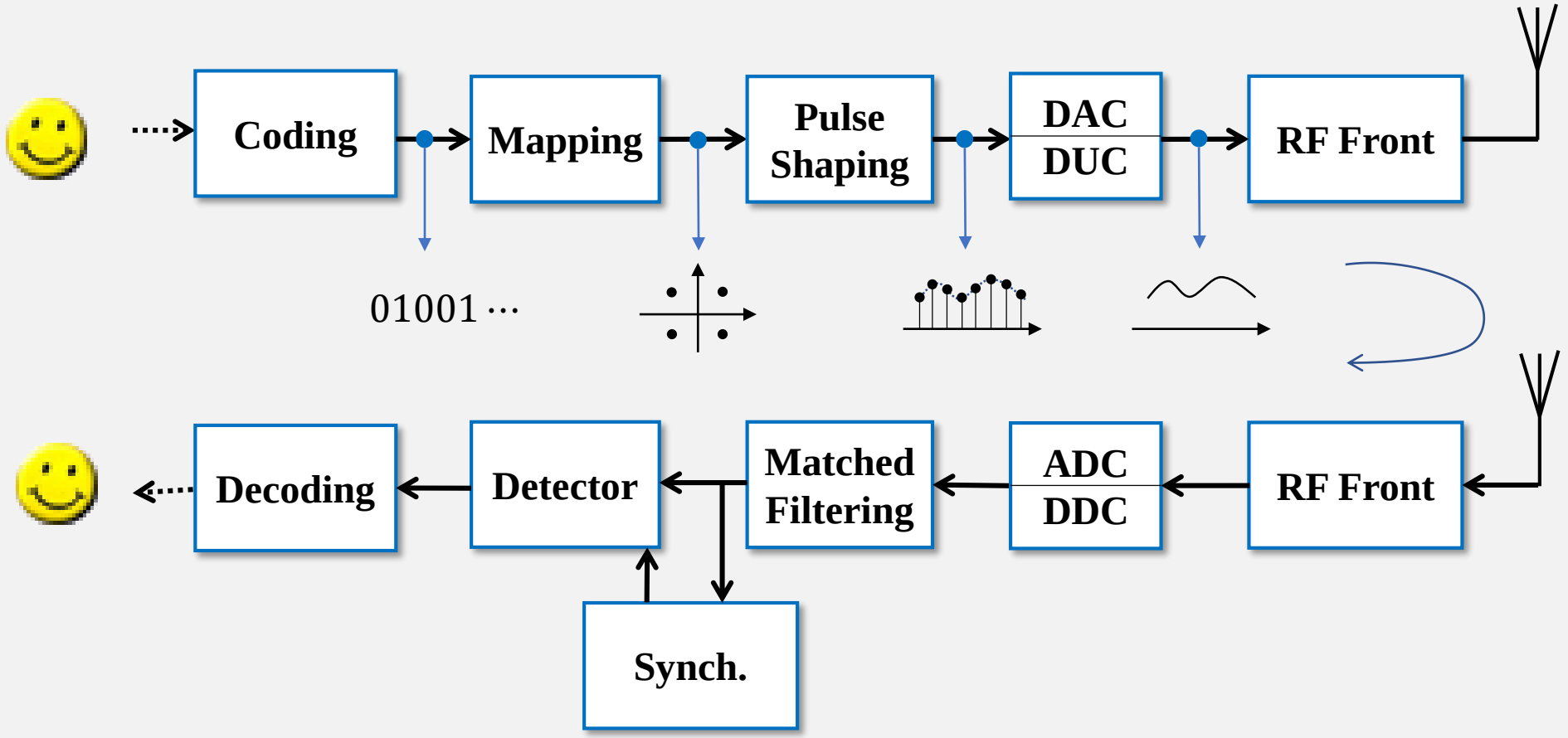
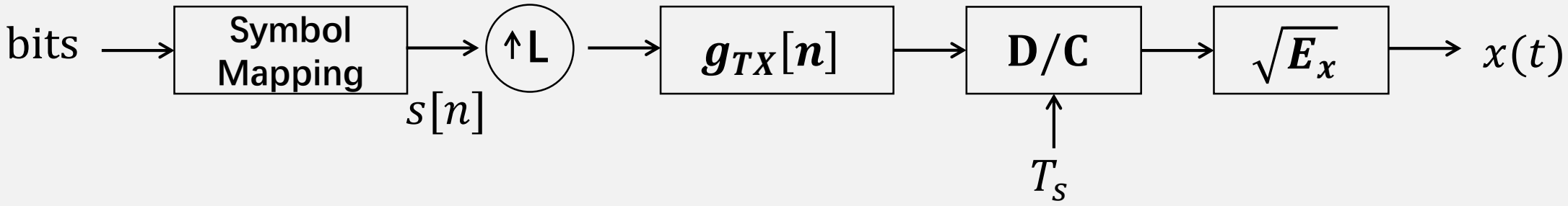
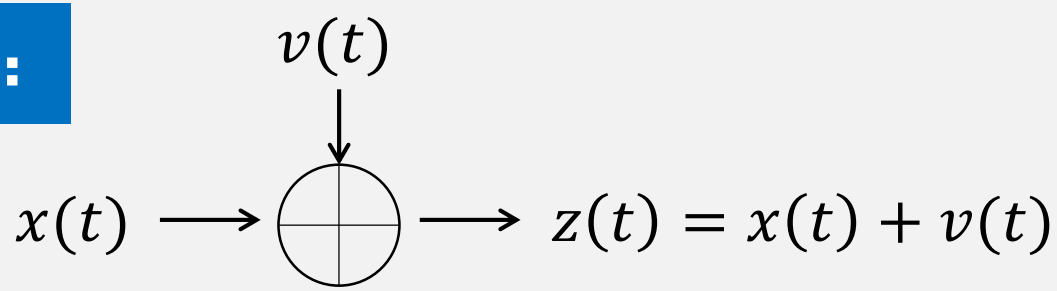


Host Computer	USRP motherboard	USRP daughterboard

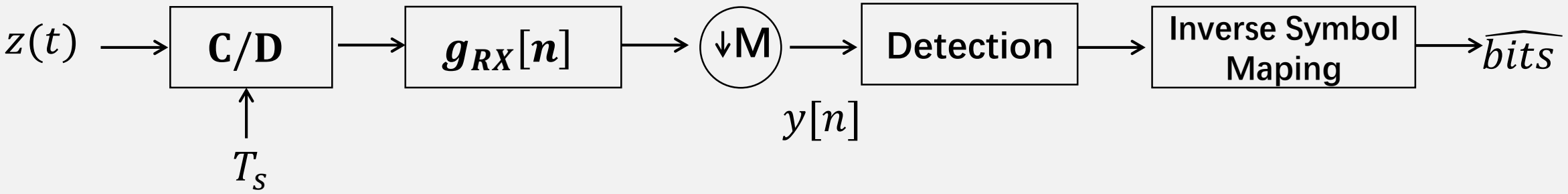
Transmitter:



AWGN Channel:



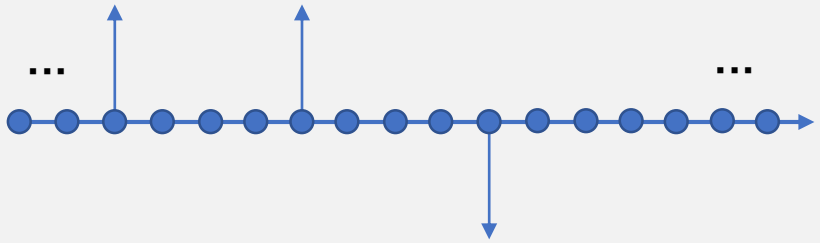
Receiver:

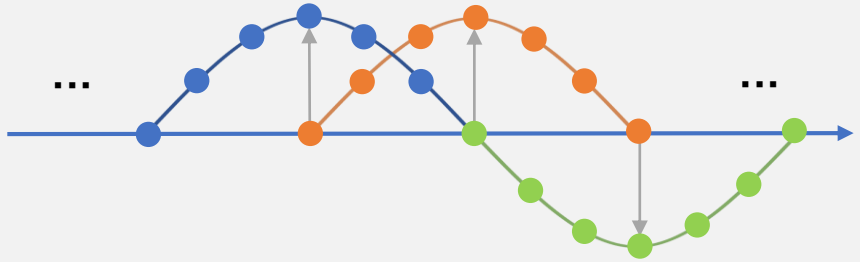


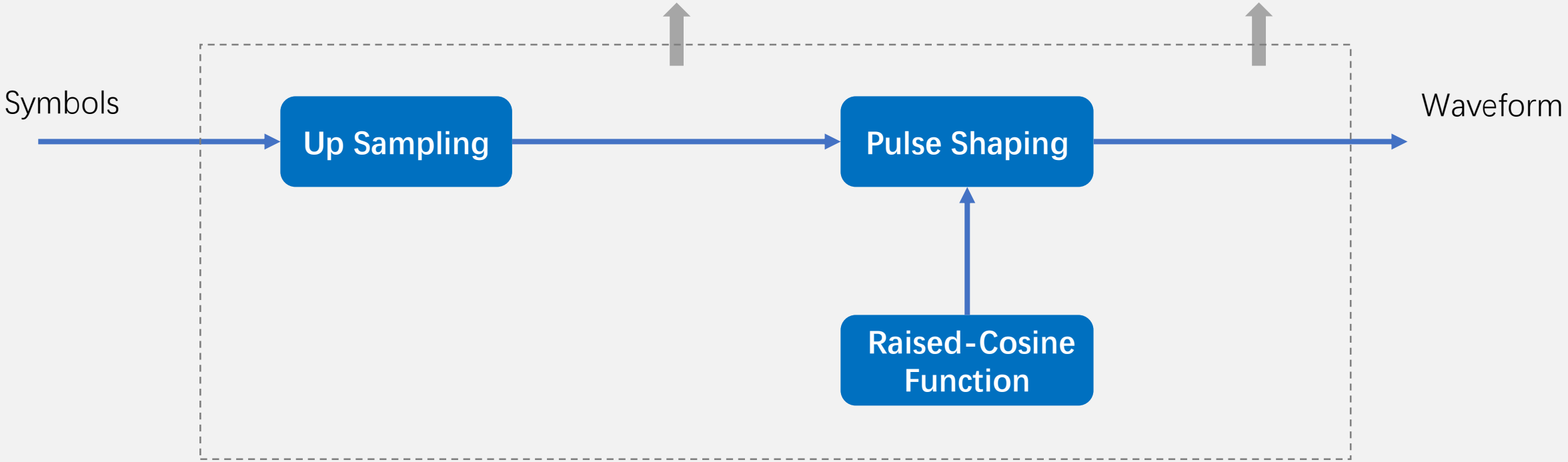
Two main goals for pulse shaping are:

- To reduce the energy of spectral sidelobes (i.e., excess bandwidth requirements).

- To reduce the time-domain pulse tails which can lead to inter-symbol interference.






Symbols
Up Sampling
Pulse Shaping
Waveform
Raised-Cosine Function

Lab 11 : Pulse Shaping and Matched Filtering

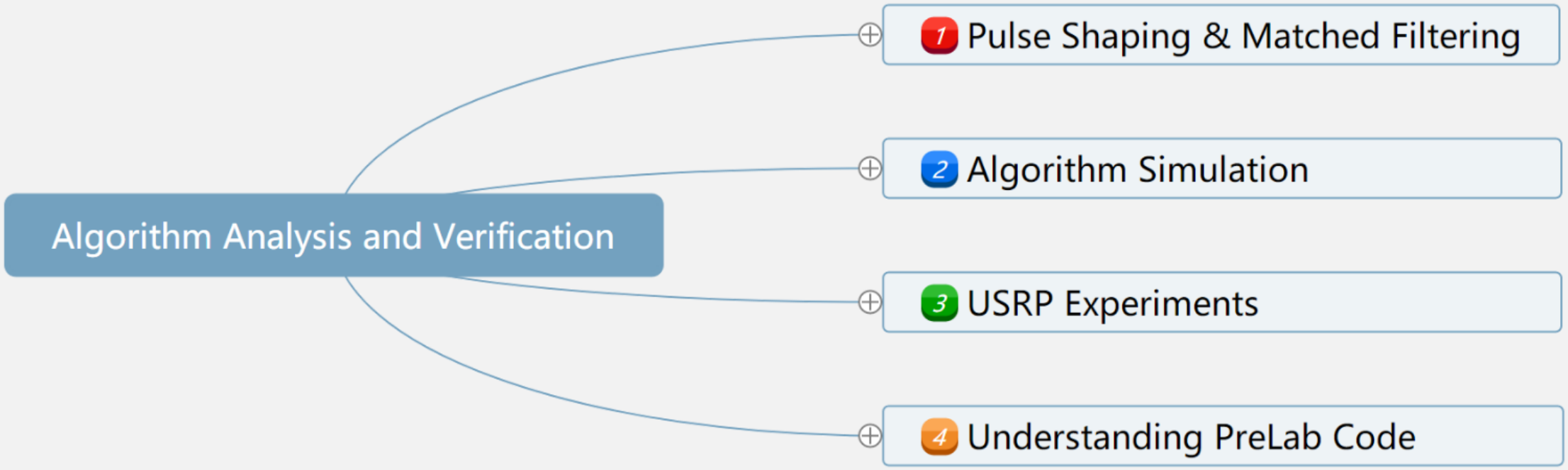
主讲人：吴光 博士
Email: wug@sustech.edu.cn

2、实验目标可视化

Demo: Pulse Shaping Function

I have an ability to

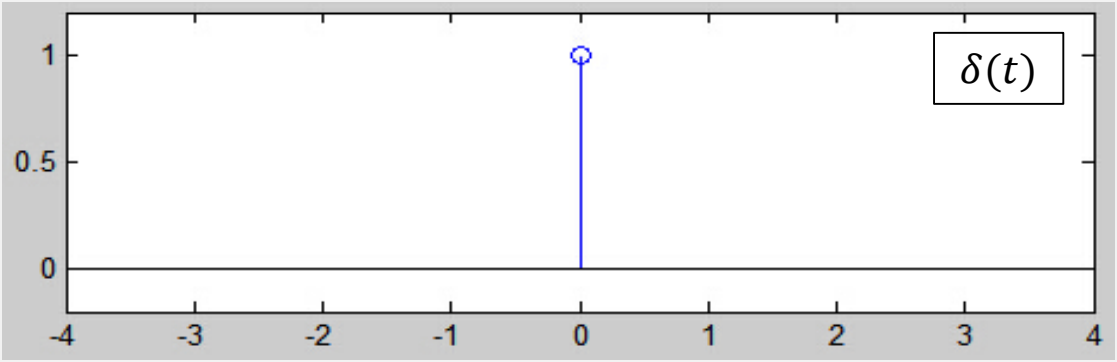
- Understand the basic principles of pulse shaping and matched filtering
- Implement the pulse shaping module and the matched filtering module by LabVIEW programming
- Do modules verification by simulation
- Use USRP platform for experimental verification
- Analyze the performance of the pulse shaping module and the matched filter module

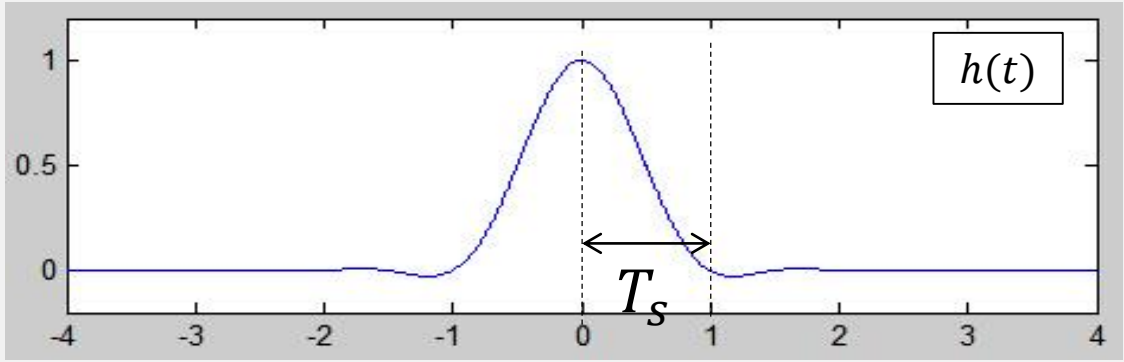

Algorithm Analysis and Verification
1 Pulse Shaping & Matched Filtering
2 Algorithm Simulation
3 USRP Experiments
4 Understanding PreLab Code

