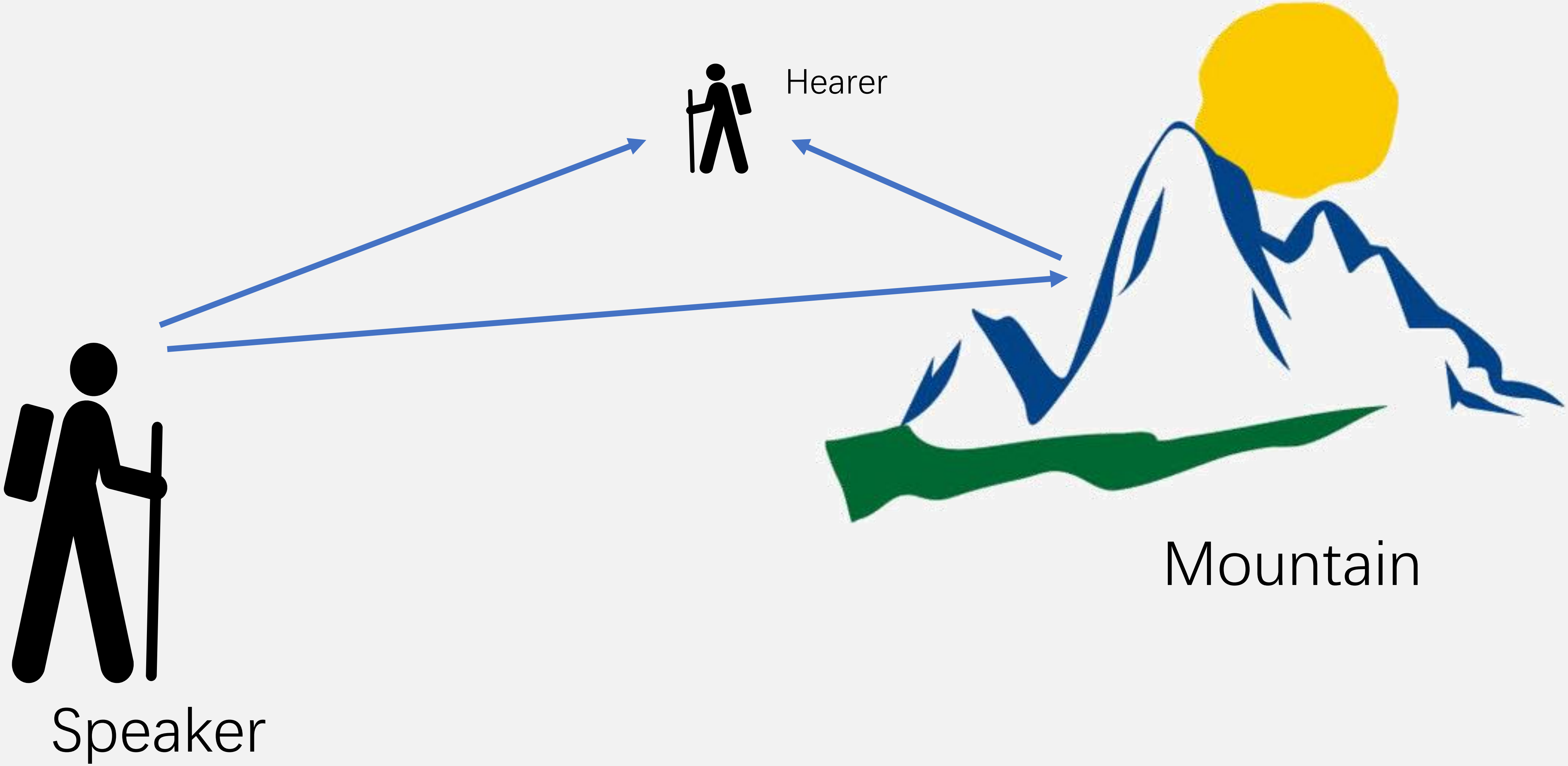
无线通信实验在线开放课程

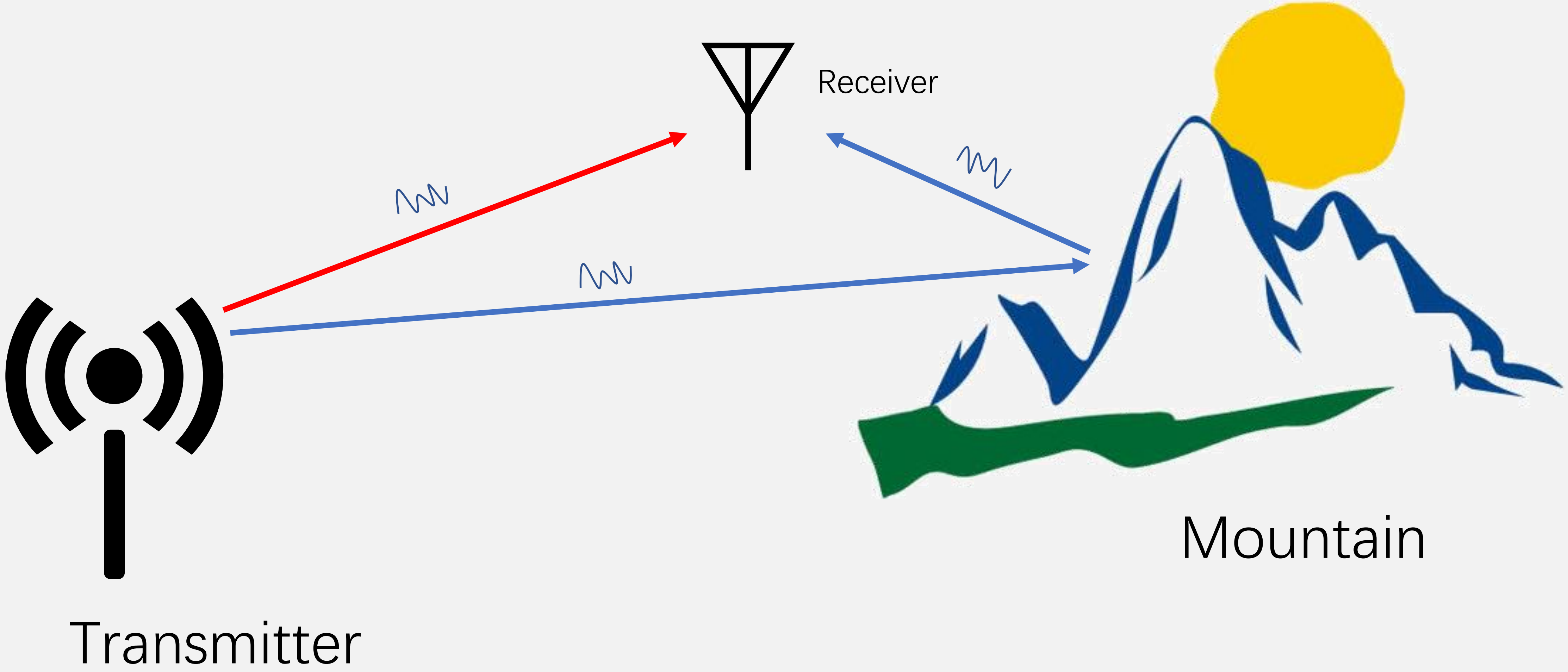
主讲人：吴光 博士

广东省教学质量工程建设项目

Echo



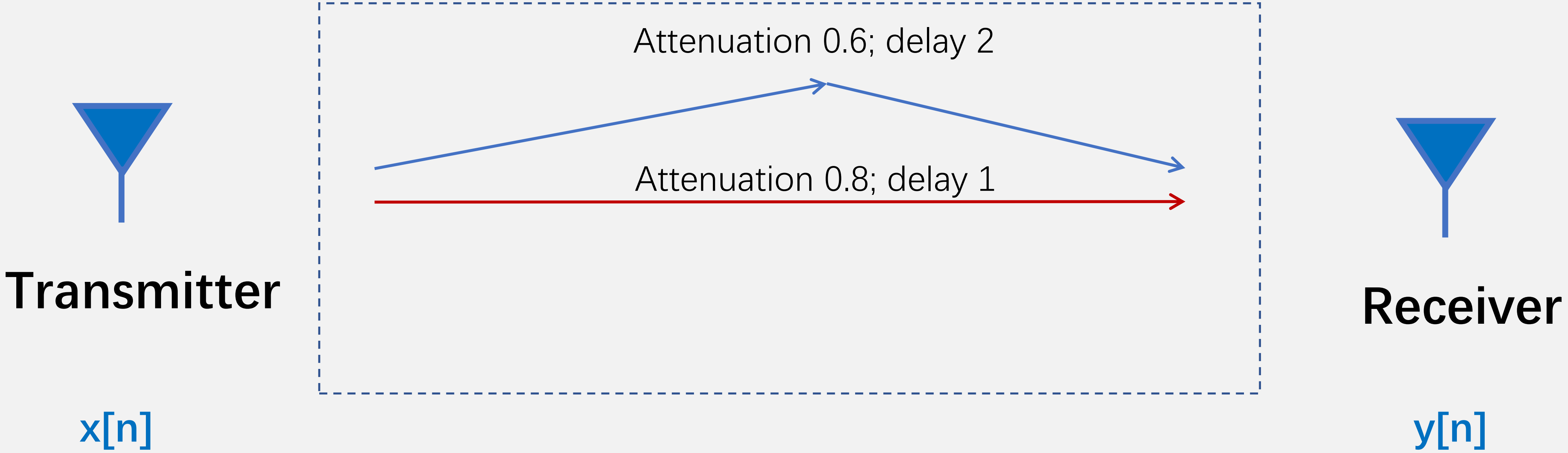
Multipath Propagation



Introduction

$y[n] = 0.8\, x[n-1] + 0.6\, x[n-2]$

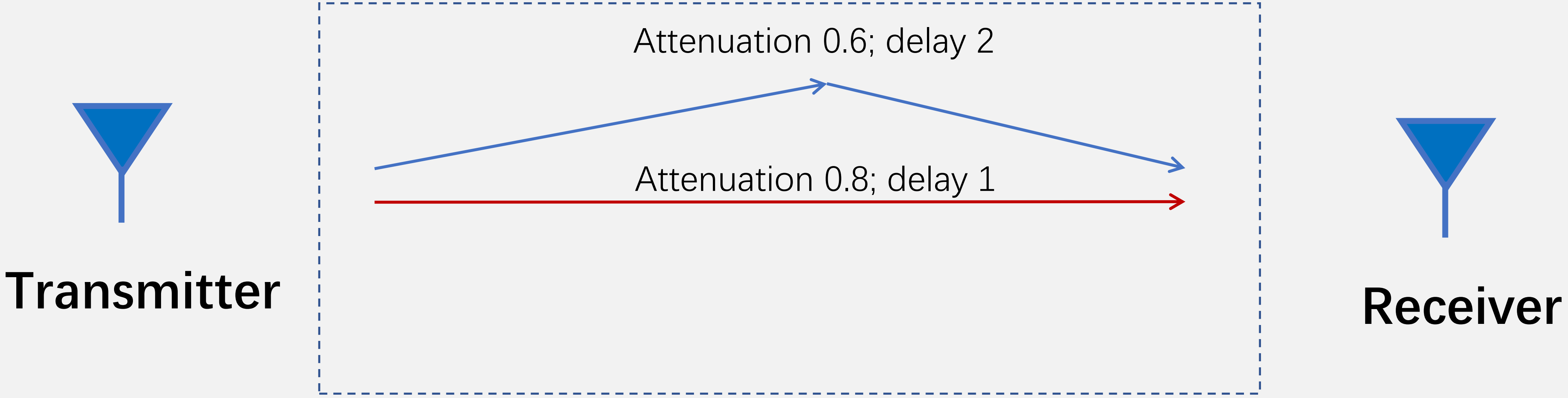
$h1[n] = 0.8\, \delta[n-1] + 0.6\, \delta[n-2]$



