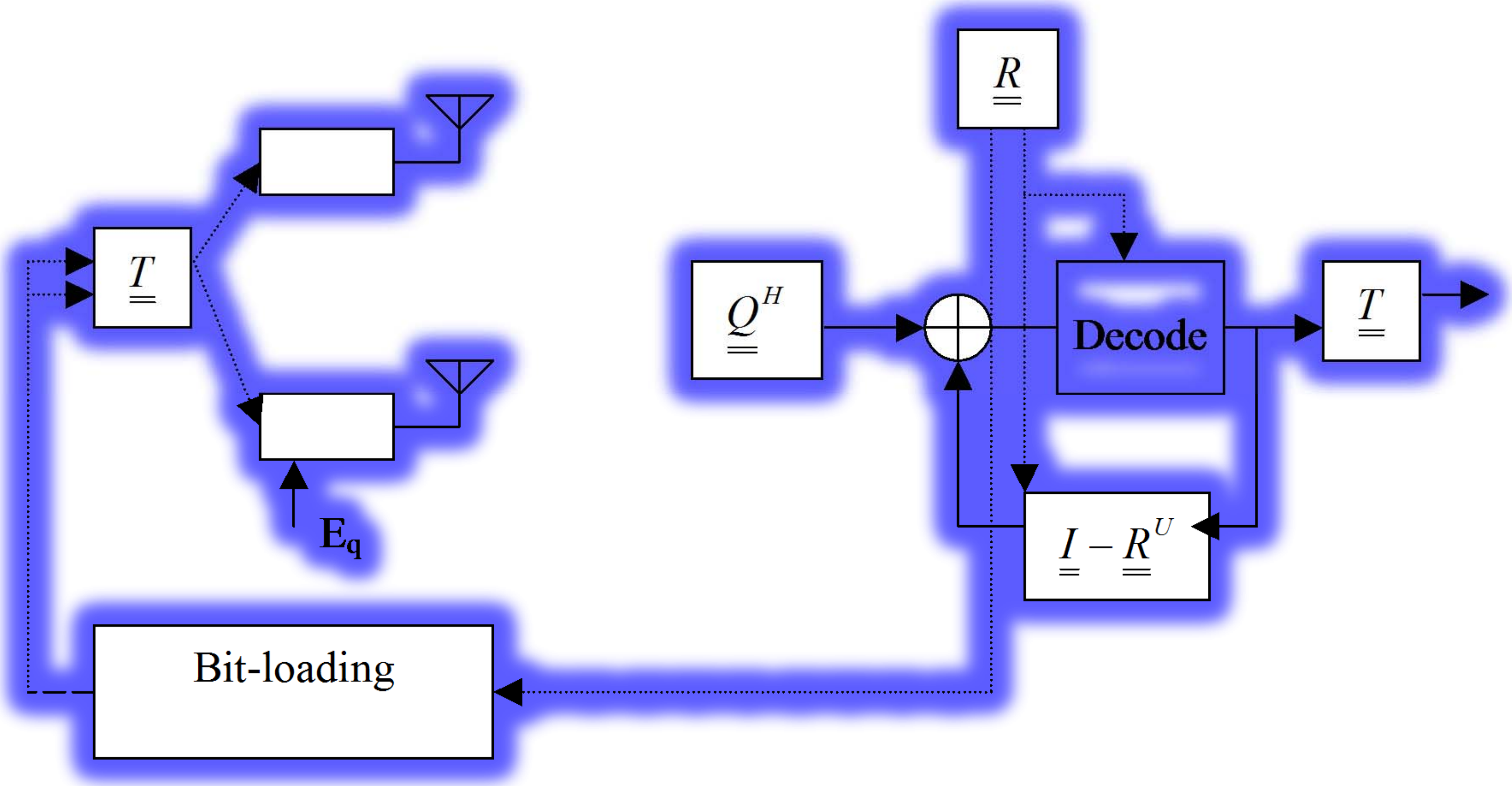
Get an estimate by thresholding in accordance to the given constellation

!!! C is strictly lower triangular¡¡¡



Multi-stream
constellation
thresholding

The labeling problem:



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MSE Beamforming and SIC

$$\underline{\underline{B}} = \left(\frac{\underline{h}_1}{\left|\underline{h}_1\right|} \quad \left[\underline{\underline{I}} - \frac{\underline{h}_1 \underline{h}_1^H E_1}{1 + \left|\underline{h}_1\right|^2 E_1} \right] \frac{\underline{h}_2}{\alpha} \right)$$

where

$$\alpha^2 = \frac{\Delta E_1 + \left|\underline{h}_2\right|^2}{1 + \left|\underline{h}_1\right|^2 E_1} \quad and \quad \Delta = \left|\underline{h}_1\right|^2 \left|\underline{h}_2\right|^2 - \left|h_{12}\right|^2$$

$$\underline{\underline{B}}^H \left[\underline{h}_1 \quad \underline{h}_2 \right] = \begin{pmatrix} \left|\underline{h}_1\right| & h_{12} / \left|\underline{h}_1\right| \\ \dfrac{h_{12}}{\sqrt{\left(1 + h_1^2 E_1\right)\left(\Delta E_1 + h_2^2\right)}} & \sqrt{\dfrac{\Delta E_1 + h_2^2}{1 + h_1^2 E_1}} \end{pmatrix}$$

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Decoding user 1 without interference of user 2 implies to decode first user 2 and then subtract the interference to user 1. Since user 2 have to be decoded with interference we will use a MSE receiver to remove interference from user 1 as much as possible.

$$MSE \quad E_2.\underline{h}_2^H.\left(\underline{\underline{I}}-\frac{\underline{h}_1.\underline{h}_1^H.E_1}{1+\left|\underline{h}_1\right|^2.E_1}\right).\underline{h}_2$$

$$r2\_MSE=\log\left(1+\frac{\left|\underline{h}_2\right|^2.E_2+E_1E_2.\Delta}{1+\left|\underline{h}_1\right|^2 E_1}\right)$$

