KOMMUNIKÁCIÓ 2X2-ES MIMO FELHASZNÁLÁSÁVAL

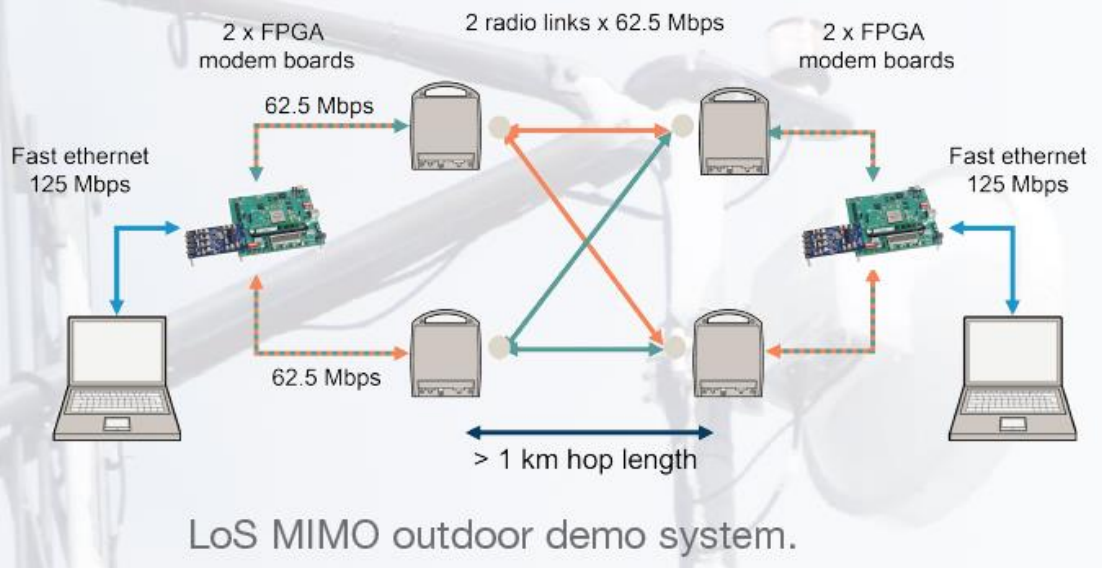
Ladvánszky János
HTE előadás
2022. 02. 09
.

OUTLINE

- 2x2 LoS MIMO model
  - reference transmission model
  - receiver analytical description
  - SIMULINK receiver model summary
  - FPGA implementation considerations and results
  - false detection cancellation method

PROJECT GOALS

- Demonstrate 2x2 MIMO transmission
  - develop and implement receiver algorithms in FPGA
  - demonstration on laboratory setup
  - demonstrate on outdoor link

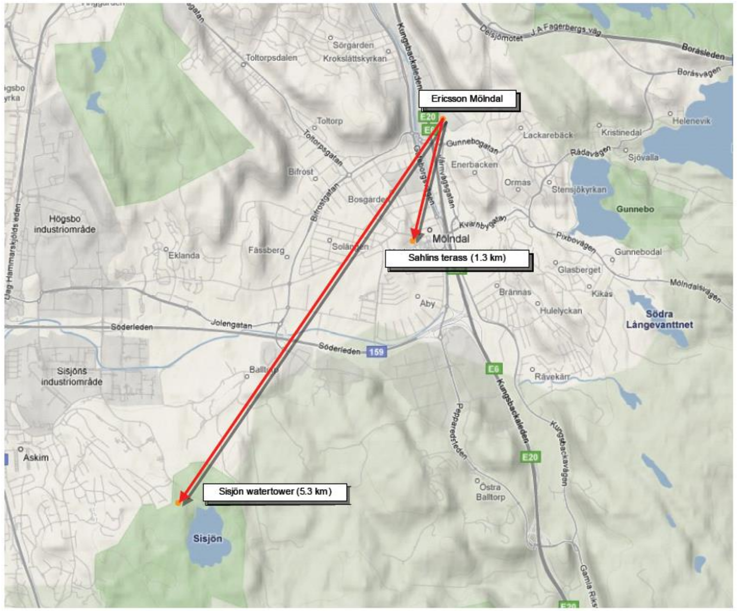


LoS MIMO outdoor demo system.

31.25 MS/s, QPSK transmission

125 MHz ADC, 250 MHz FPGA clock

Altera Stratix III evaluation board



The two test links in Gothenburg.

PARTICIPANTS

ANNA RHODIN – ERICSSON GOTHENBURG – MEASUREMENTS

GÁBOR KOVÁCS – ETH – INPUT SIMULATOR

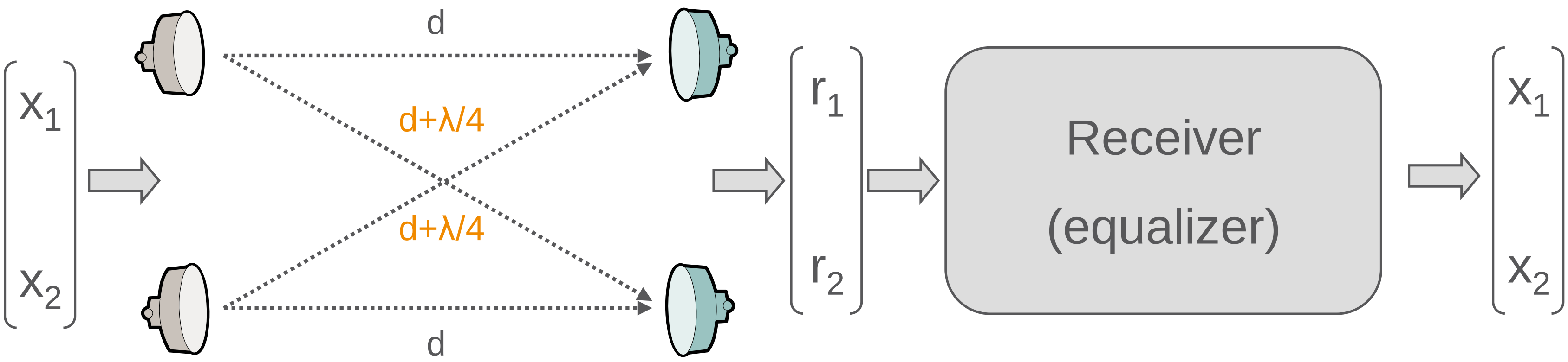
GÉZA BALÁZS – ETH- FPGA

JÁNOS LADVÁNSZKY – ETH – ALGORITHM OF RECEPTION

OUTLINE

- 2x2 LoS MIMO model
  - reference transmission model
  - receiver analytical description
  - SIMULINK receiver model summary
  - FPGA implementation considerations and results
  - false detection cancellation method

CONCEPT OF MIMO RADIOS



2x2 MIMO microwave link
(Line-of-Sight)

$$\underline{r} = \begin{pmatrix} 1 & \exp\left(-j\frac{\pi}{2}\right) \\ \exp\left(-j\frac{\pi}{2}\right) & 1 \end{pmatrix} \cdot \underline{x}$$

$$\underline{\hat{x}} = \frac{1}{2} \cdot \begin{pmatrix} 1 & e^{j\frac{\pi}{2}} \\ e^{j\frac{\pi}{2}} & 1 \end{pmatrix} \cdot \underline{r}$$

$\frac{\pi}{2} \Rightarrow \varphi(t)$ adaptive equalizer is needed!

- MCMA has been chosen for its simplicity a roboustness

EQUALIZER OVERVIEW

Choose as simple as possible: MCMA algorithm

MCMA is capable of fixing the real and imaginary parts in the constellation

For one channel: $\hat{x}(k+1) = \underline{w}^{*T}(k)\underline{r}$

Weight update:

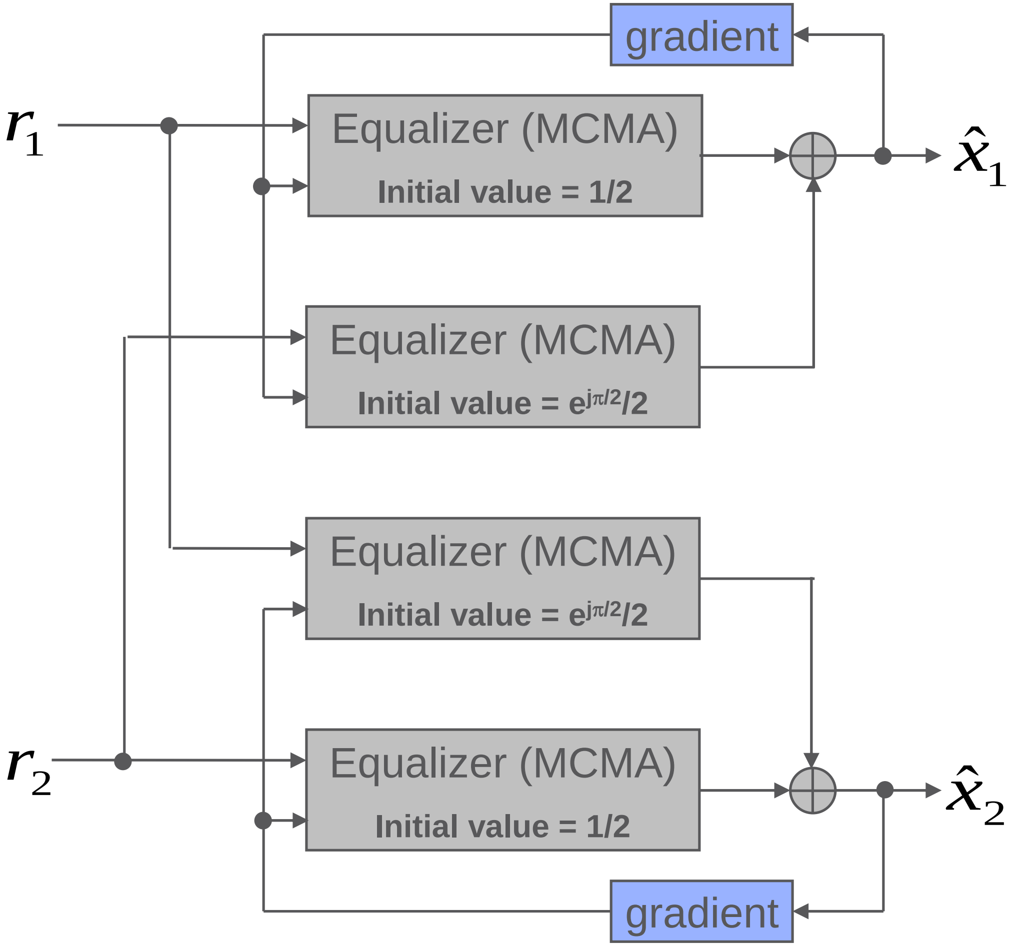
$$\underline{w}(k+1) = \underline{w}(k) - \mu_1 \operatorname{Re}(\hat{x}(k))(\operatorname{Re}(\hat{x}(k))^2 - R_{\mathrm{Re}})\underline{r} + \\ + j\mu_2 \operatorname{Im}(\hat{x}(k))(\operatorname{Im}(\hat{x}(k))^2 - R_{\mathrm{Im}})\underline{r}$$

