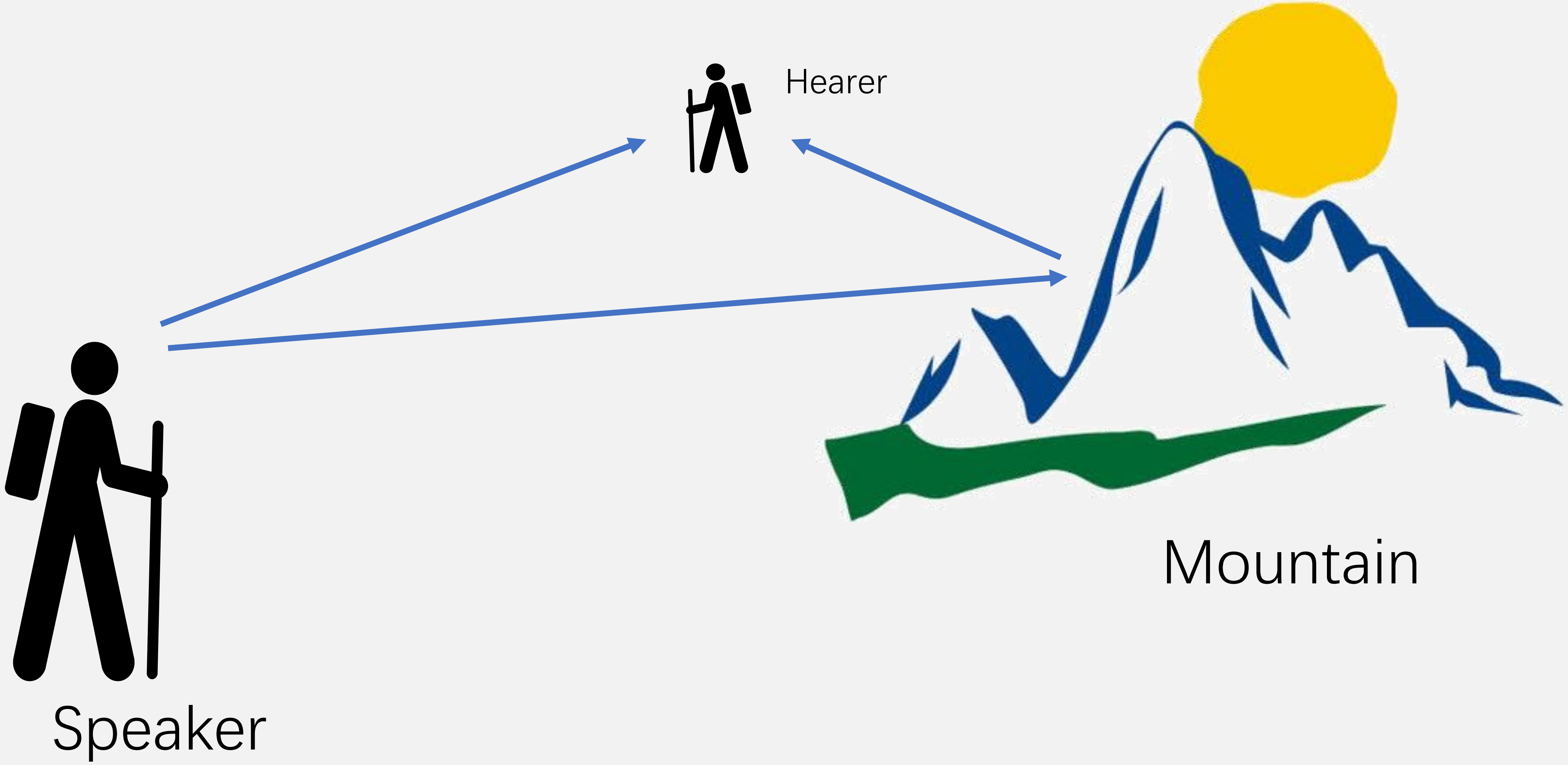
无线通信实验在线开放课程

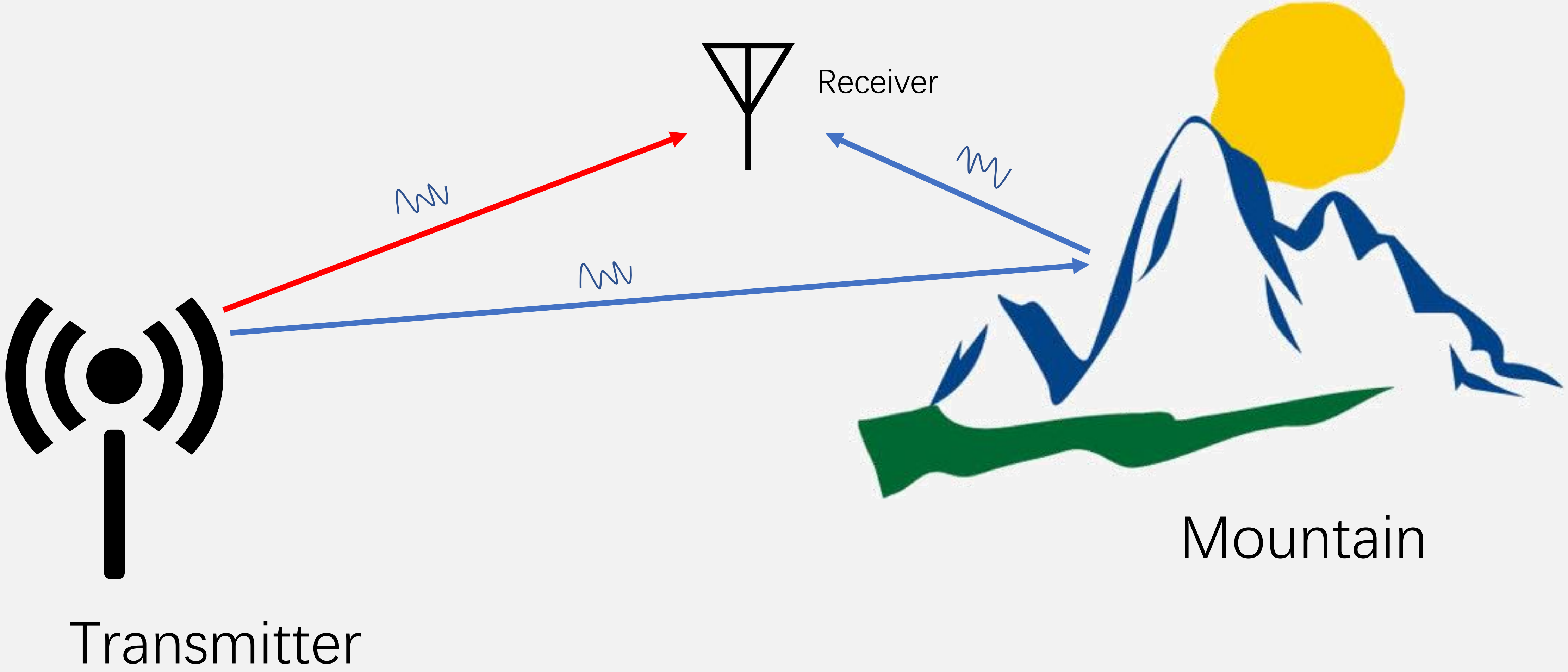
主讲人：吴光 博士

广东省教学质量工程建设项目

Echo



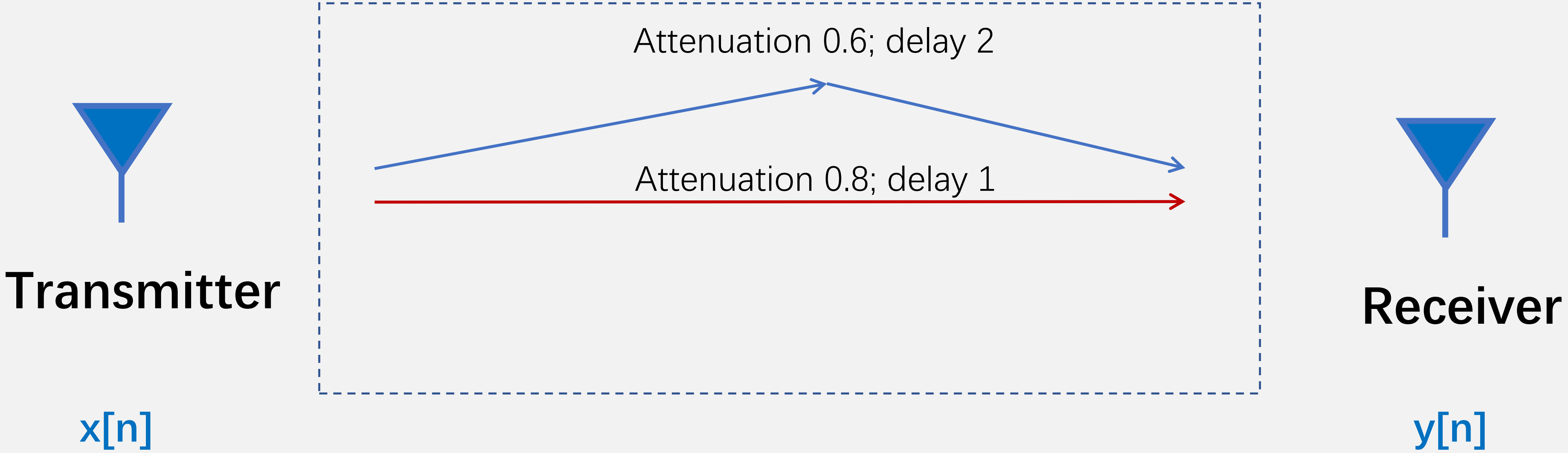
Multipath Propagation



Introduction

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

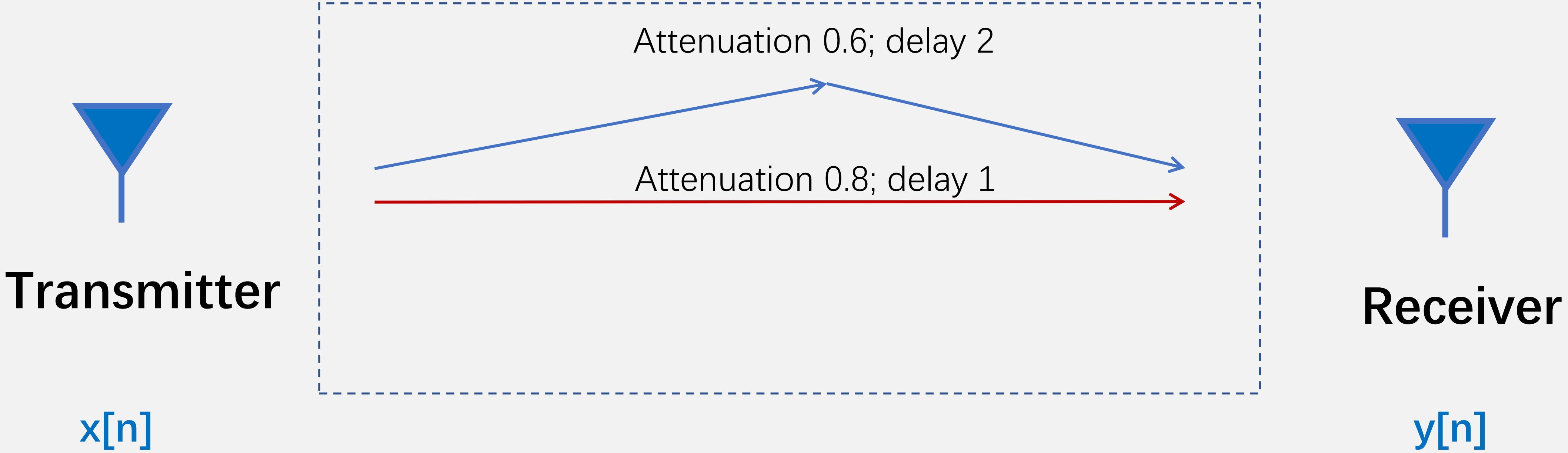
$$h1[n] = 0.8\, \delta[n-1] + 0.6\, \delta[n-2]$$