$x[n] * h1[n] = y[n]$

$y[n] = 0.8\,x[n-1] + 0.6\,x[n-2]$

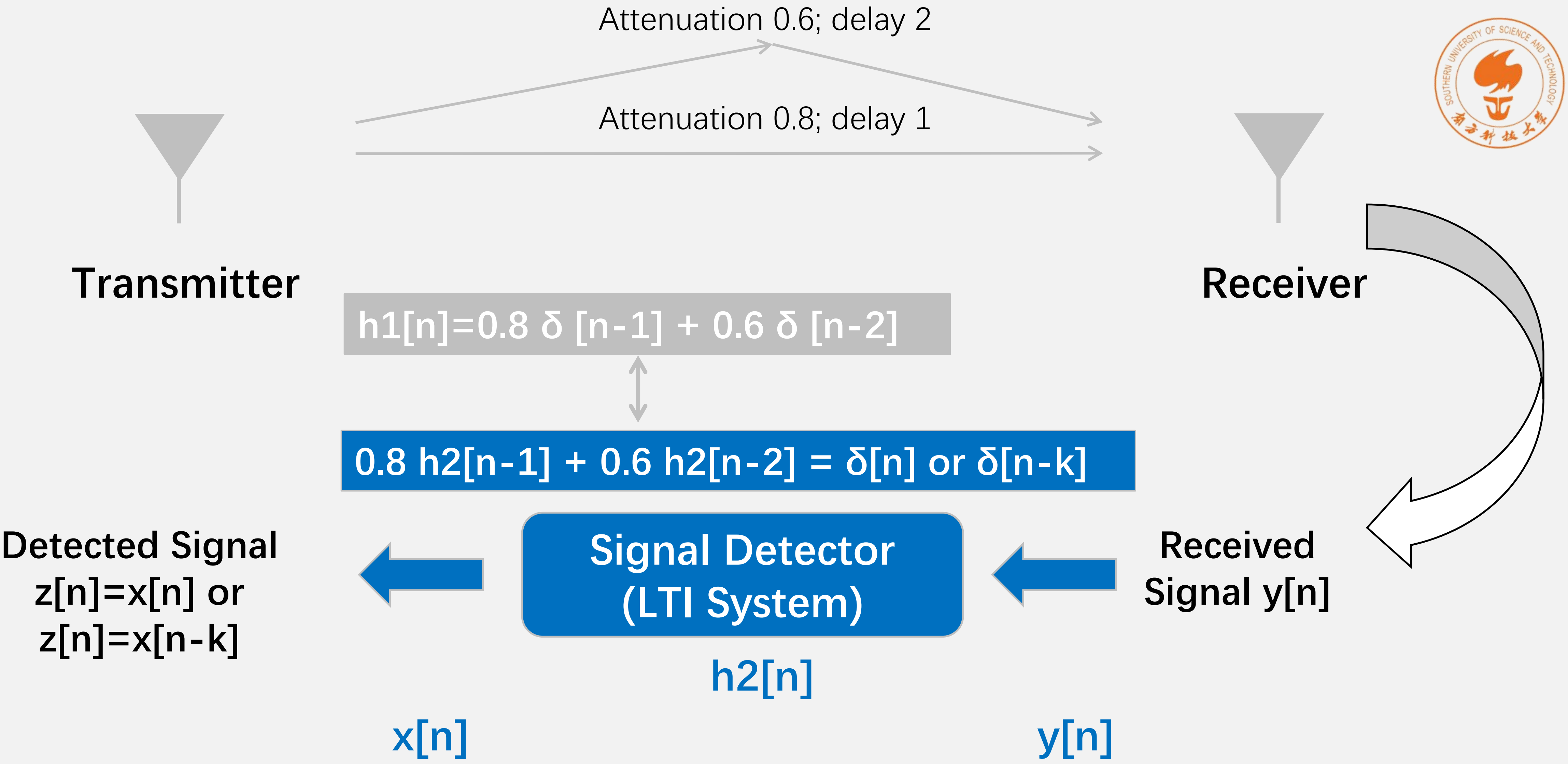
$h1[n] = 0.8\,\delta[n-1] + 0.6\,\delta[n-2]$

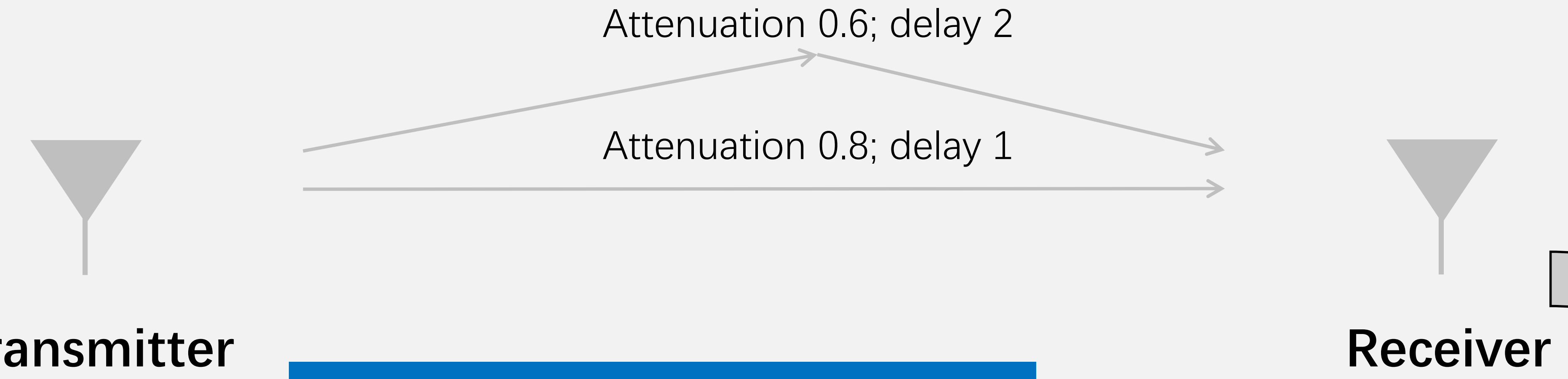


$x[n]$

$y[n]$

$x[n]*h1[n]=y[n]$


Attenuation 0.6; delay 2
Attenuation 0.8; delay 1
Transmitter
Receiver
h1[n]=0.8 δ [n-1] + 0.6 δ [n-2]
0.8 h2[n-1] + 0.6 h2[n-2] = δ[n] or δ[n-k]
Detected Signal
z[n]=x[n] or
z[n]=x[n-k]
Signal Detector
(LTI System)
Received
Signal y[n]
h2[n]
x[n]
y[n]



$h1[n]=0.8\,\delta[n-1] + 0.6\,\delta[n-2]$

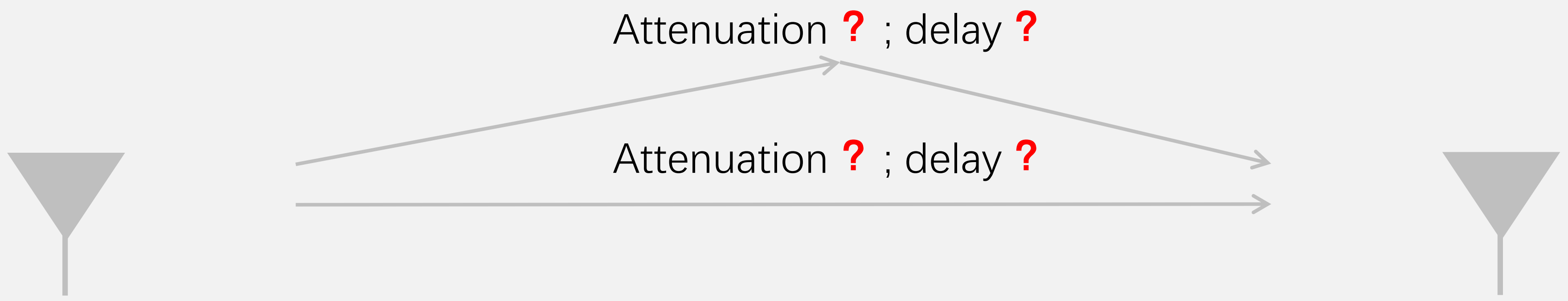
$\updownarrow$

$0.8\,h2[n-1] + 0.6\,h2[n-2] = \delta[n]$ or $\delta[n-k]$

Detected Signal $z[n]=x[n]$ or $z[n]=x[n-k]$ ← Signal Detector (LTI System) ← Received Signal $y[n]$

Impulse response: $\boxed{h2[n] * h1[n] = \delta[n] \text{ or } \delta[n-k]}$

Difference Equation: $\boxed{0.8z[n-1] + 0.6z[n-2] = y[n]}$



Transmitter **Receiver**

$h1[n]=0.8\,\delta[n-1] + 0.6\,\delta[n-2]$

$0.8\,h2[n-1] + 0.6\,h2[n-2] = \delta[n]$ or $\delta[n-k]$

Detected Signal
$z[n]=x[n]$ or
$z[n]=x[n-k]$

Signal Detector
(LTI System)