MCMA radii:

$$R_{\mathrm{Re}} = \frac{E\left[\operatorname{Re}(\hat{x})^4\right]}{E\left[\operatorname{Re}(\hat{x})^2\right]} \qquad R_{\mathrm{Im}} = \frac{E\left[\operatorname{Im}(\hat{x})^4\right]}{E\left[\operatorname{Im}(\hat{x})^2\right]}$$

EQUALIZER STRUCTURE

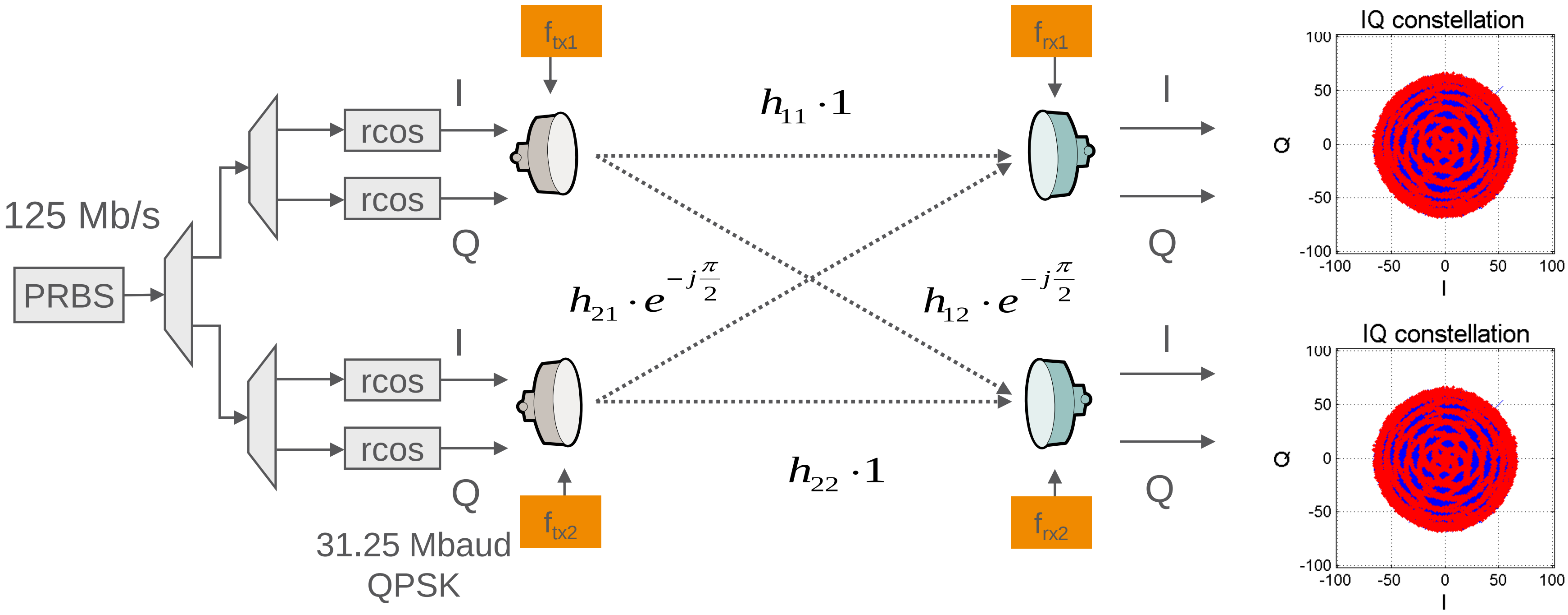
- MCMA equalizer in each path:



- 10 tap equalizer filter (125 MHz / 25MS/s = = 5 sample / symbol)
- Initial values *in the first tap*
  - ½ in the direct path
  - ½j in the cross-path
- conjugate gradient is fed back from appropriate output

PRACTICAL TRANSMISSION MODEL

- Practical imperfections:



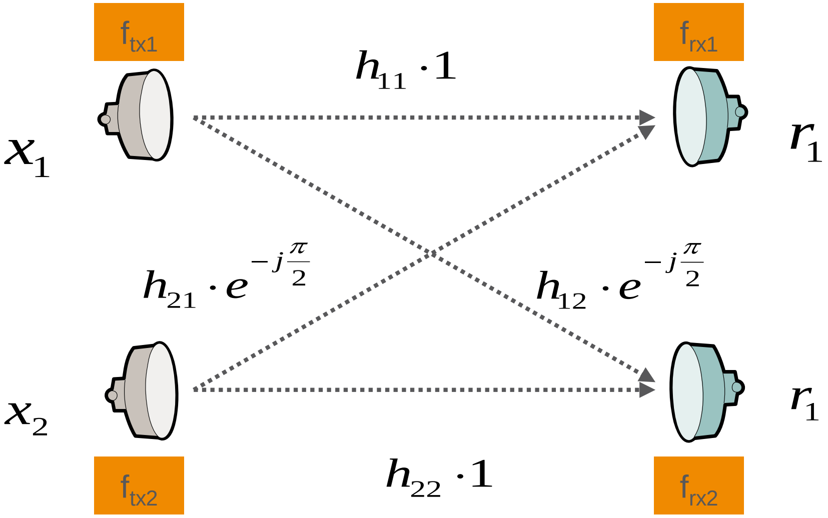
$$\underline{r} = \left\lfloor \underline{\underline{F}}_{Rx} \cdot \underline{\underline{H}} \cdot \underline{\underline{F}}_{Tx} \right\rfloor \cdot \underline{x} + \underline{N}$$

Receivers frequency deviation

LoS MIMO channel

Transmitters frequency deviation

ANALYTICAL DESCRIPTION



$$\underline{\underline{F}}_{tx} = \begin{bmatrix} e^{j(2\pi f_{tx1} t)} & 0 \\ 0 & e^{j(2\pi f_{tx2} t)} \end{bmatrix}$$

$$\underline{\underline{H}} = \begin{bmatrix} h_{11} \cdot 1 & h_{21} \cdot e^{-j\pi/2} \\ h_{12} \cdot e^{-j\pi/2} & h_{22} \cdot 1 \end{bmatrix}$$

$$\underline{\underline{F}}_{rx} = \begin{bmatrix} e^{j(2\pi f_{rx1} t - \varphi_1)} & 0 \\ 0 & e^{j(2\pi f_{rx2} t - \varphi_2)} \end{bmatrix}$$

f_{tx1}, f_{tx2}, f_{rx1}, f_{rx2} – difference from nominal frequency values

h_{11}, h_{12}, h_{21}, h_{22} – antenna gain differences + time dependent channel transfer functions

φ_1, φ_2 – random phase of receiver oscillator

- Note: multiplication operator is not exact: convolution operator should be used, as h_{xx} is the time-domain equivalent of the radio channel. However, convolution would also not be precise in the equations because multiplication by a non-constant in time is not a linear operator.