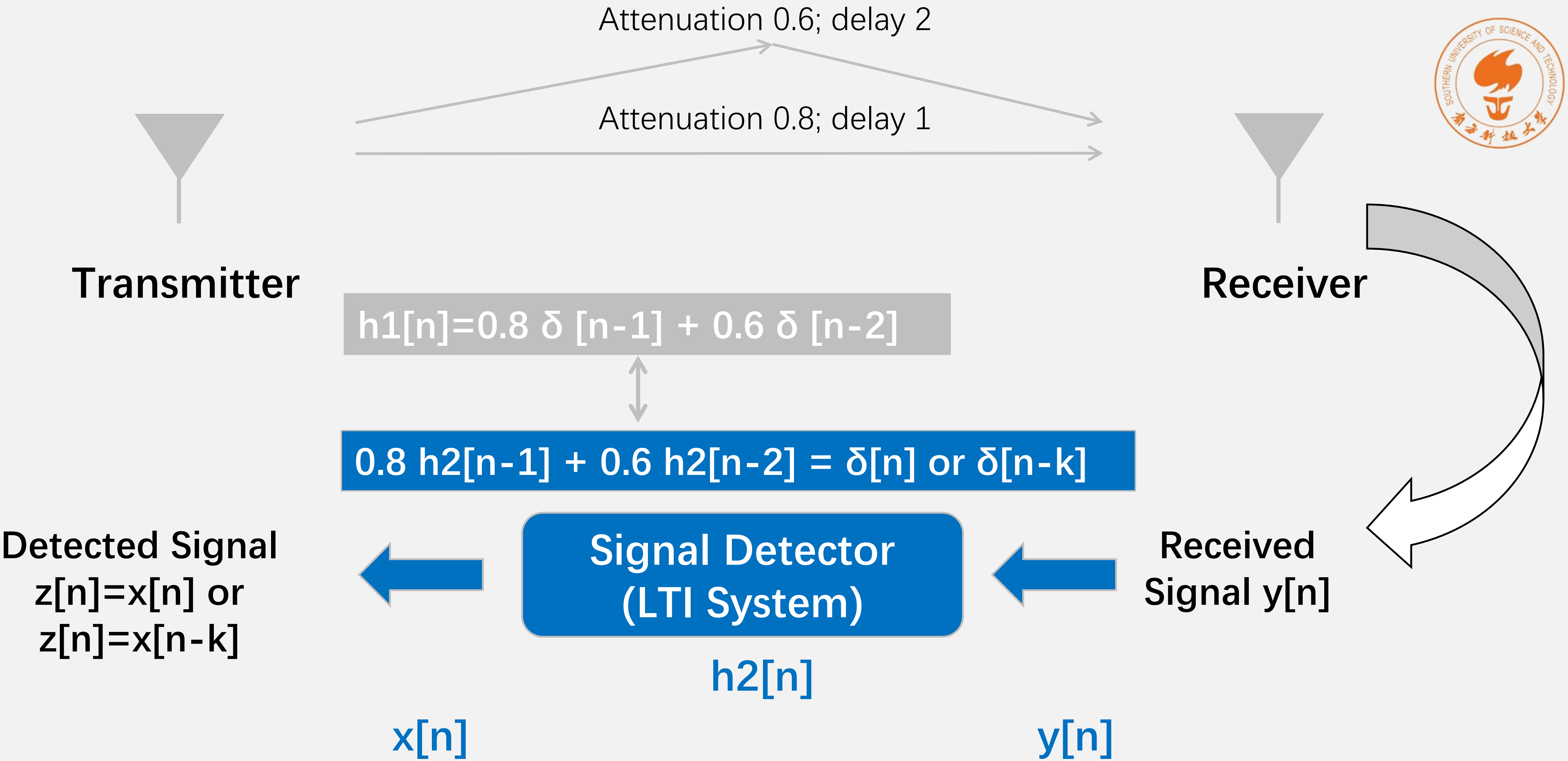
$$x[n]*h1[n]=y[n]$$

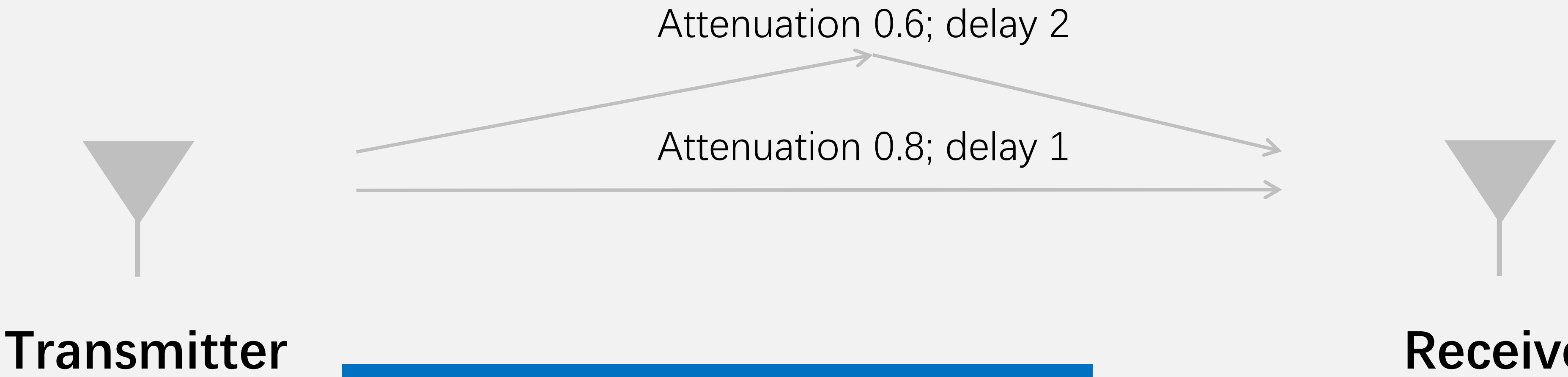
$$y[n] = 0.8\,x[n-1] + 0.6\,x[n-2]$$

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



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


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]



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

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

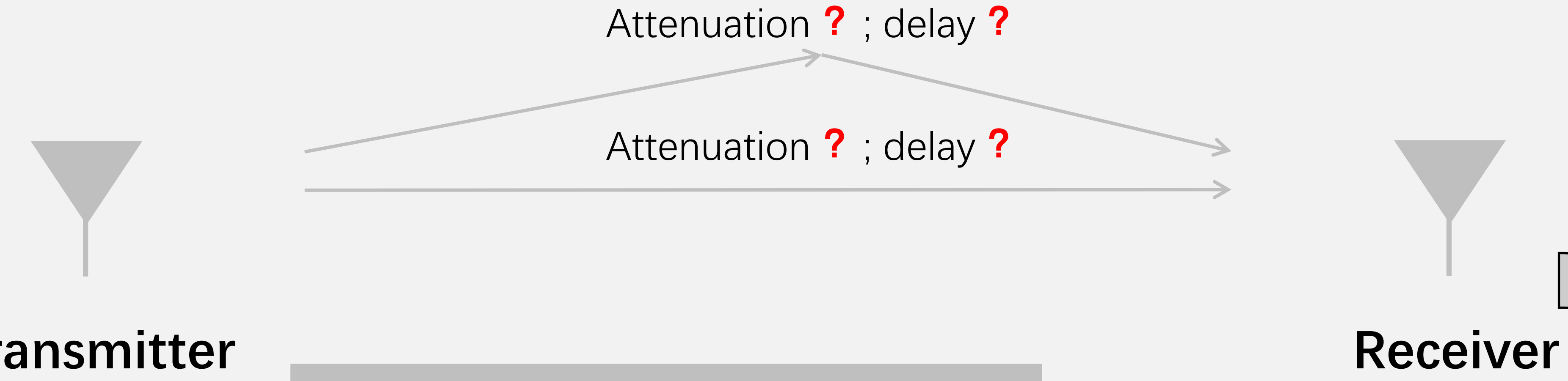
Detected Signal
$z[n]=x[n]$ or
$z[n]=x[n-k]$

Signal Detector
(LTI System)

Received
Signal $y[n]$

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

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



h1[n]=0.8 δ [n-1] + 0.6 δ [n-2]

$$h_1[n]=0.8\,\delta[n-1]+0.6\,\delta[n-2]$$

$$0.8\,h_2[n-1]+0.6\,h_2[n-2]=\delta[n] \text{ or } \delta[n-k]$$

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

Signal Detector (LTI System)