This rate corresponds to the capacity achieving rate of the previous slide

r2_MSE=r2B

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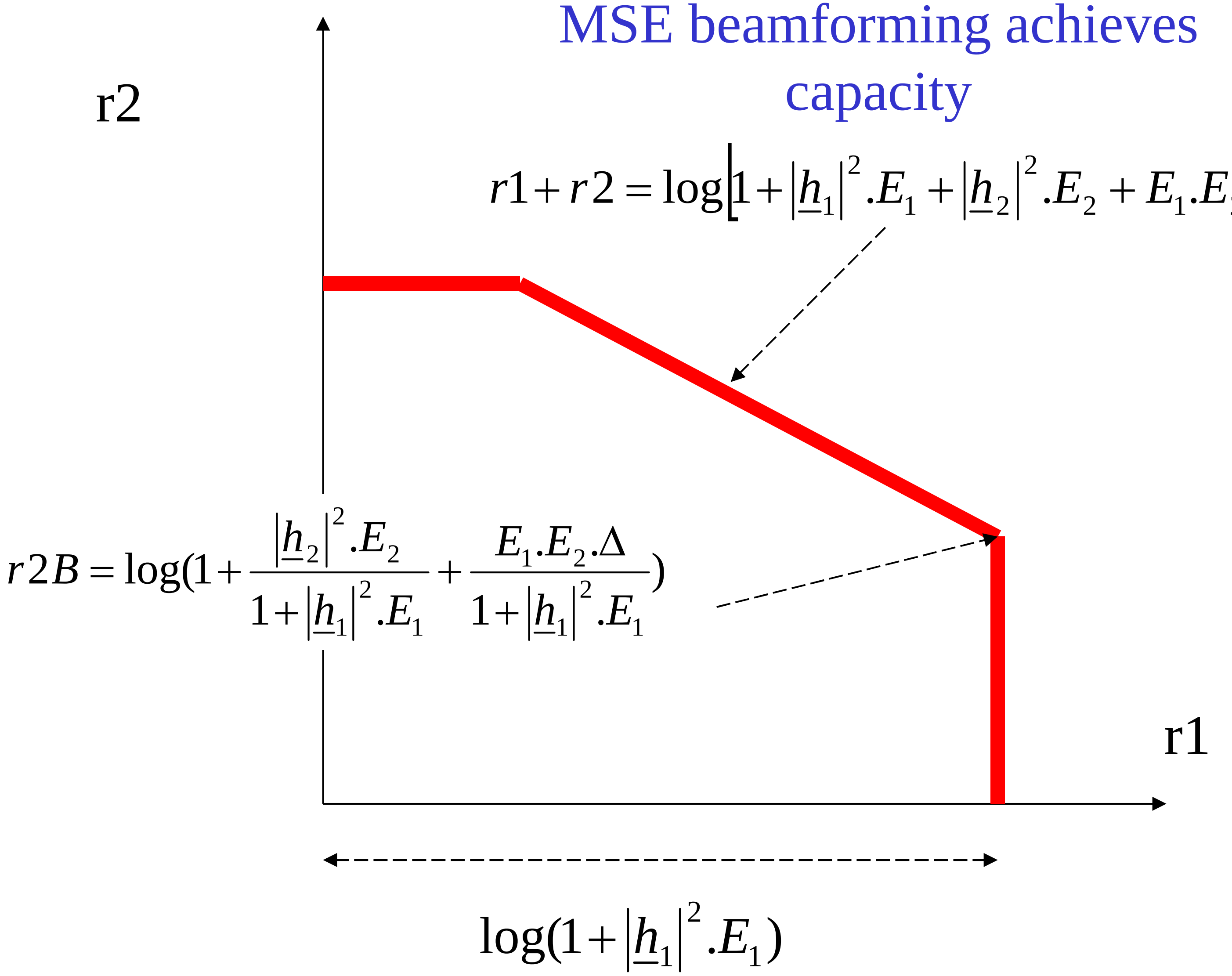
MSE beamforming achieves capacity



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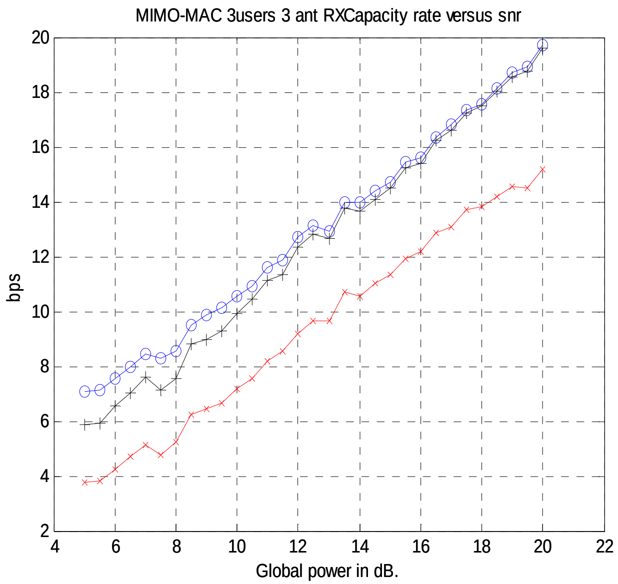
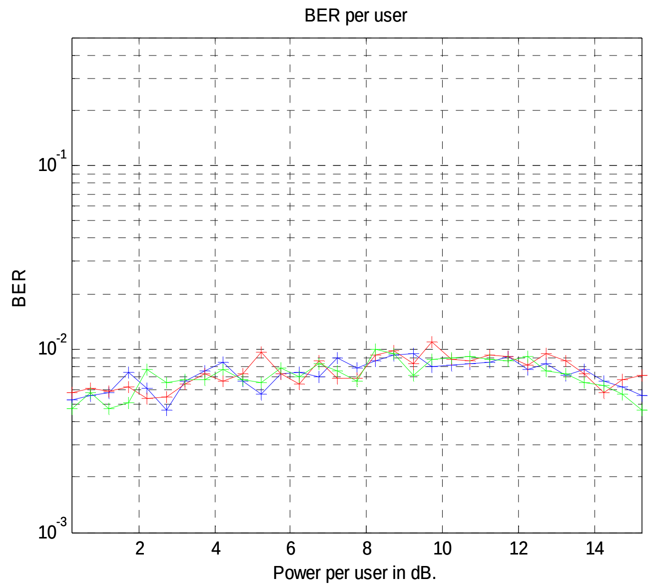
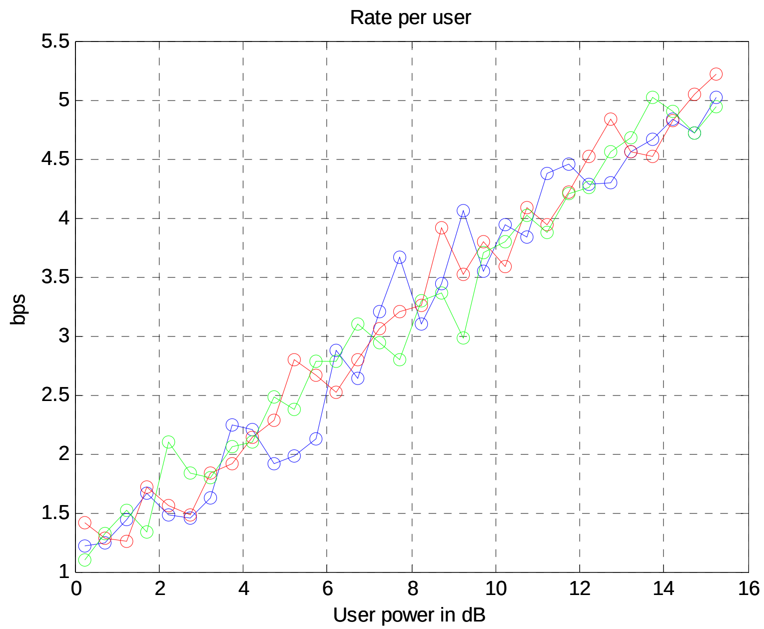