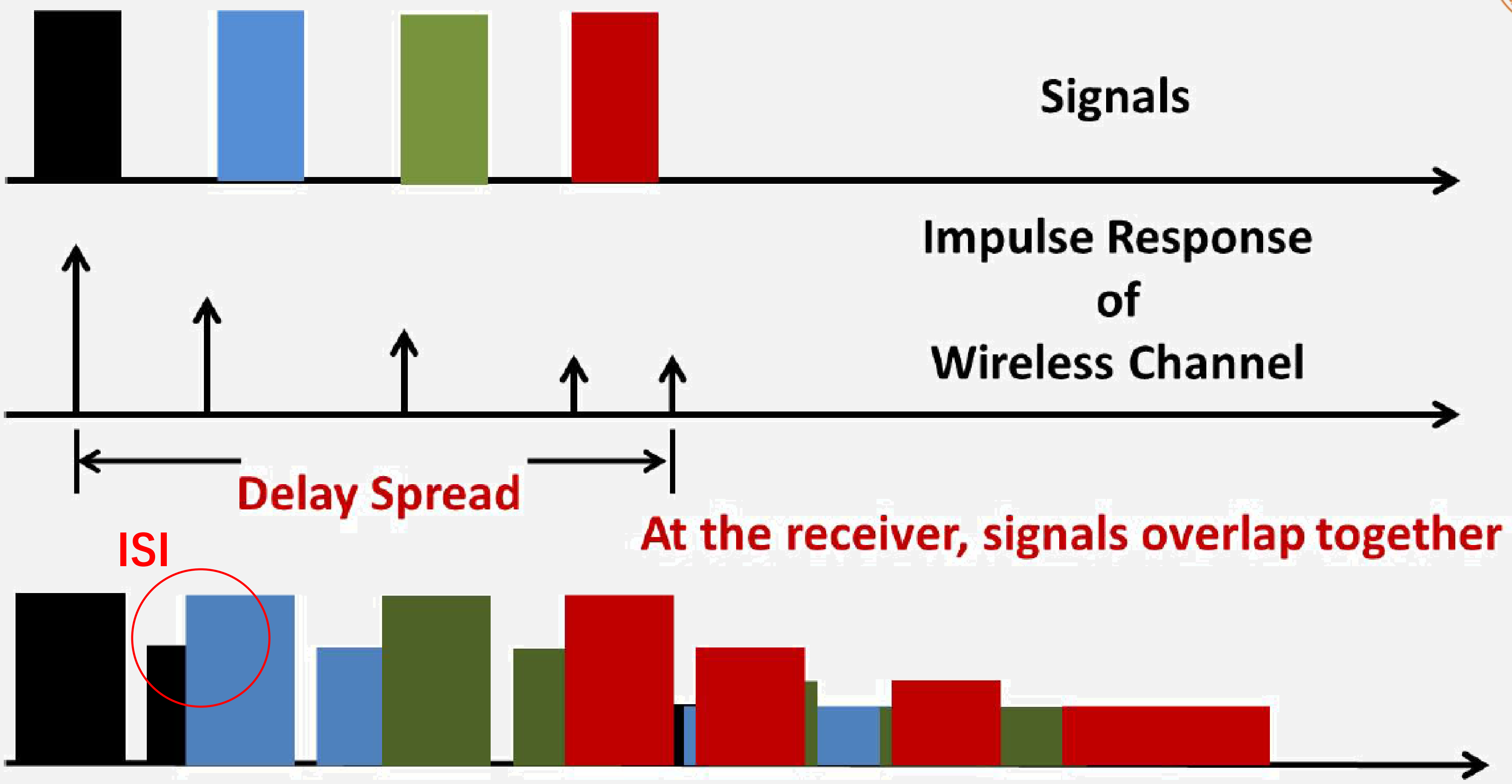
Received Signal $y[n]$

Impulse response: $h2[n] * h1[n] = \delta[n]$ or $\delta[n-k]$

Difference Equation: ? $z[n-?]$ + ? $z[n-?]$ $= y[n]$

$$x[n]*h1[n]=t[n]$$

Frequency Selective Channel

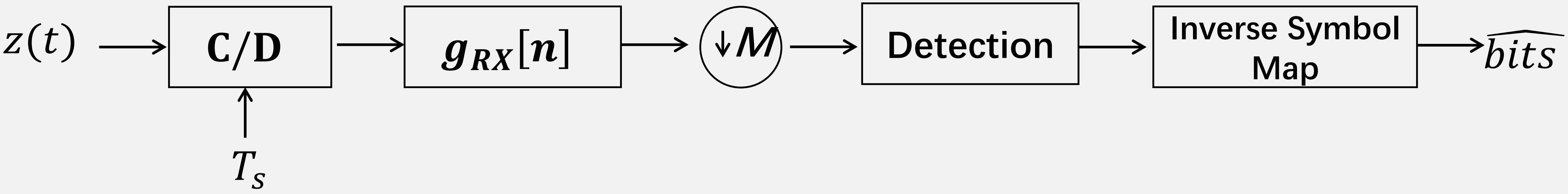

Signals
Impulse Response
of
Wireless Channel
Delay Spread
At the receiver, signals overlap together
ISI

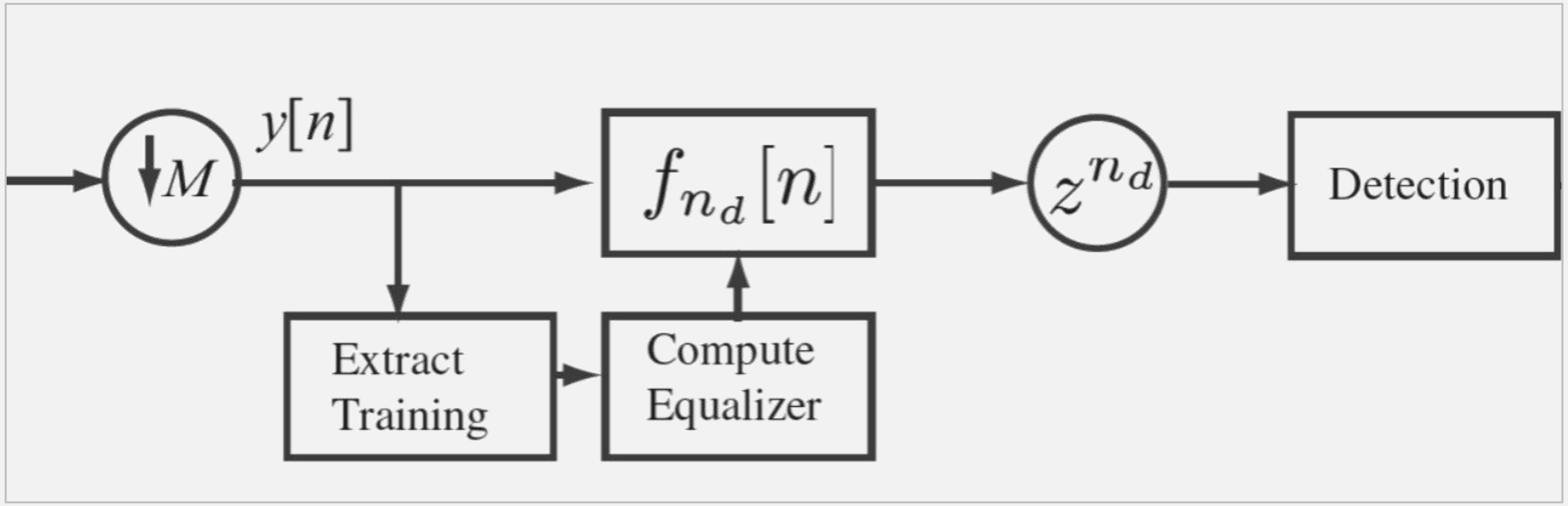
Channel Model

AWGN Frequency Selective Channel

$$\boxed{z(t) = \alpha_0 e^{j\varphi_0} x(t-\tau_0) + \alpha_1 e^{j\varphi_1} x(t-\tau_1) + v(t)}$$

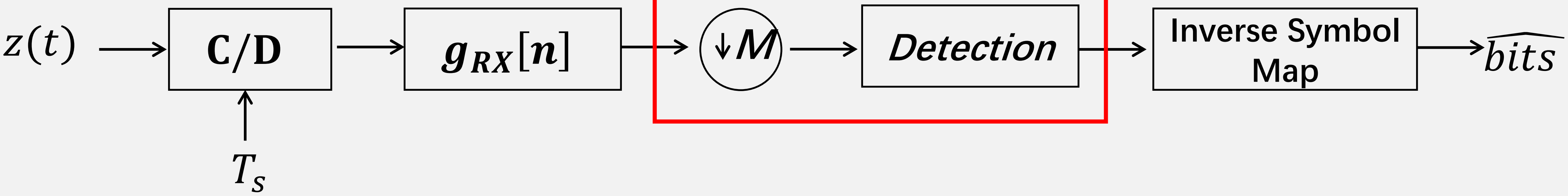
Receiver





↓M
y[n]
$f_{n_d}[n]$
z^{n_d}
Detection
Extract Training
Compute Equalizer

Receiver



$z(t)$
C/D
T_s
$g_{RX}[n]$
↓M
Detection
Inverse Symbol Map
$\widehat{bits}$

Channel estimate

Equalization

Frequency Offset Correction

Frame Synchronization

Zero Pad	Channel estimate, Equalization, Frequency Offset Correction, Frame Synchronization	Payload	Zero Pad
Packet Head	Training sequences	Key bits sequences	Guard band

Step1: $h1[n]$

Step2: $h2[n]$

Step3: $y[n]*h2[n]=x[n]*\underline{h1[n]*h2[n]}$

$\delta[n]$ or $\delta[n-k]$

Lab 13 : Channel Estimation and Equalization

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Algorithm Analysis and Verification

1. Channel Estimation
2. Indirect Equalizer Analysis
3. Algorithm Simulation
4. USRP Experiments
5. Discussion and Conclusion

Channel Estimation

$$\mathbf{Ax} = \mathbf{b}$$

$$\mathbf{Ax} = \mathbf{b}$$

$$\mathrm{N} = \mathrm{M} \qquad\qquad \mathbf{x} = \mathbf{A}^{-1}\mathbf{b}$$

$$\min ||\mathbf{Ax} - \mathbf{b}||^2$$

$\mathrm{N} > \mathrm{M}$

$$\mathrm{x}_{\mathrm{LS}} = (\mathbf{A}^*\mathbf{A})^{-1}\mathbf{A}^*\mathbf{b}$$

$$s[n] = t[n], n = 0,1, \dots, N_t - 1$$

$$y[n] = \sum_{l=0}^{L} s[l]h[n-l] + v[n]$$

$$y[0] = s[0]h[0] + v[0]$$

$$y[1] = s[0]h[1] + s[1]h[0] + v[1]$$

$$\dots$$

$$s[n] = t[n], n = 0,1, \dots, N_t - 1$$

$$y[n] = \sum_{l=0}^{L} s[l]h[n-l] + v[n]$$

$$y[n] = \sum_{l=0}^{L} h[l]t[n-l] + v[n]$$

$$s[n] = t[n], n = 0,1, \dots, N_t - 1$$

$$\{\hat{h}[0], \hat{h}[1], \dots, \hat{h}[L]\}$$

$$= \underset{\{h[0], h[1], \dots, h[L]\}}{\operatorname{argmin}} \sum_{n=L}^{N_t-1} ||y[n] - \sum_{l=0}^{L} h[l]t[n-l]\ ||^2$$

$$\underbrace{\begin{bmatrix} y[L] \\ y[L+1] \\ \vdots \\ y[N_t-1] \end{bmatrix}}_{\boldsymbol{y}} = \underbrace{\begin{bmatrix} t[L] & \cdots & t[0] \\ t[L+1] & \cdots & t[1] \\ \vdots & \ddots & \vdots \\ t[N_t-1] & \cdots & t[N_t-1-L] \end{bmatrix}}_{\boldsymbol{T}} \underbrace{\begin{bmatrix} h[0] \\ h[1] \\ \vdots \\ h[L] \end{bmatrix}}_{\boldsymbol{h}} + \underbrace{\begin{bmatrix} v[L] \\ v[L+1] \\ \vdots \\ v[N_t-1] \end{bmatrix}}_{\boldsymbol{v}}$$

$$\underbrace{\begin{bmatrix} y[L] \\ y[L+1] \\ \vdots \\ y[N_t-1] \end{bmatrix}}_{\boldsymbol{y}} = \underbrace{\begin{bmatrix} t[L] & \cdots & t[0] \\ t[L+1] & \cdots & t[1] \\ \vdots & \ddots & \vdots \\ t[N_t-1] & \cdots & t[N_t-1-L] \end{bmatrix}}_{\boldsymbol{T}} \underbrace{\begin{bmatrix} h[0] \\ h[1] \\ \vdots \\ h[L] \end{bmatrix}}_{\boldsymbol{h}} + \underbrace{\begin{bmatrix} v[L] \\ v[L+1] \\ \vdots \\ v[N_t-1] \end{bmatrix}}_{\boldsymbol{v}}$$

$$\boldsymbol{y} = \boldsymbol{T}\boldsymbol{h} + \boldsymbol{v} \qquad \mathrm{h}_{\mathrm{LS}} = (\mathbf{T}^*\mathbf{T})^{-1}\mathbf{T}^*\mathrm{y}$$

$$\underbrace{\begin{bmatrix} y[L] \\ y[L+1] \\ \vdots \\ y[N_t-1] \end{bmatrix}}_{\boldsymbol{y}} = \underbrace{\begin{bmatrix} t[L] & \cdots & t[0] \\ t[L+1] & \cdots & t[1] \\ \vdots & \ddots & \vdots \\ t[N_t-1] & \cdots & t[N_t-1-L] \end{bmatrix}}_{\boldsymbol{T}} \underbrace{\begin{bmatrix} h[0] \\ h[1] \\ \vdots \\ h[L] \end{bmatrix}}_{\boldsymbol{h}} + \underbrace{\begin{bmatrix} v[L] \\ v[L+1] \\ \vdots \\ v[N_t-1] \end{bmatrix}}_{\boldsymbol{v}}$$