Linear Time Invariant System

Pre-Lab: Linear time invariant system

$$H\{I_k\delta(t-kT_s)\} = I_k h(t-kT_s)$$



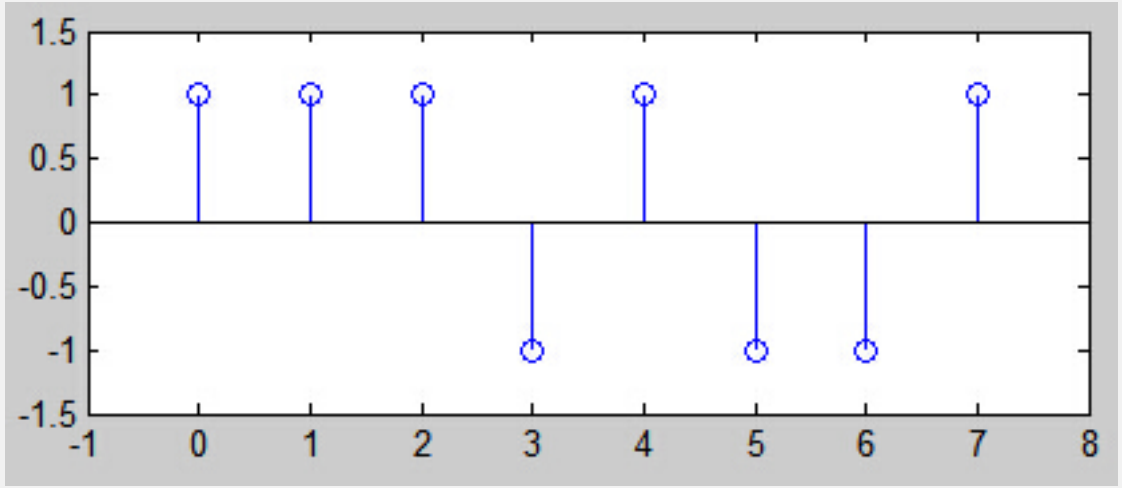


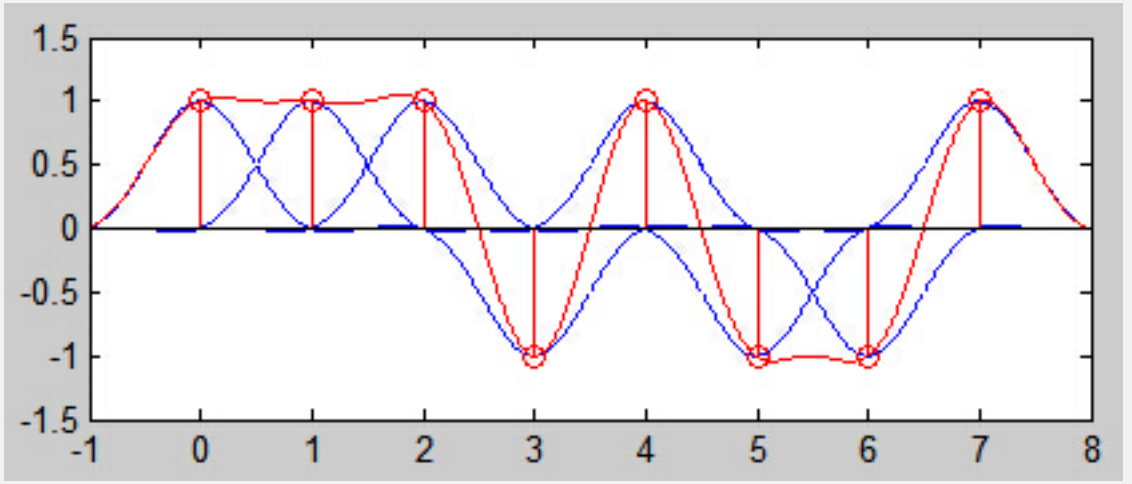
Pre-Lab: Linear time invariant system

$$H\left\{\sum_k I_k \delta(t - kT_s)\right\} = \sum_k I_k h(t - kT_s)$$

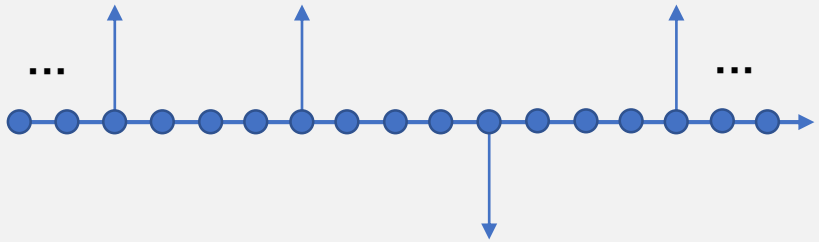
Pre-Lab: Linear time invariant system

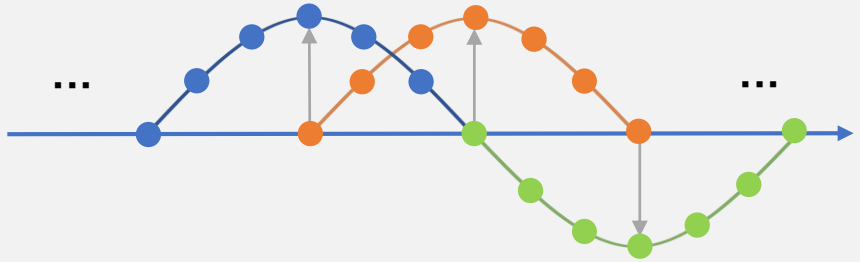
$$\sum_k I_k \delta(t - kT_s) \longrightarrow \boxed{\mathrm{H}\{\cdot\}} \longrightarrow \sum_k I_k h(t - kT_s)$$





System Model for Pulse Shaping





Up Sampling

Pulse Shaping

Raised-Cosine Function

Design of Pulse Shaping Function

$$y[n] = \sqrt{E_x}s[n] + \sqrt{E_x}\sum_{m\neq n} s[m]g\left((n-m)T_s\right) + \tilde{v}[n]$$

Design of Pulse Shaping Function

$$y[n] = \sqrt{E_x}s[n] + \sqrt{E_x}\sum_{m\neq n} s[m]g\left((n-m)T_s\right) + \tilde{v}[n]$$

$$\text{SINR} = \frac{E[|\sqrt{E_x}s[n]g(0)|^2]}{E[|g_{rx}(t) * v(t)|^2_{nT_s}] + E[|\sqrt{E_x}\sum_{m\neq n} s[m]g\left((n-m)T_s\right)|^2]}$$

Design of Pulse Shaping Function

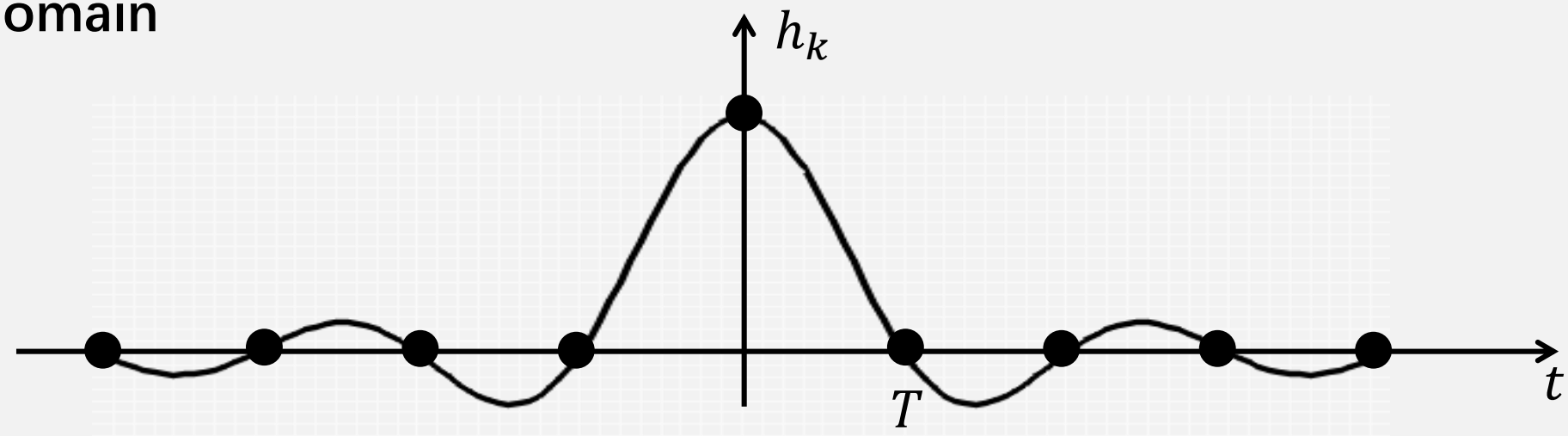
$$\mathrm{SINR} = \frac{E_x |g(0)|^2}{N_0 \int |G_{rx}(f)|^2 df + E_x \sum_{m \neq 0} |g(mT_s)|^2}$$

$$\mathrm{SINR} = \frac{E[|\sqrt{E_x} s[n] g(0)|^2]}{E[|g_{rx}(t) * v(t)|^2_{nT_s}] + E[|\sqrt{E_x} \sum_{m \neq n} s[m] g((n-m)T_s)|^2]}$$

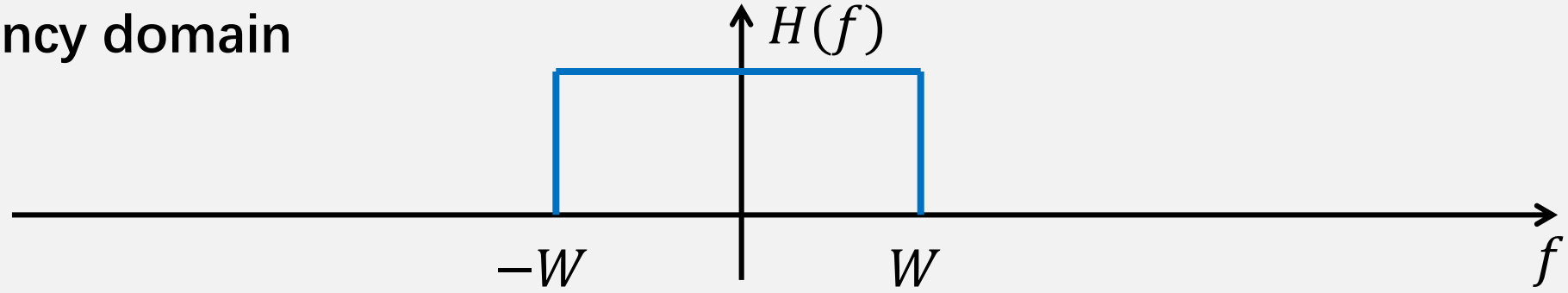
Nyquist Pulse

$$g(nT_s) = \begin{cases} 1, & n = 0 \\ 0, & n \neq 0 \end{cases} \quad \Longleftrightarrow \quad \frac{1}{T_s} \sum_{k=-\infty}^{+\infty} G\left(f - \frac{k}{T_s}\right) = 1$$