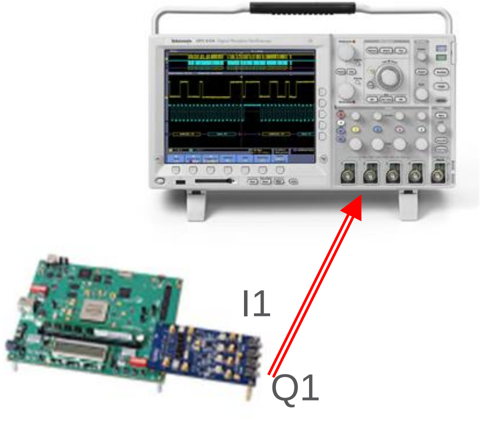
TEST WAVEFORM GENERATION (1)

- Basis for understanding LoS MIMO channels and to provide test signals for receivers:
  - adjustable parameters (can be time dependent):
    - $f_{tx1,}$ $f_{tx2,}$ $f_{rx1,}$ f_{rx2} – frequency difference from nominal
    - φ_{12}, φ_{21} – cross-channel phase difference (eg. mast swing)
    - symbol rate (*25 MHz in measured data*)
    - sampling rate (125 MHz)
    - AWGN level
  - Implemented functionalities:
    - random input bit stream (PRBS) with RRCOS filter for QPSK
    - time dependent transmitter & receiver frequency matrices
    - time dependent MIMO channel matrix (only complex coefficient, no radio channel modelling)

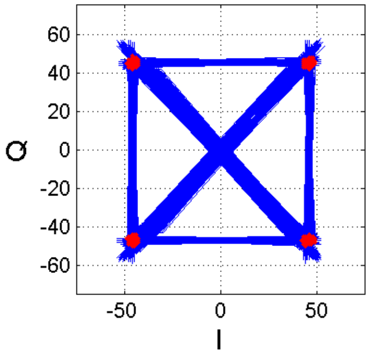
TEST WAVEFORM GENERATION (2)

- Test waveform generators:

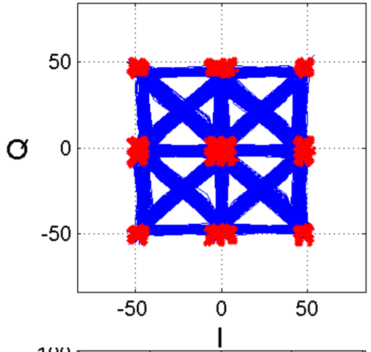
MATLAB SIMULINK



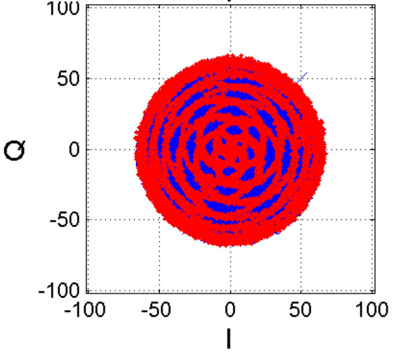
Altera Stratix III development board +
+ DAC/ADC extension cards



- output constellation
  - only one source
  - no channel
  - no rotation



- output constellation
  - both source transmit
  - channel enabled
  - no rotation

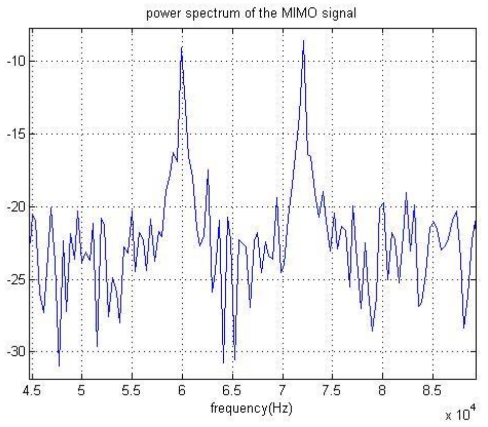


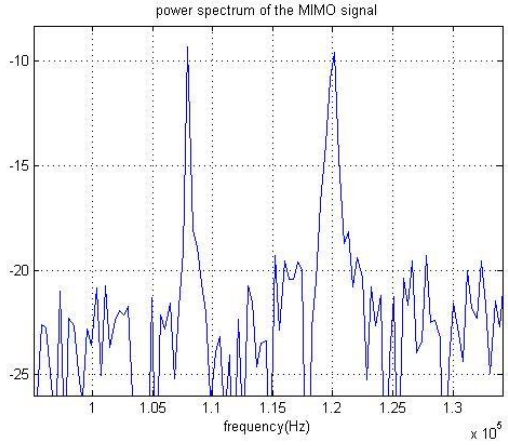
- output constellation
  - both source transmit
  - channel enabled
  - both transmitters and receivers enabled

Measured at FPGA output

SIMULATION EXAMPLE

- How to compensate for the frequency deviations?
  - Problem: $f_{tx1}, f_{tx2}, f_{rx1}, f_{rx2}$ are not explicitly present in the received signal:





$$f_{tx1} = 3kHz;\ f_{tx2} = 6kHz;$$

$$f_{rx1} = 12kHz;\ f_{rx2} = 24kHz$$

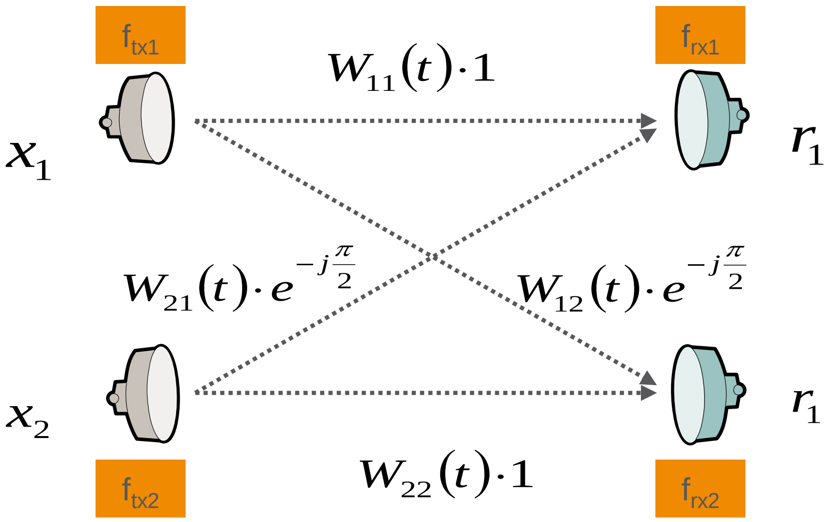
$$(f_{tx1} + f_{rx1}) \cdot 4 = 60kHz \qquad (f_{tx1} + f_{rx2}) \cdot 4 = 108kHz$$

$$(f_{tx2} + f_{rx1}) \cdot 4 = 72kHz \qquad (f_{tx2} + f_{rx2}) \cdot 4 = 120kHz$$

In the spectra the frequencies appear combined, and not separately as they are needed in the synchronization

ANALYTICAL DESCRIPTION

- These frequency combinations can also be derived analitically



$$\underline{\underline{F}}_{tx} = \begin{bmatrix} e^{j(2\pi f_{tx1} t)} & 0 \\ 0 & e^{j(2\pi f_{tx2} t)} \end{bmatrix}$$

$$\underline{\underline{H}} = \begin{bmatrix} h_{11}\cdot 1 & h_{21}\cdot e^{-j\pi/2} \\ h_{12}\cdot e^{-j\pi/2} & h_{22}\cdot 1 \end{bmatrix}$$

$$\underline{\underline{F}}_{rx} = \begin{bmatrix} e^{j(2\pi f_{rx1} t-\varphi_1)} & 0 \\ 0 & e^{j(2\pi f_{rx2} t-\varphi_2)} \end{bmatrix}$$

$$\underline{r} = \left\lfloor \underline{\underline{F}}_{Rx}\cdot \underline{\underline{H}}\cdot \underline{\underline{F}}_{Tx} \right\rfloor \cdot \underline{x} + \underline{N}$$

$$r_1 = h_{11}\cdot 1\cdot e^{j(2\pi(\boxed{f_{tx1}+f_{rx1}})t-\varphi_1)}\cdot x_1 + h_{21}\cdot e^{-j\pi/2}\cdot e^{j(2\pi(\boxed{f_{tx2}+f_{rx1}})t-\varphi_1)}\cdot x_2$$

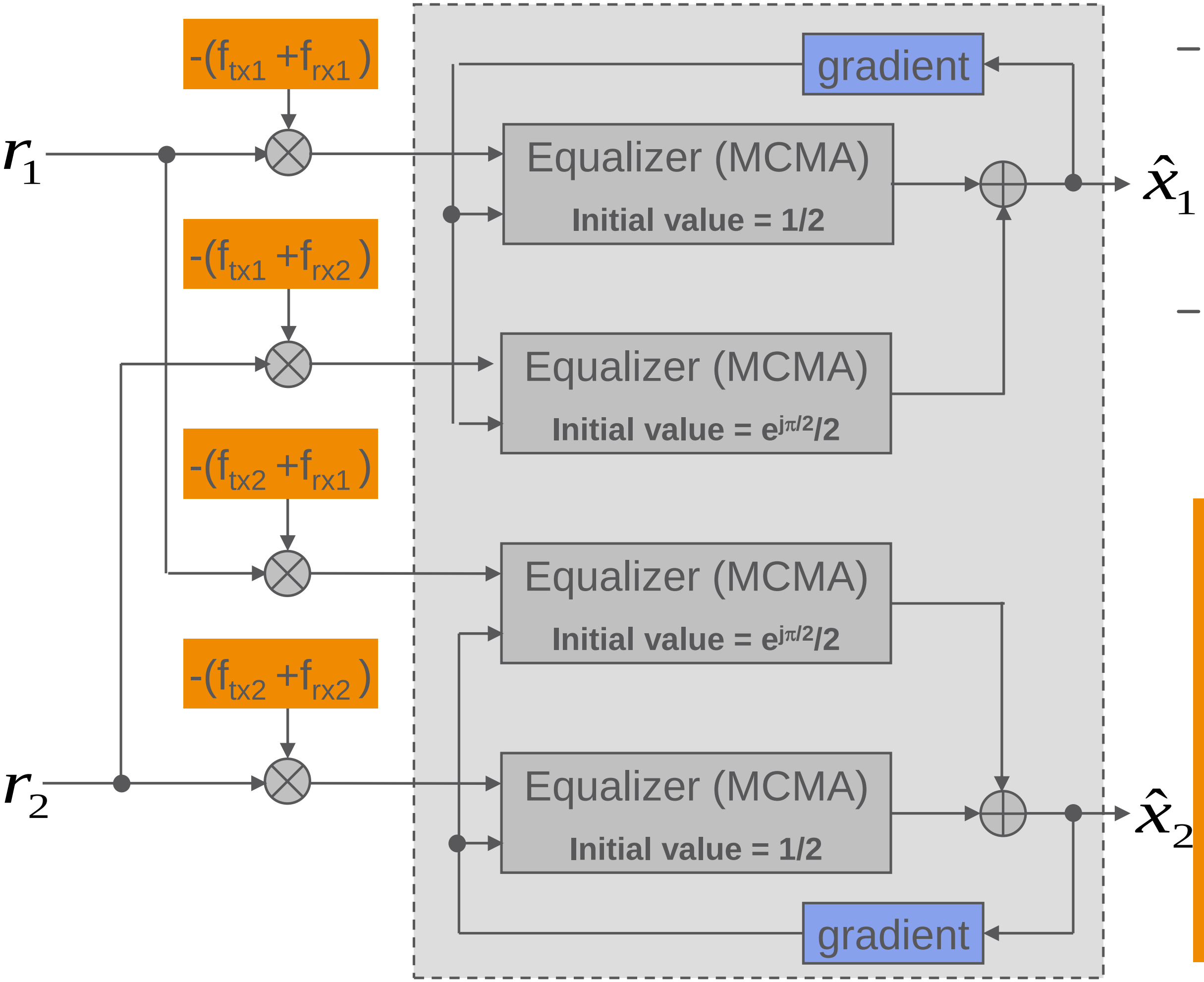
$$r_2 = h_{12}\cdot e^{-j\pi/2}\cdot e^{j(2\pi(\boxed{f_{tx1}+f_{rx2}})t-\varphi_2)}\cdot x_1 + h_{22}\cdot 1\cdot e^{j(2\pi(\boxed{f_{tx2}+f_{rx2}})t-\varphi_2)}\cdot x_2$$