$$\boldsymbol{y} = \boldsymbol{T}\boldsymbol{h} + \boldsymbol{v} \qquad \mathrm{h}_{\mathrm{LS}} = (\mathbf{T}^*\mathbf{T})^{-1}\mathbf{T}^*\mathrm{y}$$

$$N_t - L \geq L + 1 \qquad N_t \geq 2L + 1$$

Algorithm Analysis and Verification

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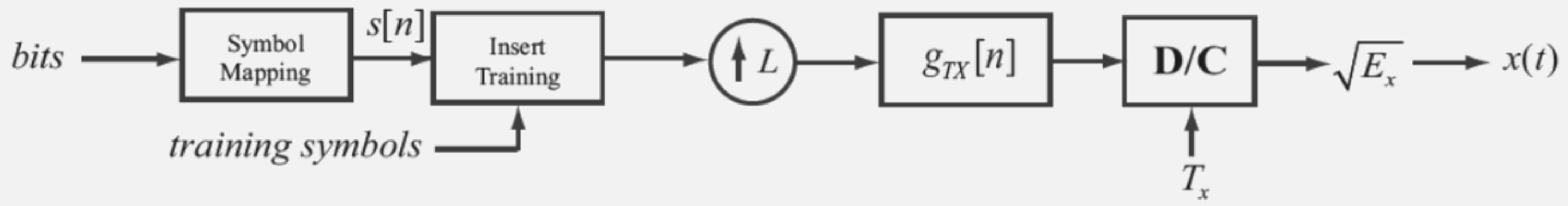
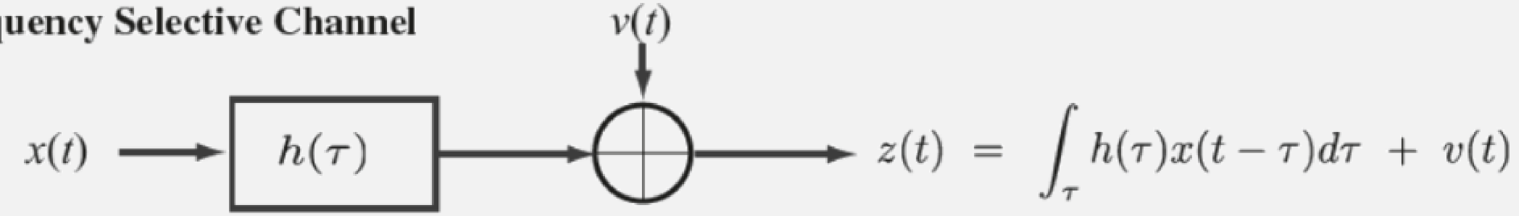
Programming for Channel Estimation

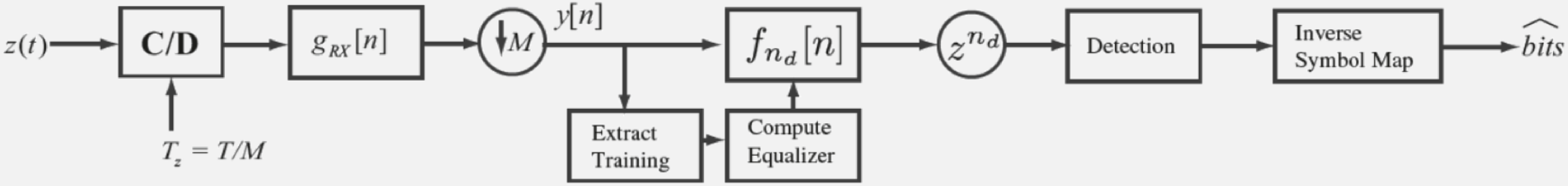
Transmitter

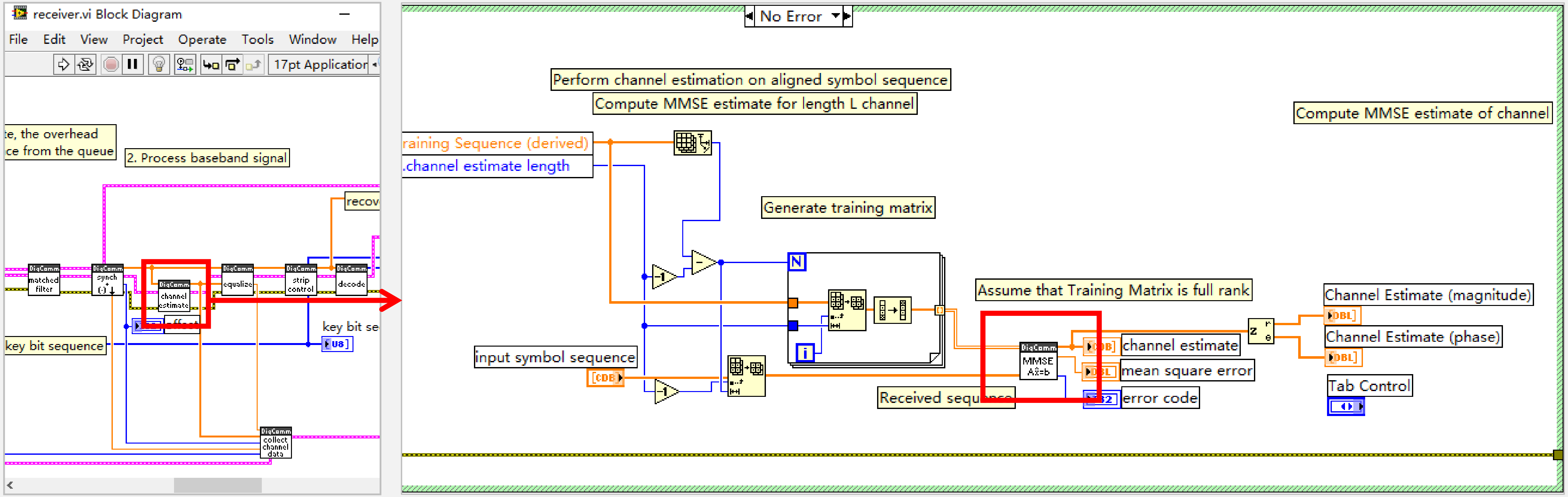


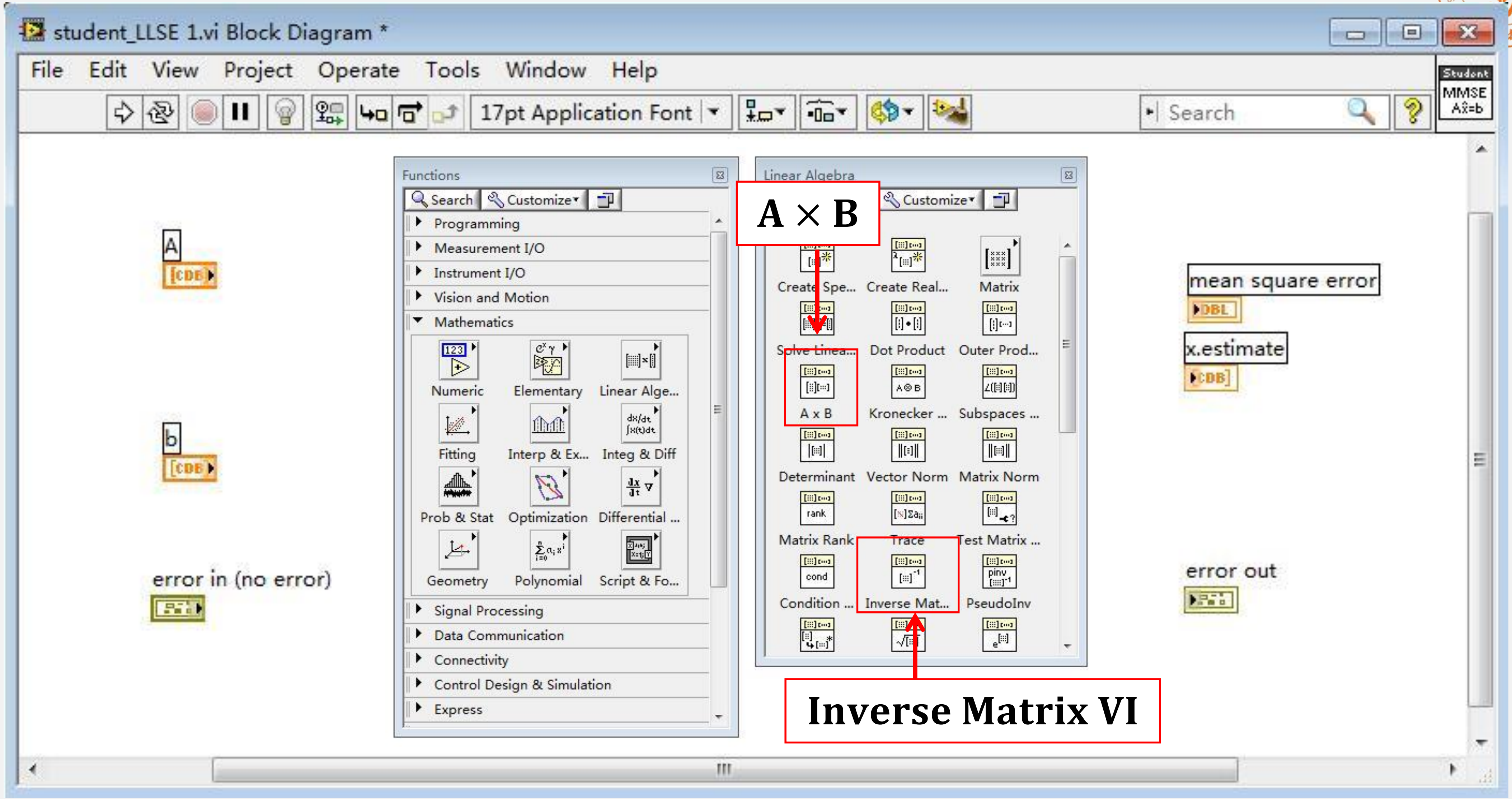
AWGN Frequency Selective Channel



Receiver




receiver.vi Block Diagram
File Edit View Project Operate Tools Window Help
17pt Application
te, the overhead
ce from the queue
2. Process baseband signal
recov
matched filter
synch
channel estimate
equalize
strip control
decode
key bit sequence
key bit se
U8
collect channel data
No Error
Perform channel estimation on aligned symbol sequence
Compute MMSE estimate for length L channel
raining Sequence (derived)
.channel estimate length
Generate training matrix
N
i
input symbol sequence
CDB
Assume that Training Matrix is full rank
MMSE
channel estimate
mean square error
error code
Received sequence
Compute MMSE estimate of channel
Channel Estimate (magnitude)
DBL
Channel Estimate (phase)
DBL
Tab Control