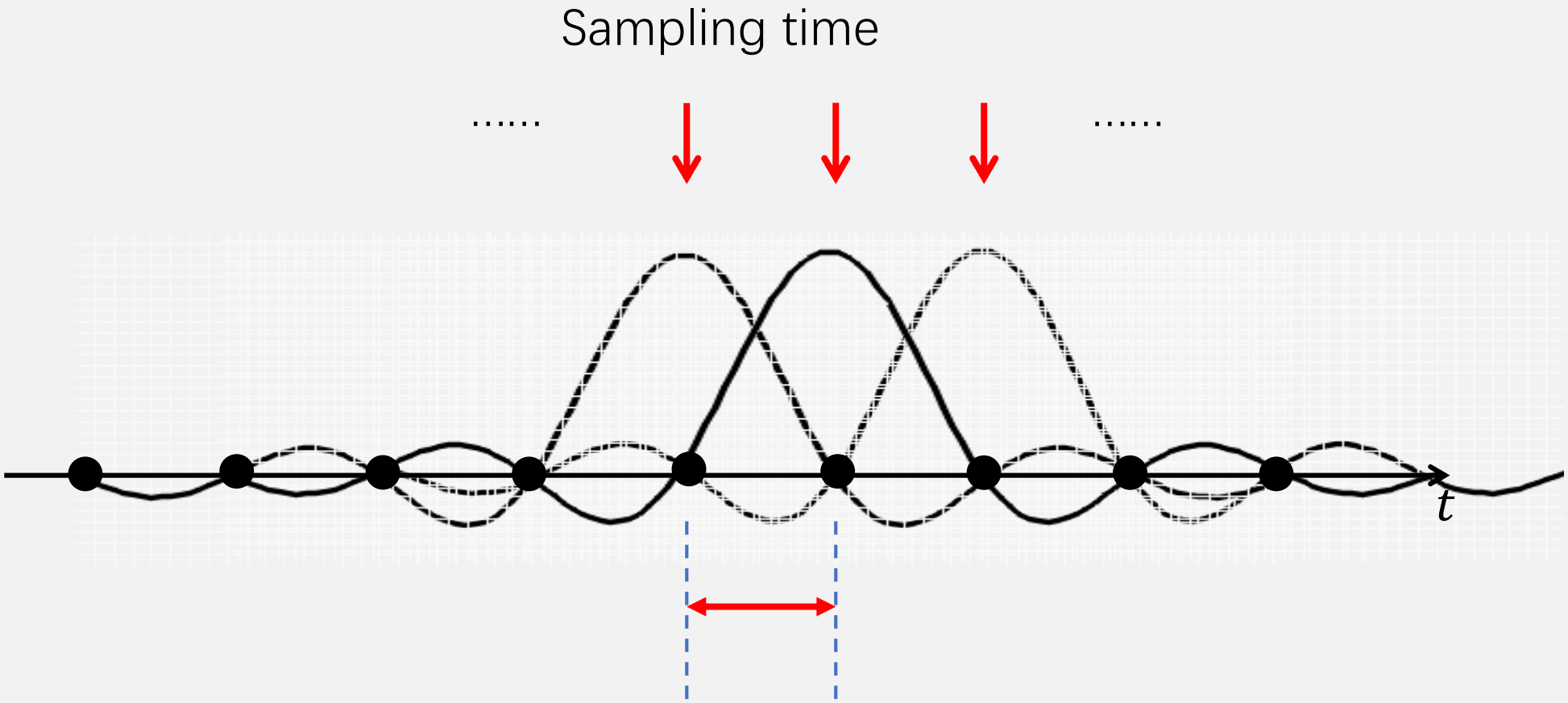
- Time domain



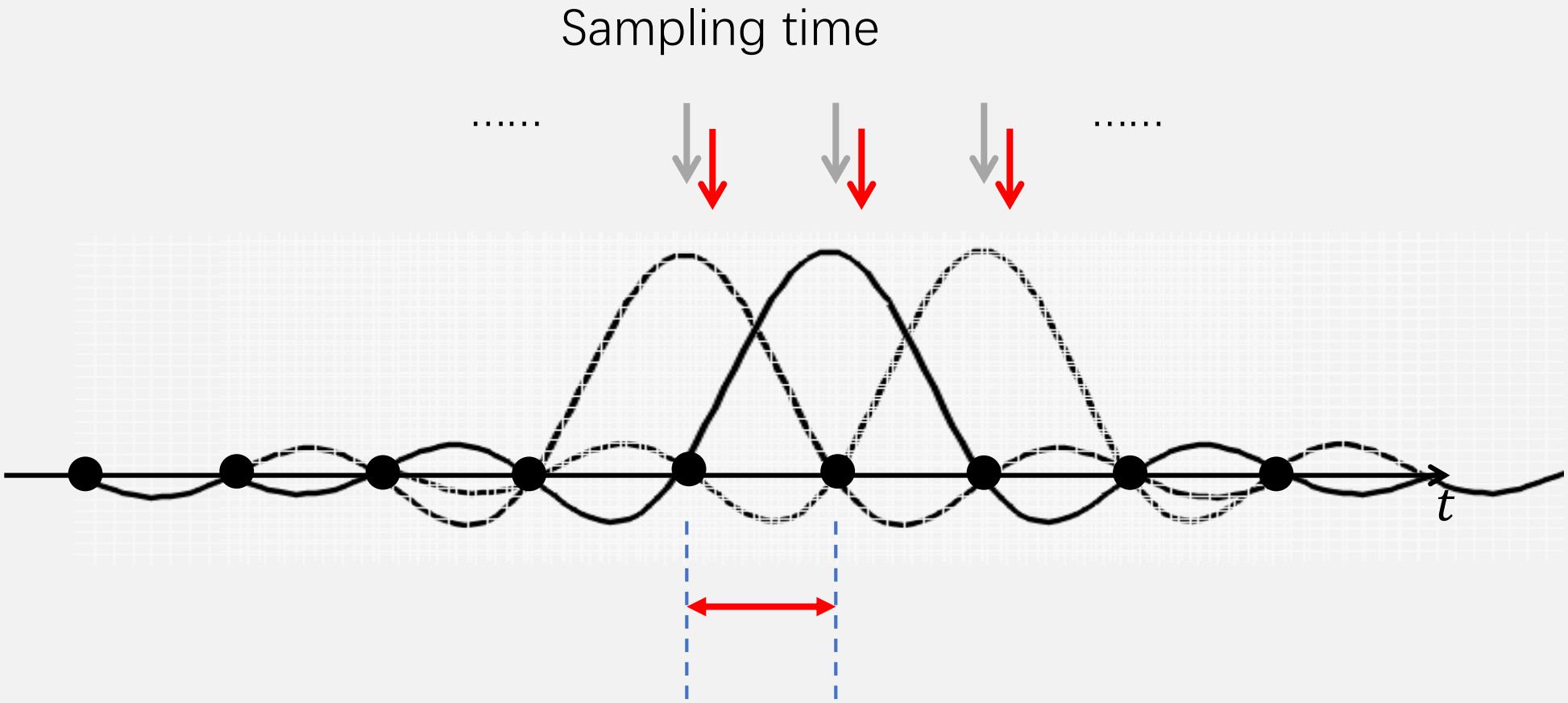
- Frequency domain



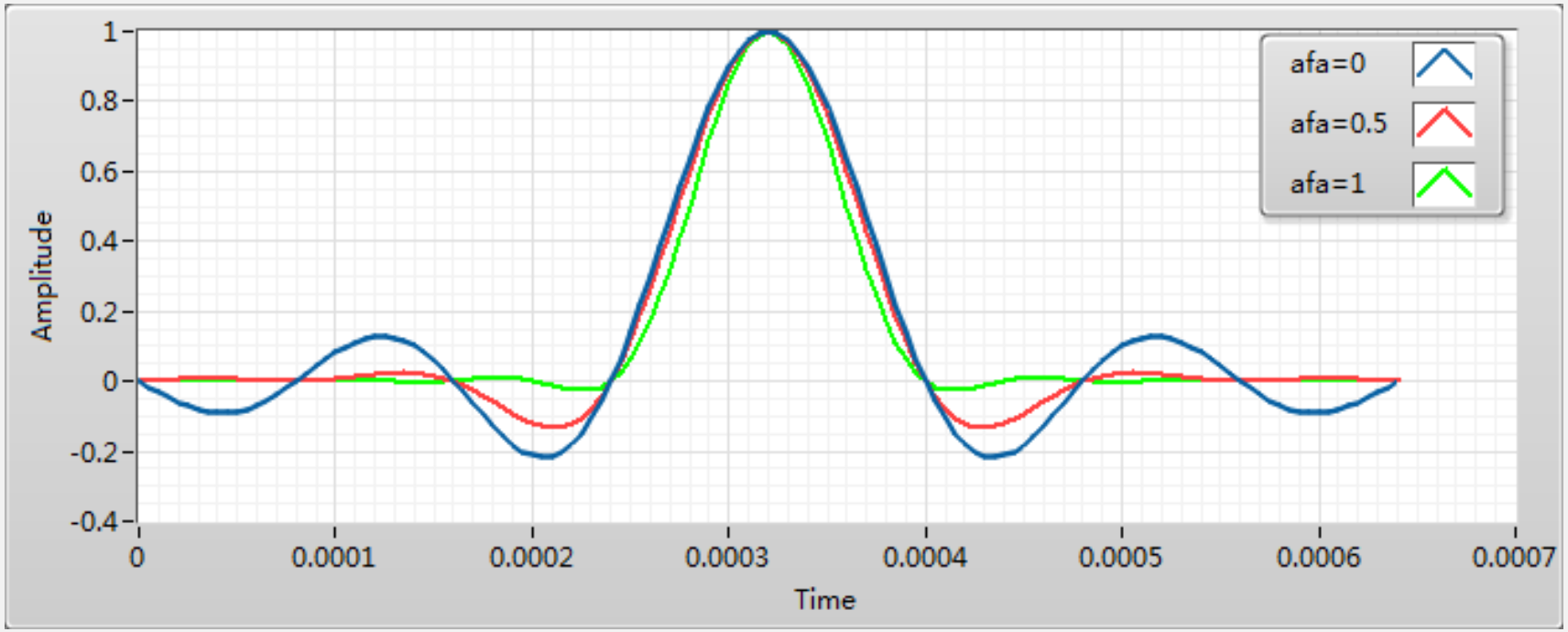
Nyquist ISI criterion

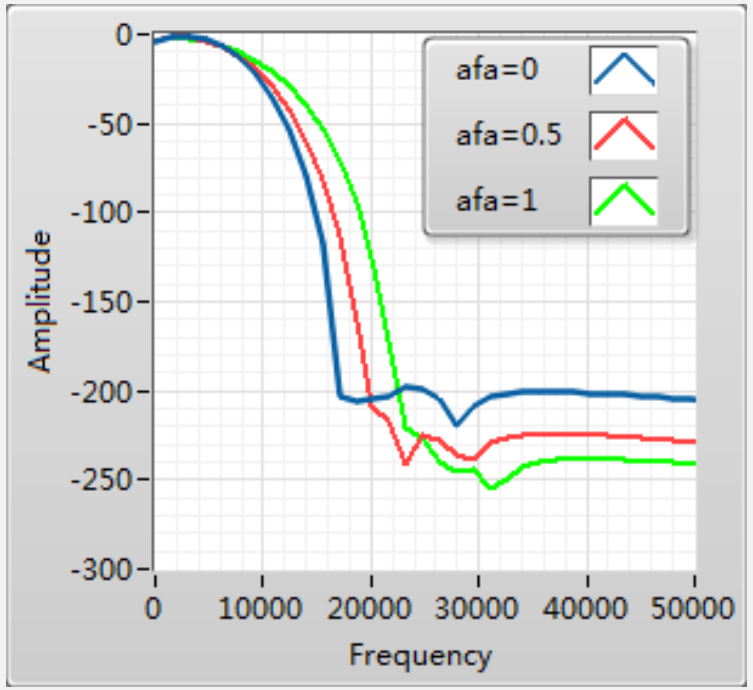


Nyquist ISI criterion



$$g_{\mathrm{rc}} = \frac{\sin \pi t / T}{\pi t / T} \frac{\cos(\pi \alpha t)}{1 - 4\alpha^2 t^2 / T^2}$$





Raised-Cosine Function

$$g_{\mathrm{rc}} = \frac{\sin \pi t/T}{\pi t/T} \frac{\cos(\pi \alpha t)}{1 - 4\alpha^2 t^2/T^2}$$

$$g_{\mathrm{sqrc}}(t) = \frac{4\alpha}{\pi\sqrt{T}} \frac{\cos\left[(1+\alpha)\pi t/T\right] + \dfrac{\sin[(1-\alpha)\pi t/T]}{4\alpha t/T}}{1 - (4\alpha t/T)^2}$$

System Model for Matched Filtering

$$\mathrm{SINR} = \frac{E_x |g(0)|^2}{N_0 \int |G_{rx}(f)|^2 df + E_x \sum_{m \neq 0} |g(mT_s)|^2}$$

$$g(0) = \int g_{rx}^*(-t) g_{tx}(t) dt$$

$$|g(0)|^2 = |\int g_{rx}(-t)g_{tx}(t)dt\,|^2$$

$$\leq \int |g_{tx}(t)|^2 dt \int |g_{rx}(t)|^2 dt$$

$$= \int |g_{rx}(t)|^2 dt$$

$$g_{rx}(t) = g_{tx}^*(-t)$$

$g_{tx}(t)$

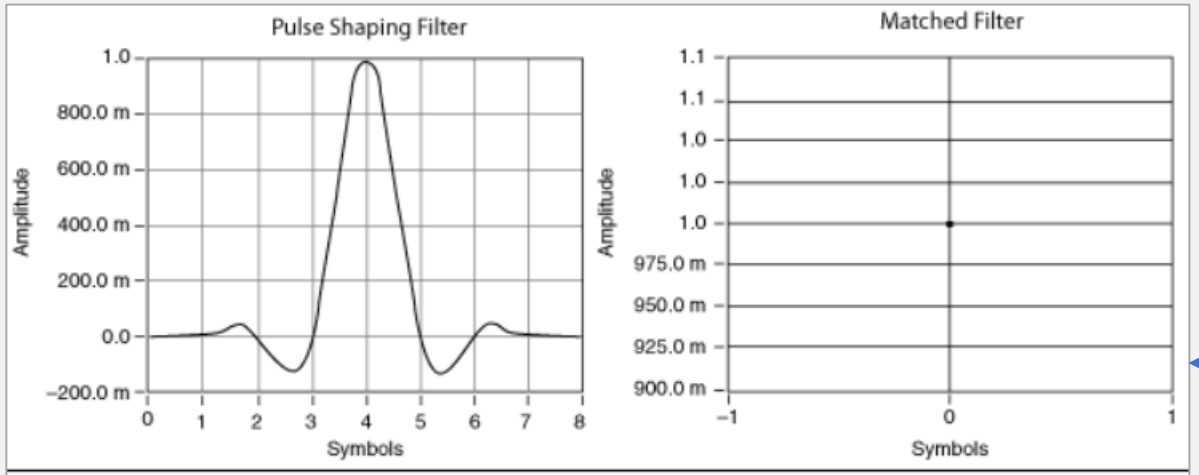
$$g_{\mathrm{sqrc}}(t) = \frac{4\alpha}{\pi\sqrt{T}} \frac{\cos\left[(1+\alpha)\pi t/T\right] + \dfrac{\sin[(1-\alpha)\pi t/T]}{4\alpha t/T}}{1-(4\alpha t/T)^2}$$

$$h_R(t) = g(-t)$$

$g_{rx}(t)$

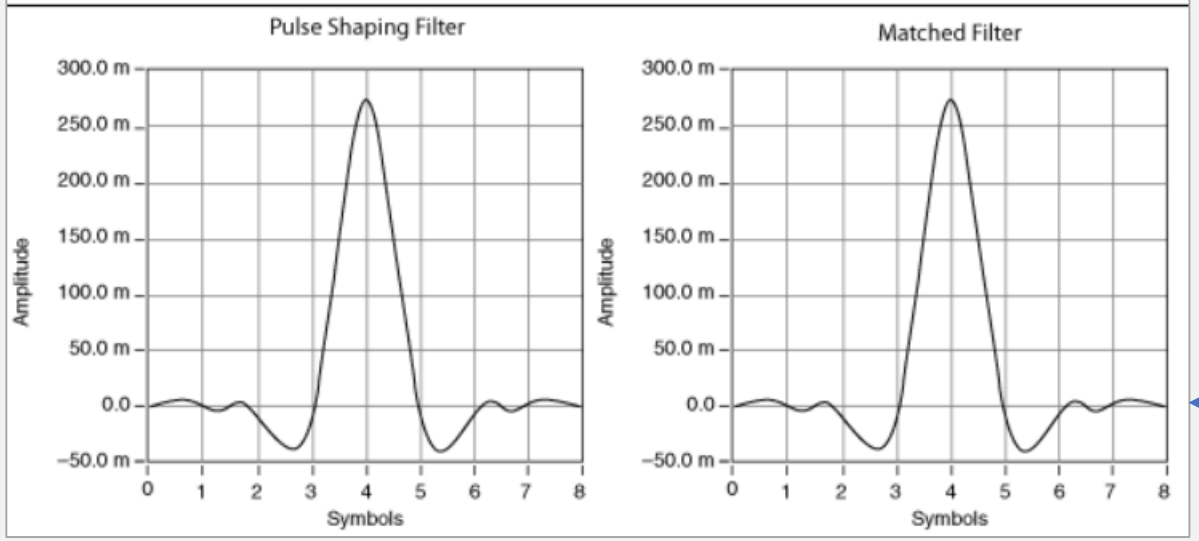
$$g_{\mathrm{sqrc}}(t) = \frac{4\alpha}{\pi\sqrt{T}} \frac{\cos\left[(1+\alpha)\pi t/T\right] + \dfrac{\sin[(1-\alpha)\pi t/T]}{4\alpha t/T}}{1-(4\alpha t/T)^2}$$