OUTLINE

- 2x2 LoS MIMO model
  - reference transmission model
  - receiver analytical description
  - SIMULINK receiver model summary
  - FPGA implementation considerations and results
  - false detection cancellation method

RECEIVER STRUCTURE (1)

- Frequency compensations and equalization architecture:

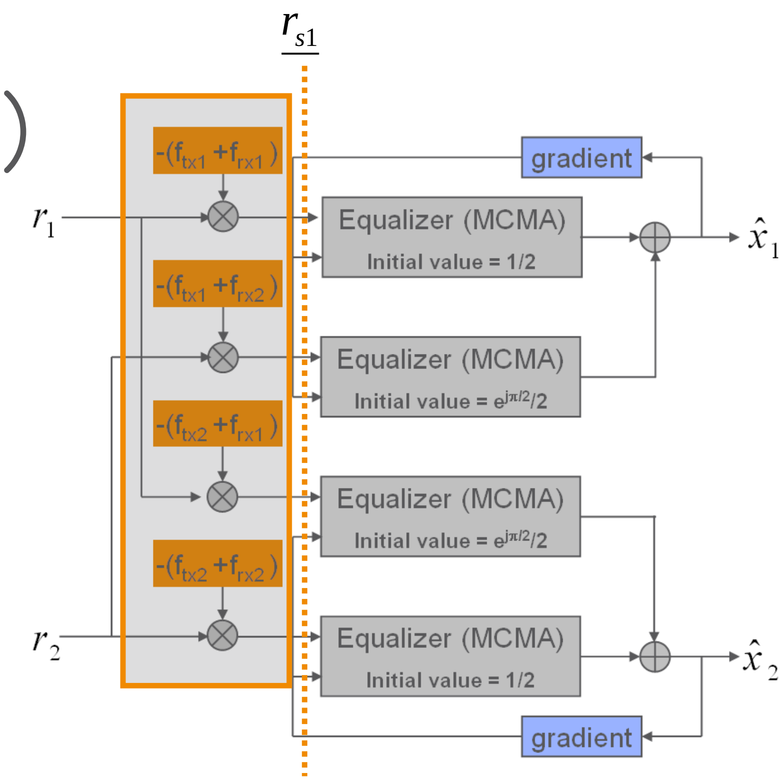


- First stage compensates for the frequency rotations:
  - Tx1 in upper pair
  - Tx2 in lower pair
- Second stage equalizes MIMO radio channel effect as described earlier.

Major advantage:

All rotation cancelled, though equalizers (*theoretically*) do not need to compenasate for any constellation rotation!

RECEIVER STRUCTURE (2)



› Matrix description of the first stage:

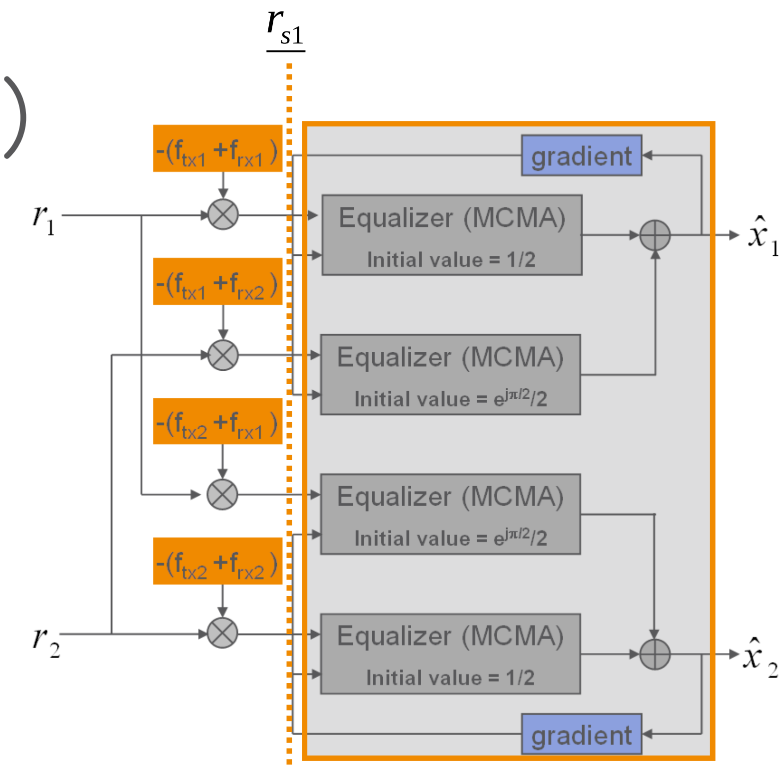
- Tx1 rotation is compensated in upper left corner
- Tx2 rotation is compensated in lower right corner

$$\underline{r}_{s1} = \begin{bmatrix} e^{-j2\pi(f_{tx1}+f_{rx1})t} & 0 \\ 0 & e^{-j2\pi(f_{tx1}+f_{rx2})t} \\ e^{-j2\pi(f_{tx2}+f_{rx1})t} & 0 \\ 0 & e^{-j2\pi(f_{tx2}+f_{rx2})t} \end{bmatrix} \begin{bmatrix} h_{11}\cdot e^{-j\varphi_1}\cdot e^{j2\pi(f_{tx1}+f_{rx1})t} & h_{21}\cdot e^{-j\varphi_2}\cdot e^{-j\frac{\pi}{2}}\cdot e^{j2\pi(f_{tx2}+f_{rx1})t} \\ h_{12}\cdot e^{-j\varphi_1}\cdot e^{-j\frac{\pi}{2}}\cdot e^{j2\pi(f_{tx1}+f_{rx2})t} & h_{22}\cdot e^{-j\varphi_2}\cdot e^{j2\pi(f_{tx2}+f_{rx2})t} \end{bmatrix} \underline{x} =$$

$$= \begin{bmatrix} h_{11}\cdot e^{-j\varphi_1} & h_{21}\cdot e^{-j\varphi_2}\cdot e^{-j\frac{\pi}{2}}\cdot e^{j2\pi(f_{tx2}-f_{tx1})} \\ h_{12}\cdot e^{-j\varphi_1}\cdot e^{-j\frac{\pi}{2}} & h_{22}\cdot e^{-j\varphi_2}\cdot e^{j2\pi(f_{tx2}-f_{tx1})} \\ h_{11}\cdot e^{-j\varphi_1}\cdot e^{j2\pi(f_{tx1}-f_{tx2})} & h_{21}\cdot e^{-j\varphi_2}\cdot e^{-j\frac{\pi}{2}} \\ h_{12}\cdot e^{-j\varphi_1}\cdot e^{-j\frac{\pi}{2}}\cdot e^{j2\pi(f_{tx1}-f_{tx2})} & h_{22}\cdot e^{-j\varphi_2} \end{bmatrix} \underline{x}$$

RECEIVER STRUCTURE (3)

- Matrix description of the second stage:
  - equalizer need to compensate
    - for different level of loss in MIMO channel paths
    - random oscillator phases
    - MIMO cross-path components
  - no rotation compensation is required from the equalizer



$$\underline{\hat{x}} = \frac{1}{2}\begin{bmatrix} h_{11}^{-1}\cdot e^{j\varphi_1} & h_{12}^{-1}\cdot e^{j\varphi_1}\cdot e^{j\frac{\pi}{2}} & 0 & 0 \\ 0 & 0 & h_{21}^{-1}\cdot e^{j\varphi_2}\cdot e^{j\frac{\pi}{2}} & h_{22}^{-1}\cdot e^{j\varphi_2} \end{bmatrix} \begin{bmatrix} h_{11}\cdot e^{-j\varphi_1} & h_{21}\cdot e^{-j\varphi_2}\cdot e^{-j\frac{\pi}{2}}\cdot e^{j2\pi(f_{tx2}-f_{tx1})t} \\ h_{12}\cdot e^{-j\varphi_1}\cdot e^{-j\frac{\pi}{2}} & h_{22}\cdot e^{-j\varphi_2}\cdot e^{j2\pi(f_{tx2}-f_{tx1})t} \\ h_{11}\cdot e^{-j\varphi_1}\cdot e^{j2\pi(f_{tx1}-f_{tx2})t} & h_{21}\cdot e^{-j\varphi_2}\cdot e^{-j\frac{\pi}{2}} \\ h_{12}\cdot e^{-j\varphi_1}\cdot e^{-j\frac{\pi}{2}}\cdot e^{j2\pi(f_{tx1}-f_{tx2})t} & h_{22}\cdot e^{-j\varphi_2} \end{bmatrix} \underline{x} =$$