student_LLSE 1.vi Block Diagram *
File Edit View Project Operate Tools Window Help
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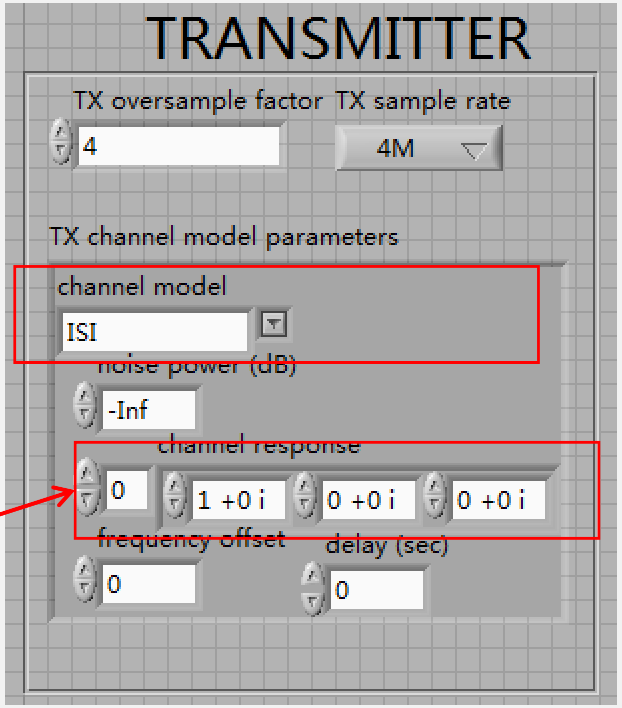
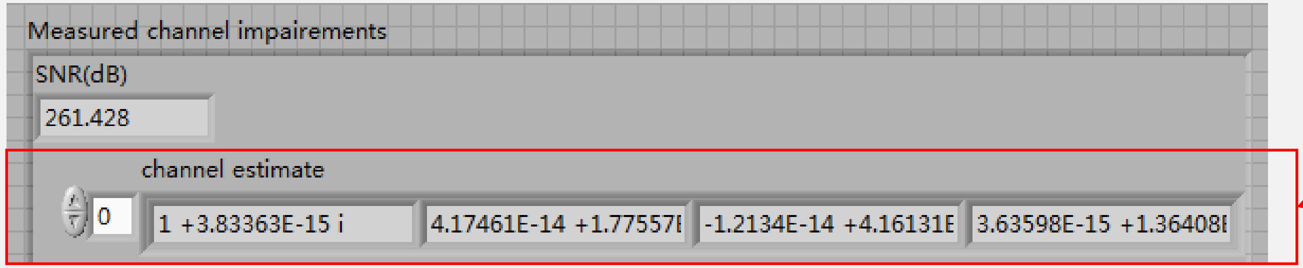
Search
Student MMSE Ax̂=b
A
b
error in (no error)
Functions
Search
Customize
Programming
Measurement I/O
Instrument I/O
Vision and Motion
Mathematics
Numeric
Elementary
Linear Alge...
Fitting
Interp & Ex...
Integ & Diff
Prob & Stat
Optimization
Differential ...
Geometry
Polynomial
Script & Fo...
Signal Processing
Data Communication
Connectivity
Control Design & Simulation
Express
Linear Algebra
A × B
Customize
Create Spe...
Create Real...
Matrix
Solve Linea...
Dot Product
Outer Prod...
A x B
Kronecker ...
Subspaces ...
Determinant
Vector Norm
Matrix Norm
Matrix Rank
Trace
Test Matrix ...
Condition ...
Inverse Mat...
PseudoInv
Inverse Matrix VI
mean square error
DBL
x.estimate
error out

Simulation setup

Test your block diagram with these parameters!

Set the channel model: ISI

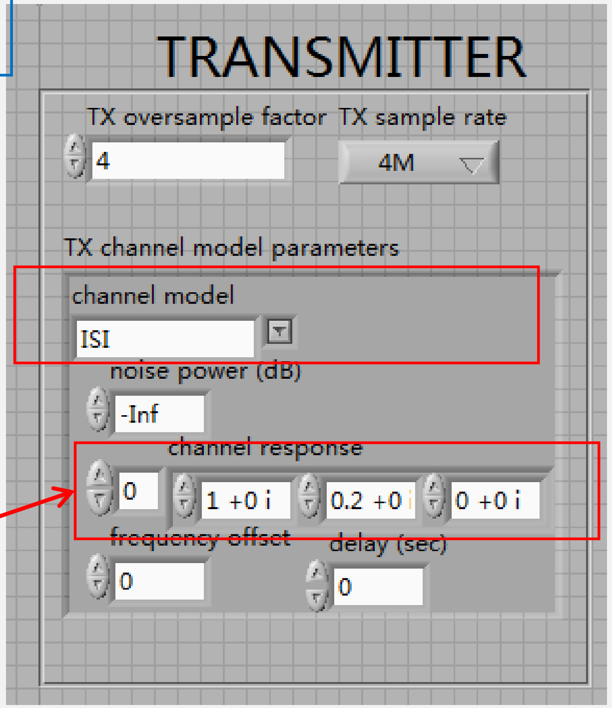


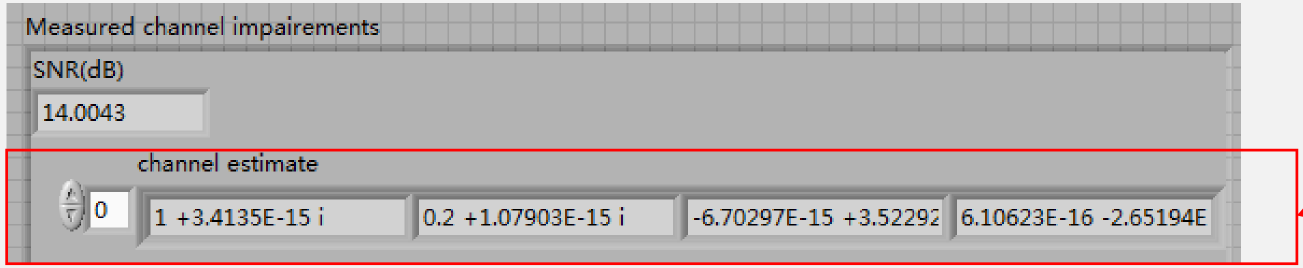


Simulation setup

Test your block diagram with these parameters!

Configure the channel model: ISI





Demo: Linear Equalization

$$z[n] = \sum_{l=0}^{L_f} f_{n_d}[l]y[n-l] \approx \hat{s}[n-n_d]$$

$$f_{n_d}(n) * \hat{h}_c(n) = \delta(n-n_d)$$

$$\sum_{l=0}^{L_f} f_{n_d}[l]\hat{h}[n-l] \approx \delta[\mathrm{n}-n_d]$$

$$z[n] = \sum_{l=0}^{L_f} f_{n_d}[l]y[n-l] \approx \hat{s}[n-n_d]$$

$$f_{n_d}(n) * \hat{h}_c(n) = \delta(n-n_d)$$

$$\sum_{l=0}^{L_f} f_{n_d}[l]\hat{h}[n-l] \approx \delta[\mathrm{n}-n_d]$$

$$\underbrace{\begin{bmatrix} \hat{h}[0] & 0 & \cdots & \cdots \\ \hat{h}[1] & \hat{h}[0] & 0 & \cdots \\ \vdots & \ddots & \ddots & \vdots \\ \hat{h}[L] & & & \\ 0 & \hat{h}[L] & \cdots & \cdots \\ \vdots & & & \end{bmatrix}}_{\widehat{\boldsymbol{H}}}$$

$$\underbrace{\begin{bmatrix} \hat{h}[0] & 0 & \cdots & \cdots \\ \hat{h}[1] & \hat{h}[0] & 0 & \cdots \\ \vdots & \ddots & \ddots & \vdots \\ \hat{h}[L] & & & \\ 0 & \hat{h}[L] & \cdots & \cdots \\ \vdots & & & \end{bmatrix}}_{\widehat{\boldsymbol{H}}} \underbrace{\begin{bmatrix} f[0] \\ f[1] \\ \vdots \\ \vdots \\ \vdots \\ f[L_f] \end{bmatrix}}_{\boldsymbol{f}} = \underbrace{\begin{bmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ \vdots \\ 0 \end{bmatrix}}_{\boldsymbol{e}_{n_d}}$$

n_d+1

$$\underbrace{\begin{bmatrix} \hat{h}[0] & 0 & \cdots & \cdots \\ \hat{h}[1] & \hat{h}[0] & 0 & \cdots \\ \vdots & \ddots & \ddots & \vdots \\ \hat{h}[L] & & & \\ 0 & \hat{h}[L] & \cdots & \cdots \\ \vdots & & & \end{bmatrix}}_{\widehat{\boldsymbol{H}}} \underbrace{\begin{bmatrix} f[0] \\ f[1] \\ \vdots \\ \vdots \\ \vdots \\ f[L_f] \end{bmatrix}}_{\boldsymbol{f}} = \underbrace{\begin{bmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ \vdots \\ 0 \end{bmatrix}}_{\boldsymbol{e}_{n_d}}$$

n_d+1

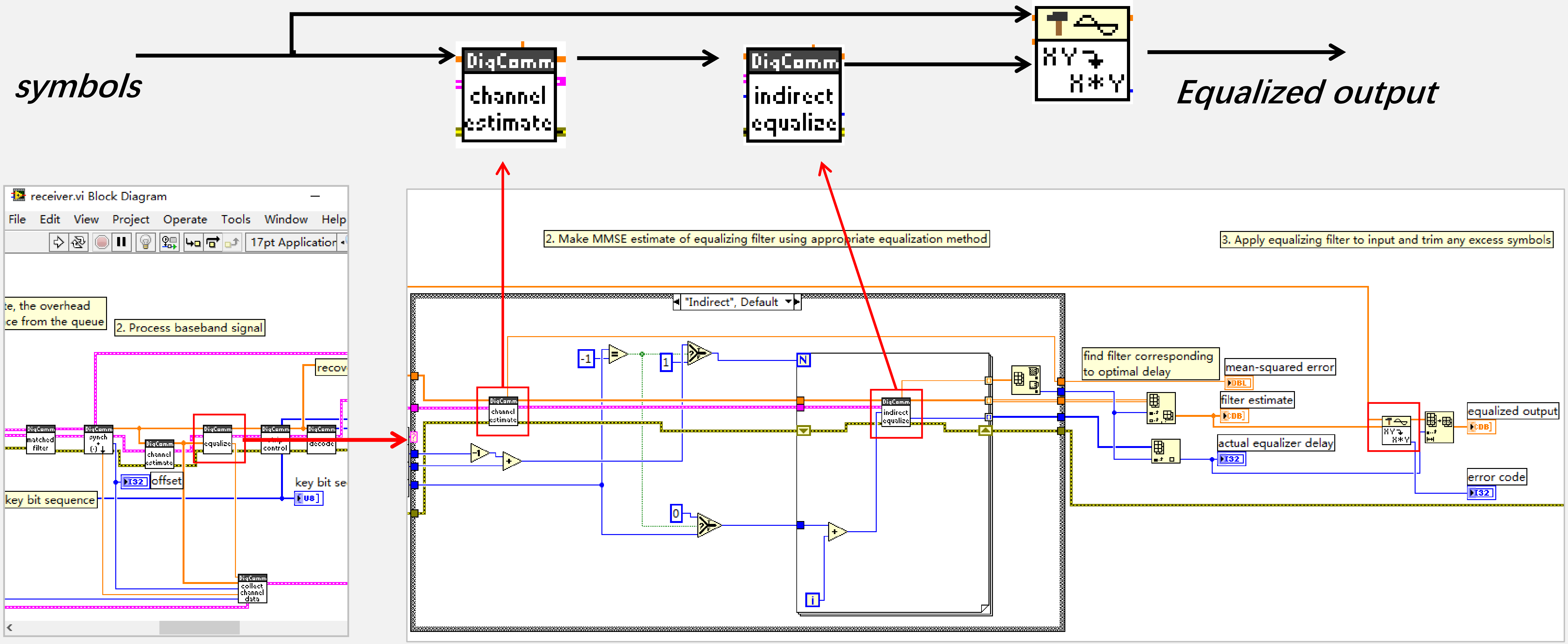
$$\hat{\boldsymbol{f}}\boldsymbol{n_d} = \left(\widehat{\boldsymbol{H}}^*\widehat{\boldsymbol{H}}\right)^{-1}\widehat{\boldsymbol{H}}^*\boldsymbol{e}_{n_d}$$

$$J_f[n_d] = ||\,\widehat{\boldsymbol{H}}\hat{\boldsymbol{f}} - \boldsymbol{e}_{n_d}||^2$$