BER=10^{-2}



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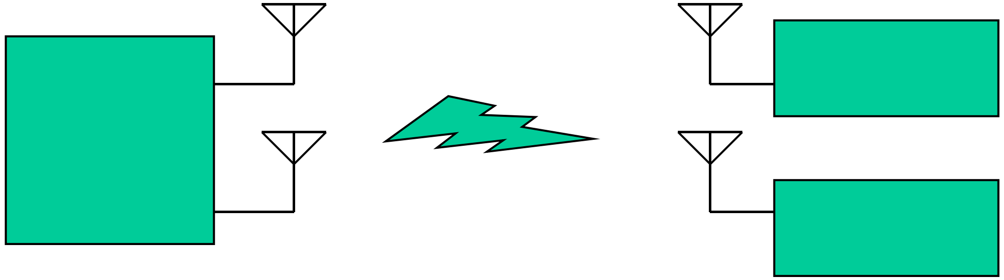
MIMO Broadcast (MIMO-BC)



The Rx cannot diagonalice the channel

$$r1 = \log\left(1 + |\underline{h}_1|^2 E_1\right) \Rightarrow \frac{2^{r1} - 1}{|\underline{h}_1|^2} = E_1$$

$$r2 = \log\left(1 + |\underline{h}_2|^2 E_2\right) \Rightarrow \frac{2^{r2} - 1}{|\underline{h}_2|^2} = E_2$$

The capacity region is set when forzing a global power for the Tx.

$$E_T = \frac{2^{r1} - 1}{|\underline{h}_1|^2} + \frac{2^{r2} - 1}{|\underline{h}_2|^2}$$

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BC Channel Capacity

Maximize sum-rate with the constrain of maximum Tx power

From the PTP formula

$$r1 + r2 = \log\left(1 + \left|\underline{h}_1\right|^2 E_1 + \left|\underline{h}_2\right|^2 E_2 + \Delta E_1 E_2\right)$$

$$s.t. \quad E_T = E_1 + E_2$$

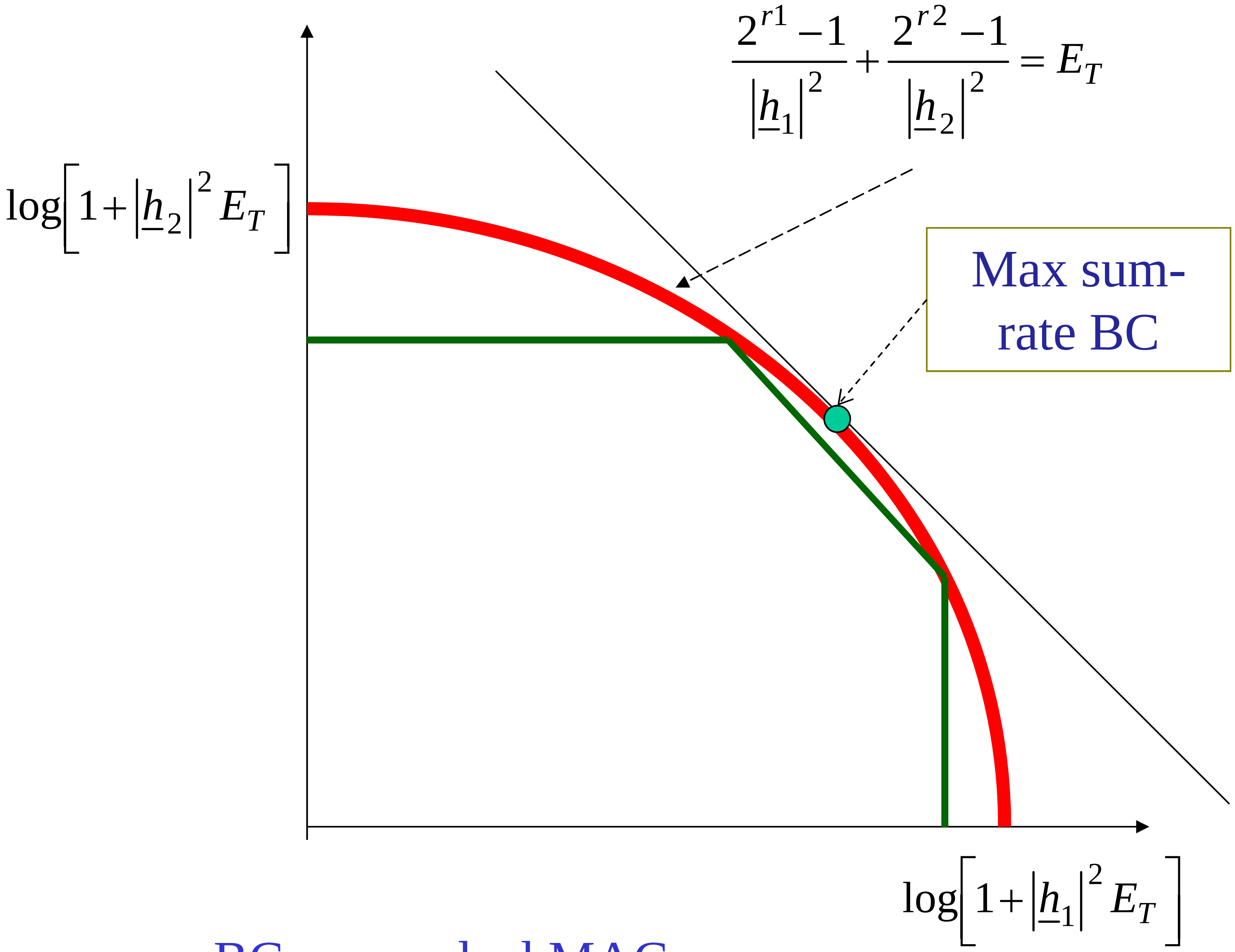
The optimum power allocation is…..

$$E_1 = \frac{E_T}{2} + \frac{\left|\underline{h}_1\right|^2 - \left|\underline{h}_2\right|^2}{2\Delta}$$

$$E_2 = \frac{E_T}{2} - \frac{\left|\underline{h}_1\right|^2 - \left|\underline{h}_2\right|^2}{2\Delta}$$

And the sum-rate maximized is

$$r1 + r2\Big|_{\max} = 2\log 2\left(\Delta^{0.5}\frac{E_T}{2} + \frac{\left|\underline{h}_1\right|^2 + \left|\underline{h}_2\right|^2}{2\Delta^{0.5}}\right) - \frac{\left|\underline{h}_{12}\right|^2}{\Delta}$$



BC versus dual MAC

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ZF Beamforming for MIMO_BC

Tx diagonalices the channel but it has to use ZF since no cooperation is available at thereceivers.