Pulse shaping → Channel → Matched Filtering



MT Generate Filter Coefficients.vi

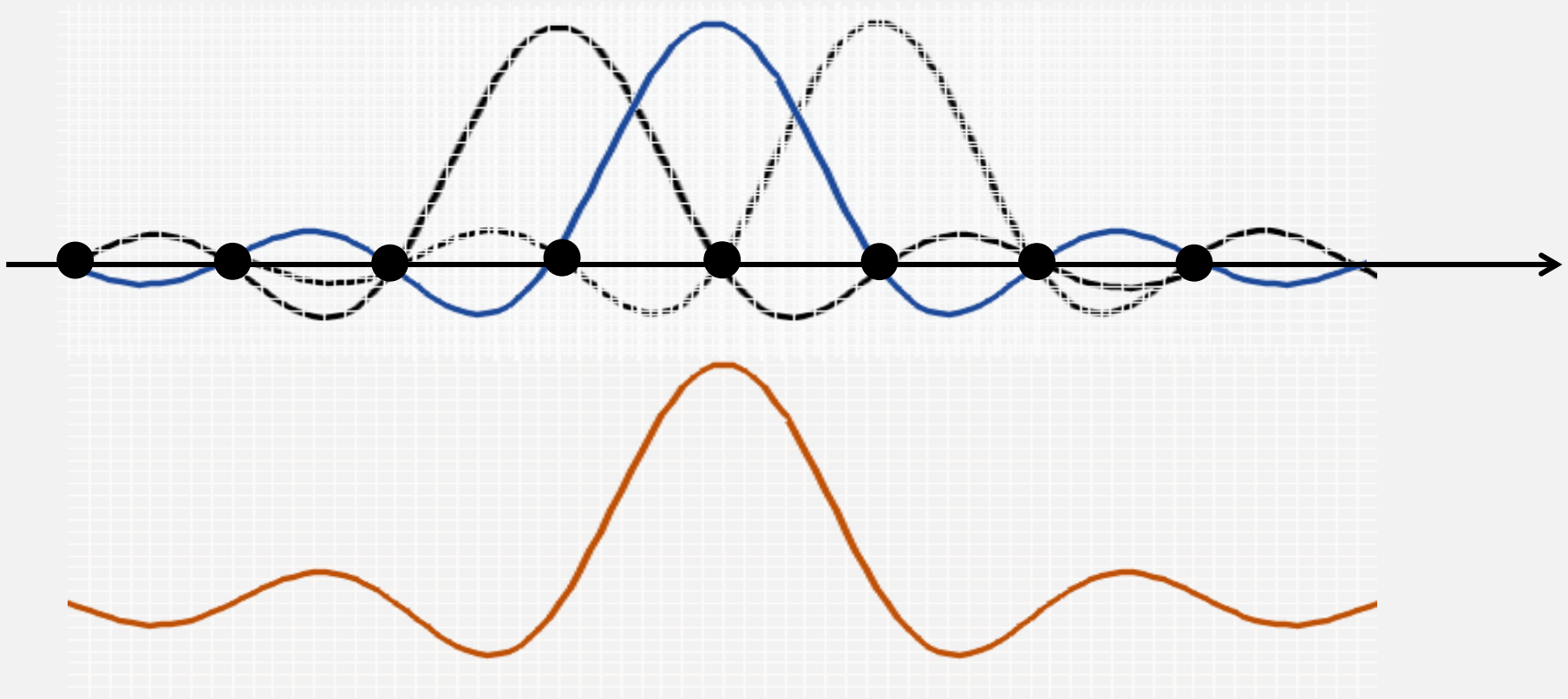
Raised-cosine function



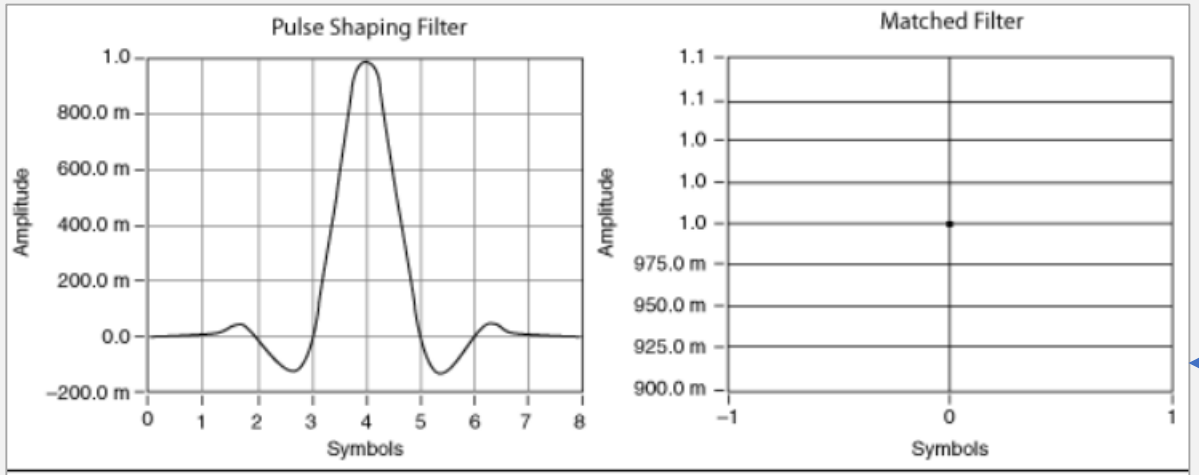
Square root Raised-cosine function

$I_T(n)$ → Pulse shaping → Channel → Matched filtering → $I_R(n)$

$h_p(n)$ $h_c(n) = \delta(n)$ $h_R(n)$

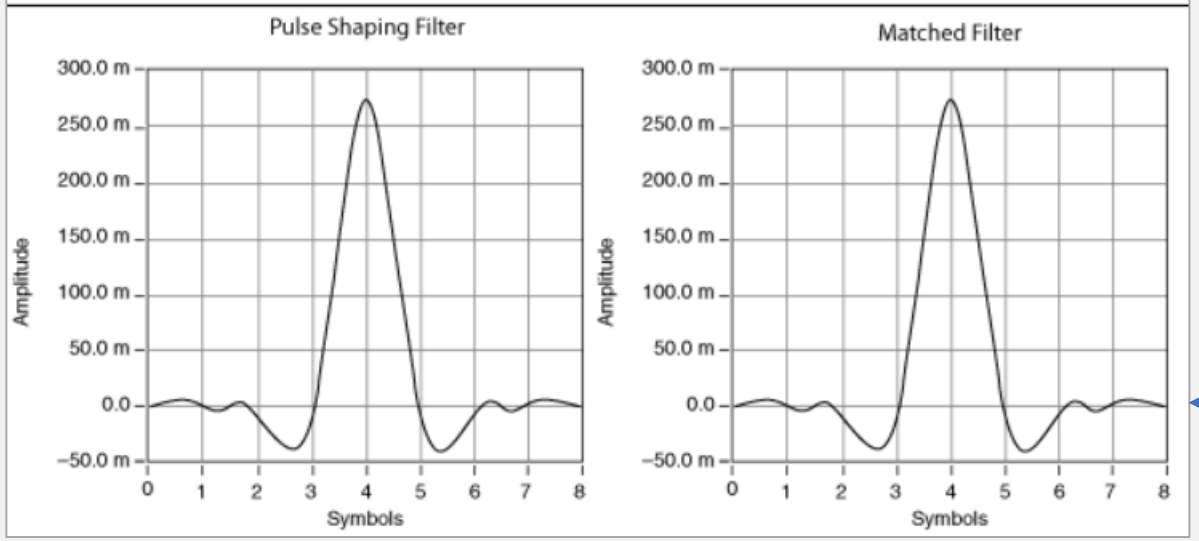


Pulse shaping → Channel → Matched Filtering

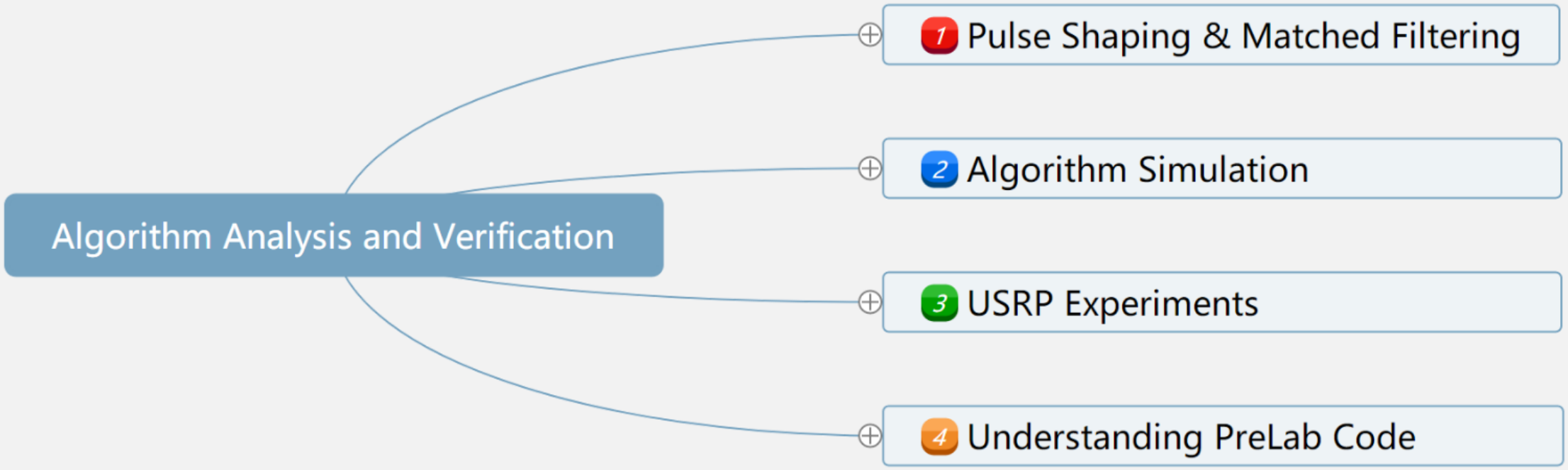


MT Generate Filter Coefficients.vi

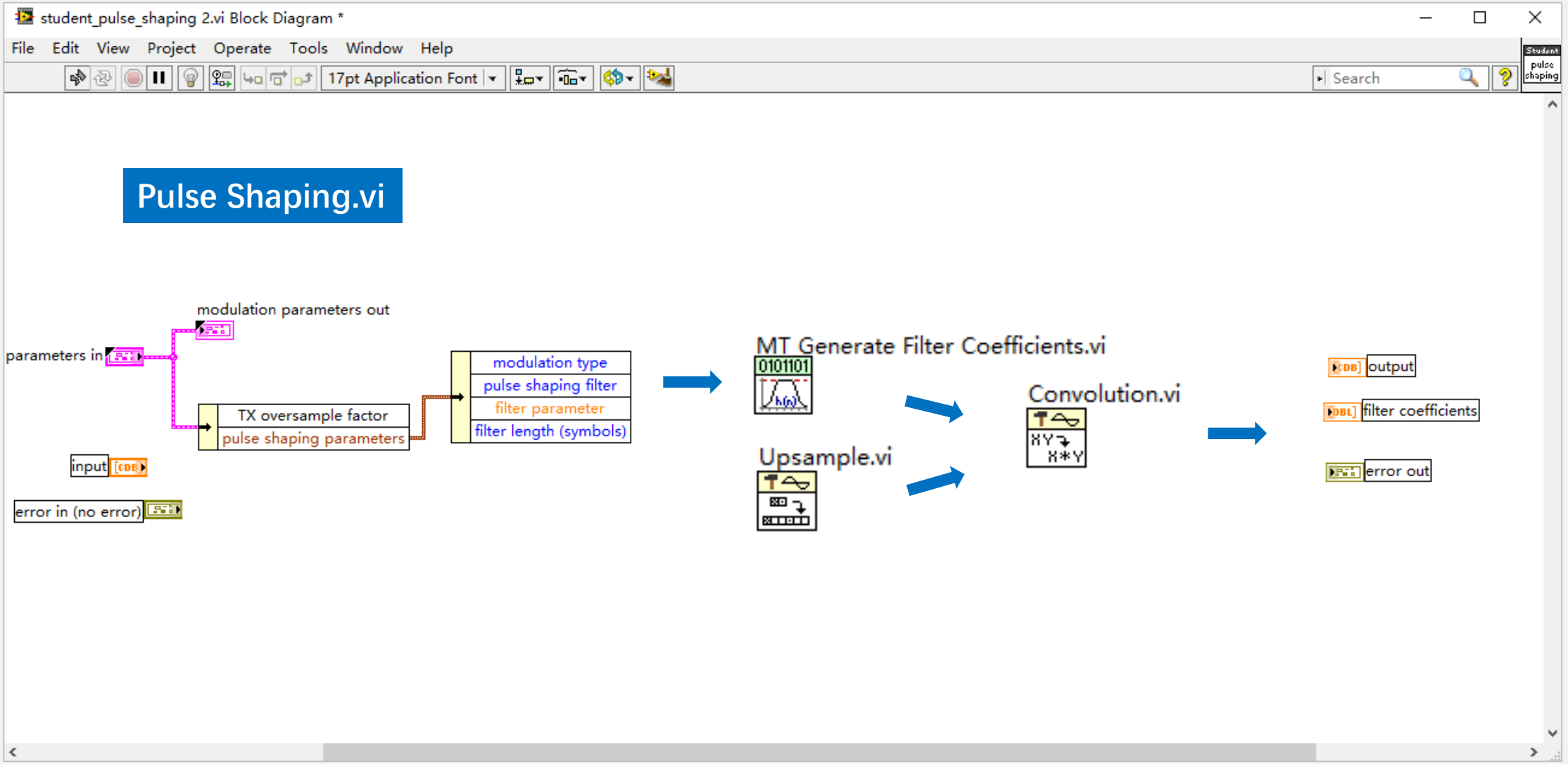
Raised-cosine function

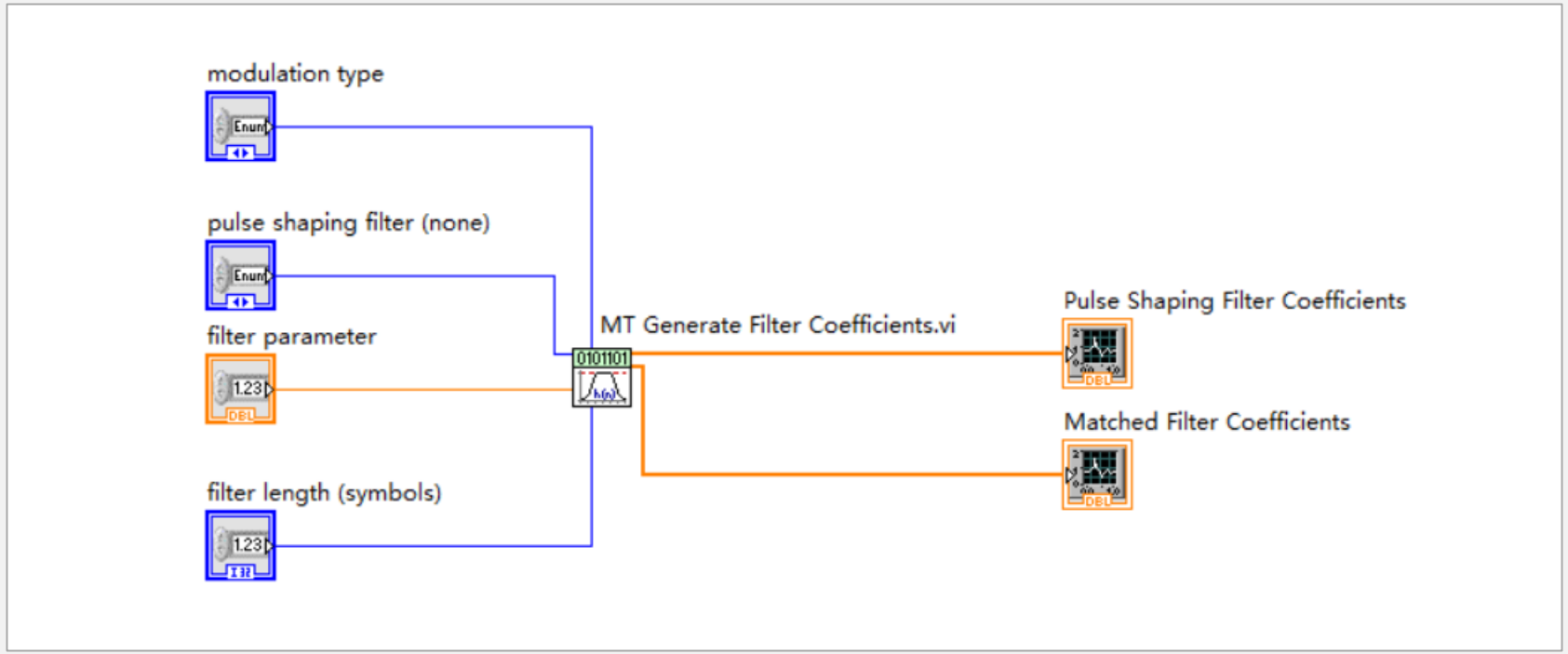


Square root Raised-cosine function


Algorithm Analysis and Verification
1 Pulse Shaping & Matched Filtering
2 Algorithm Simulation
3 USRP Experiments
4 Understanding PreLab Code

Programming for Pulse Shaping


student_pulse_shaping 2.vi Block Diagram *
File Edit View Project Operate Tools Window Help
17pt Application Font
Search
Student pulse shaping
Pulse Shaping.vi
modulation parameters out
parameters in
TX oversample factor
pulse shaping parameters
modulation type
pulse shaping filter
filter parameter
filter length (symbols)
input
error in (no error)
MT Generate Filter Coefficients.vi
0101101
Upsample.vi
Convolution.vi
output
filter coefficients
error out


modulation type
Enum
pulse shaping filter (none)
Enum
filter parameter
1.23
DBL
filter length (symbols)
1.23
I32
0101101
MT Generate Filter Coefficients.vi
Pulse Shaping Filter Coefficients
DBL
Matched Filter Coefficients
DBL

filter length (symbols) 16

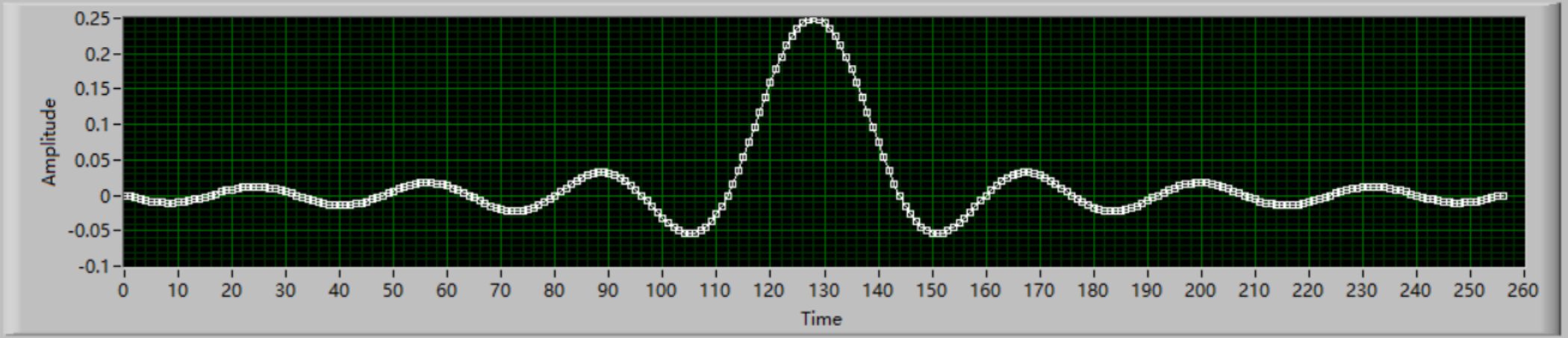
pulse shaping filter (none) Root Raised Cos