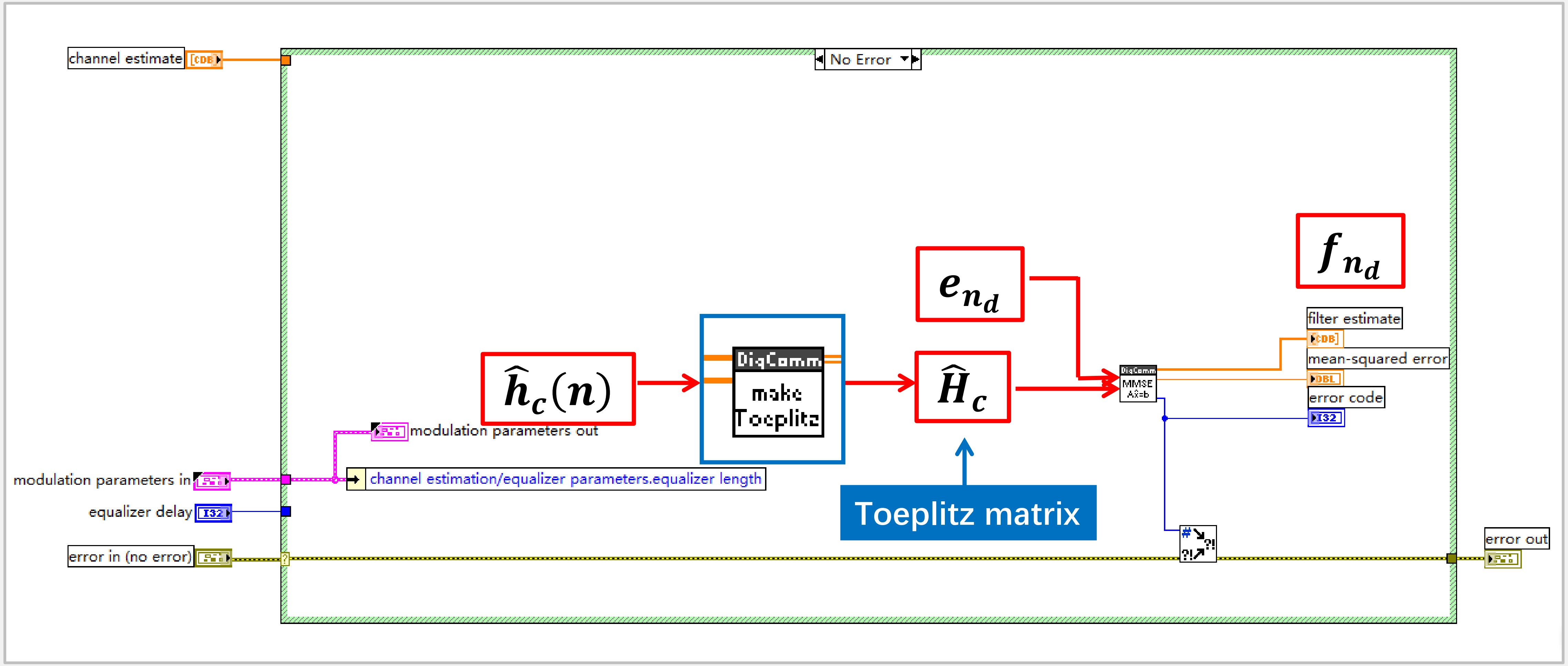
Programming for Equalization

7、均衡编程

Equalizer.vi



Indirect_equalizer.vi



Channel response: $h[0] = 1, h[1] = 0.35e^{j\pi/4}$

Sample rate: 2M

Oversample factor: 20

Noise power: -Inf

Channel est. length: 4

Toeplitz Array

1 -5.39022E-15 i	0 +0 i	0 +0 i	0 +0 i
0.24745 +0.24745 i	1 -5.39022E-15 i	0 +0 i	0 +0 i
-3.51021E-15 +4.06793E-15 i	0.24745 +0.24745 i	1 -5.39022E-15 i	0 +0 i
-8.36831E-15 +1.00614E-16 i	-3.51021E-15 +4.06793E-15 i	0.24745 +0.24745 i	1 -5.39022E-15 i
0 +0 i	-8.36831E-15 +1.00614E-16 i	-3.51021E-15 +4.06793E-15 i	0.24745 +0.24745 i
0 +0 i	0 +0 i	-8.36831E-15 +1.00614E-16 i	-3.51021E-15 +4.06793E-15 i
0 +0 i	0 +0 i	0 +0 i	-8.36831E-15 +1.00614E-16 i

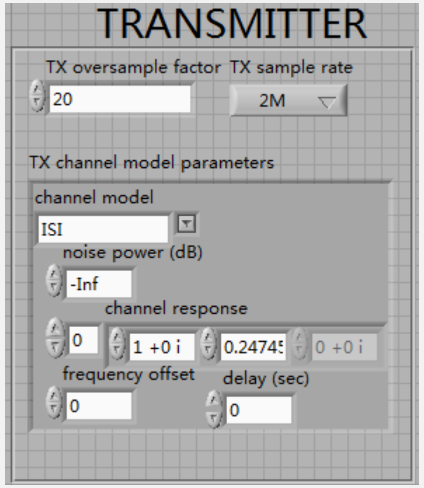
row

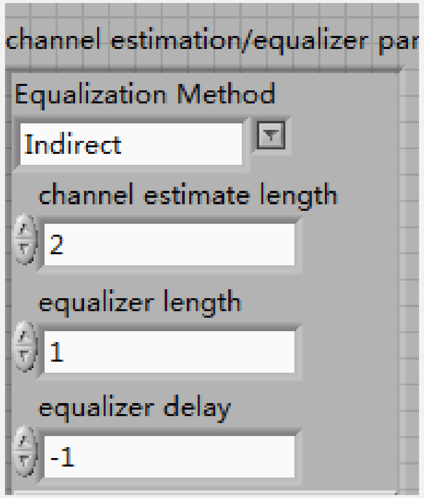
1 -5.39022E-15 i	0 +0 i	0 +0 i	0 +0 i

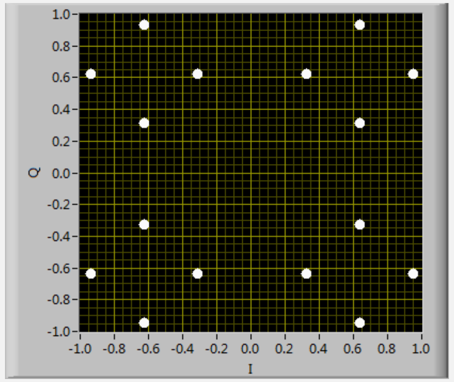
column

1 -5.39022E-15	0.24745 +0.247	-3.51021E-15 +	-8.36831E-15 +	0 +0 i	0 +0 i	0 +0 i

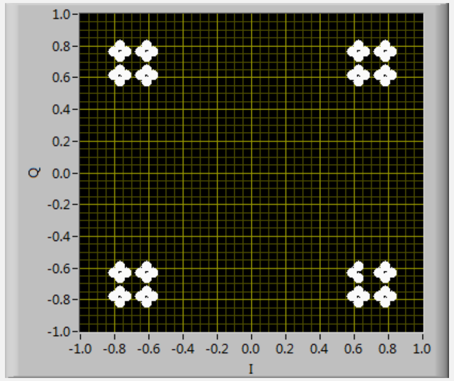
Toeplitz matrix



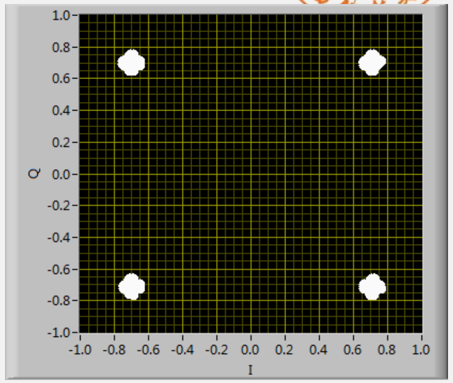




Length=1



Length=2



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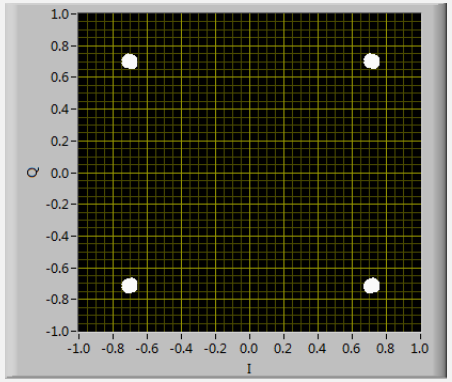

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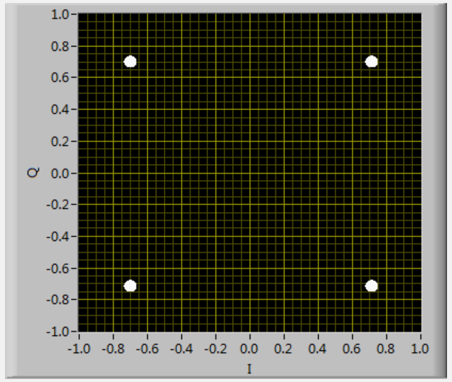

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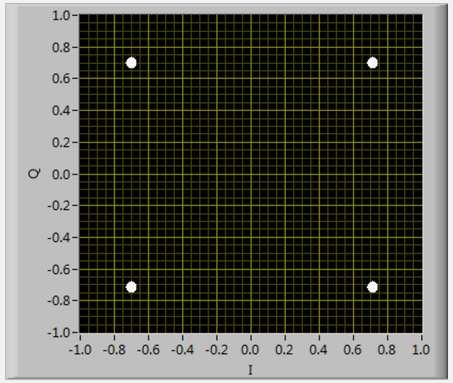

Length=6

Algorithm Analysis and Verification

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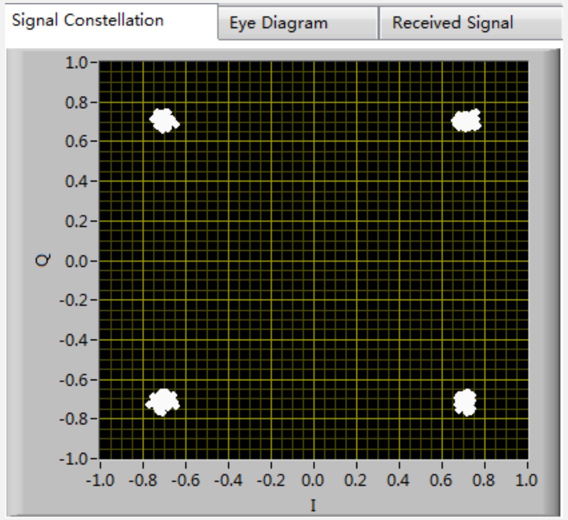
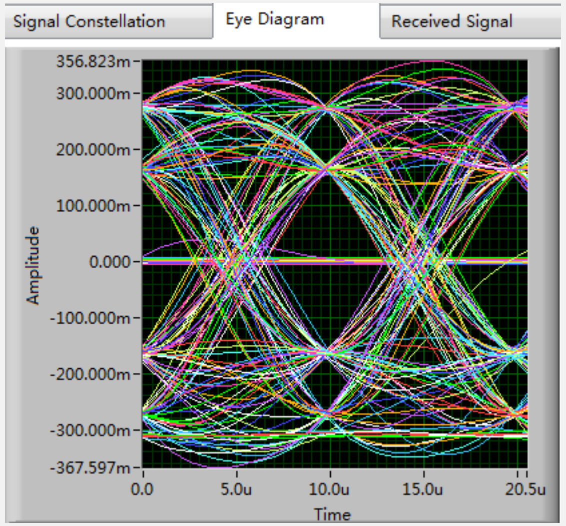
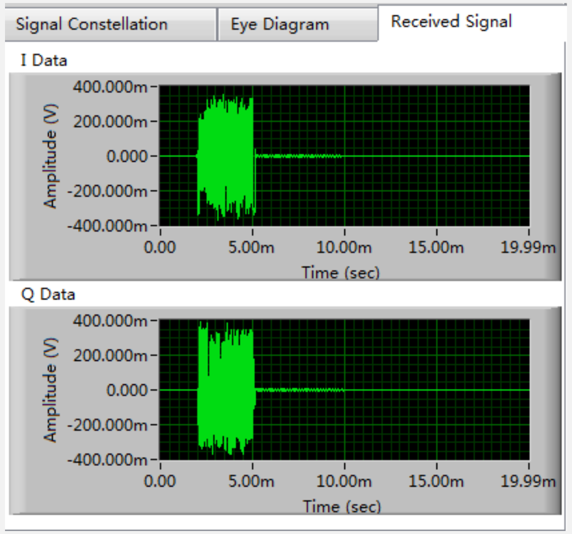
USRP experiment







channel estimation/equalizer parameters

Equalization Method

Direct

channel estimate length

3

equalizer length

1

equalizer delay

-1

(set delay to -1 for equalizer to choose optimal delay)