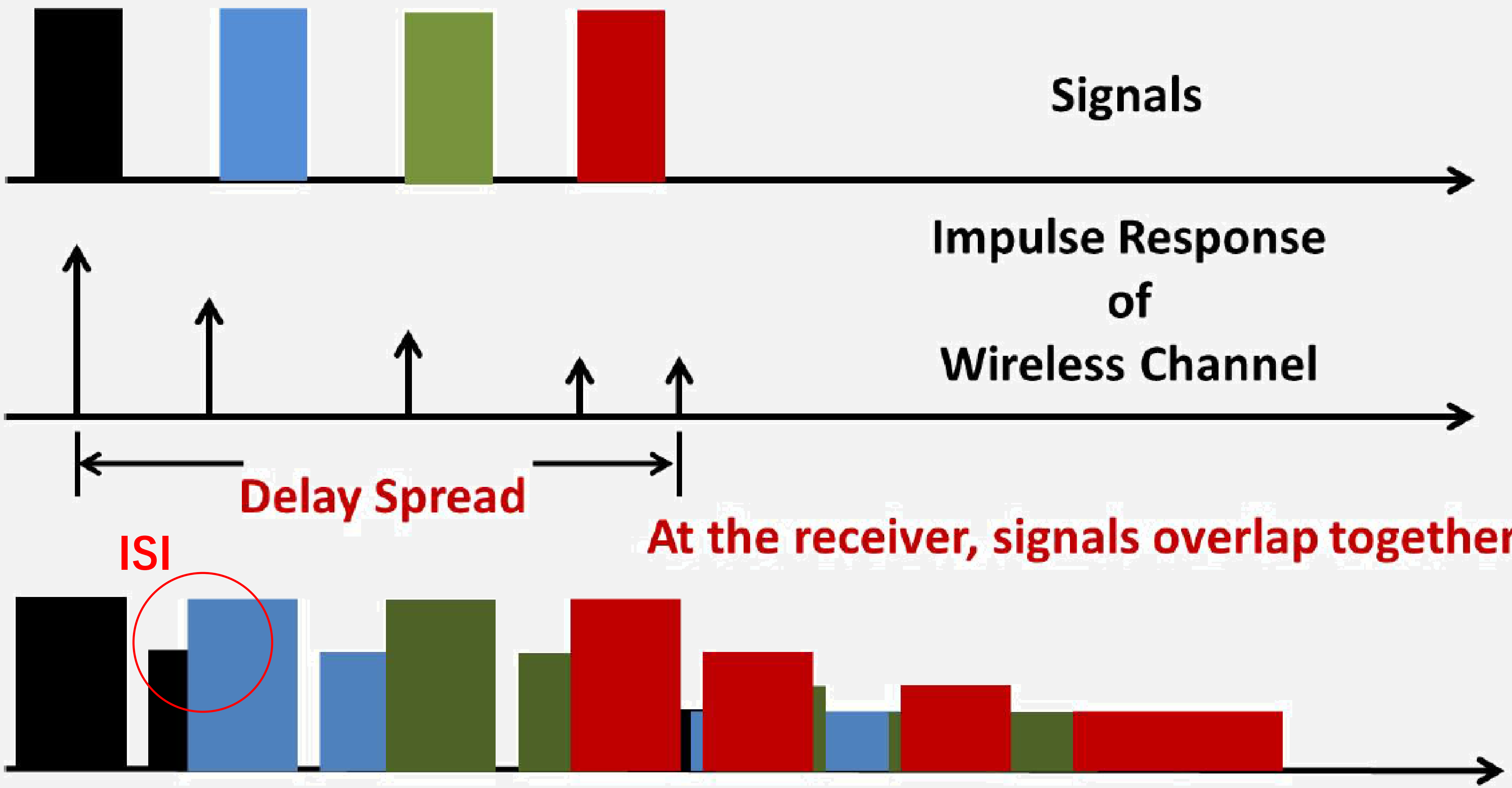
Received Signal $y[n]$

Impulse response: $h_2[n] * h_1[n] = \delta[n]$ or $\delta[n-k]$

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

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

Frequency Selective Channel

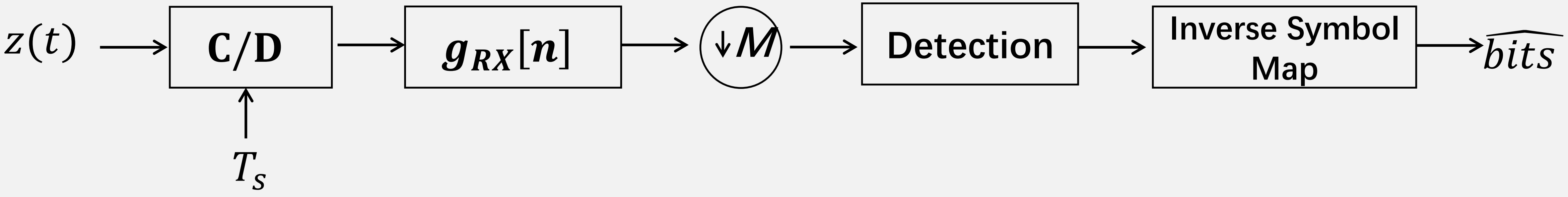

Signals
Impulse Response
of
Wireless Channel
Delay Spread
ISI
At the receiver, signals overlap together

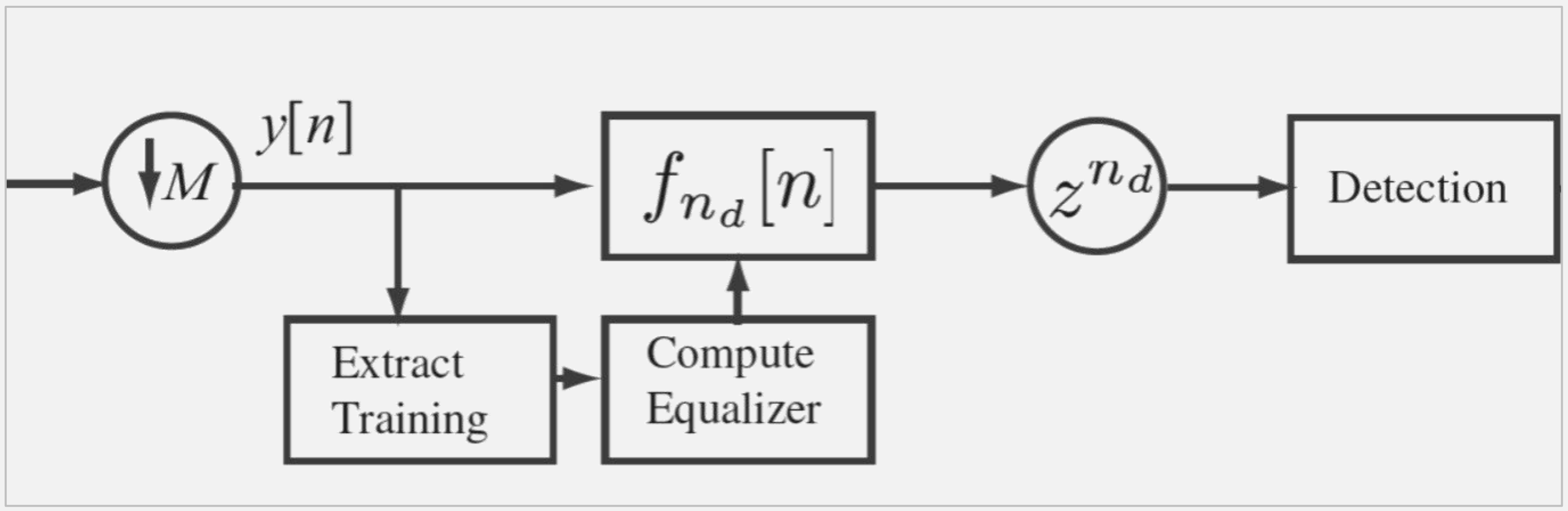
Channel Model

AWGN Frequency Selective Channel

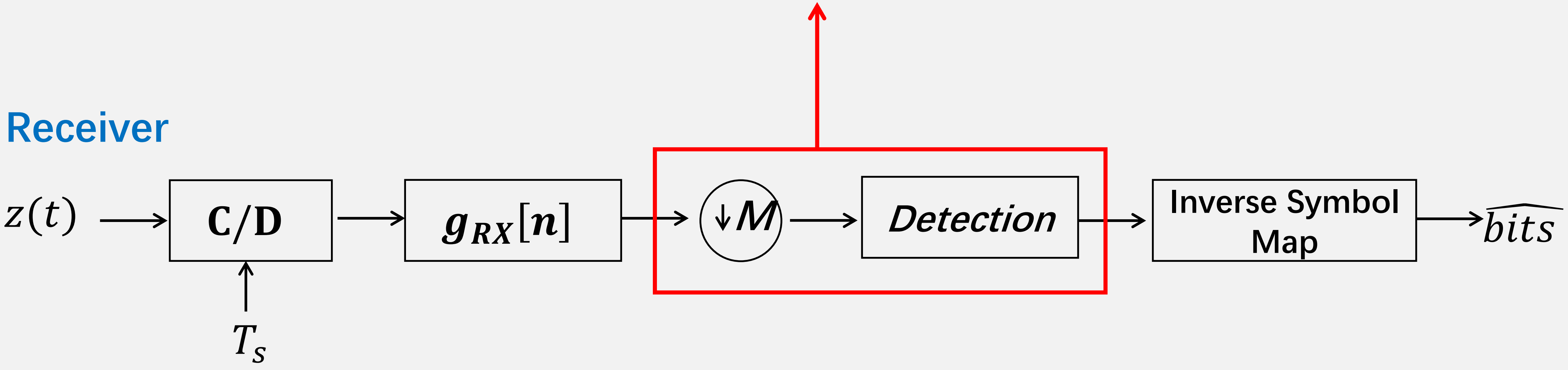
$$\boxed{z(t) = \alpha_0 e^{j\varphi_0} x(t-\tau_0) + \alpha_1 e^{j\varphi_1} x(t-\tau_1) + v(t)}$$

Receiver




y[n]
M
$f_{n_d}[n]$
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 | Packet Head

Training sequences

Payload | Key bits sequences

Zero Pad | Guard band

Step1: h1[n]

Step2: h2[n]

find.

$$\text{Step3: } y[n]*h2[n]=x[n]*\underbrace{h1[n]*h2[n]}_{\delta[n] \text{ or } \delta[n-k]}$$

Equalization.

Lab 13 : Channel Estimation and Equalization

主讲人：吴光 博士
Email: wug@sustech.edu.cn

Algorithm Analysis and Verification

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

Channel Estimation

$$\mathbf{A}\mathbf{x} = \mathbf{b}$$

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

$$\mathrm{N} = \mathrm{M}$$

$$\mathbf{x} = \mathbf{A}^{-1}\mathbf{b}$$

$$\min ||\mathbf{A}\mathbf{x} - \mathbf{b}||^2$$

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

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

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

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

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

$$\dots$$

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

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

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

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

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

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

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

满秩，列向量线性无关

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

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

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

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

列向量线性无关满足的条件.