$$\underline{\underline{B}} = \left(\left[\underline{\underline{I}} - \frac{\underline{h}_2 \underline{h}_2^H}{\left|\underline{h}_2\right|^2} \right] \frac{\underline{h}_1}{(1-\phi)^{1/2} . \left|\underline{h}_1\right|} \quad \left[\underline{\underline{I}} - \frac{\underline{h}_1 \underline{h}_1^H}{\left|\underline{h}_1\right|^2} \right] \frac{\underline{h}_2}{(1-\phi)^{1/2} . \left|\underline{h}_2\right|} \right)$$

The rate achieved by every user is:

$$r1 = \log\left[1 + (1-\phi)\left|\underline{h}_1\right|^2 E_1 \right]$$

$$r2 = \log\left[1 + (1-\phi)\left|\underline{h}_2\right|^2 E_2 \right]$$

$$\frac{2^{r1}-1}{\left|\underline{h}_1\right|^2} + \frac{2^{r2}-1}{\left|\underline{h}_2\right|^2} = (1-\phi)E_T$$

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And the ZF max. sum-rate is:

$$r1 + r2 = \log\left[1 + \left(\frac{|h_{12}|^2}{|\underline{h}_1|^2 |\underline{h}_2|^2}\right)\left(|\underline{h}_1|^2 E_1 + |\underline{h}_2|^2 E_2 + \Delta E_1 E_2\right)\right]$$

Loss due to the use of Zero-Forcing Beamforming

Using lower triangular zero forcing

$$\underline{\underline{B}} = \left(\underline{h}_1 \quad \left[\underline{\underline{I}} - \frac{\underline{h}_1 \underline{h}_1^H}{\left|\underline{h}_1\right|^2} \right] \frac{\underline{h}_2}{(1-\phi)^{1/2} . \left|\underline{h}_2\right|} \right)$$

Detect stream1 precancel interference of stream 1 on stream 2

$$r1 = \log\left[1 + \left|\underline{h}_1\right|^2 E_1\right]$$

$$r2 = \log\left[1 + (1-\phi)\left|\underline{h}_2\right|^2 E_2\right]$$

Later on it will be explained how the interference term is removed

$$\frac{2^{r1}}{\left|\underline{h}_1\right|^2} + \frac{2^{r2}}{(1-\phi)\left|\underline{h}_2\right|^2} = E_T + \left(\frac{1}{\left|\underline{h}_1\right|^2} + \frac{1}{(1-\phi).\left|\underline{h}_2\right|^2} \right)$$

The sum-rate is:

$$r1 + r2 = \log\left[1 + \left|\underline{h}_1\right|^2 E_1 + (1-\phi)\left|\underline{h}_2\right|^2 E_2 + \Delta E_1 E_2\right]$$

Loss due for the "semi-ZF" or QR beamforming and "writing in a dirty space"

DPC A Signal Processing Formulation

From the likelihood, we can define the following error

$$\underline{\underline{R}}_0^{-0.5}\left(\underline{X}_{Rn}-\underline{\underline{H}}\,\underline{\underline{B}}\,\underline{s}_n\right)\Rightarrow\left|\underline{\varepsilon}_n\right|^2=\left|\underline{\underline{R}}_0^{-0.5}\underline{X}_{Rn}-\underline{\underline{R}}_0^{-0.5}\underline{\underline{H}}\,\underline{\underline{B}}\,\underline{s}_n\right|^2$$

Now, suing the QR decomposition for the global channel

$$\underline{\underline{R}}_0^{-0.5}\underline{\underline{H}}=\underline{\underline{R}}^H\underline{\underline{Q}}^H$$

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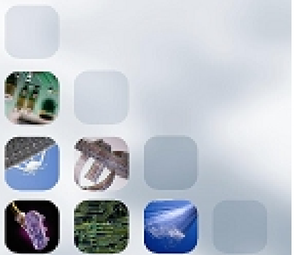
Then, using the beamforming matrix B equal to Q, we have:

$$\underline{\underline{B}}=\underline{\underline{Q}}\qquad\underline{\varepsilon}_n=\underline{Y}_n-\underline{\underline{R}}^H\underline{s}_n\quad\text{where}\quad\underline{Y}_n=\underline{\underline{R}}_0^{-0.5}\underline{X}_{Rn}$$



Now…..

$$\text{with}\quad\underline{\underline{R}}^H=\mathrm{diag}\left(\underline{\underline{R}}^H\right)\underline{\underline{R}}_a\quad\text{being }\mathrm{diag}\left(\underline{\underline{R}}_a\right)\text{is the identity matrix}$$

Let us define the input streams vector as $\underline{s}_n = \underline{\underline{R}}_a^{-1}\underline{v}_n$

We have

$$\underline{s}_n = \underline{\underline{R}}_a^{-1}\underline{v}_n$$

$$\underline{\underline{R}}_a\underline{s}_n = \underline{v}_n$$

$$diag(\underline{\underline{R}}_H) = \underline{\underline{D}}$$

$$\underline{\varepsilon}_n = \underline{Y}_n - \underline{\underline{D}}\,\underline{\underline{R}}_a\underline{s}_n = \underline{Y}_n - \underline{\underline{D}}\underline{v}_n$$

This is the AGC of each receiver

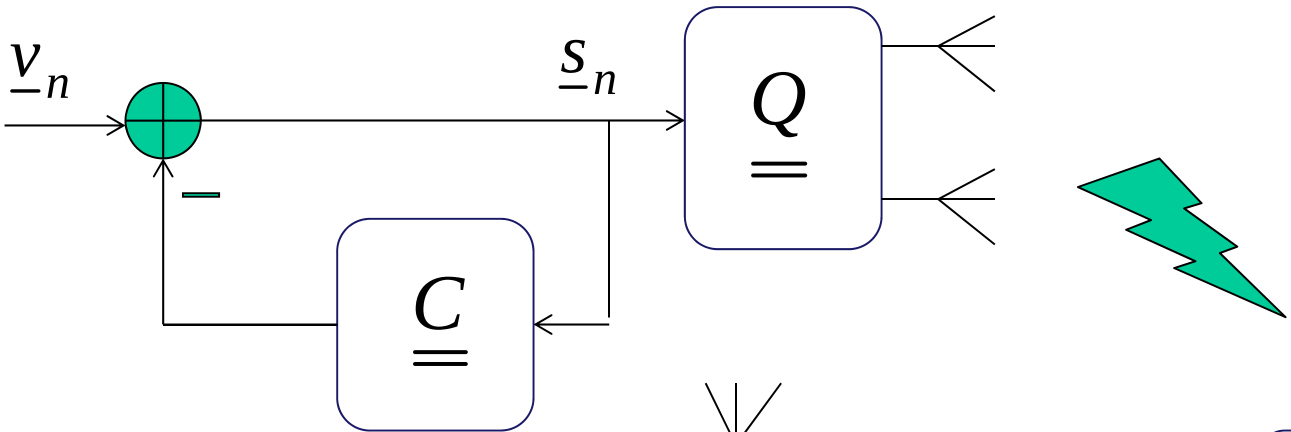
!!! The receiver can de decentralized, so each receiver decodes its message¡¡¡