Measured channel impairements

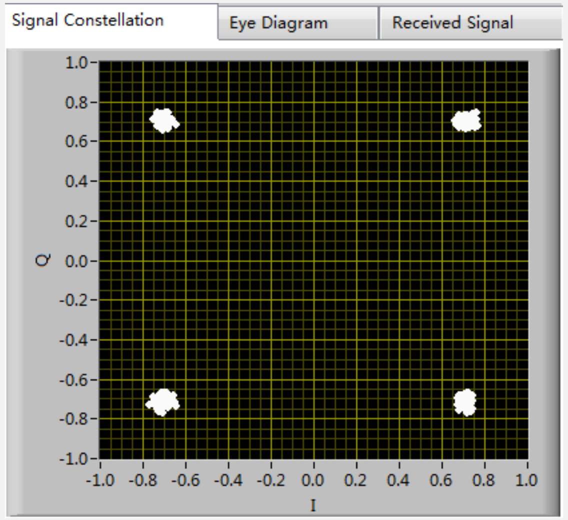
SNR(dB)	freq. offset	delay
17.8897	-3.75422	0.001978

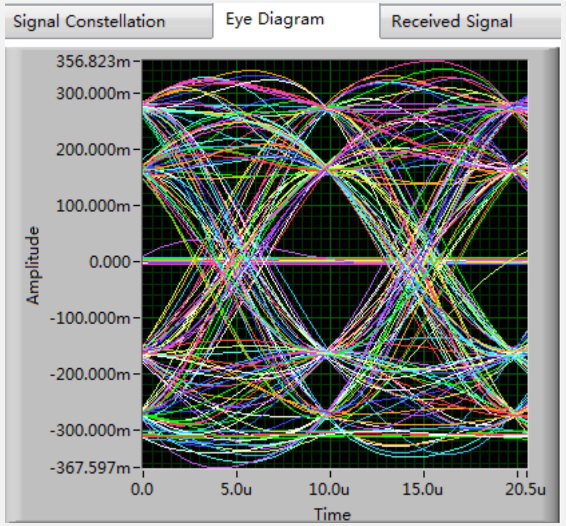
channel estimate

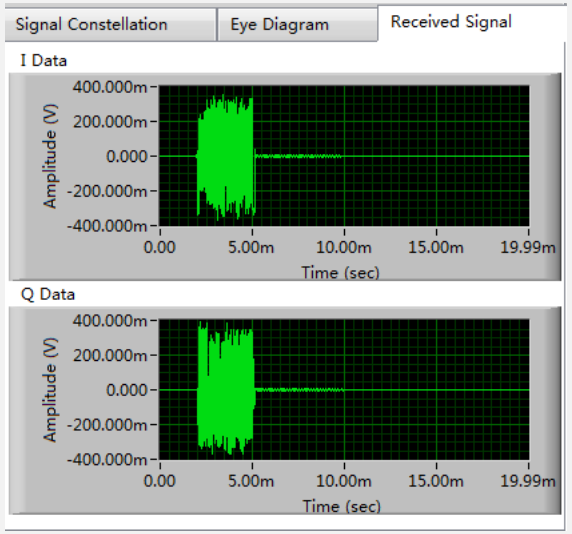
0

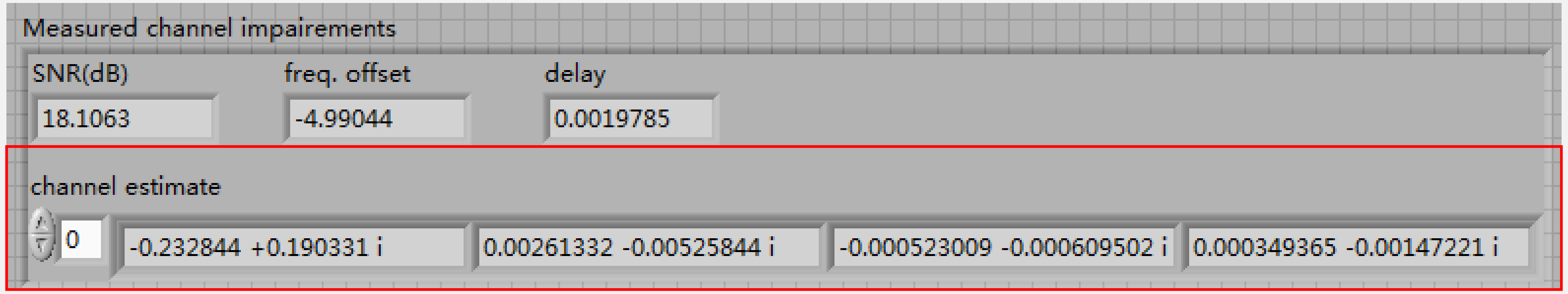
-0.30781 -0.0760347 i	0.00611528 +0.000331755 i	-0.000283157 -0.000255807 i

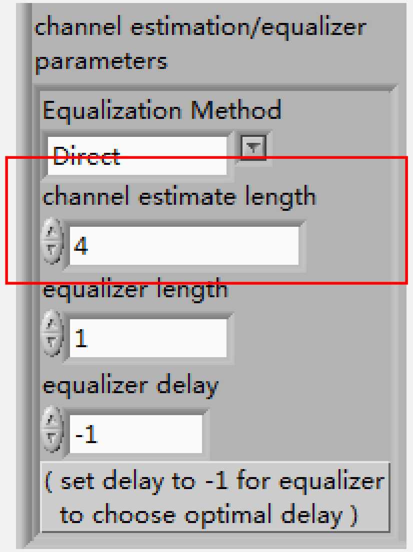
USRP experiment











channel estimation/equalizer parameters

Equalization Method

Indirect

channel estimate length

3

equalizer length

1

equalizer delay

-1

(set delay to -1 for equalizer to choose optimal delay)

Measured channel impairements

SNR(dB)

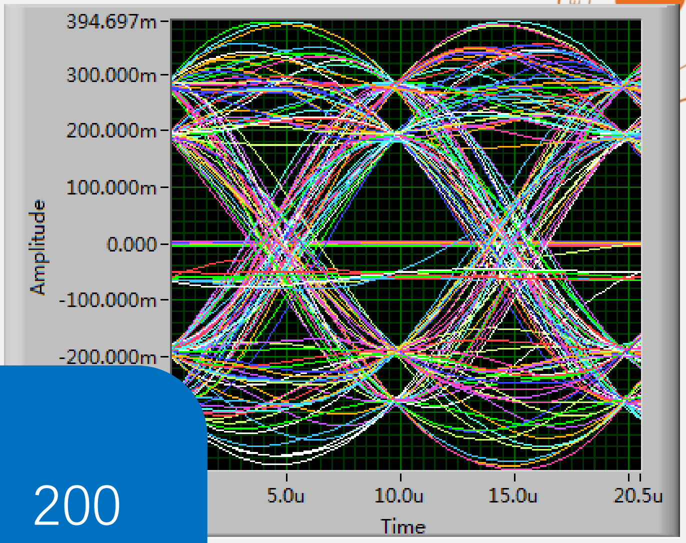
25.8855

channel estimate

0	0.25697	0.00534	-0.0013

freq. offset

-1.85903



TX Sample rate: 20M

TX Oversample factor: 200

RX Sample rate: 2M

RX Oversample factor: 20

Symbol rate: 100k

channel estimation/equalizer parameters

Equalization Method

Indirect

channel estimate length

3

equalizer length

6

equalizer delay

-1

(set delay to -1 for equalizer to choose optimal delay)

Measured channel

SNR(dB)