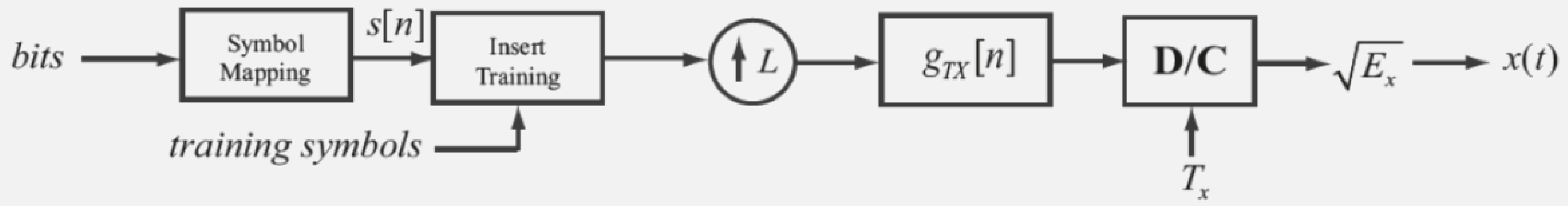
$$N_t - L \geq L + 1 \qquad N_t \geq 2L + 1$$

Algorithm Analysis and Verification

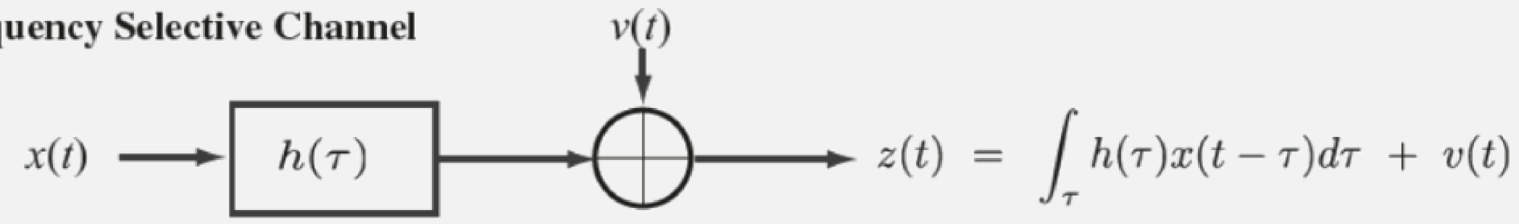
1. Channel Estimation
2. Indirect Equalizer Analysis
3. Algorithm Simulation
4. USRP Experiments
5. Discussion and Conclusion

Programming for Channel Estimation

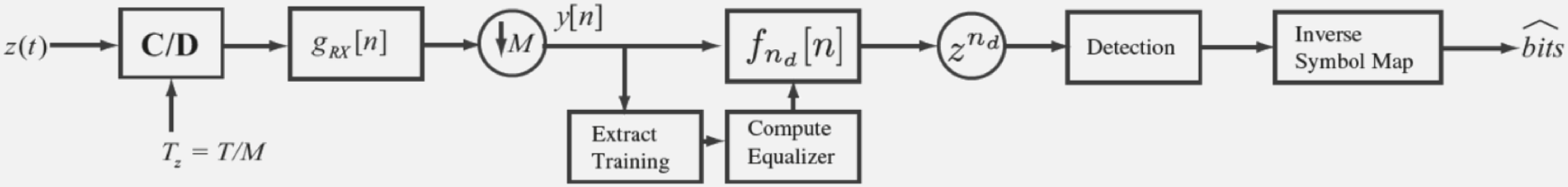
Transmitter

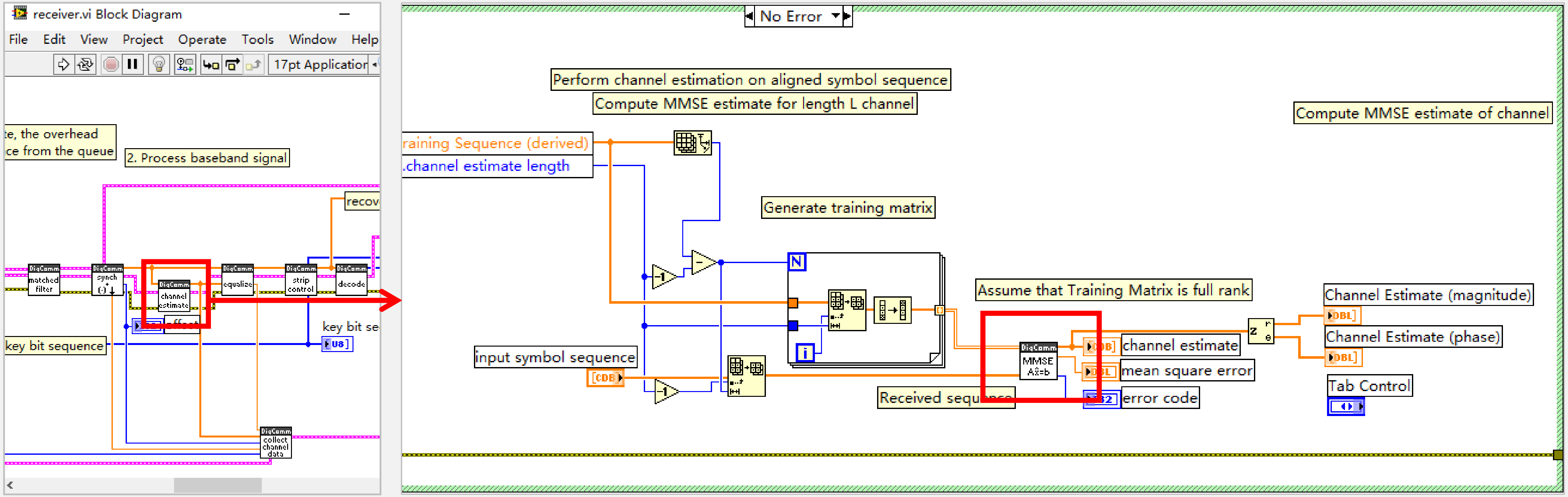


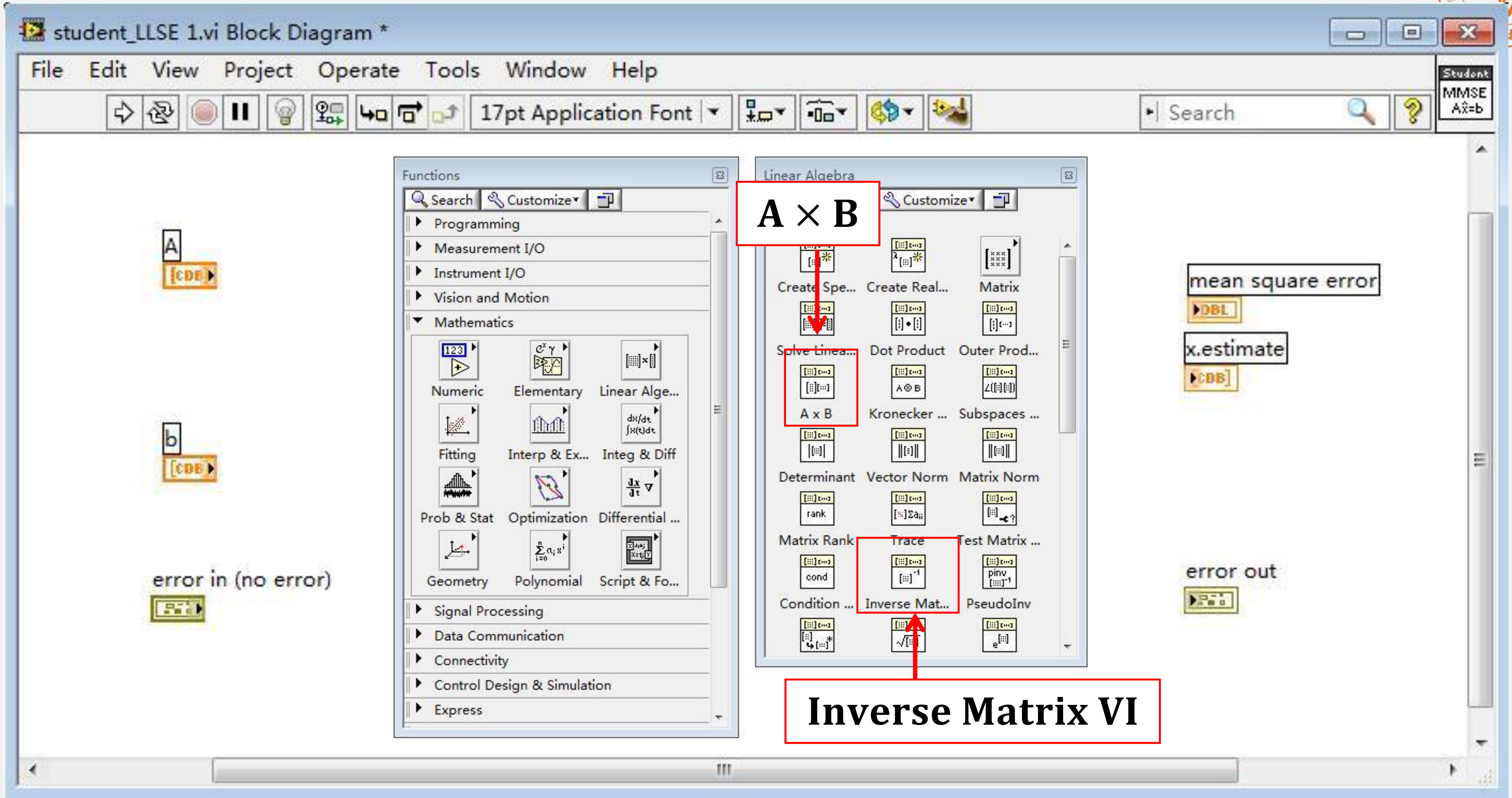
AWGN Frequency Selective Channel



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
DiqComm
matched filter
synch
equalize
strip control
decode
channel estimate
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
Compute MMSE estimate of channel
raining Sequence (derived)
.channel estimate length
Generate training matrix
N
i
Assume that Training Matrix is full rank
input symbol sequence
CDB
MMSE
Received sequ
channel estimate
mean square error
error code
Channel Estimate (magnitude)
Channel Estimate (phase)
DBL
Tab Control

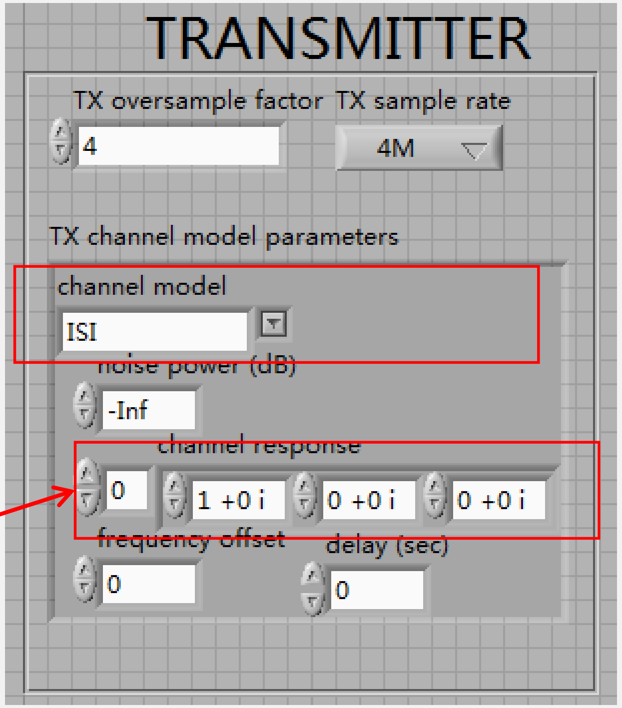


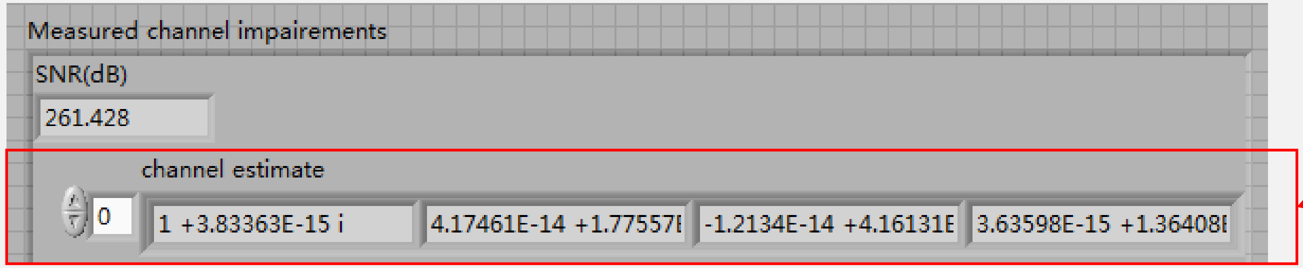
student_LLSE 1.vi Block Diagram *
File
Edit
View
Project
Operate
Tools
Window
Help
17pt Application Font
Search
A
b
error in (no error)
Functions
Search
Customize
Programming
Measurement I/O
Instrument I/O
Vision and Motion
Mathematics
Numeric
Elementary
Linear Alge...
Fitting
Interp & Ex...
Integ & Diff
Prob & Stat
Optimization
Differential ...
Geometry
Polynomial
Script & Fo...
Signal Processing
Data Communication
Connectivity
Control Design & Simulation
Express
Linear Algebra
Customize
A × B
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
x.estimate
error out

Simulation setup

Test your block diagram with these parameters!