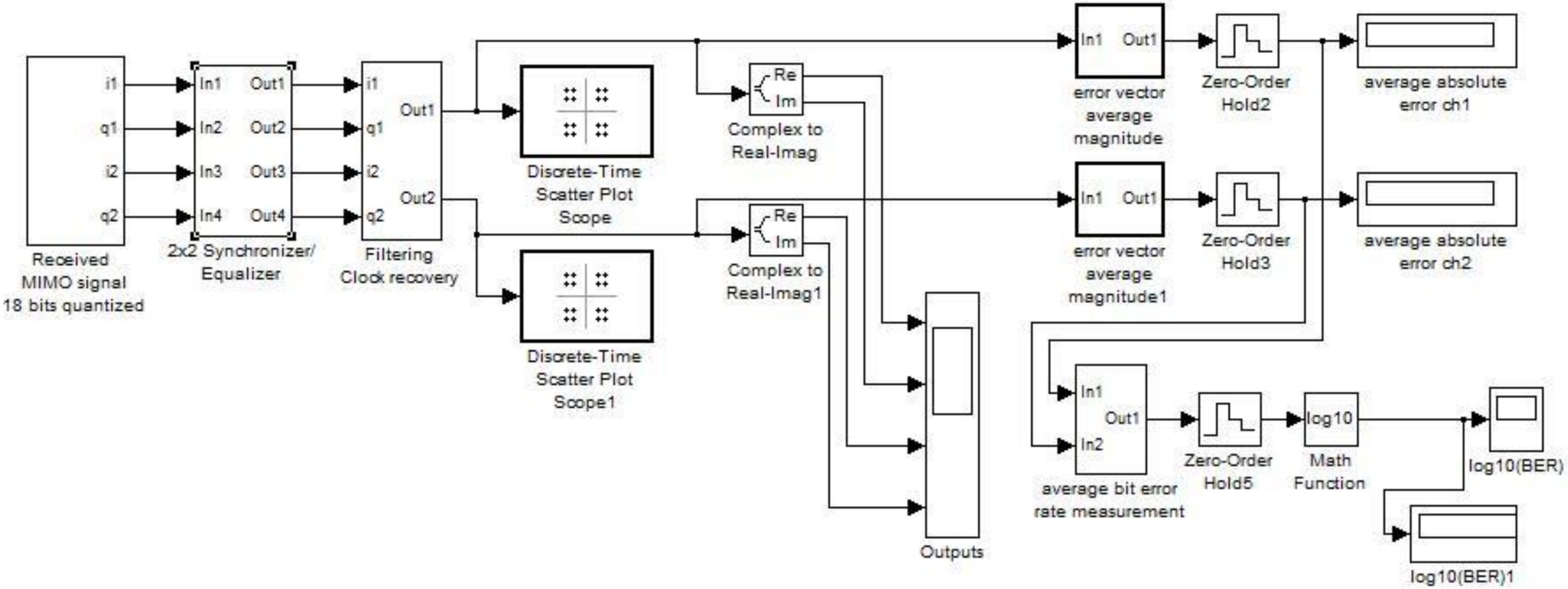
$$= \frac{1}{2}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\underline{x}$$

$$h_{11}\cdot h_{21} = h_{12}\cdot h_{22}$$

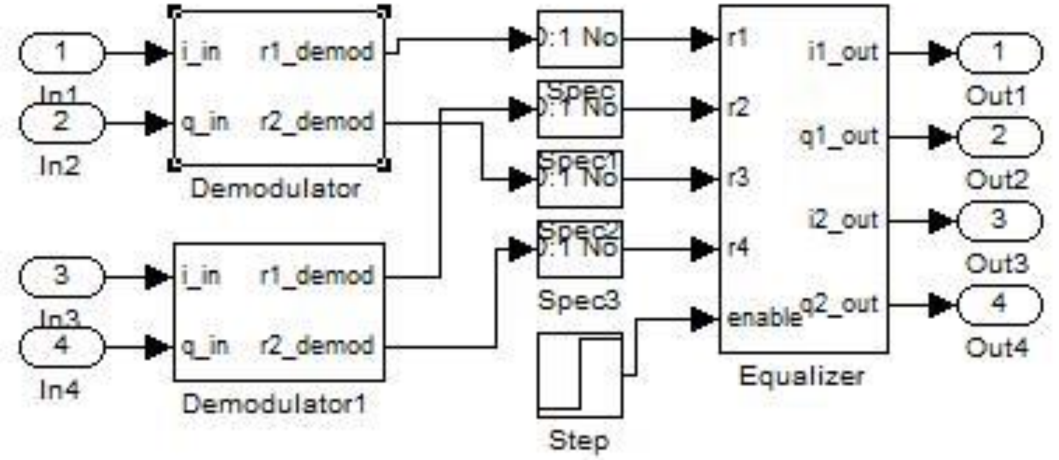
OUTLINE

- 2x2 LoS MIMO model
  - reference transmission model
  - receiver analytical description
  - SIMULINK receiver model summary
  - FPGA implementation considerations and results
  - false detection cancellation method