filter parameter 0

modulation type QAM

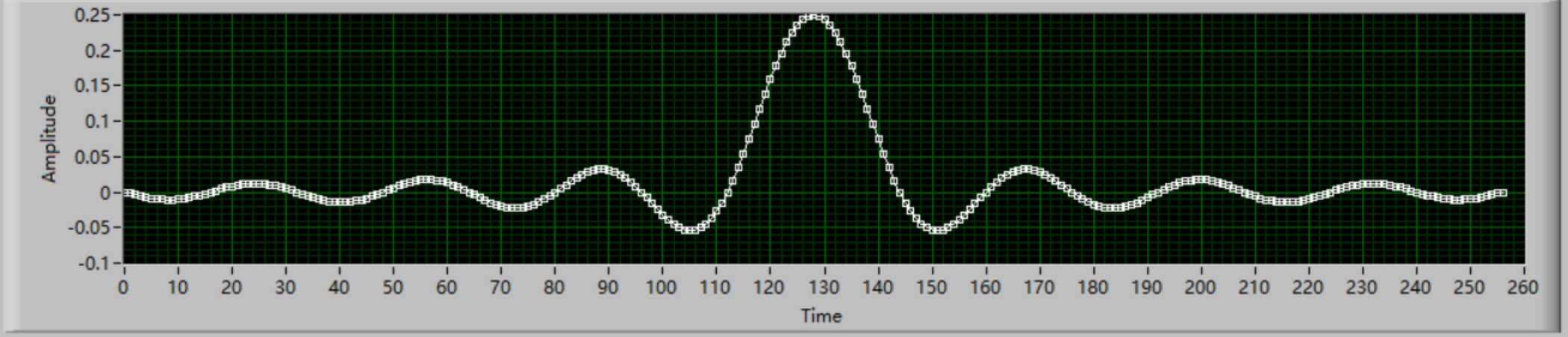
Pulse Shaping Filter Coefficients

Plot 0



Matched Filter Coefficients

Plot 0



filter length (symbols) 16

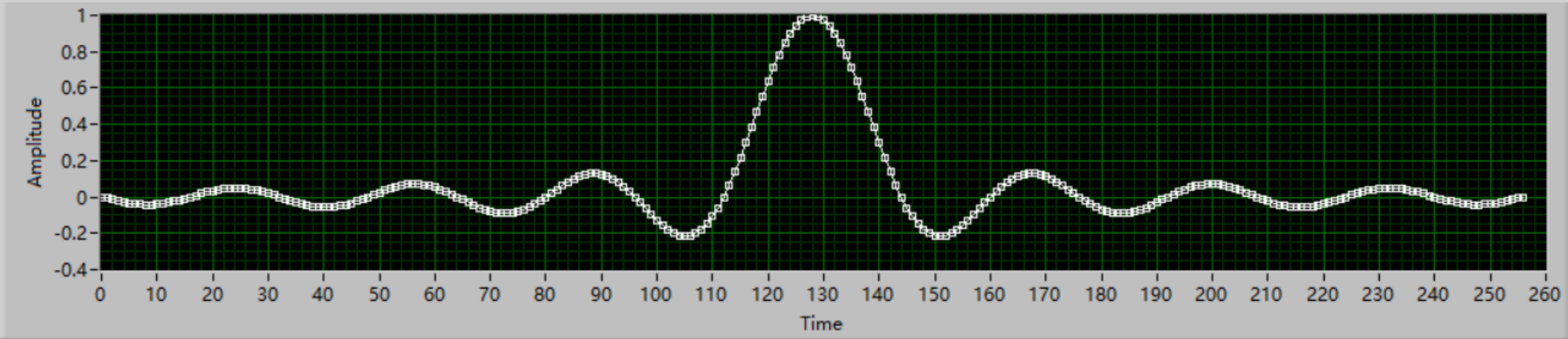
pulse shaping filter (none) Raised Cosine