Set the channel model: ISI

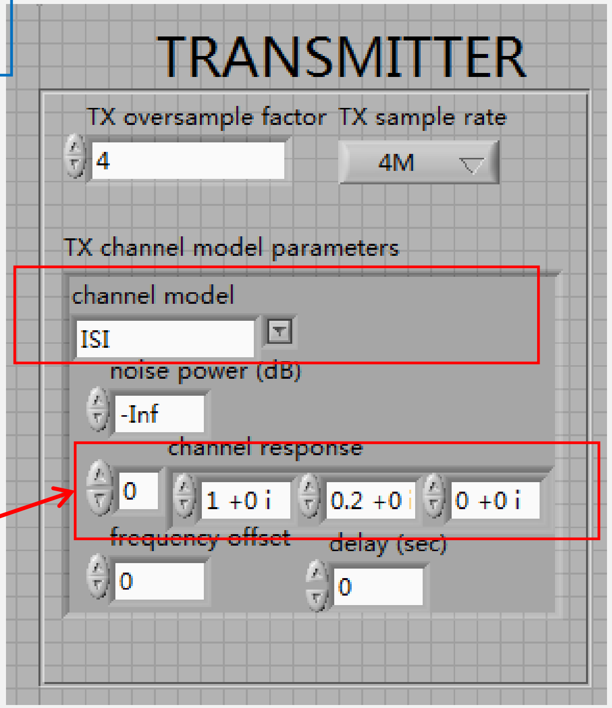


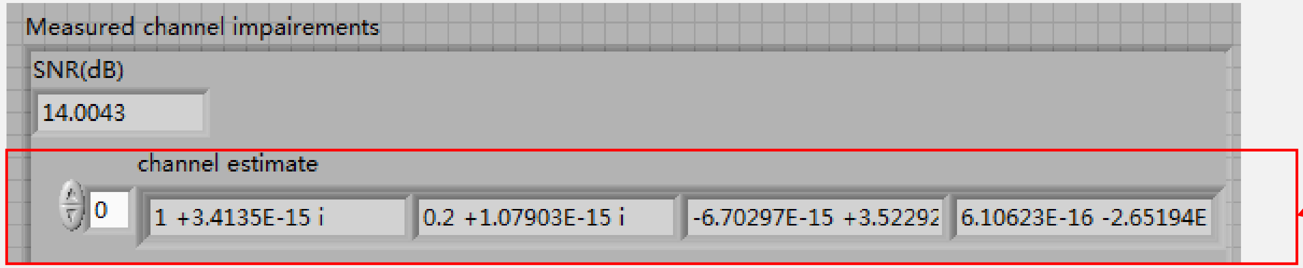


Simulation setup

Test your block diagram with these parameters!

Configure the channel model: ISI





Demo: Linear Equalization

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

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

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

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

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

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

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

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

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

残差.

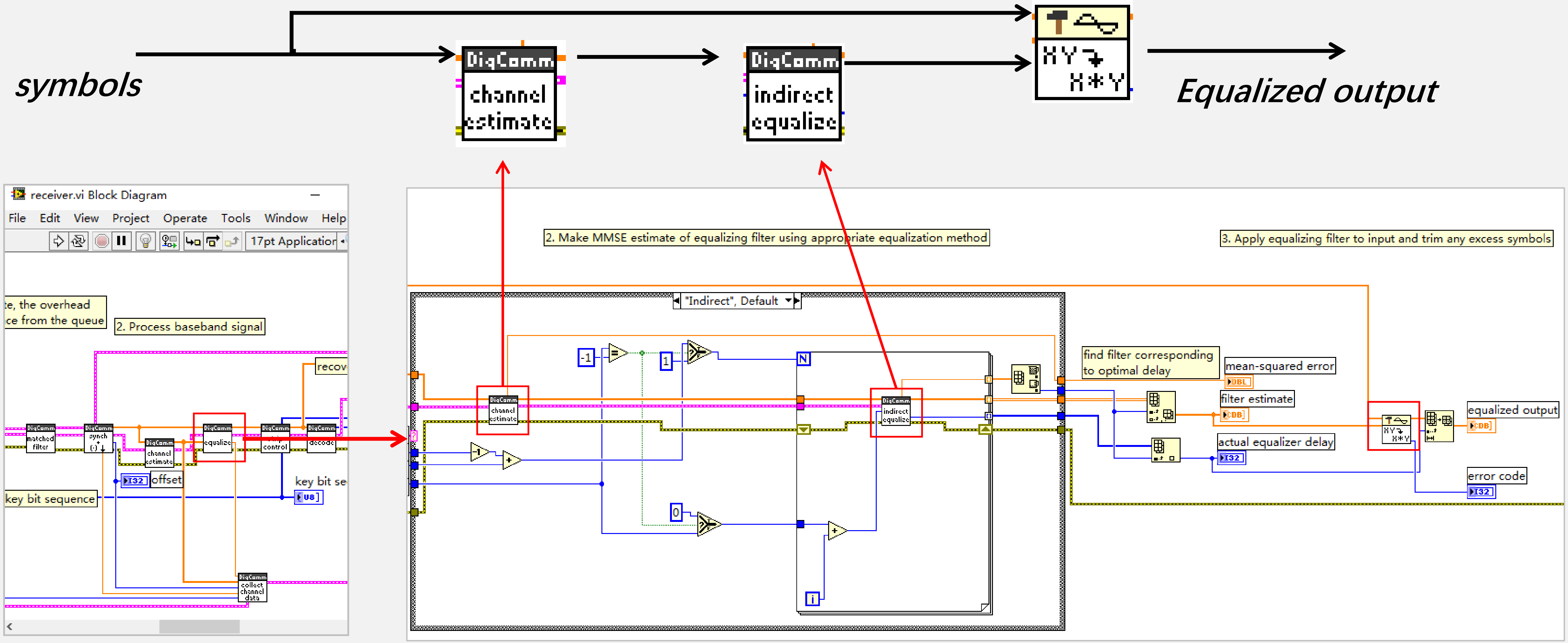
$$\hat{\boldsymbol{f}}\boldsymbol{n_d} = \left(\widehat{\boldsymbol{H}}^*\widehat{\boldsymbol{H}}\right)^{-1}\widehat{\boldsymbol{H}}^*\boldsymbol{e}_{n_d}$$

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

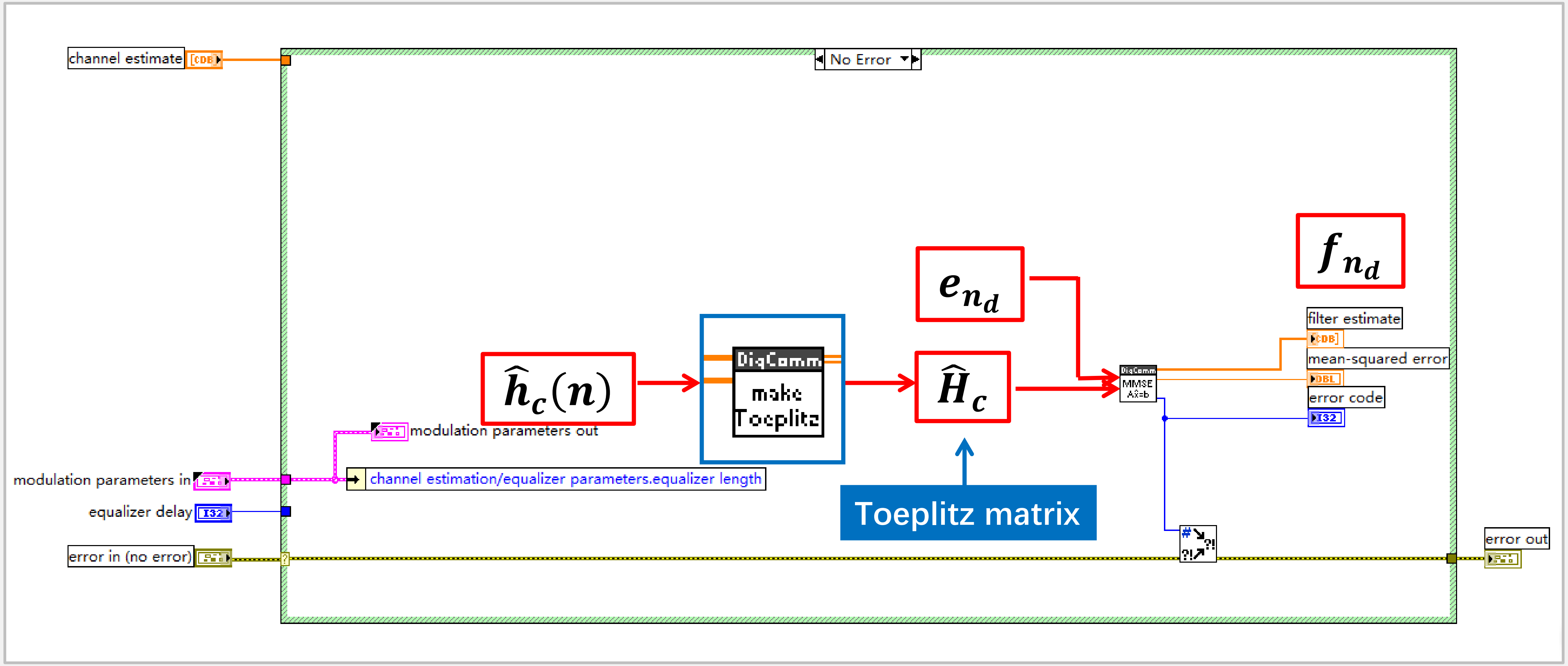
Programming for Equalization

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

信号长度.