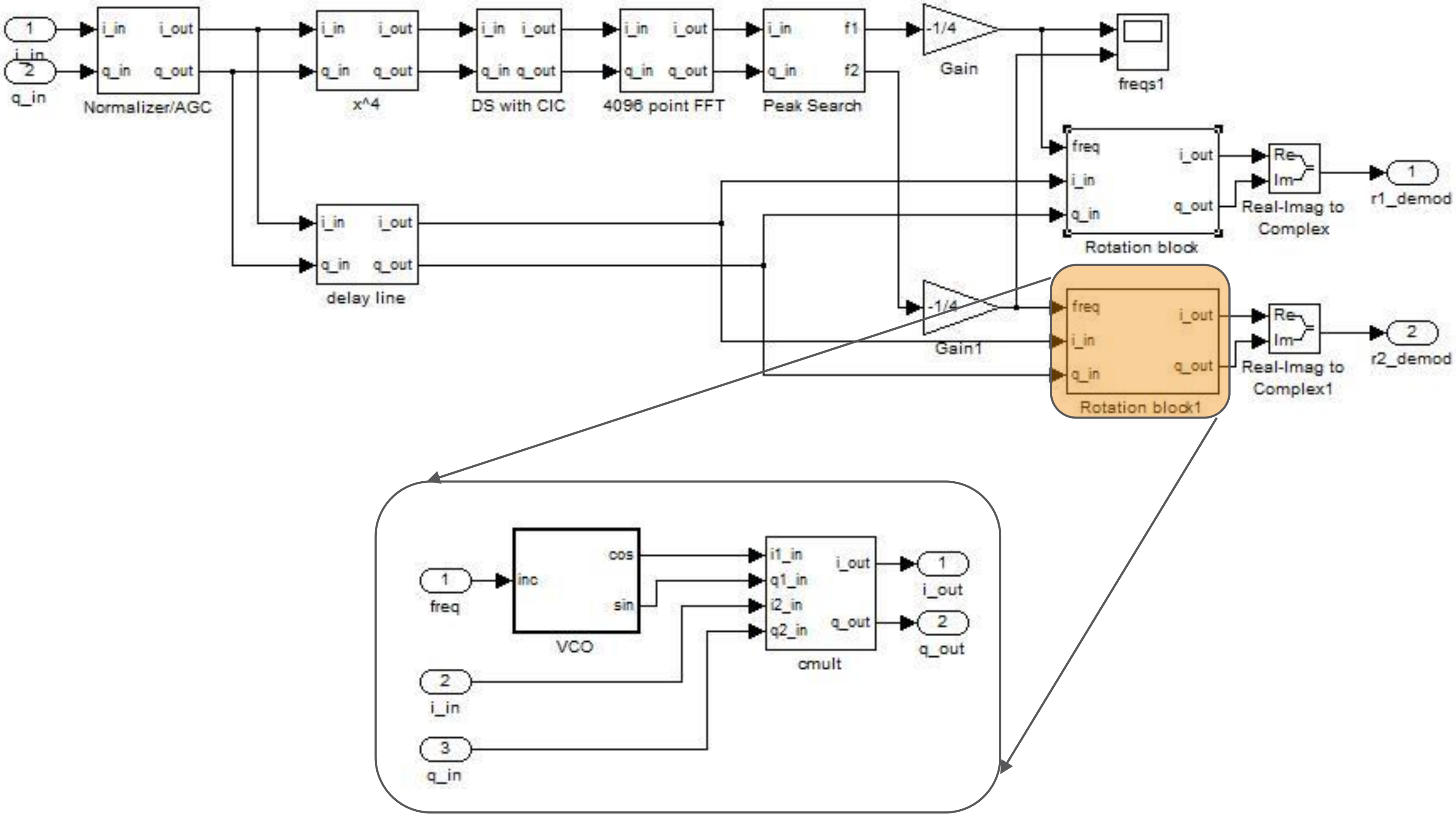
SIMULINK SYSTEM DIAGRAM



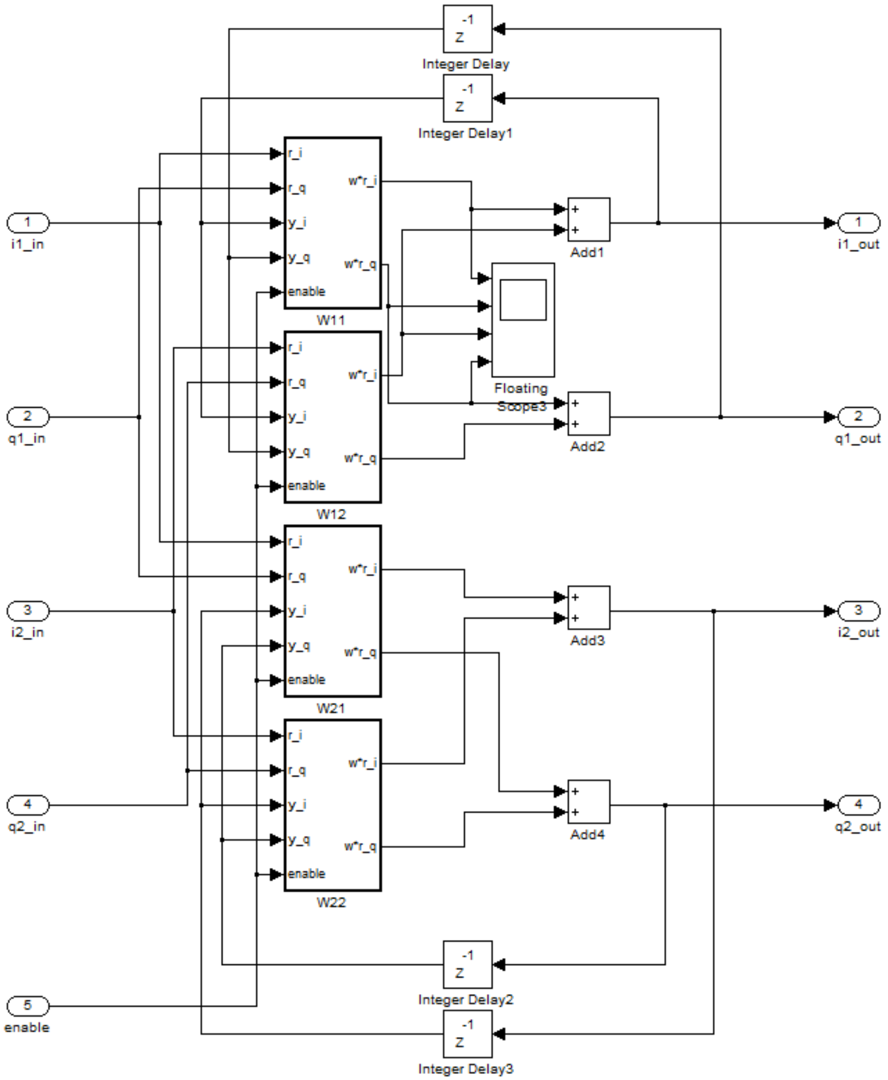
SYNCHRONIZER/EQUALIZER



DEMODULATOR AND ROTATOR

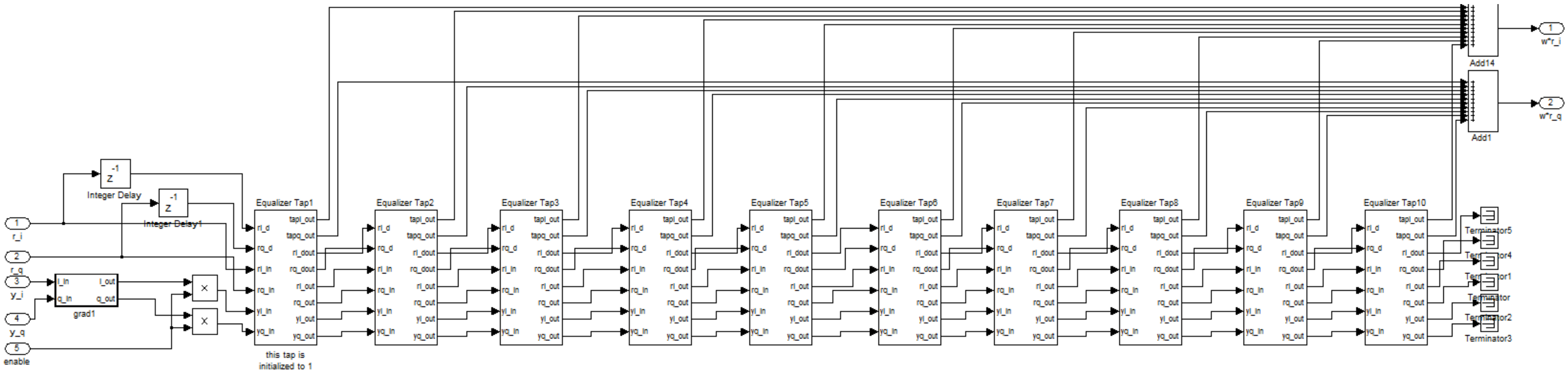


EQUALIZER BLOCK DIAGRAM



- Gradient block is placed in the equalizer module

EQUALIZER MODULE



QUANTITATIVE MEASURE OF RECEIVER ALGORITHM QUALITY

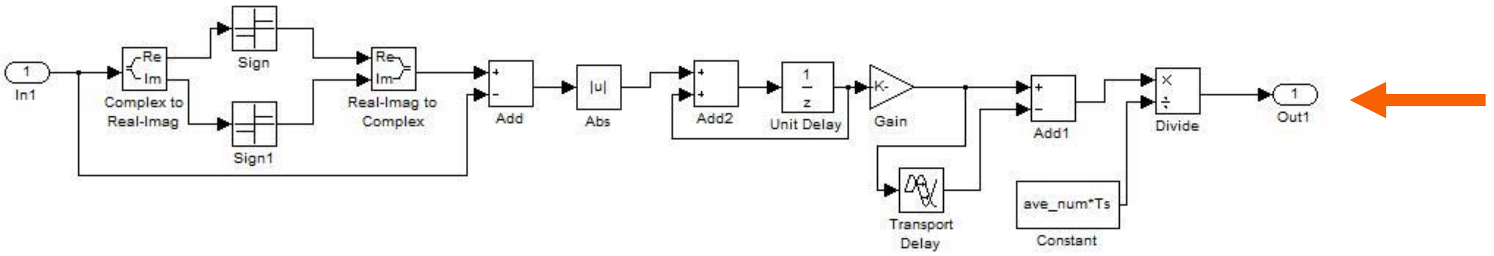
Average bit error rate as a function of time: $BER = erfc(1/\varepsilon)$

where ε is the average deviation from the ideal constellation point

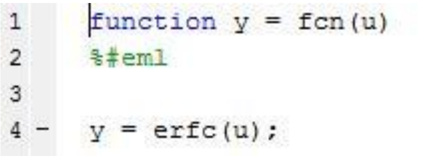
that is obtained by sign() function

Condition: The erroneous constellation point is in the same quadrant

as the error-free one

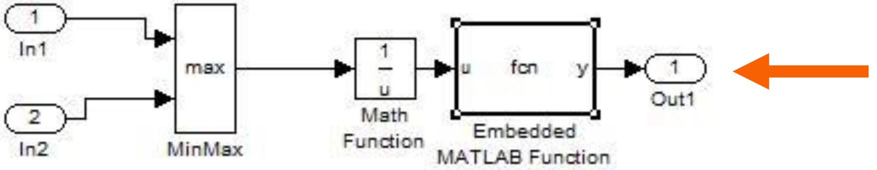


ε



```
function y = fcn(u)
%#eml

y = erfc(u);
```



BER

OUTLINE

- 2x2 LoS MIMO model
  - reference transmission model
  - receiver analytical description
  - SIMULINK receiver model summary
  - FPGA implementation considerations and results
  - false detection cancellation method

RECEIVED SIGNAL DECOMPOSITION

- Another analytical form of the received signal:

$$r_1 = \boxed{h_{11} \cdot e^{j(\varphi_{11}+2\pi\Delta f_{11}t)}} \cdot \boxed{e^{j(2\pi(f_{tx1}+f_{rx1})t)}} \cdot \boxed{x_1} + \boxed{h_{21} \cdot e^{j(\varphi_{12}+2\pi\Delta f_{12}t)} \cdot e^{-j\pi/2}} \cdot \boxed{e^{j(2\pi(f_{tx2}+f_{rx1})t)}} \cdot \boxed{x_2}$$