30.0754

channel estimate

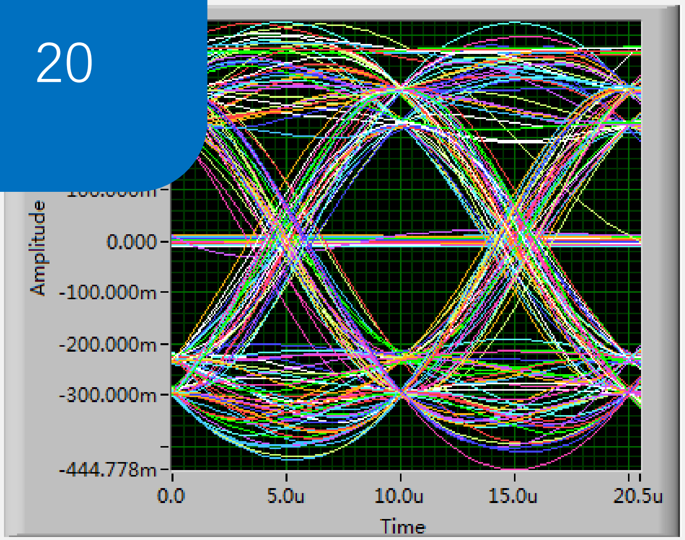
0	0.37046	0.00184	-0.0002

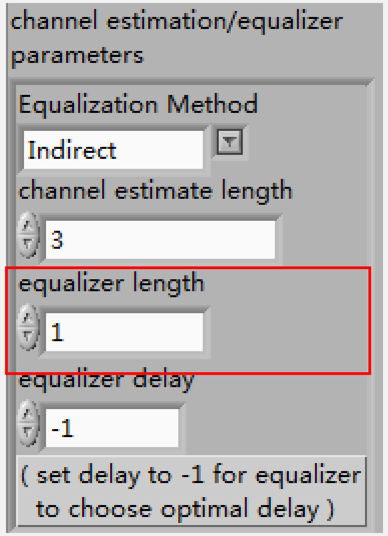
freq. offset

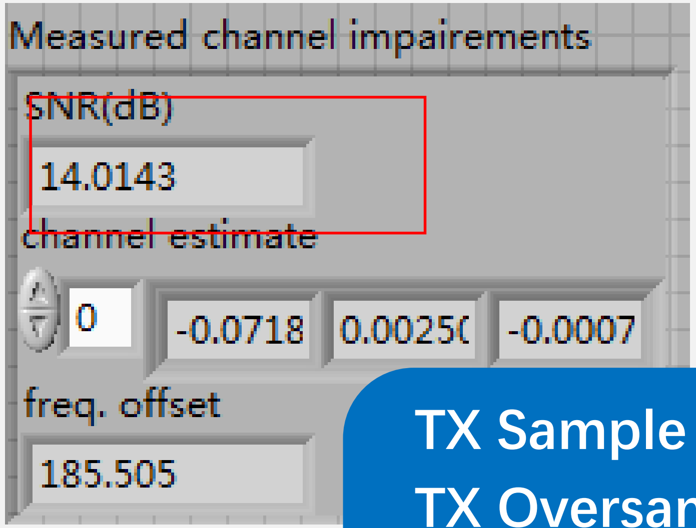
1.53805

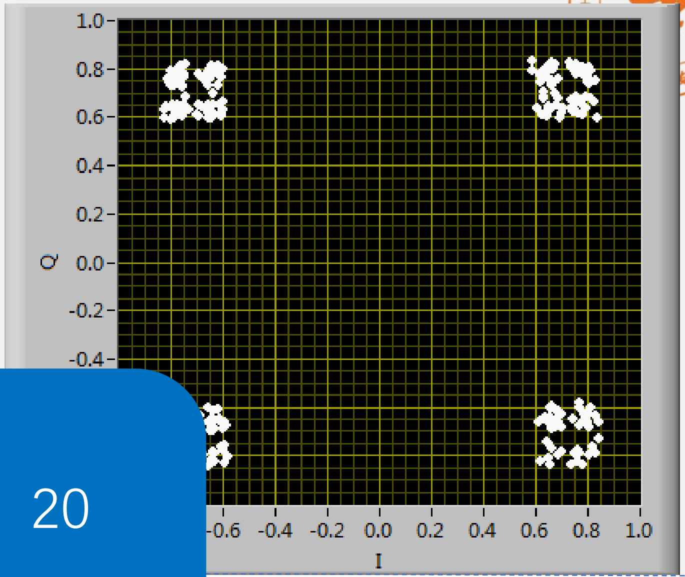
delay

0.000978

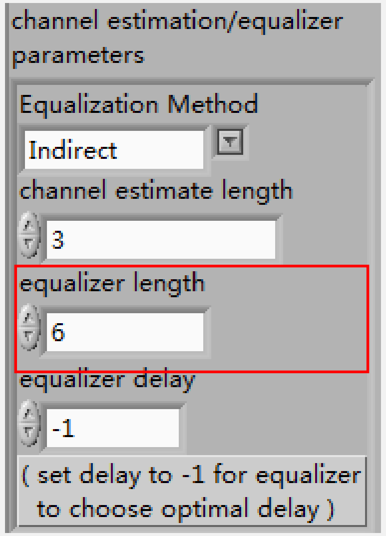


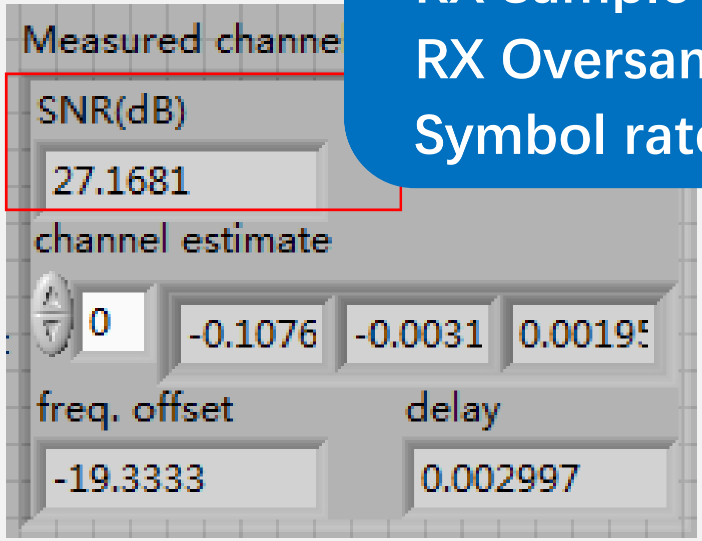


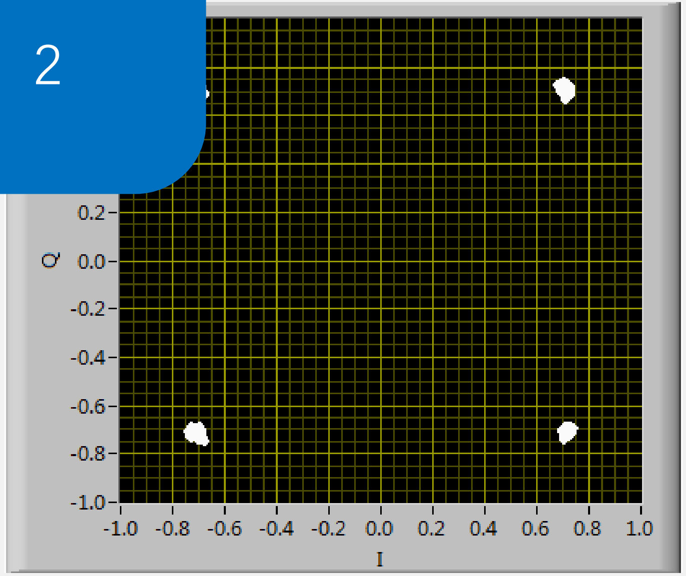


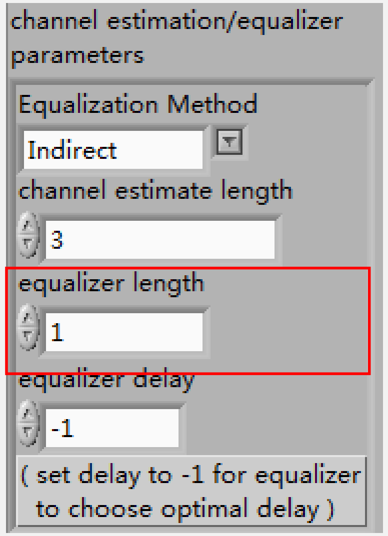


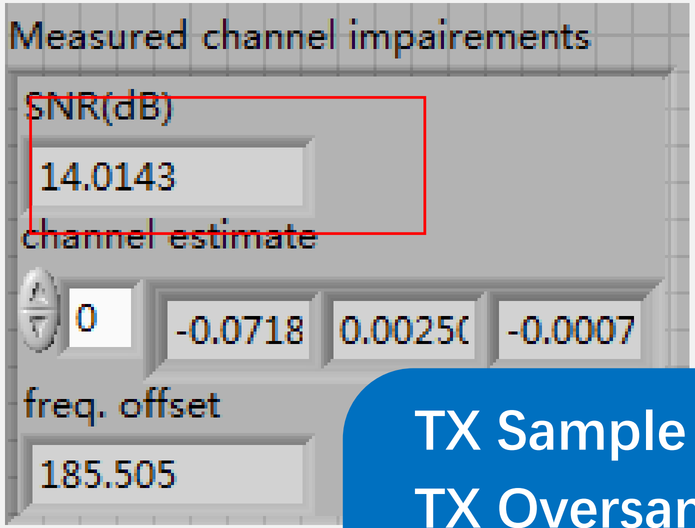
TX Sample rate: 20M
TX Oversample factor: 20
RX Sample rate: 2M
RX Oversample factor: 2
Symbol rate: 1M

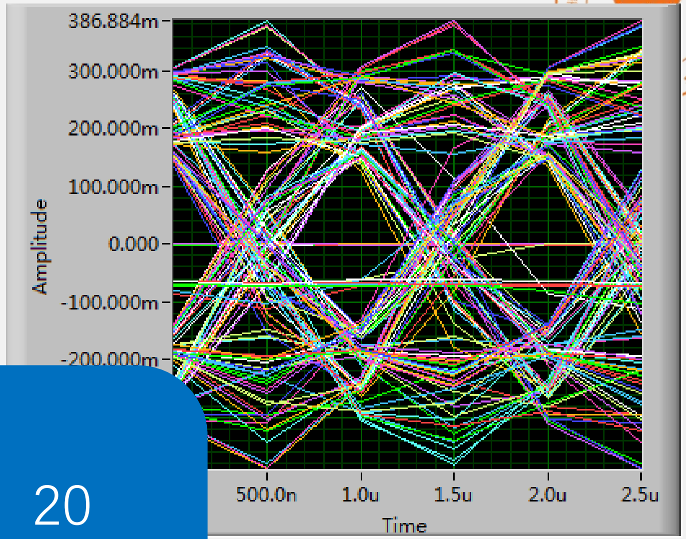




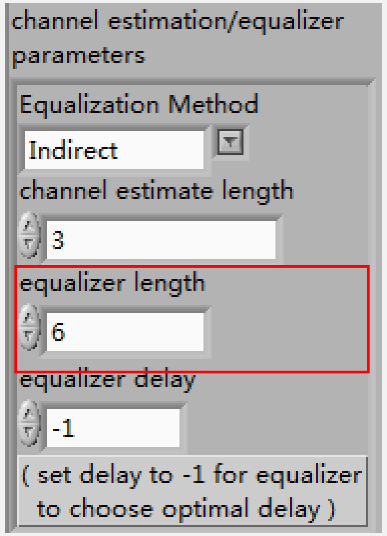


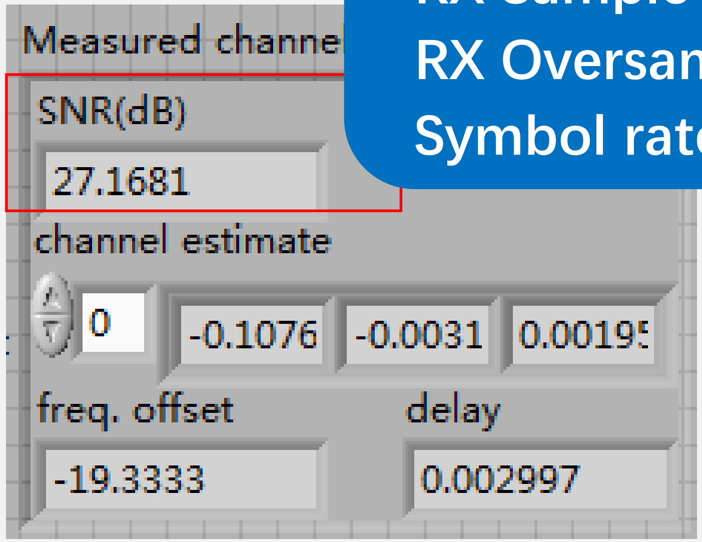


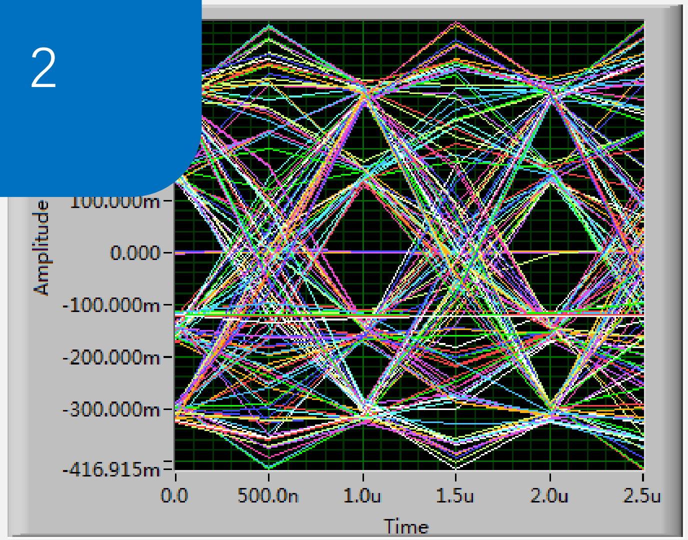




TX Sample rate: 20M
TX Oversample factor: 20
RX Sample rate: 2M
RX Oversample factor: 2
Symbol rate: 1M







Algorithm Analysis and Verification

1. Channel Estimation
2. Indirect Equalizer Analysis
3. Algorithm Simulation
4. USRP Experiments
5. Discussion and Conclusion

- Question ?