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

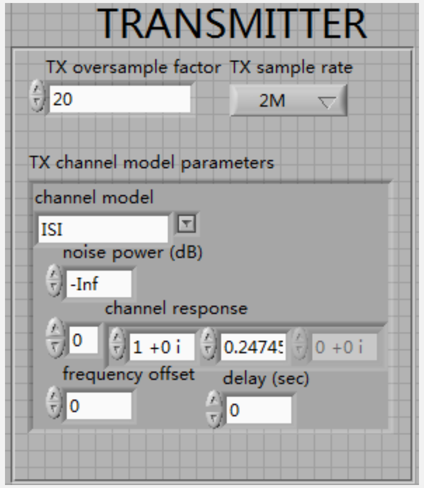
row

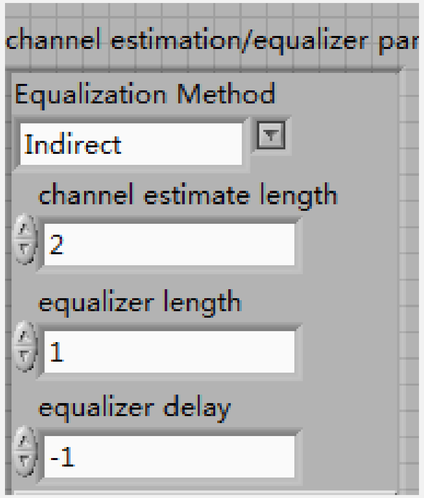
1 -5.39022E-15 i	0 +0 i	0 +0 i	0 +0 i

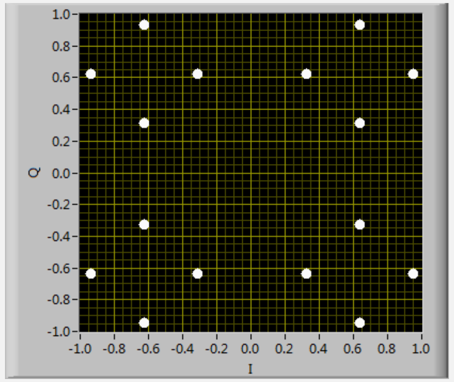
column

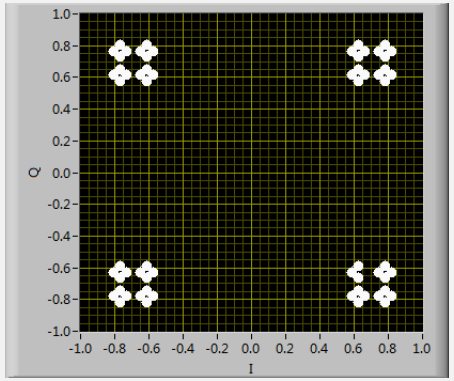
1 -5.39022E-15	0.24745 +0.247	-3.51021E-15 +	-8.36831E-15 +	0 +0 i	0 +0 i	0 +0 i