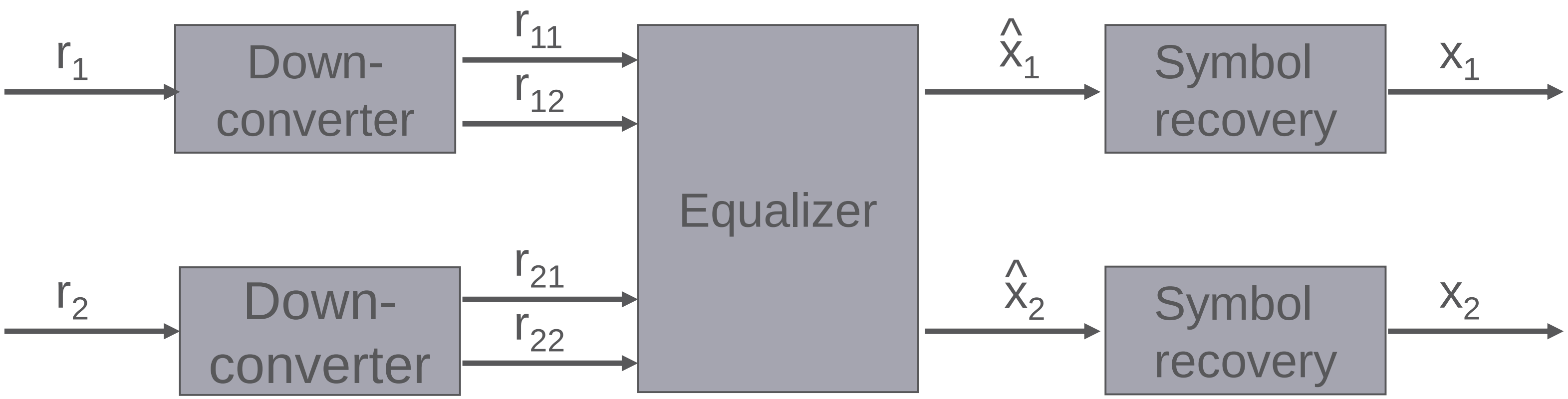
$$r_2 = \boxed{h_{12} \cdot e^{j(\varphi_{21}+2\pi\Delta f_{21}t)} \cdot e^{-j\pi/2}} \cdot \boxed{e^{j(2\pi(f_{tx1}+f_{rx2})t)}} \cdot \boxed{x_1} + \boxed{h_{22} \cdot e^{j(\varphi_{22}+2\pi\Delta f_{22}t)}} \cdot \boxed{e^{j(2\pi(f_{tx2}+f_{rx2})t)}} \cdot \boxed{x_2}$$

- Exact measurement of frequencies is not possible (discrete Fourier transform):
  - Δf_{11}, Δf_{12}, Δf_{21}, Δf_{22} – frequency measurement error

- Factors that change ‘slowly’ over time
- Factors that can change fast over time
- Factors that change very rapidly over time

RECEIVER BLOCK DIAGRAM

- Slow changes will be compensated by the equalizers
- Moderate to fast changes will be compensated by the downconverter
- The transmitted data stream is the fastest changing signal, its timing will be decoded, and the signal sampled by the timing recovery block



OUTLINE

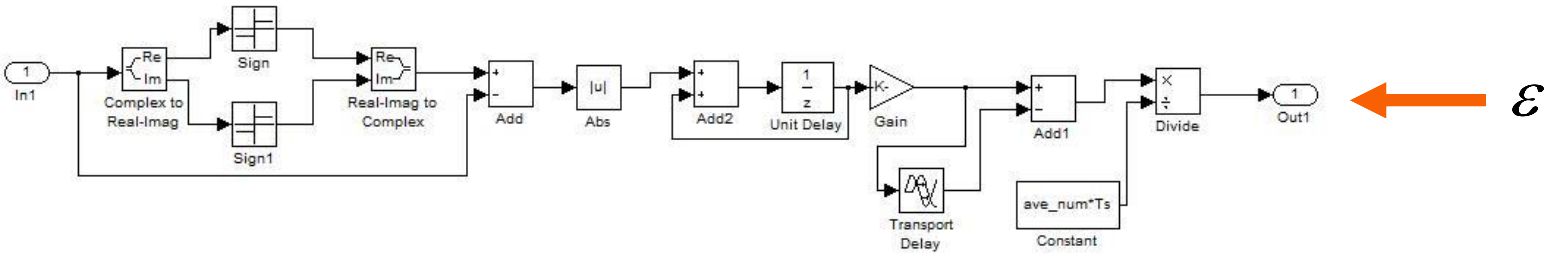
- 2x2 LoS MIMO model
  - reference transmission model
  - receiver analytical description
  - SIMULINK receiver model summary
  - FPGA implementation considerations and results
  - false detection cancellation method

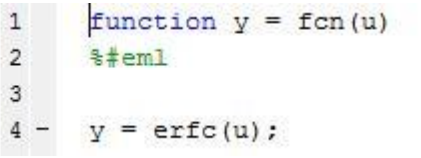
QUANTITATIVE MEASURE OF RECEIVER ALGORITHM QUALITY

Average bit error rate as a function of time: $BER = erfc(1/\varepsilon)$

where ε is the average deviation from the ideal constellation point that is obtained by sign() function

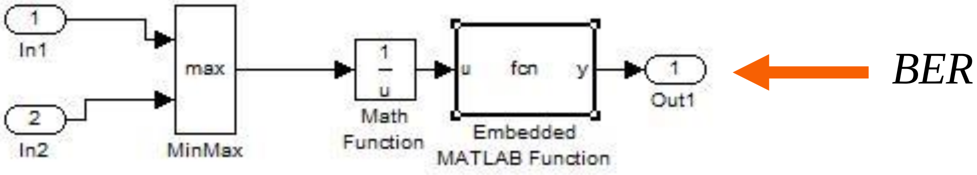
Condition: The erroneous constellation point is in the same quadrant as the error-free one



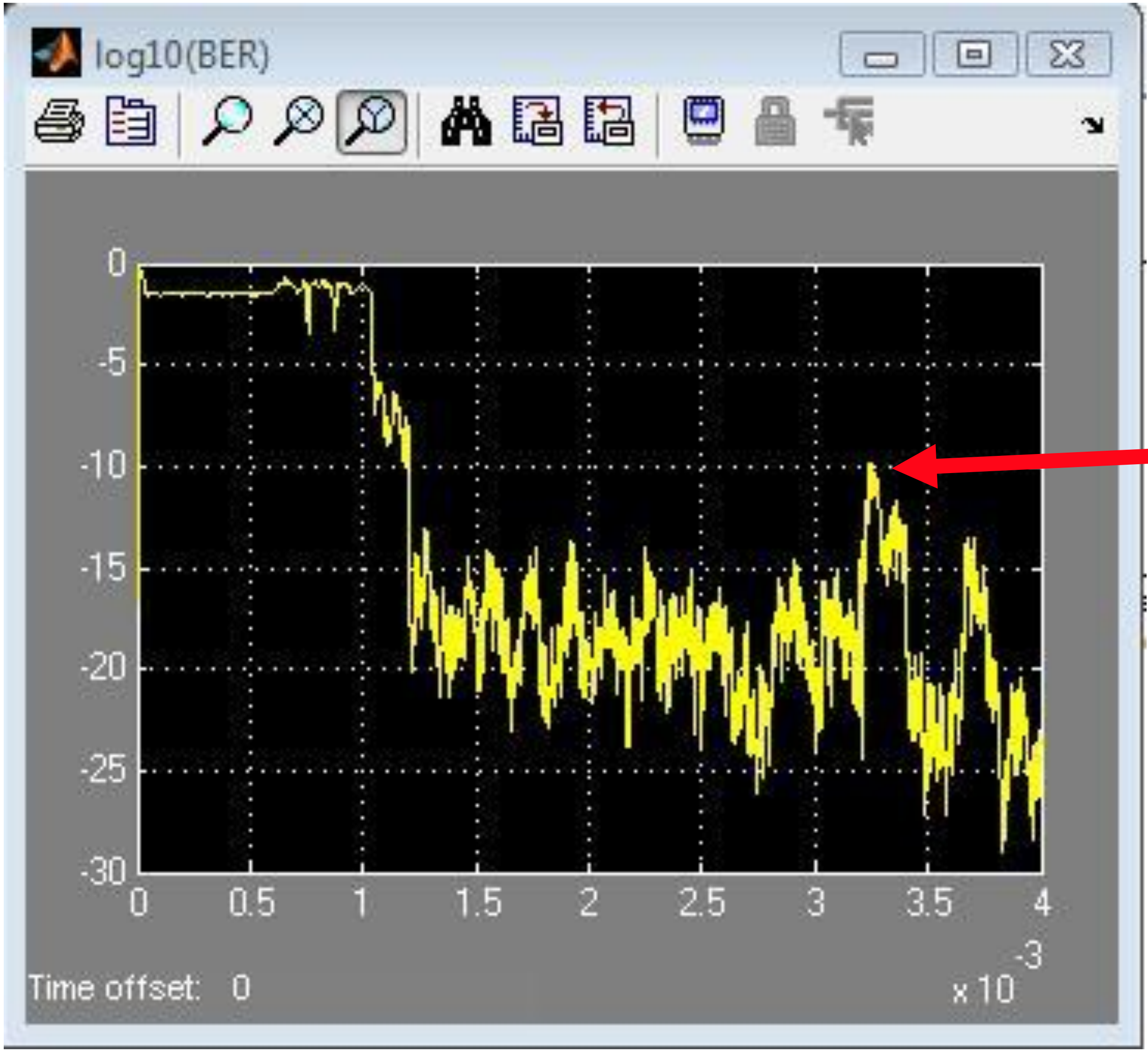


```
function y = fcn(u)
%#eml

y = erfc(u);
```



BIT ERROR RATE



What is this?