filter parameter 0

modulation type QAM

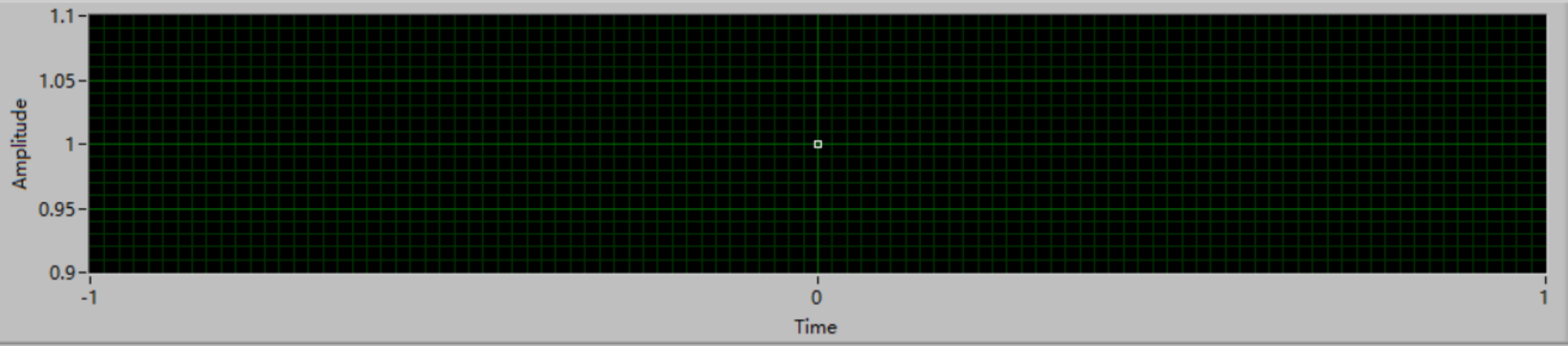
Pulse Shaping Filter Coefficients

Plot 0

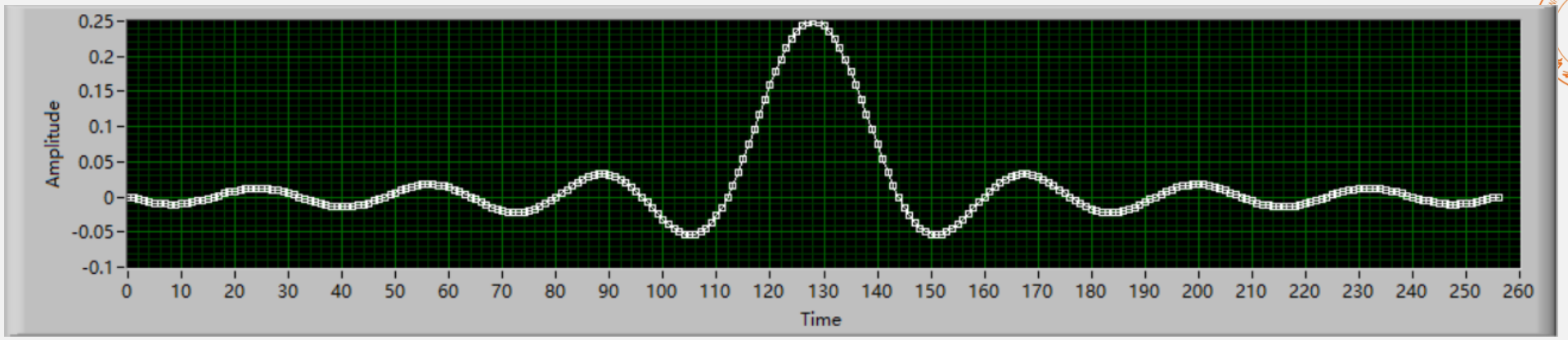


Matched Filter Coefficients

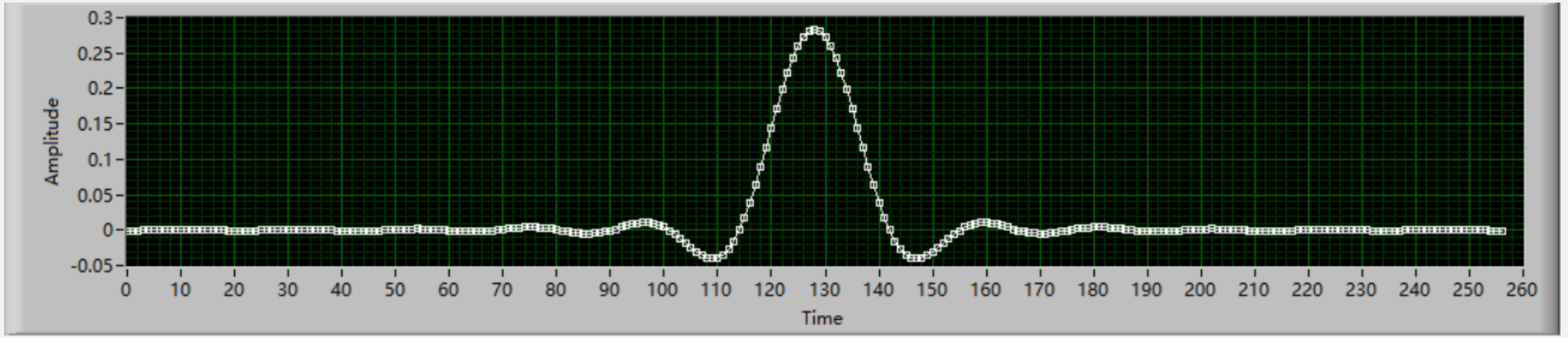
Plot 0



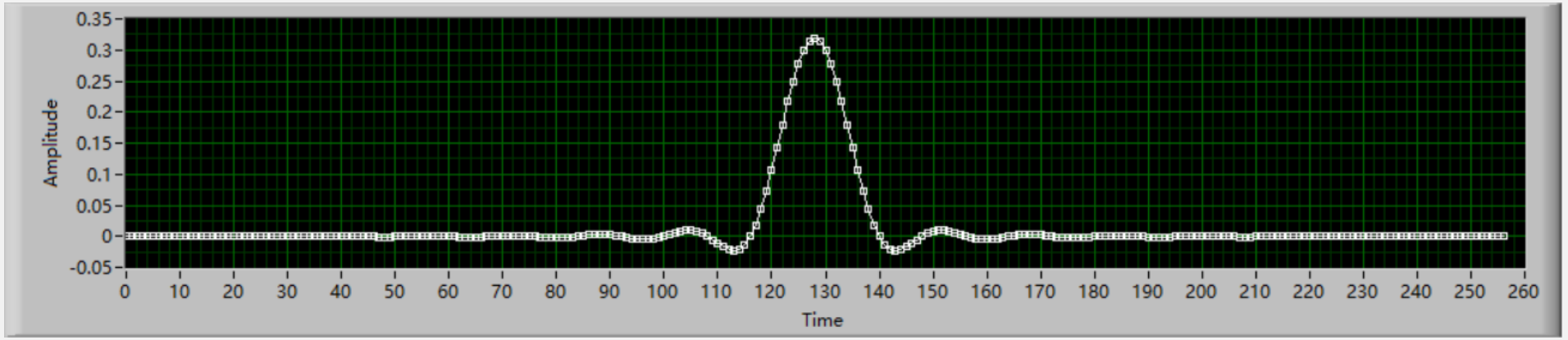
$\alpha = 0$



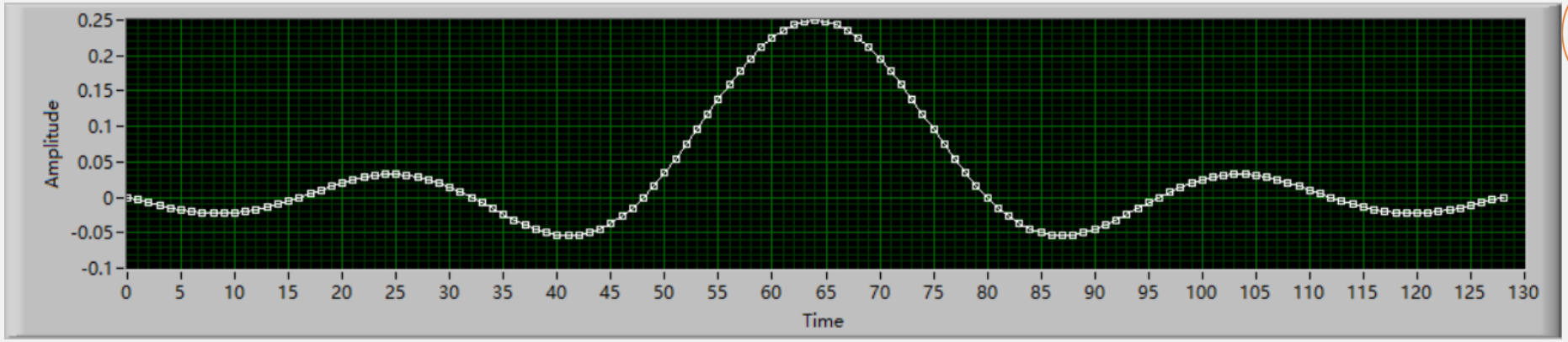
$\alpha = 0.5$



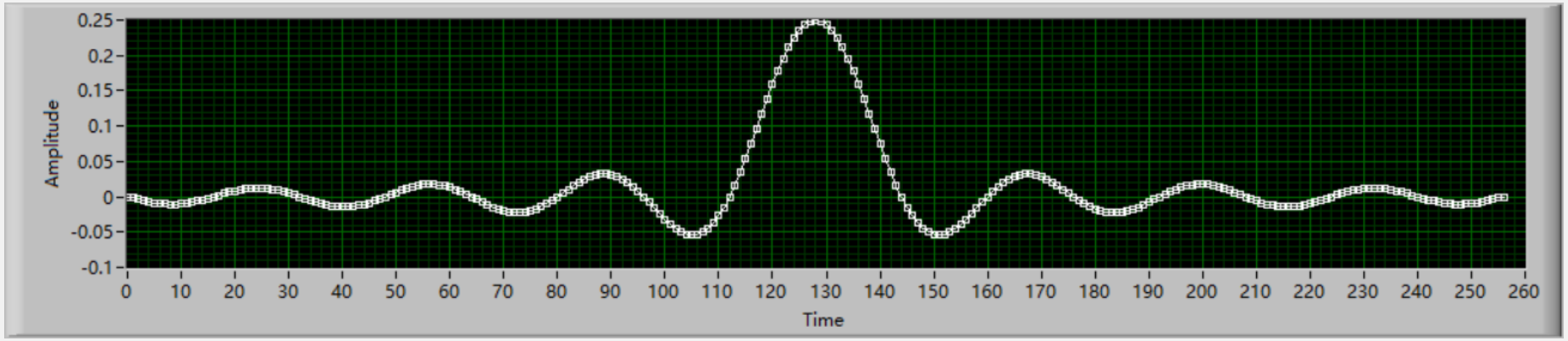
$\alpha = 1$



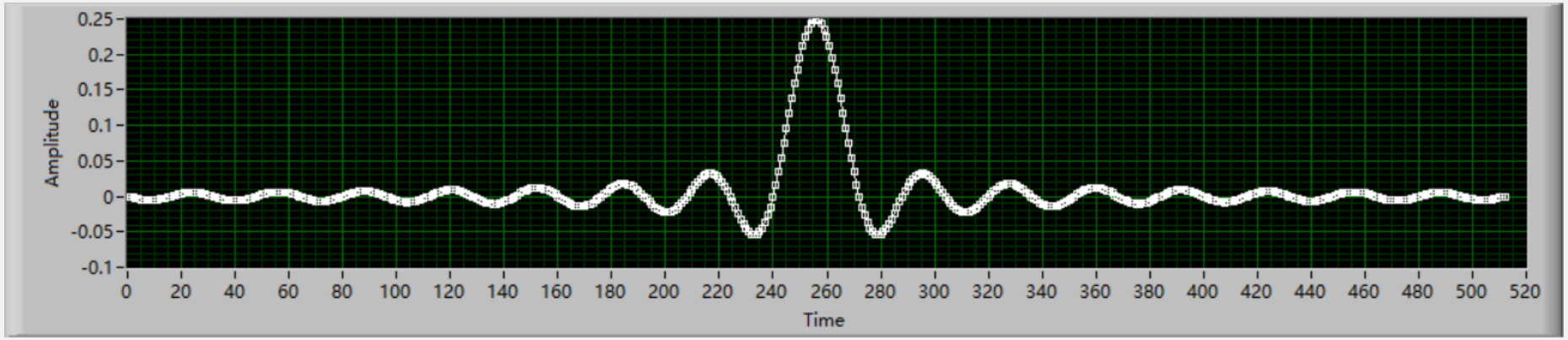
Filter Length = **8**



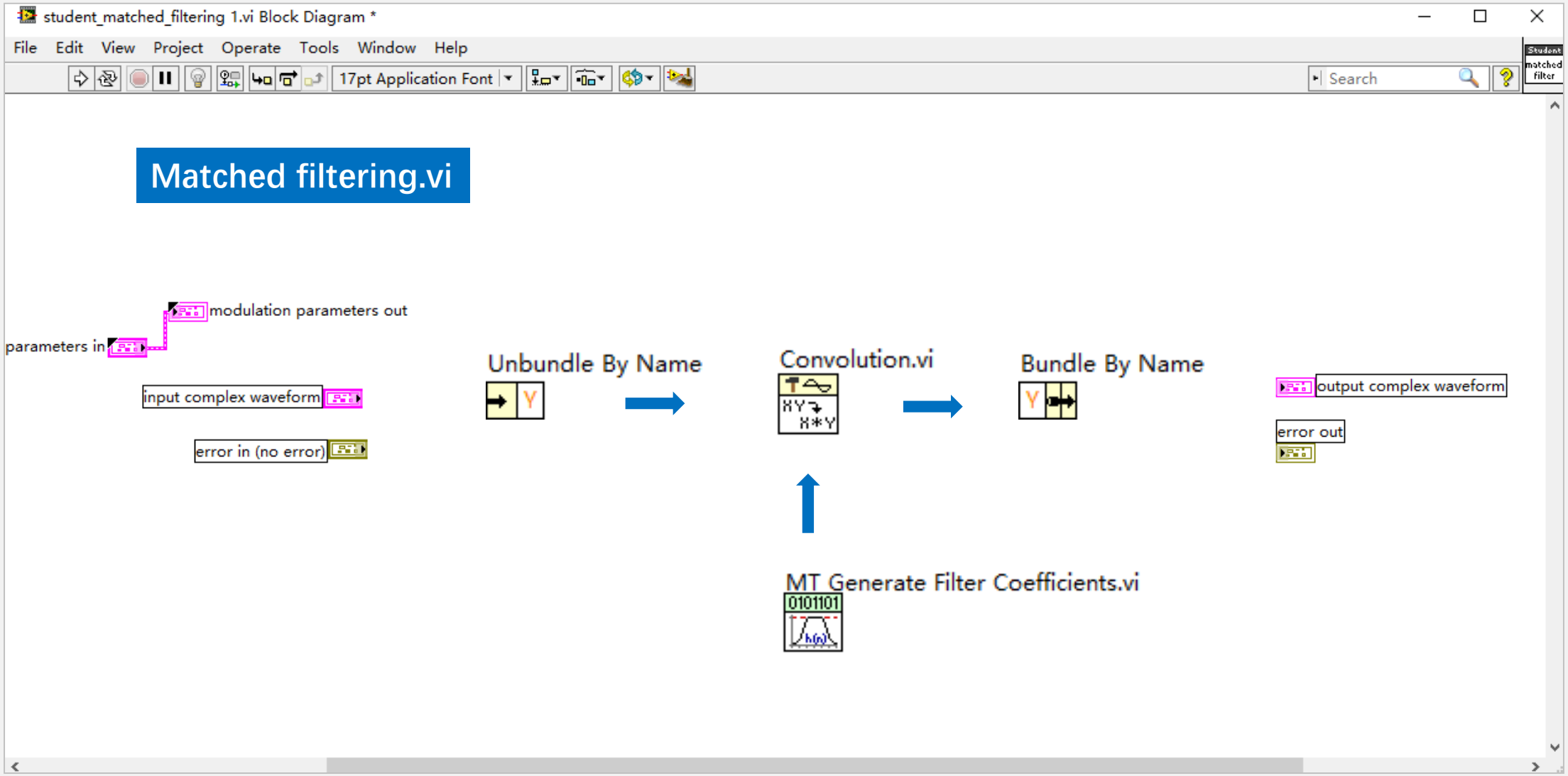
Filter Length = **16**



Filter Length = **32**



Programming for Matched Filtering


student_matched_filtering 1.vi Block Diagram *
File Edit View Project Operate Tools Window Help
17pt Application Font
Search
Matched filtering.vi
modulation parameters out
parameters in
input complex waveform
error in (no error)
Unbundle By Name
Convolution.vi
Bundle By Name
output complex waveform
error out
MT Generate Filter Coefficients.vi

System Testing

TRANSMITTER

TX oversample factor: 4
TX sample rate: 4M

TX channel model parameters

channel model: AWGN
noise power (dB): -Inf
channel response: 0 | 0 +0 i | 0 +0 i | 0 +0 i
frequency offset: 0
delay (sec): 0

RECEIVER

RX oversample factor: 4
RX Sample Rate: 4M

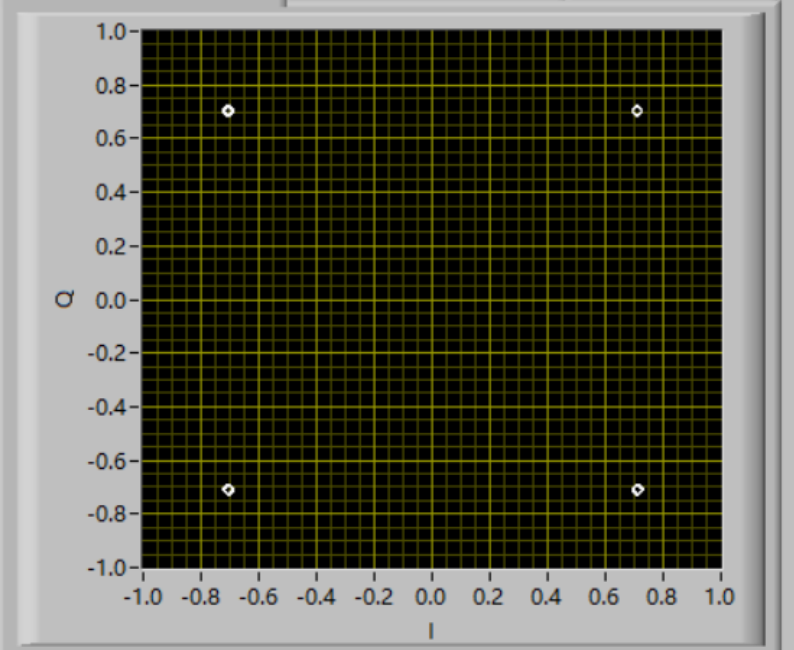
synchronization options

Synchronization Method: Timing
fixed offset: 0
Symbol Timing Recovery Method: Max Energy
Frame Detection Method: Sliding
Correct Frequency Offset

channel estimation equalizer parameters

Equalization Method: Direct
channel estimate length: 4
equalizer length: 4
equalizer delay: -1
(set delay to -1 for equalizer to choose optimal delay)

Spectrum | Power Delay Profile
Received Constellation | Received Eye Diagram | Received Signal



SHARED

modulation type: QPSK
packet length (bits): 500
Iterations: 1
control information for packet header/tail

Training Sequence Type: Length 11 Barker Sequence
Zero Pad Length: 8

Tx pulse shaping
modulation type: PSK
pulse shaping filter: Root Raised
filter parameter: 0.5
filter length (symbols): 8

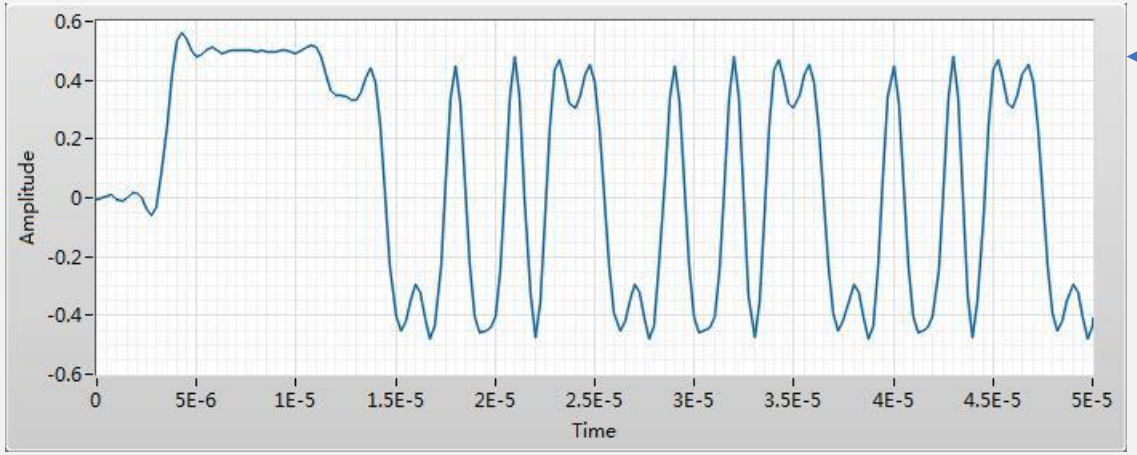
Rx matched filtering
modulation type: PSK
pulse shaping filter: Root Raised
filter parameter: 0.5
filter length (symbols): 8

error out
status
code: 0
source

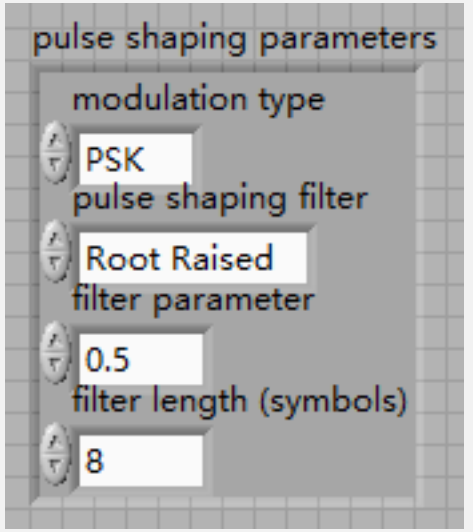
Measured channel impairements
SNR(dB): 44.3835
delay: 4E-6
freq. offset: 1.64538
channel estimate: 0
1.00018 +6.55884E-5 i
0.000180549 -8.10286E-5 i
0.000422062 +3.94874E-5 i
5.13721E-5 +7.82814E-5 i

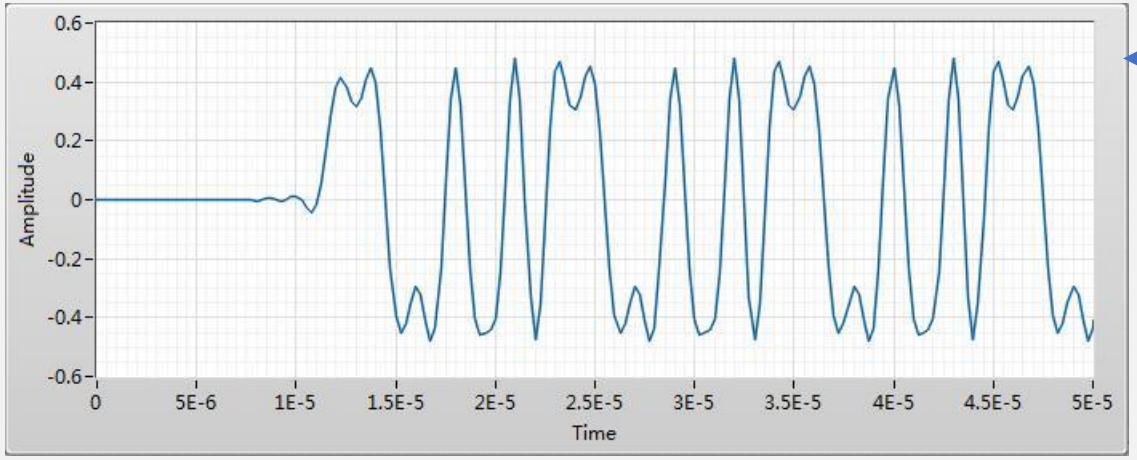
average BER: 0.000000
estimated offset: 32
error statistic: 16.000000