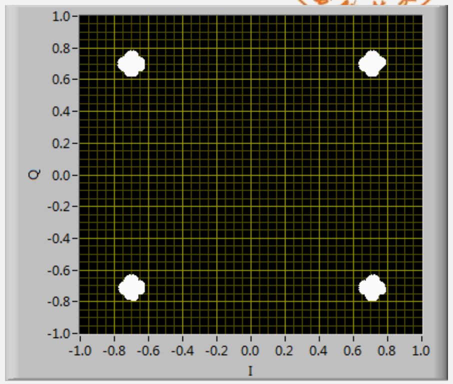
Toeplitz matrix

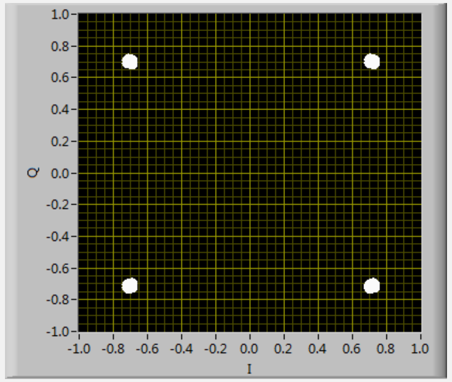


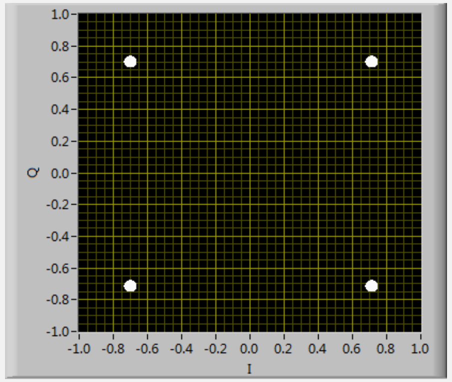


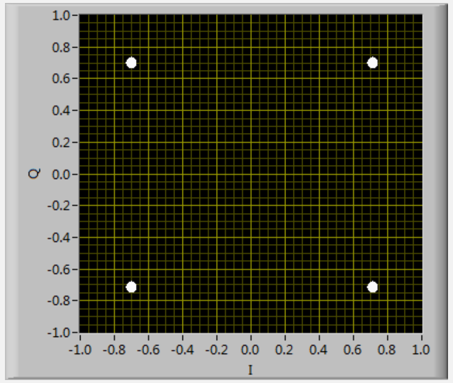

Length=1


Length=2


Length=3


Length=4

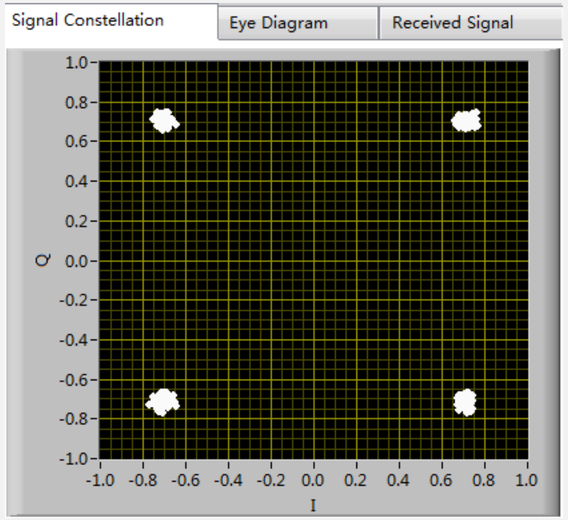

Length=5

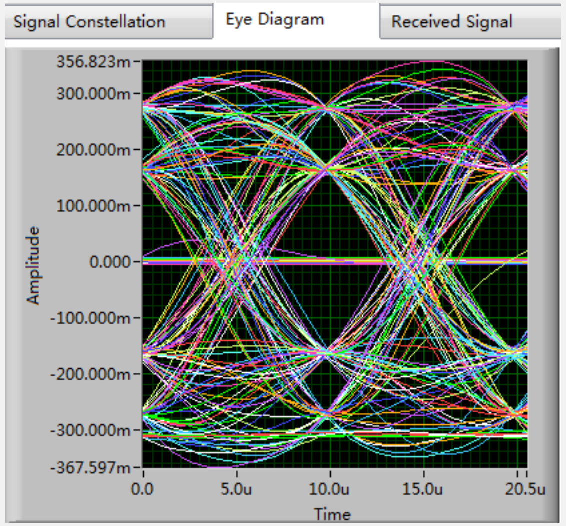

Length=6

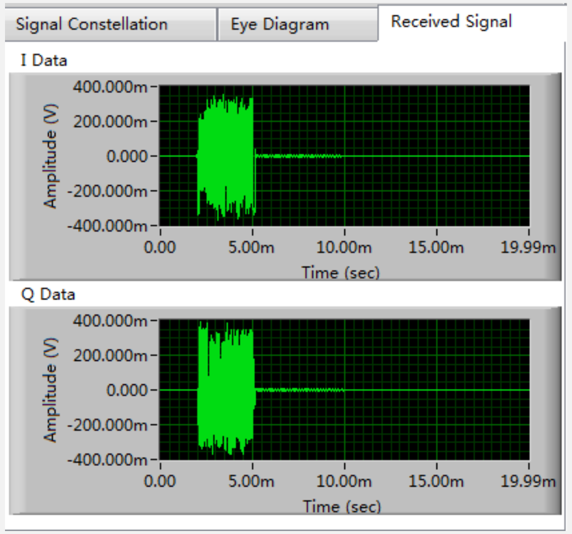
Algorithm Analysis and Verification

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

USRP experiment







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

channel estimation/equalizer parameters

Equalization Method: Direct

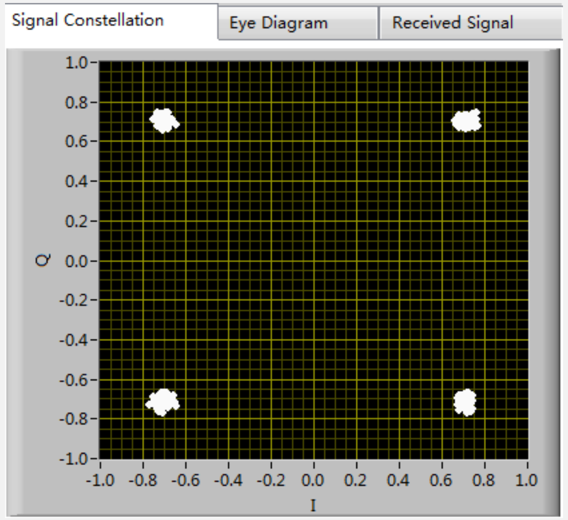
channel estimate length: 3

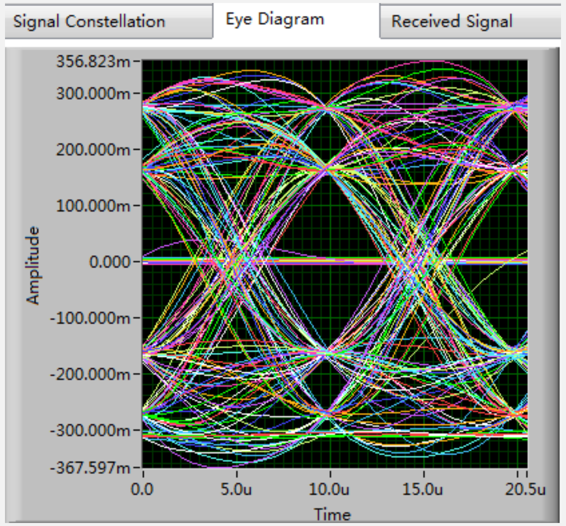
equalizer length: 1

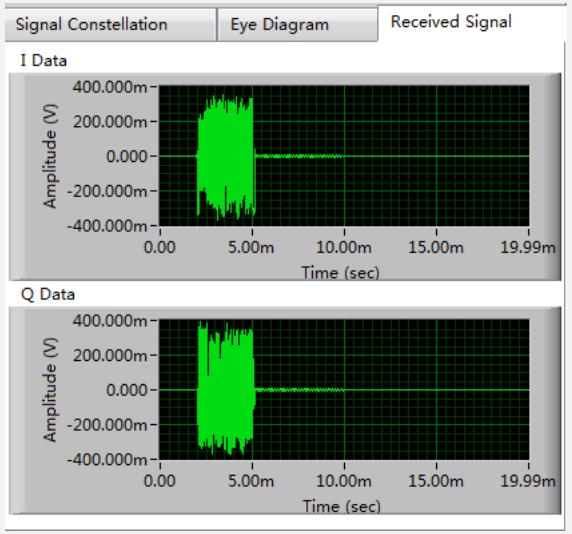
equalizer delay: -1

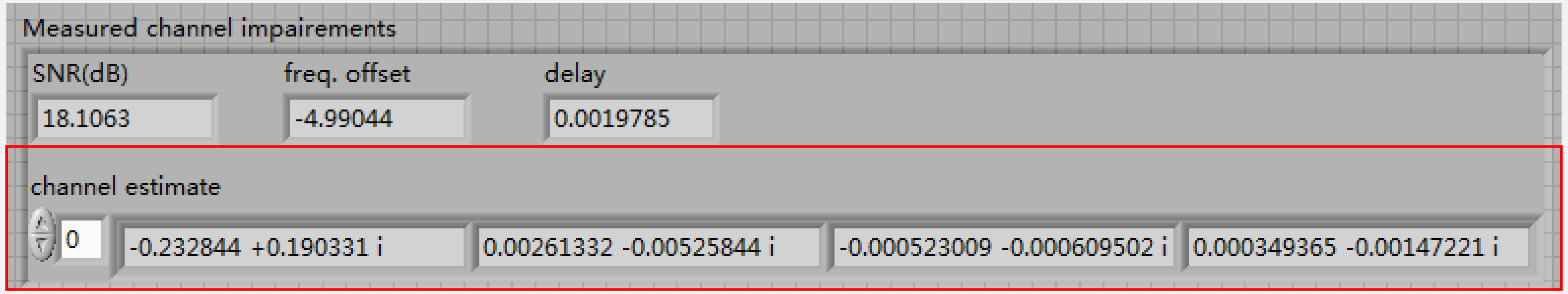
(set delay to -1 for equalizer to choose optimal delay)