FALSE DETECTION CANCELLATION

Types of false detection

- Weaker form: i and q signals at the same channel exchange and one of them has opposite sign (no information loss)
- Stronger form: signals at different channels coincide (information loss)

Reason of false detection: Rotation of different equalizer coefficients without having a fixed angle difference between them

Appearance: Sudden increase in BER

Defense: Compensating rotations with fixed angle difference between different equalizer channels

NEW CONCEPT OF FALSE DETECTION CANCELLATION

Restriction for rotation of weighting factors in neighbouring channels

Ideal case: $w_{11}=1$, $w_{12}=j$

Rotation is allowed with nearly 90º phase difference

Detection of phase difference: _ $\delta = \left|\frac{w_{12} - jw_{11}}{w_{12} + jw_{11}}\right| * 2$

Restriction: $\delta < K$

Limiting cases: if $w_{12} = jw_{11}$ then $\delta = 0$

if $w_{12} = -jw_{11}$ then $\delta \to \infty$

r_1
r_2

Receiver
(equalizer)

x_1
x_2

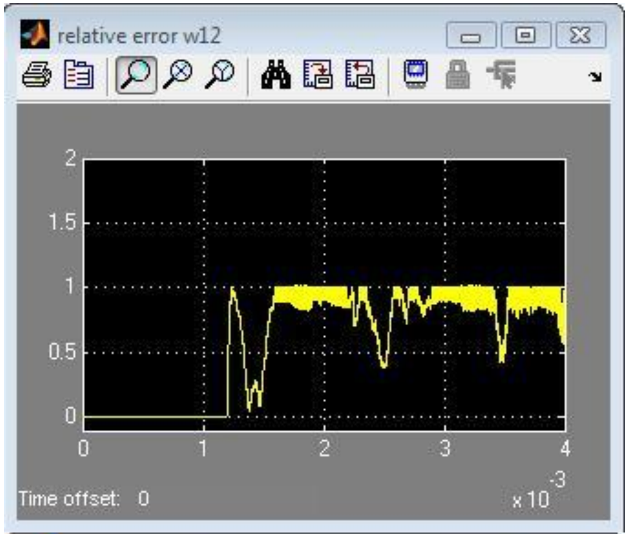
good locking:

$$\underline{\hat{x}} = \frac{1}{2}\cdot\begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix}\cdot\underline{r}$$

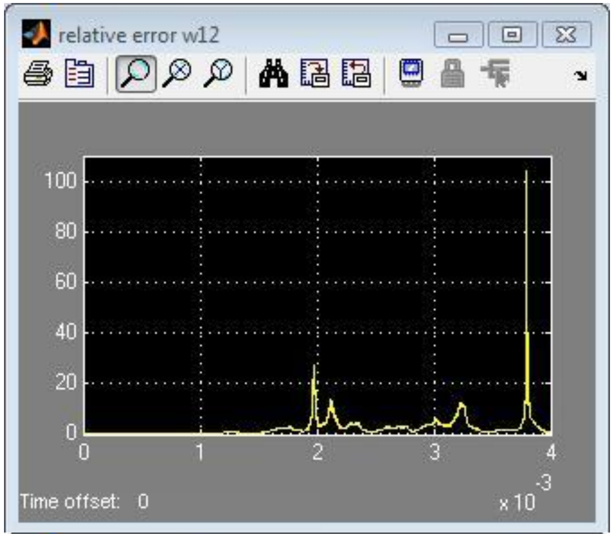
false locking:

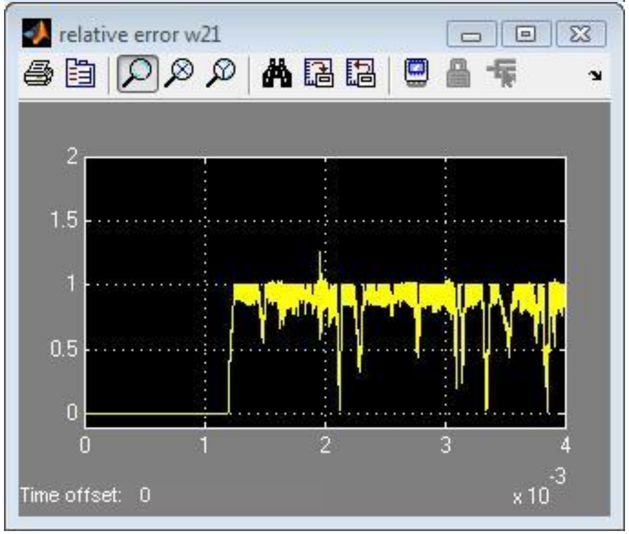
$$\underline{\hat{x}} = \frac{1}{2}\cdot\begin{pmatrix} 1 & j \\ -j & 1 \end{pmatrix}\cdot\underline{r}$$

COEFFICIENT RESTRICTION WITH MEASURED DATA

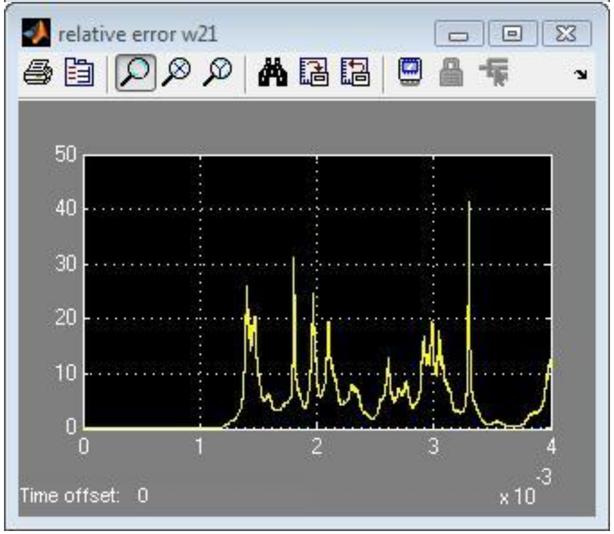


cancellation on

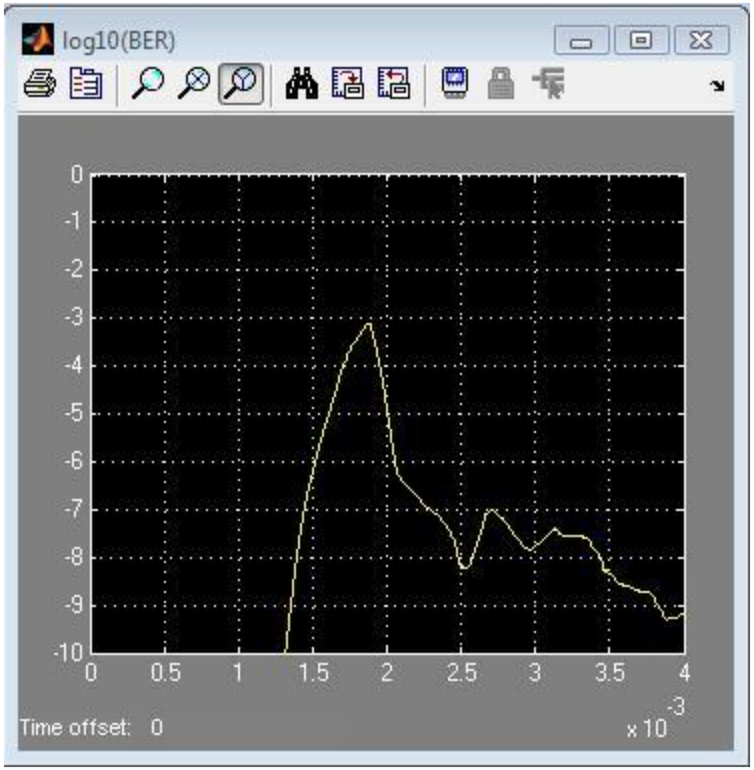




cancellation off

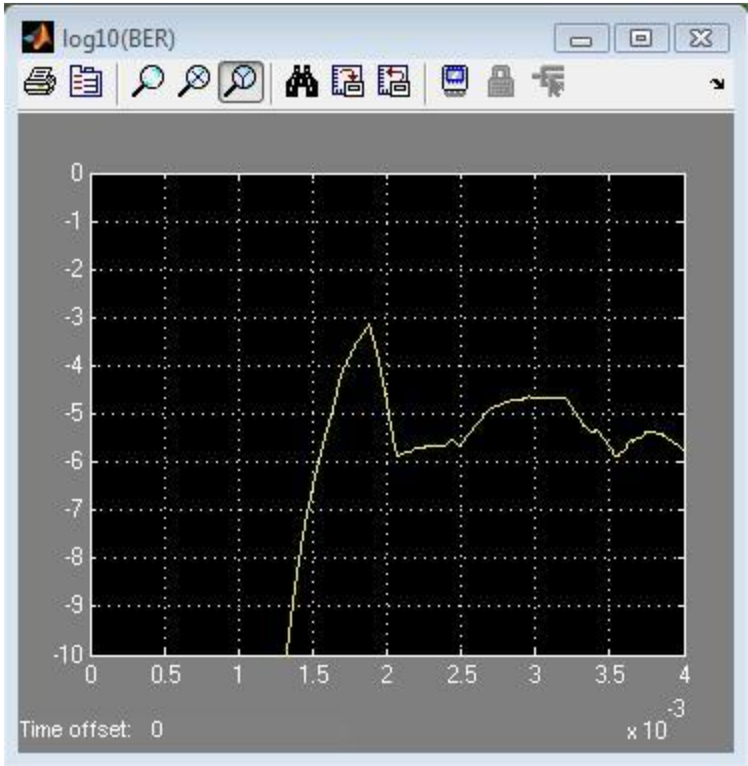


BIT ERROR RATE, MEAS. NO. 4



cancellation on

cancellation off



OBSERVATIONS

- False detection cancellation does not necessarily result in worse bit error rate
- If bit error rate is worse then it is still acceptable
- Advantage: Much simpler than earlier ideas, fits better for FPGA realization
- Still needs to be verified, improved

CONCLUSIONS

- A 2x2 receiver was shown based on FFT approach. All rotations were intended to be compensated before the equalizer
- In practice, not all rotations are compensated and rotated equalizer coefficients are required, resulting in false detection. To eliminate this effect, a method for false detection cancellation was shown

KÖSZÖNET

Vámos Ábelnek és Dr. Verebély Pálnak, akik ezt a projectet lehetővé tették.

Q&A