Lab simulation



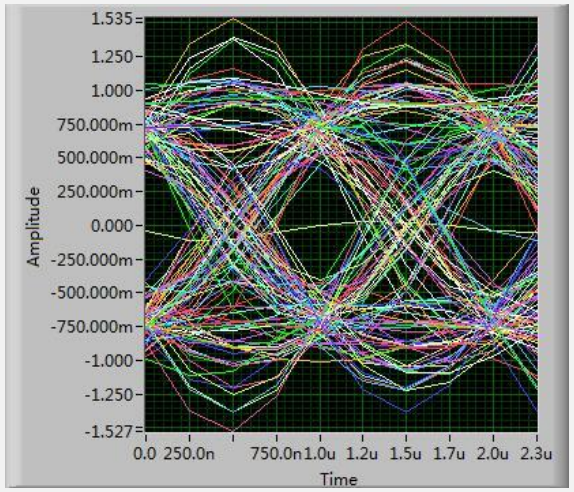
I signal



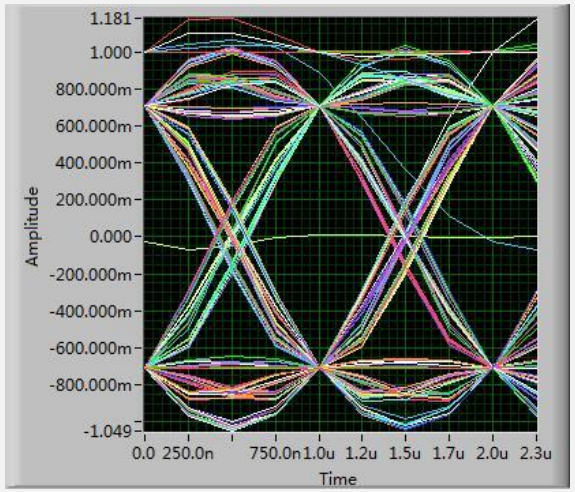


Q signal

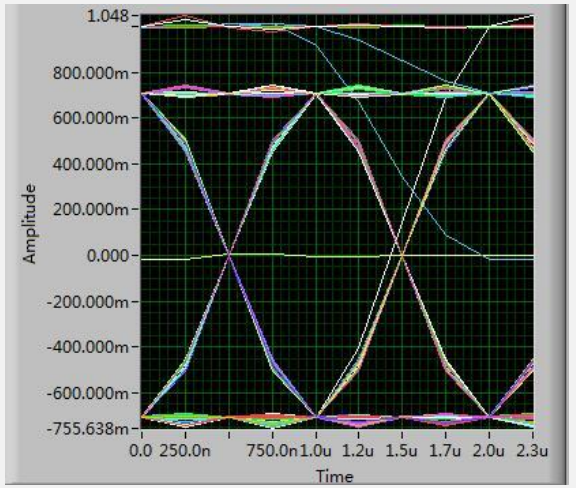
Eye Diagram and constellation



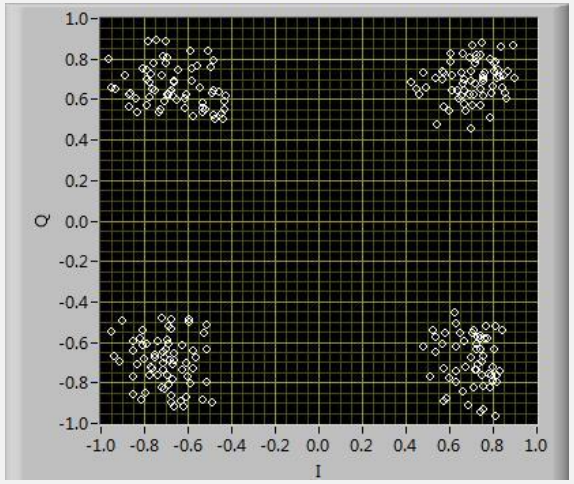
$\alpha = 0$

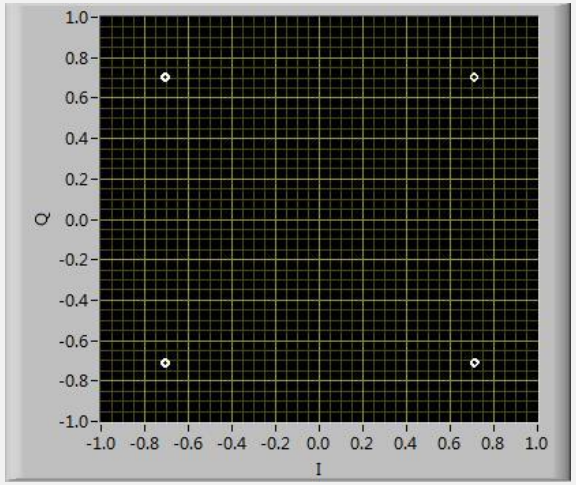


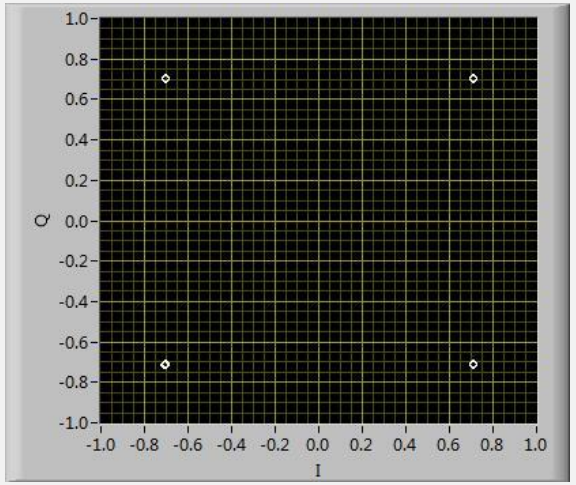
$\alpha = 0.5$



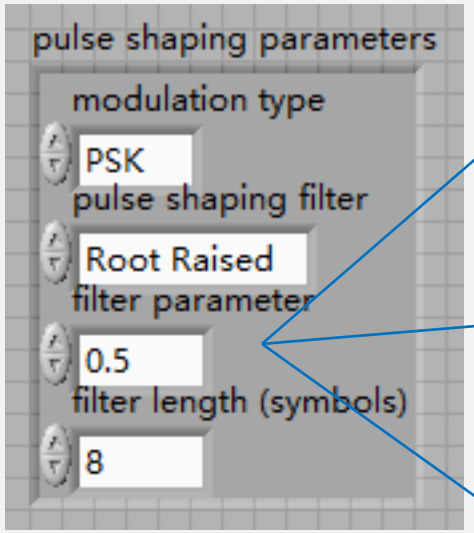
$\alpha = 1$







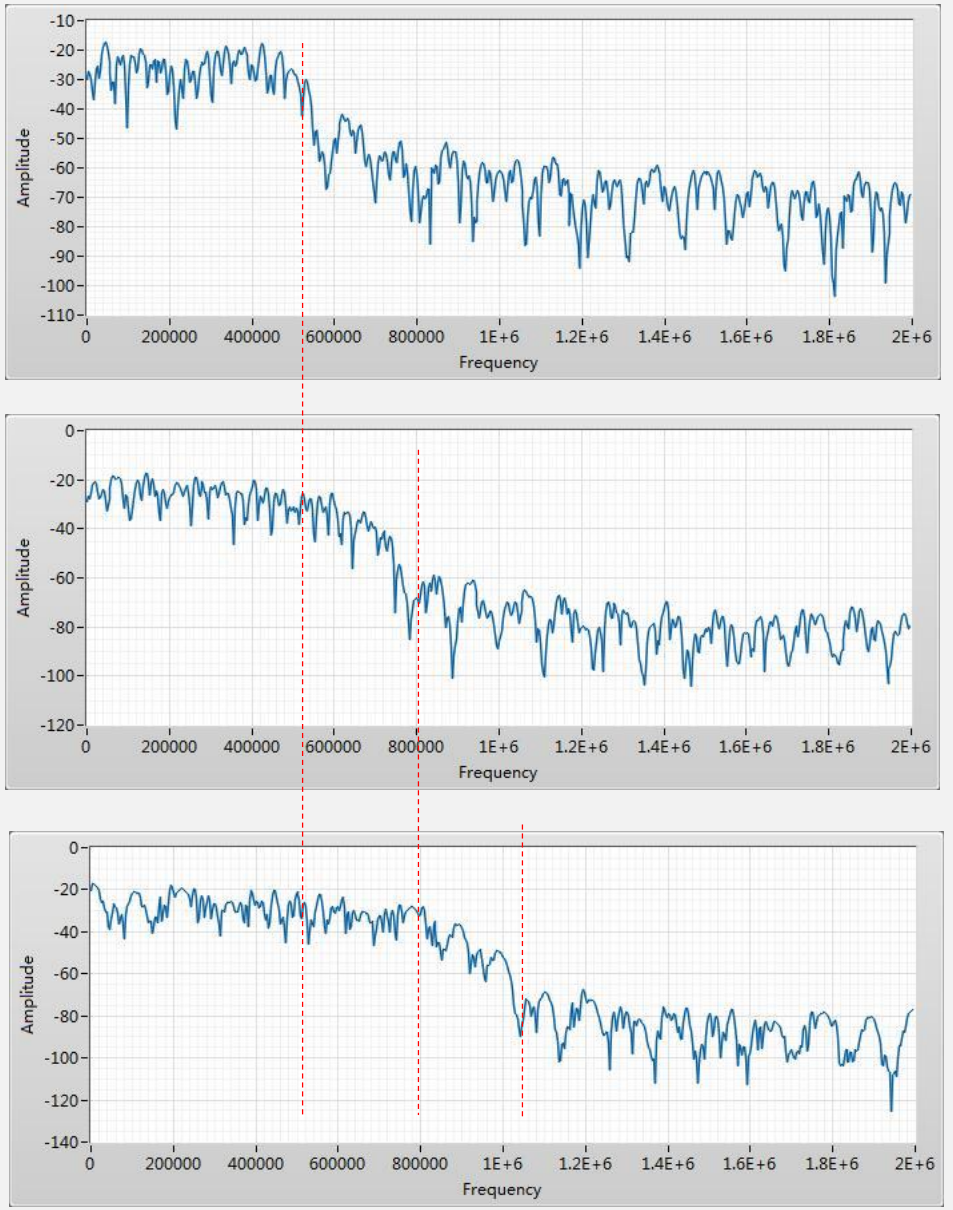
Bandwidth



$\alpha = 0$

$\alpha = 0.5$

$\alpha = 1$



Testing for Matched Filtering

TRANSMITTER

TX oversample factor: 4
TX sample rate: 4M

TX channel model parameters

channel model: AWGN
noise power (dB): -Inf
channel response: 0 | 0 +0 i | 0 +0 i | 0 +0 i
frequency offset: 0
delay (sec): 0

RECEIVER

RX oversample factor: 4
RX Sample Rate: 4M

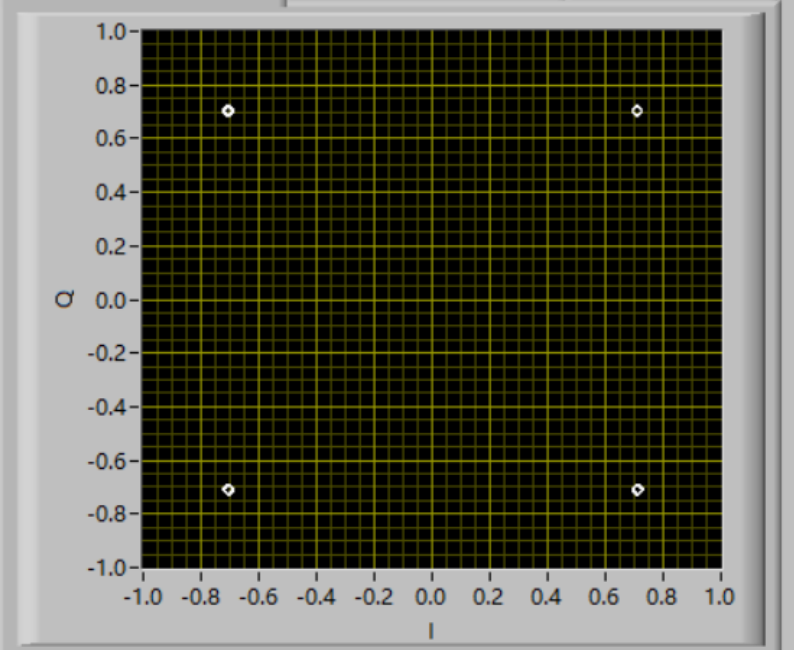
synchronization options

Synchronization Method: Timing
fixed offset: 0
Symbol Timing Recovery Method: Max Energy
Frame Detection Method: Sliding
Correct Frequency Offset

channel estimation equalizer parameters

Equalization Method: Direct
channel estimate length: 4
equalizer length: 4
equalizer delay: -1
(set delay to -1 for equalizer to choose optimal delay)

Spectrum | Power Delay Profile
Received Constellation | Received Eye Diagram | Received Signal



SHARED

modulation type: QPSK
packet length (bits): 500
Iterations: 1
control information for packet header/tail

Training Sequence Type: Length 11 Barker Sequence
Zero Pad Length: 8

Tx pulse shaping
modulation type: PSK
pulse shaping filter: Root Raised
filter parameter: 0.5
filter length (symbols): 8

Rx matched filtering
modulation type: PSK
pulse shaping filter: Root Raised
filter parameter: 0.5
filter length (symbols): 8

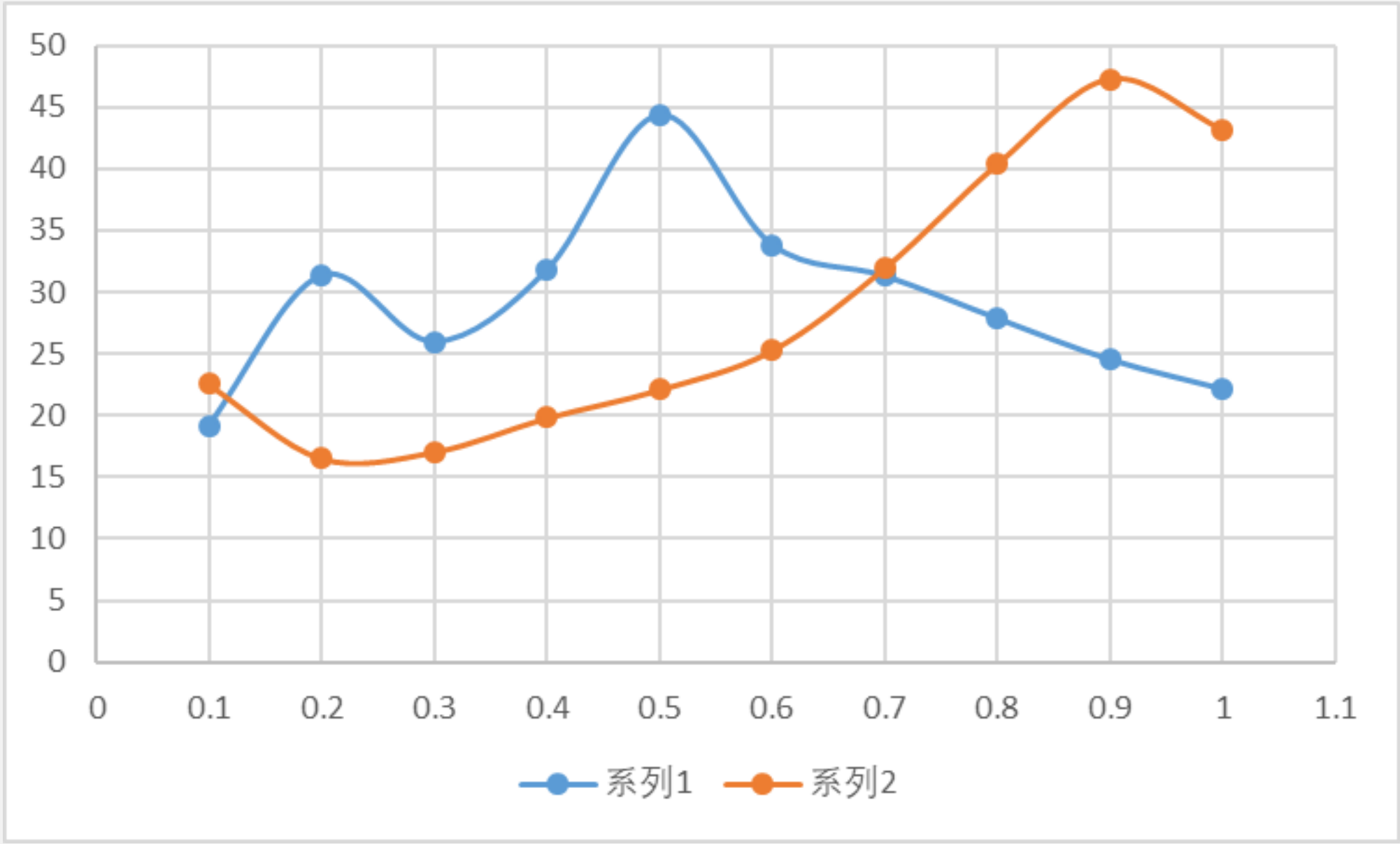
error out
status
code: 0
source

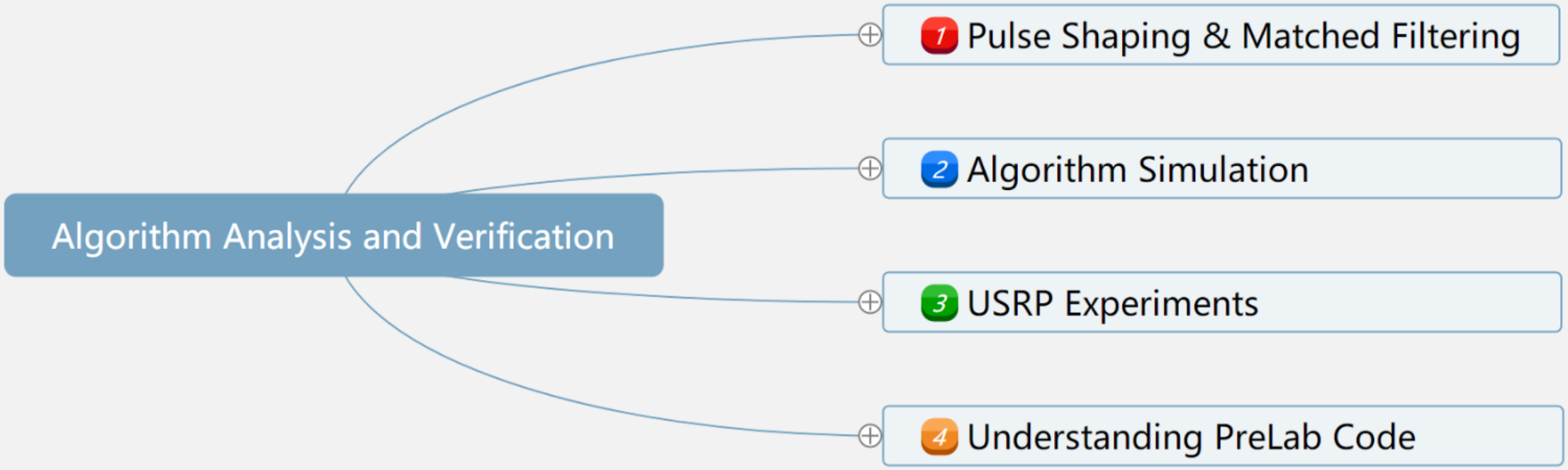
Measured channel impairements
SNR(dB): 44.3835
delay: 4E-6
freq. offset: 1.64538
channel estimate: 0
1.00018 +6.55884E-5 i
0.000180549 -8.10286E-5 i
0.000422062 +3.94874E-5 i
5.13721E-5 +7.82814E-5 i

average BER: 0.000000
estimated offset: 32
error statistic: 16.000000

Tx α	Rx α									
0.5	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
SNR										
1.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
SNR										