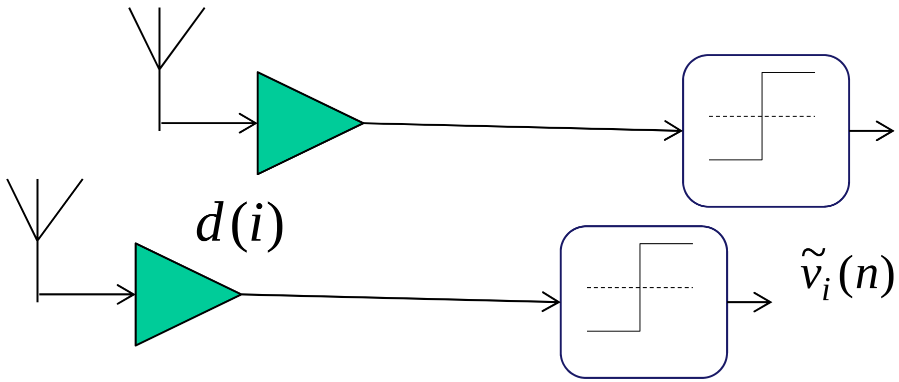
Thus if the input is vector v_n instead of s_n we solve the problem for the BC scenario

Since….. $\underline{s}_n = \underline{\underline{R}}_a^{-1} \underline{v}_n$

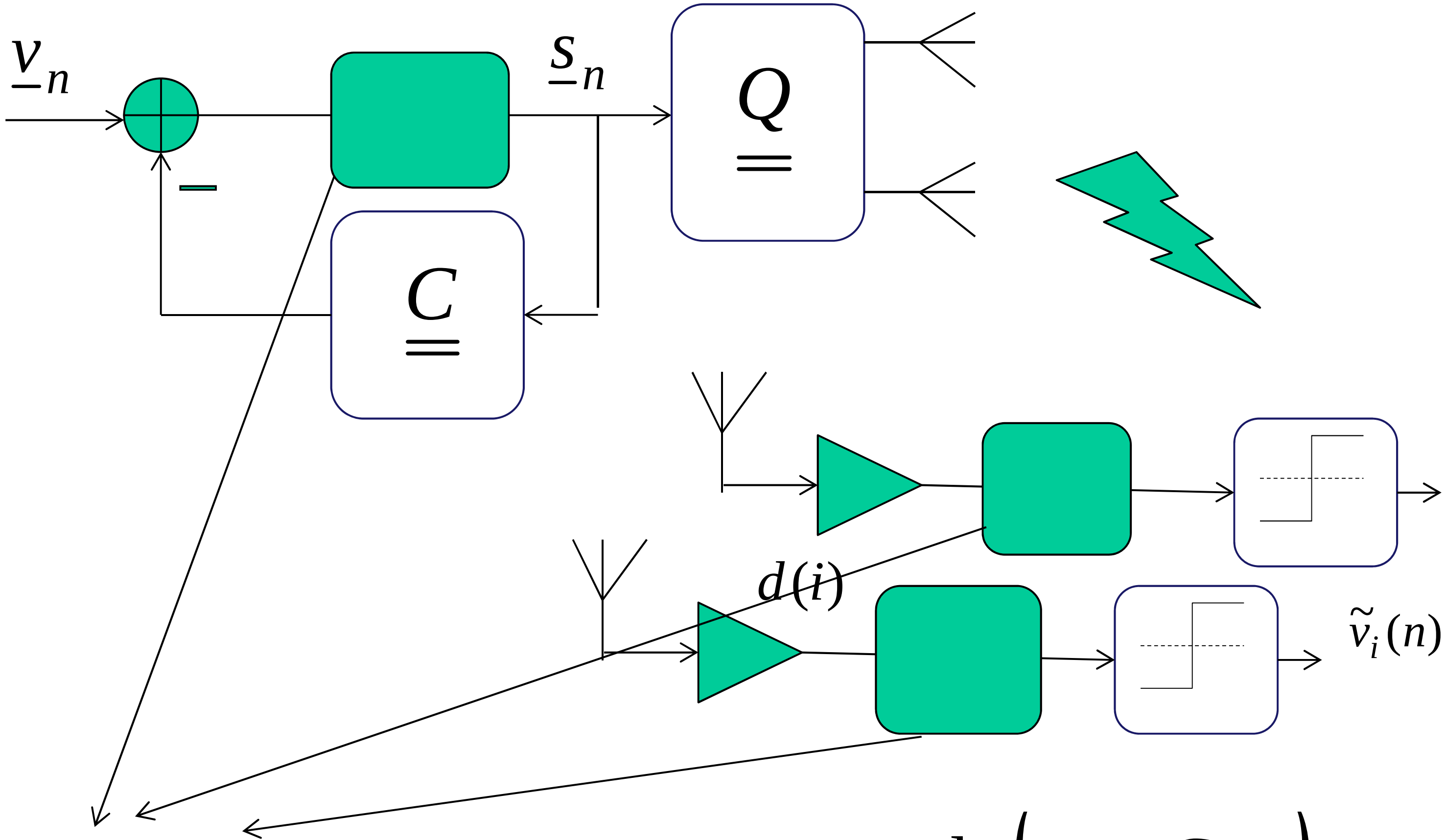
$\underline{\underline{R}}_a = \underline{\underline{I}} + \underline{\underline{C}}$ ← This matrix is strict lower triangular

then $\underline{s}_n + \underline{\underline{C}}\underline{s}_n = \underline{v}_n \Rightarrow \underline{s}_n = \underline{v}_n - \underline{\underline{C}}\underline{s}_n$





!The problem is to control the transmitted power ¡

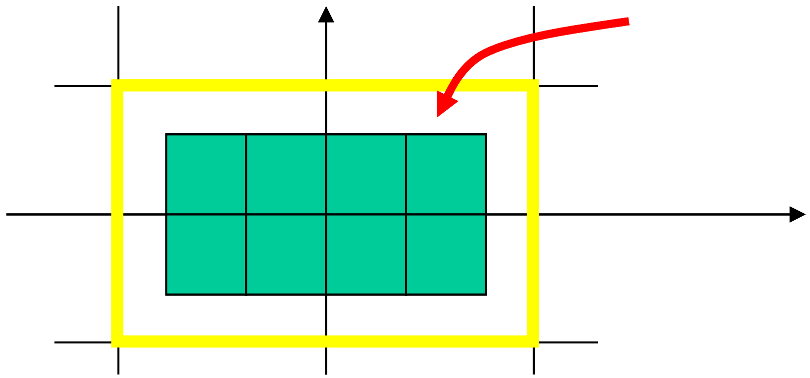


Modulus operation

$$\underline{s}_n = \mathrm{mod}_L\left(\underline{v}_n - \underline{\underline{C}}\,\underline{s}_n\right)$$

$$E_T \approx \frac{L^2}{3}$$

The modulus operation have to be introduced independently
For in-phase and quadrature components of the constellation



Thresholds for modulus operation on a 8QAM constellation

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The uniform distribution within the limits of the basic modulus operation (thresholds set equal to the maximum plus half the symbol separation distance) provides a power equal to the square of the maximum divided by 3.