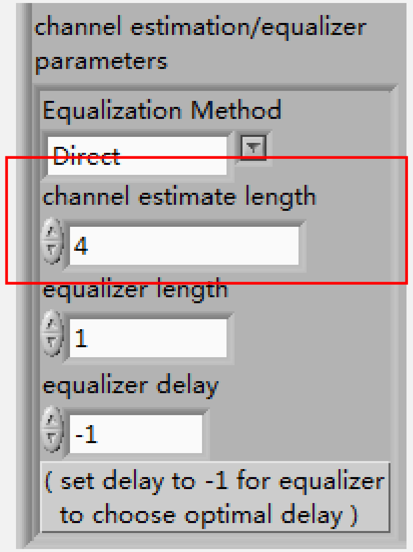
USRP experiment

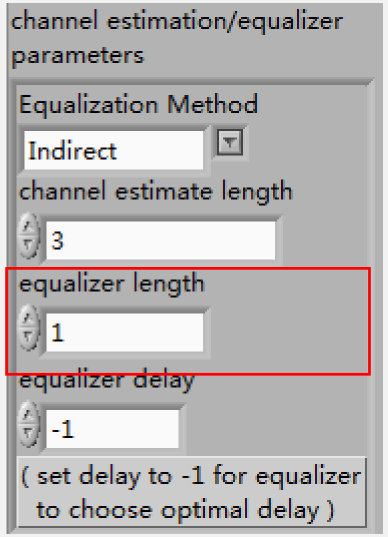


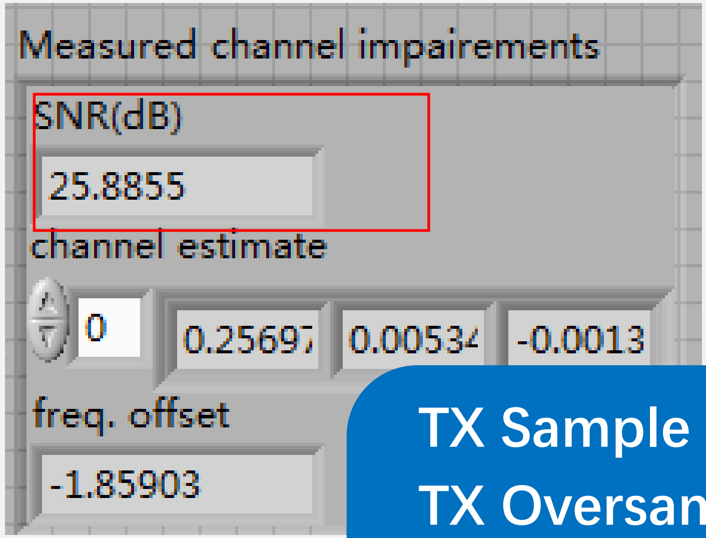


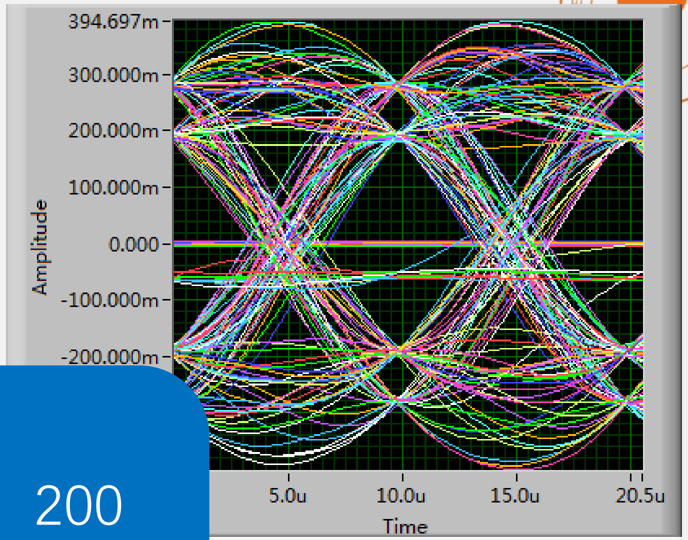












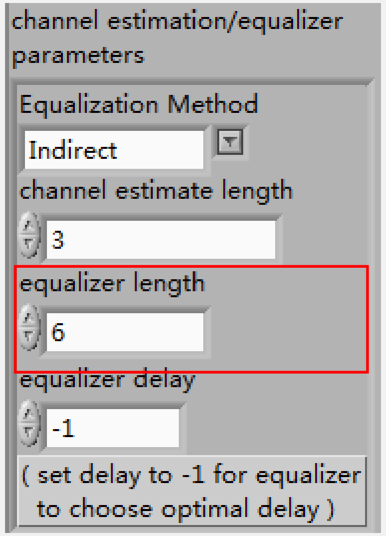
TX Sample rate: 20M

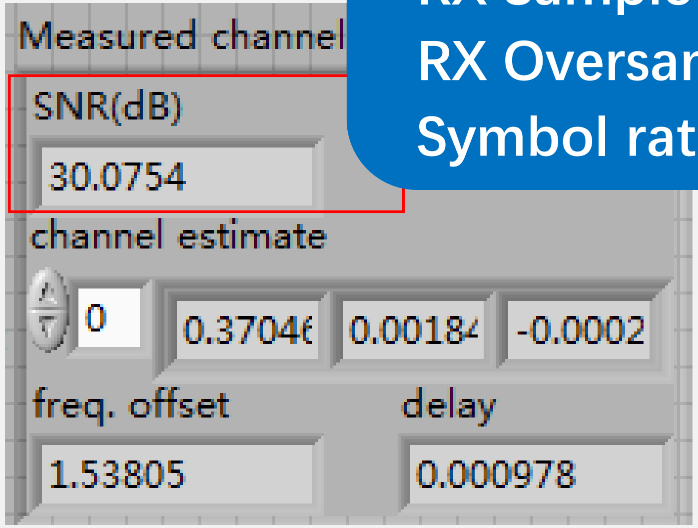
TX Oversample factor: 200

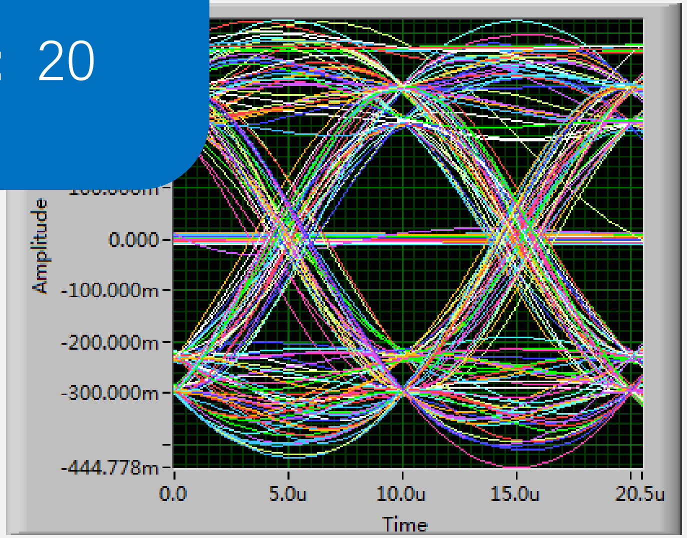
RX Sample rate: 2M

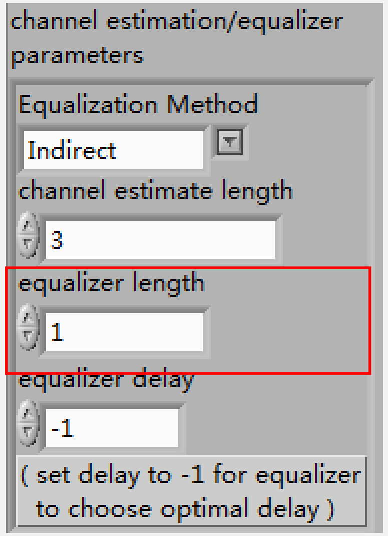
RX Oversample factor: 20

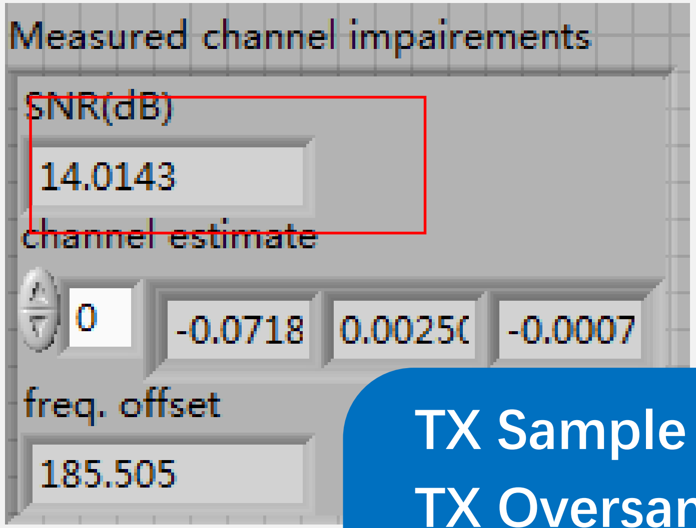
Symbol rate: 100k

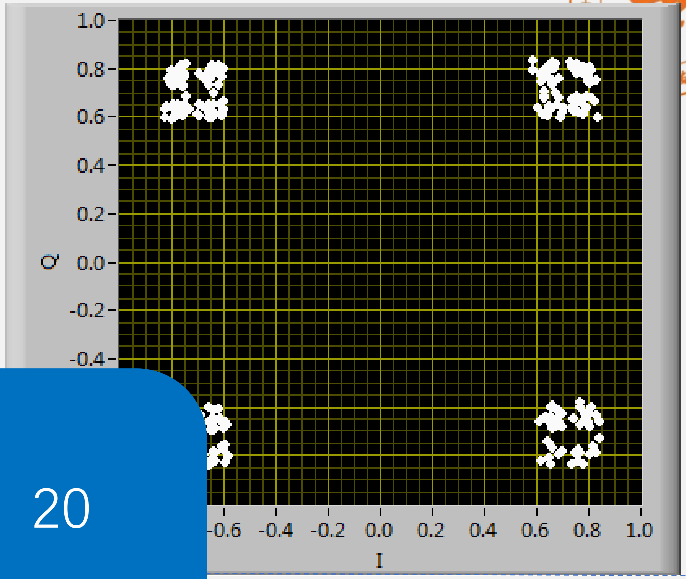


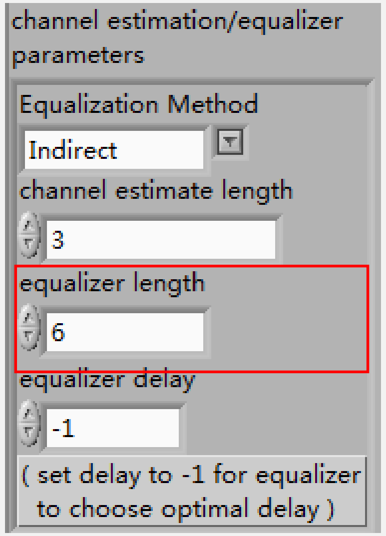


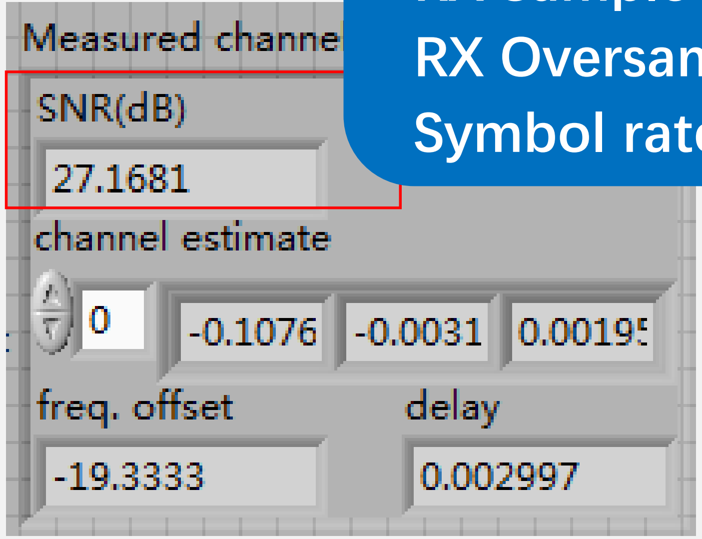


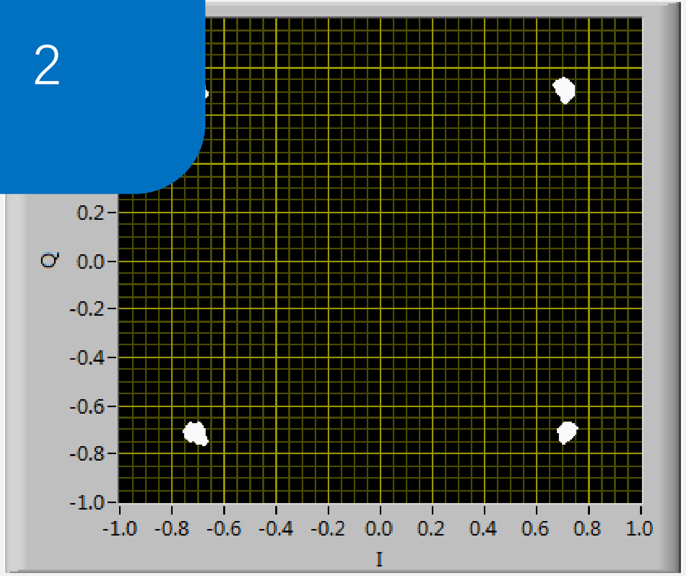












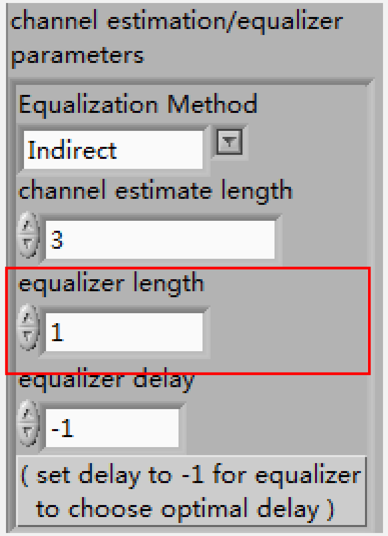
TX Sample rate: 20M

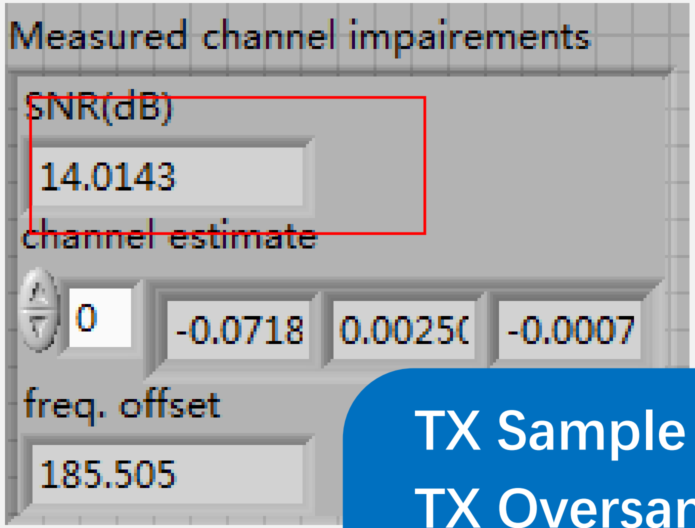
TX Oversample factor: 20

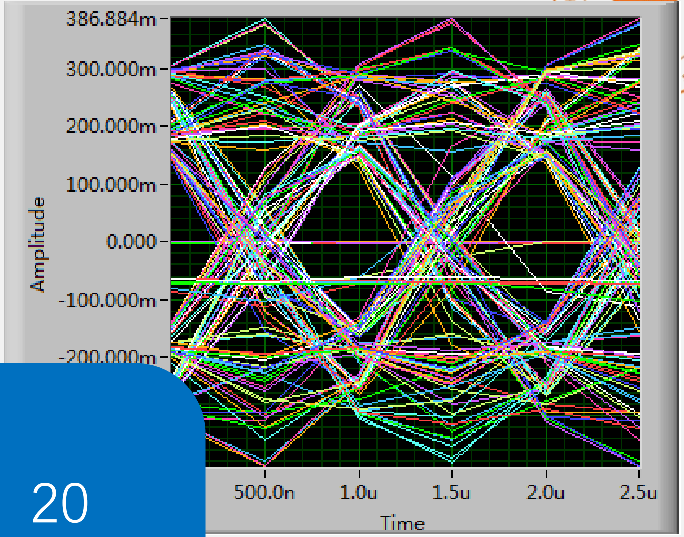
RX Sample rate: 2M

RX Oversample factor: 2

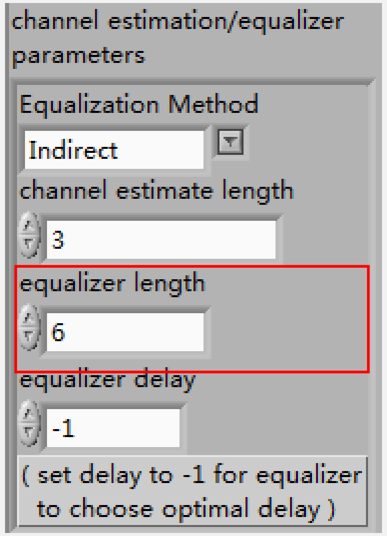
Symbol rate: 1M

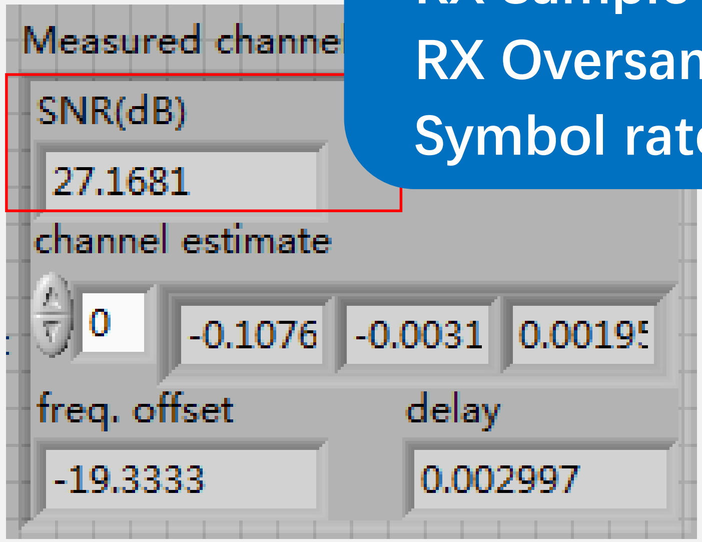


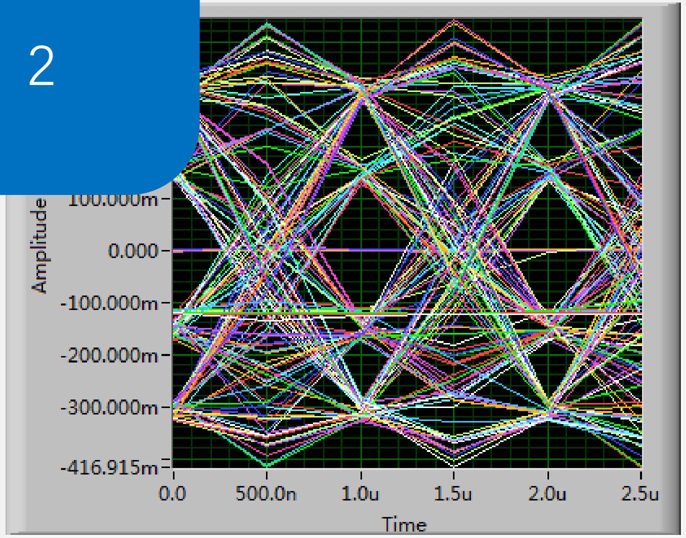




TX Sample rate: 20M
TX Oversample factor: 20
RX Sample rate: 2M
RX Oversample factor: 2
Symbol rate: 1M







Algorithm Analysis and Verification

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

- **Question ?**