Modulation	Modulus at:		
Unit Power	In-phase	Quadrat.	Excess Power
BPSK	2	0	1.24 dB.
QPSK	2/sqrt(2)	2/sqrt(2)	1.24 dB.
8-QAM	4/sqrt(6)	2/sqrt(2)	0.45 dB.
16-QAM	4/sqrt(10)	4/sqrt(10)	0.28 dB.
32-QAM	8/sqrt(26)	4/sqrt(10)	0.11 dB.
64-QAM	8/sqrt(42)	8/sqrt(42)	0.06 dB.

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The users have to be re-labeled such that the diagonal terms of the R matrix are in strict decreasing order.

To solve the labeling problem we need the generalized qr decomposition, where matrix T is a permutation that provides the diagonals of R in decreasing order. This is in accordance with the scheduling, whenever power is included within the QR.

$$\underline{\underline{R}}_0^{-0.5}.\underline{\underline{H}} = \underline{\underline{Q}}.\underline{\underline{R}}.\underline{\underline{T}}^H$$

The new error is:

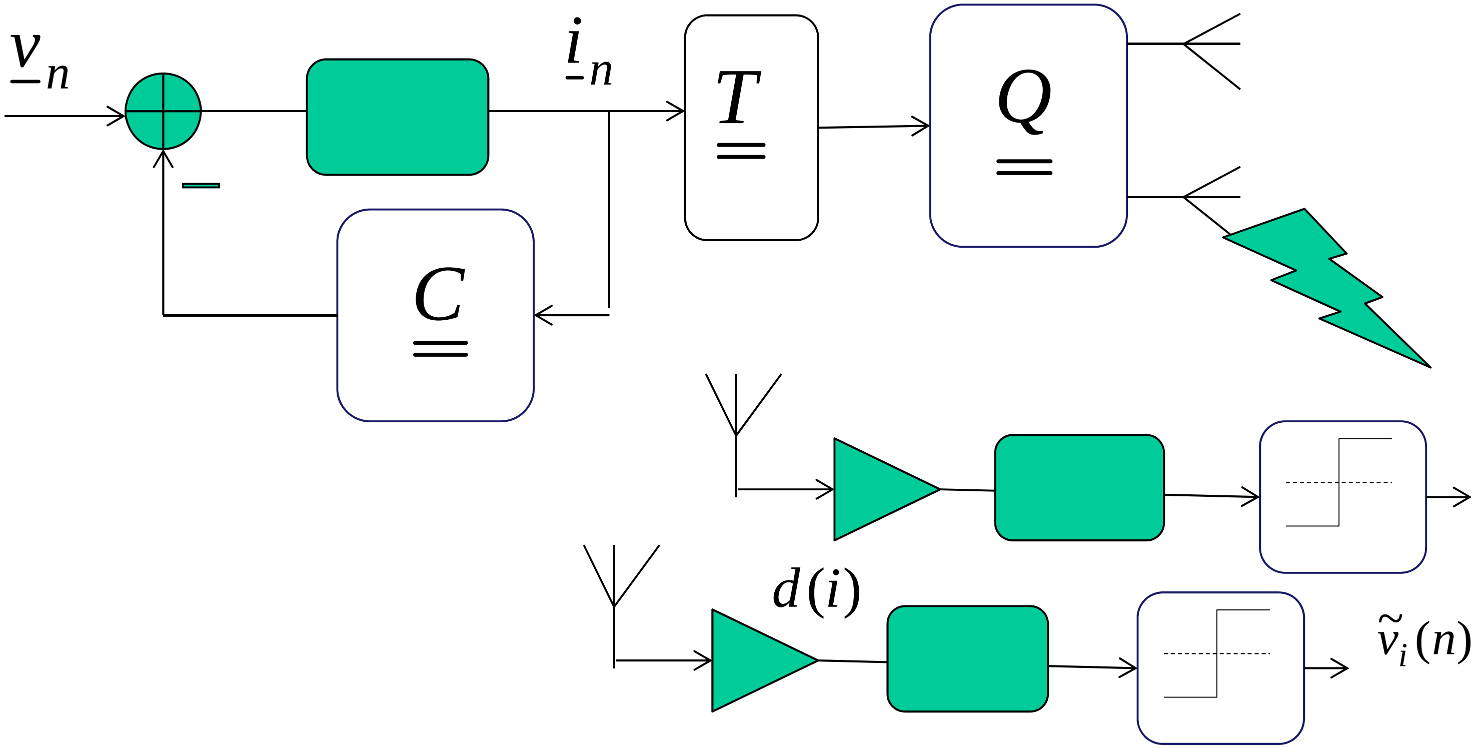
$$\underline{\underline{R}}_0^{-0.5}.\underline{X}_{Rn} - \underline{\underline{R}}_0^{-0.5}.\underline{\underline{H}}.\underline{\underline{B}}\underline{s}_n = \underline{\underline{R}}_0^{-0.5}.\underline{X}_{Rn} - diag(diag(\underline{\underline{R}})).\underline{\underline{R}}_a.\underline{\underline{T}}^H\underline{s}_n$$

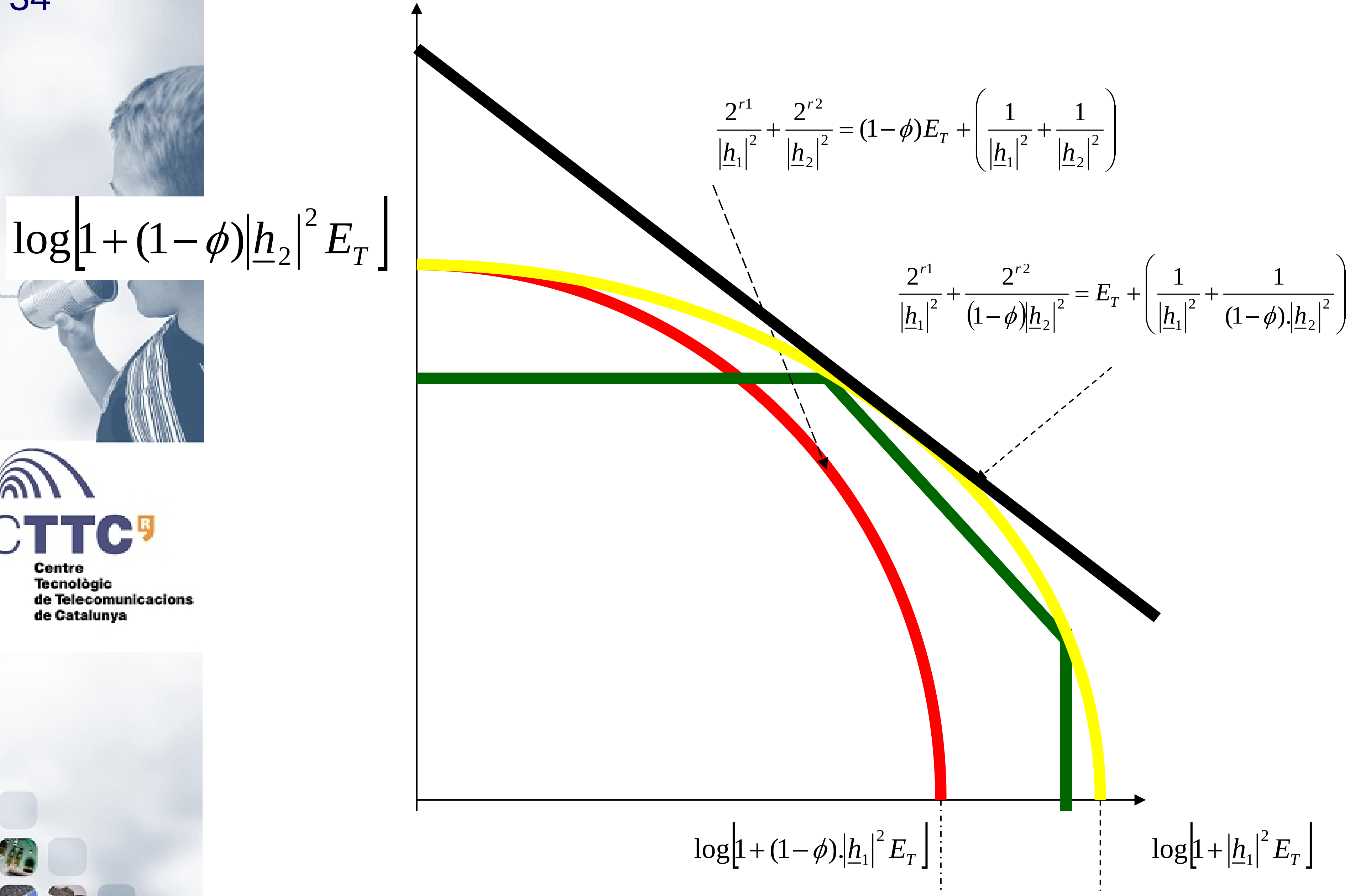
and

$$\underline{\underline{R}}_0^{-0.5}.\underline{X}_{Rn} - .\underline{\underline{Q}}.diag(diag(\underline{\underline{R}})).\underline{\underline{R}}_a.\underline{\underline{T}}^H\underline{\underline{T}}\,\underline{i}_n$$

$$\underline{s}_n = \underline{\underline{T}}\,\underline{i}_n \Rightarrow \underline{i}_n = \underline{\underline{T}}^H\underline{s}_n$$

Thus the final scheme is:





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MSE Beamforming

$$\underline{\underline{B}} = \left(\frac{\underline{h}_1}{\left|\underline{h}_1\right|} \quad \left[\underline{\underline{I}} - \frac{E_1 \underline{h}_1 \underline{h}_1^H}{1 + E_1 \left|\underline{h}_1\right|^2} \right] \frac{\underline{h}_2}{(1-\phi)^{1/2} \cdot \left|\underline{h}_2\right|} \right)$$

$$\underline{b}_2^H \underline{b}_2 = \frac{\left(h_2^2 + \Delta E_1\right)\left(1 + h_1^2 E_1\right) - h_{12}^2 E_1}{\left(1 + h_1^2 E_1\right)^2}$$

$$\underline{\underline{H}}\,\underline{\underline{B}} = \begin{pmatrix} \underline{h}_1^H \\ \underline{h}_2^H \end{pmatrix} \underline{\underline{B}} = \begin{pmatrix} h1b1 & h1b2 \\ h2b1 & h2b2 \end{pmatrix}$$

Removed by the
TH precoder

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$$SNR1 = \frac{h_1^2 E_1^{BC}}{1+(h1b2)^2 E_2^{BC}} = \frac{h_1^2 E_1^{BC}}{1+\Phi^2 E_2^{BC}}$$

$$h1b2 = \frac{\left(h_{12}/1+h_1^2 E_1\right)}{(\ldots\ldots.)} = \frac{h_{12}}{\sqrt{\left(\Delta E_1 + h_2^2\right) + \Delta E_1\left(1+h_1^2 E_1\right)}} = \Phi$$

$$1-\Phi^2 E_1 = \frac{\left(\Delta E_1 + h_2^2\right)\left(1+h_1^2 E_1\right)}{\left(\Delta E_1 + h_2^2\right) + \Delta E_1\left(1+h_1^2 E_1\right)}$$

$$SNR1 = \frac{h_1^2 E_1^{BC}}{1+(h1b2)^2 E_2^{BC}} = \frac{h_1^2 E_1^{BC}}{1+\Phi^2 E_2^{BC}} = h_1^2 E_1$$

$$E_1^{BC} = E_1\left(1+\Phi^2 E_2^{BC}\right)$$

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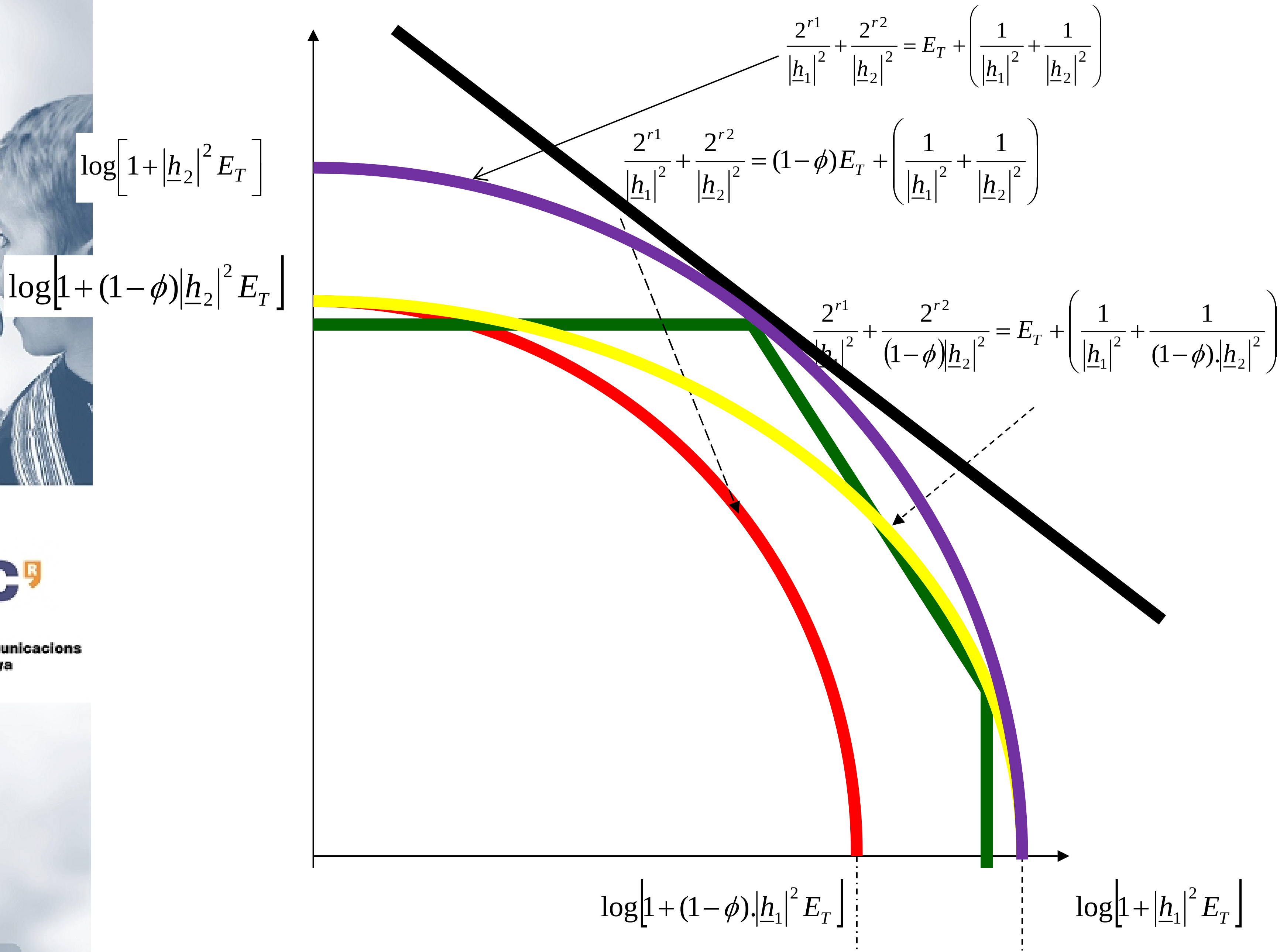
$$SNR2 = (h2b2)^2 E_2^{BC} = \frac{\Delta E_1 + h_2^2}{1 + h_1^2 E_1} E_2$$

$$(h2b2)^2 = \frac{\left(\frac{\Delta E_1 + h_2^2}{1 + h_1^2 E_1}\right)^2}{\frac{(1 + h_1^2 E_1)(\Delta E_1 + h_2^2) - h_{12}^2 E_1}{(1 + h_1^2 E_1)^2}}$$

$$E_2^{BC} = \left(1 - \frac{h_{12}^2 E_1}{(1 + h_1^2 E_1)(\Delta E_1 + h_2^2)}\right) E_2 \Rightarrow E_2^{BC} = (1 - \Gamma^2 E_1) E_2$$

$$E_1^{BC} = E_1 (1 + \Phi^2 E_2^{BC}) \quad with \quad \Phi^2 = \frac{\Gamma^2}{1 - \Gamma^2 E_1} \Rightarrow E_1^{BC} = (1 + \Gamma^2 E_2) E_1$$



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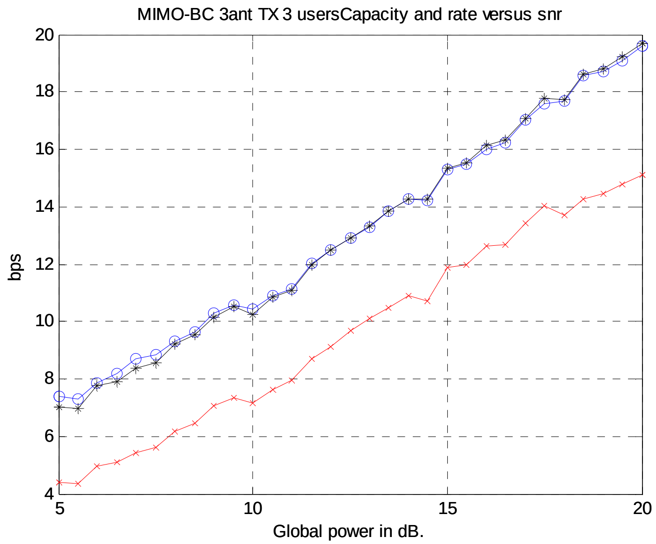
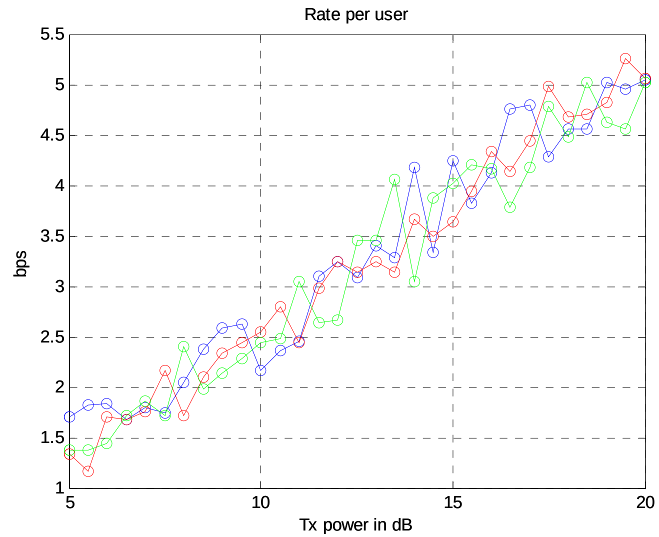
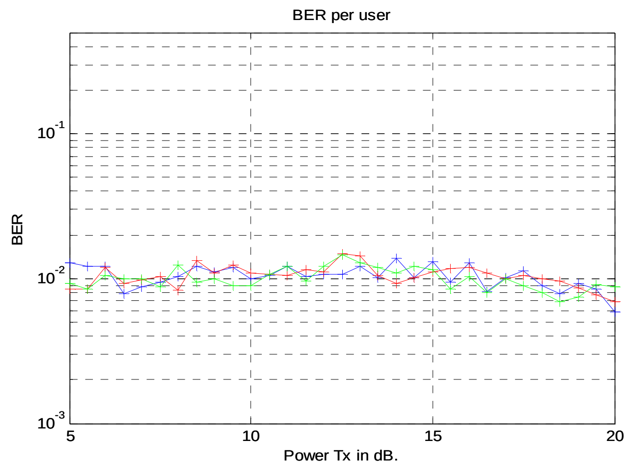
MIMO-BC: Broadcast 3 users from a BS with 3 antennas, BER target equal to 10^{-2}. Transposition and modulus operation at Tx and Rx, 50 channel realizations.







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