SNR




Algorithm Analysis and Verification
1 Pulse Shaping & Matched Filtering
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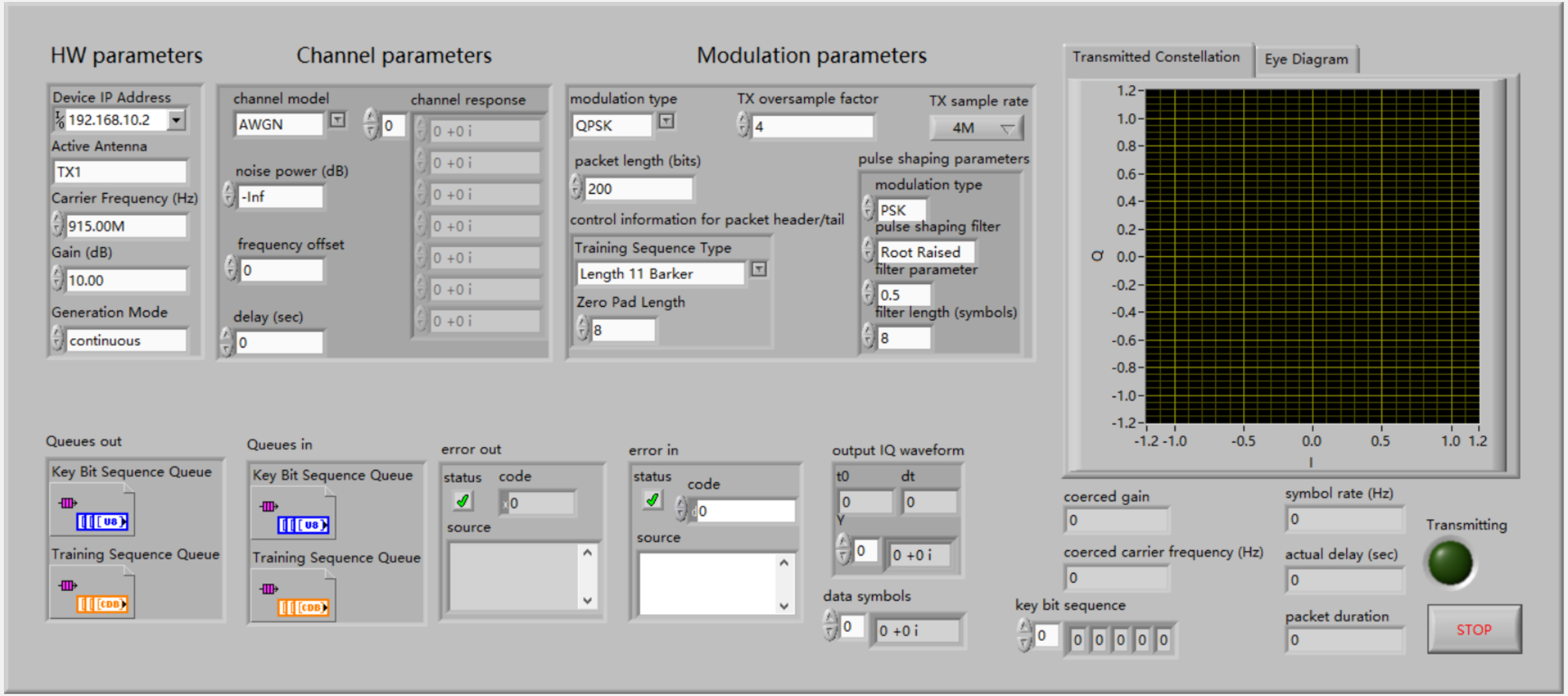
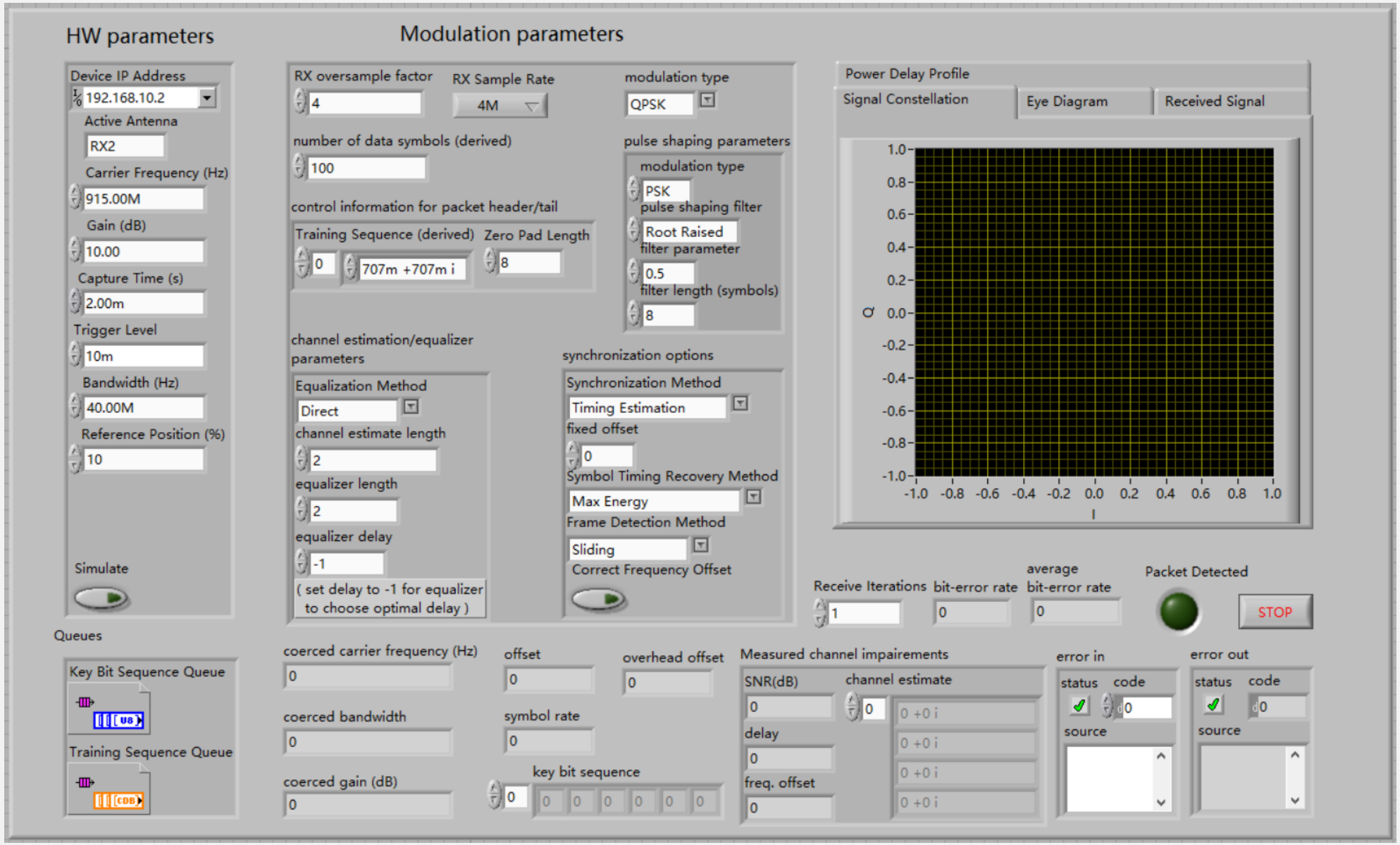
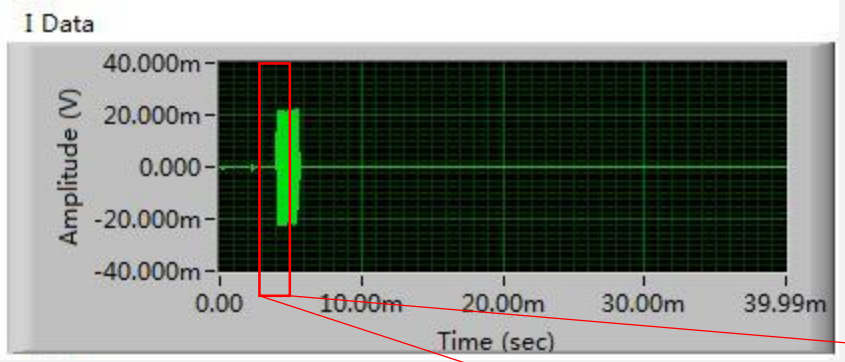
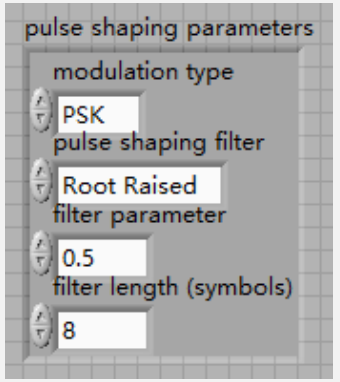
USRP Experiment

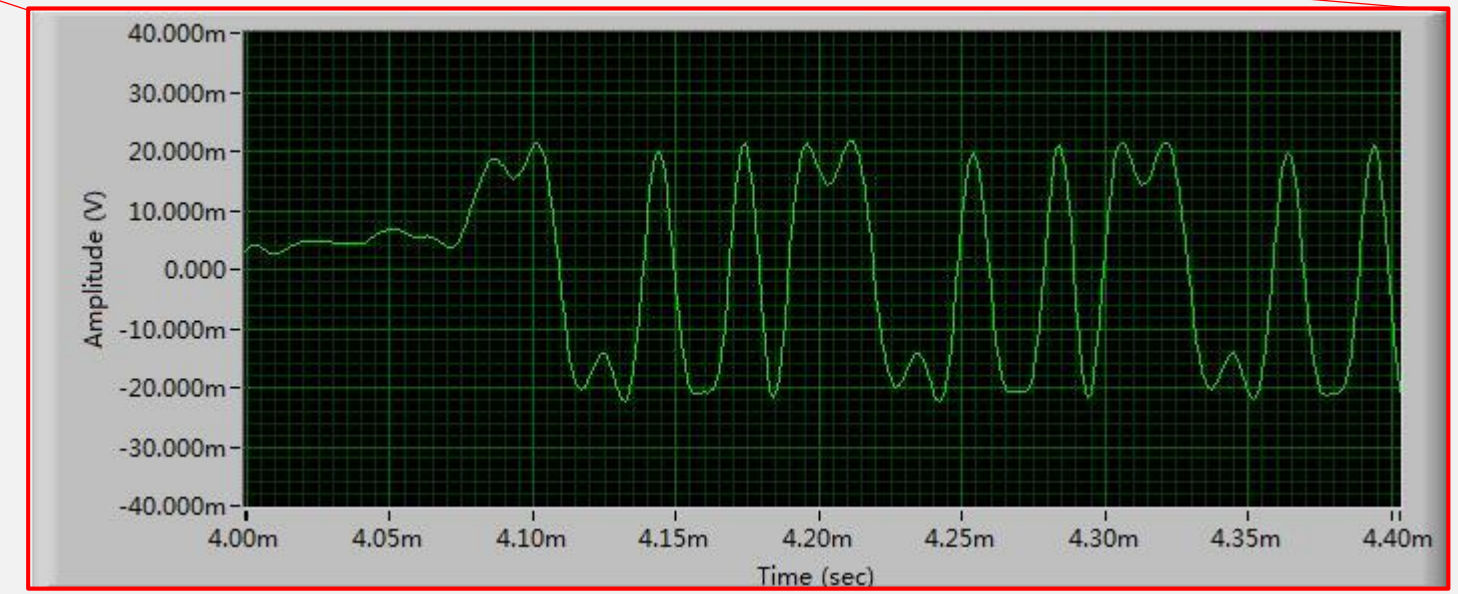

HW parameters
Device IP Address
192.168.10.2
Active Antenna
TX1
Carrier Frequency (Hz)
915.00M
Gain (dB)
10.00
Generation Mode
continuous
Channel parameters
channel model
AWGN
noise power (dB)
-Inf
frequency offset
0
delay (sec)
0
channel response
0 +0 i
Modulation parameters
modulation type
QPSK
TX oversample factor
4
TX sample rate
4M
packet length (bits)
200
control information for packet header/tail
Training Sequence Type
Length 11 Barker
Zero Pad Length
8
pulse shaping parameters
modulation type
PSK
pulse shaping filter
Root Raised
filter parameter
0.5
filter length (symbols)
8
Transmitted Constellation
Eye Diagram
Q
I
Queues out
Key Bit Sequence Queue
Training Sequence Queue
Queues in
Key Bit Sequence Queue
Training Sequence Queue
error out
status
code
source
error in
status
code
source
output IQ waveform
t0
dt
Y
data symbols
key bit sequence
coerced gain
coerced carrier frequency (Hz)
symbol rate (Hz)
actual delay (sec)
packet duration
Transmitting
STOP


HW parameters
Device IP Address
192.168.10.2
Active Antenna
RX2
Carrier Frequency (Hz)
915.00M
Gain (dB)
10.00
Capture Time (s)
2.00m
Trigger Level
10m
Bandwidth (Hz)
40.00M
Reference Position (%)
10
Simulate
Modulation parameters
RX oversample factor
4
RX Sample Rate
4M
modulation type
QPSK
number of data symbols (derived)
100
pulse shaping parameters
modulation type
PSK
pulse shaping filter
Root Raised
filter parameter
0.5
filter length (symbols)
8
control information for packet header/tail
Training Sequence (derived)
0
707m +707m i
Zero Pad Length
8
channel estimation/equalizer parameters
Equalization Method
Direct
channel estimate length
2
equalizer length
2
equalizer delay
-1
(set delay to -1 for equalizer to choose optimal delay)
synchronization options
Synchronization Method
Timing Estimation
fixed offset
0
Symbol Timing Recovery Method
Max Energy
Frame Detection Method
Sliding
Correct Frequency Offset
Power Delay Profile
Signal Constellation
Eye Diagram
Received Signal
Q
I
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Receive Iterations
1
bit-error rate
0
average bit-error rate
0
Packet Detected
STOP
Queues
Key Bit Sequence Queue
U8
Training Sequence Queue
CDB
coerced carrier frequency (Hz)
0
offset
0
overhead offset
0
coerced bandwidth
0
symbol rate
0
coerced gain (dB)
0
key bit sequence
0
0 0 0 0 0 0
Measured channel impairements
SNR(dB)
0
channel estimate
0
0 +0 i
0 +0 i
0 +0 i
0 +0 i
delay
0
freq. offset
0
error in
status
code
0
source
error out
status
code
0
source

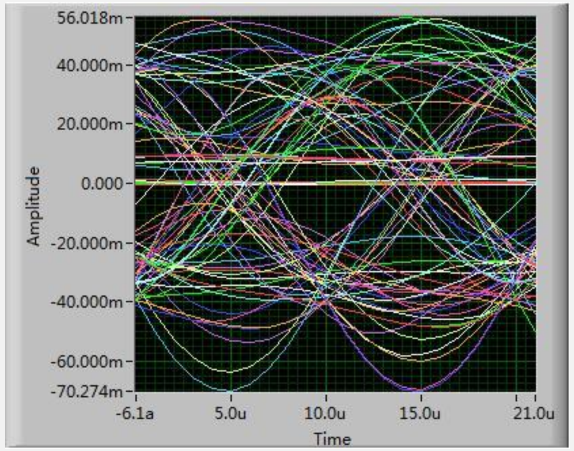
USRP Experiment

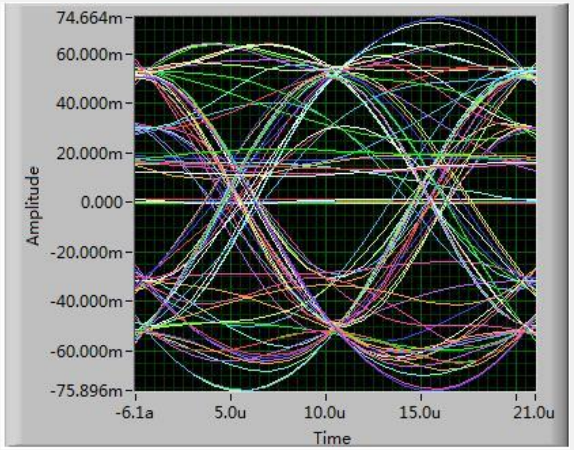


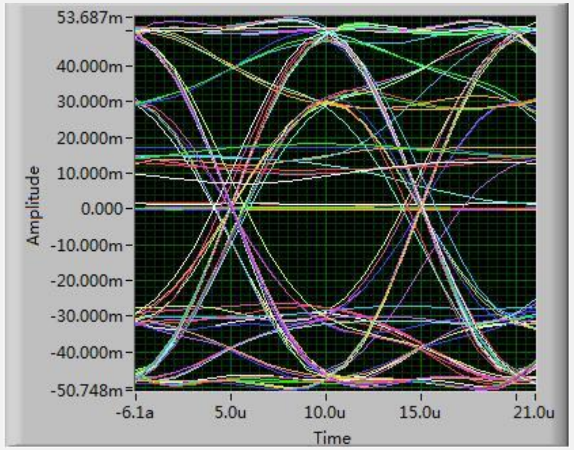




Eye Diagram and constellation



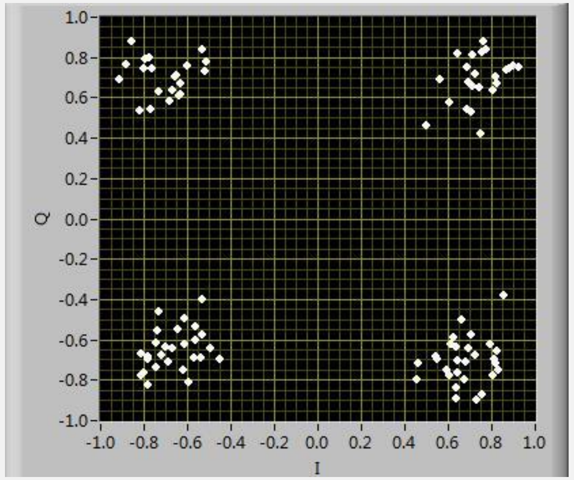


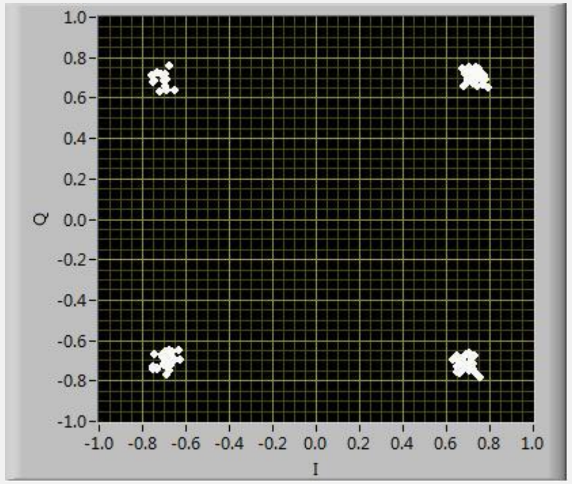


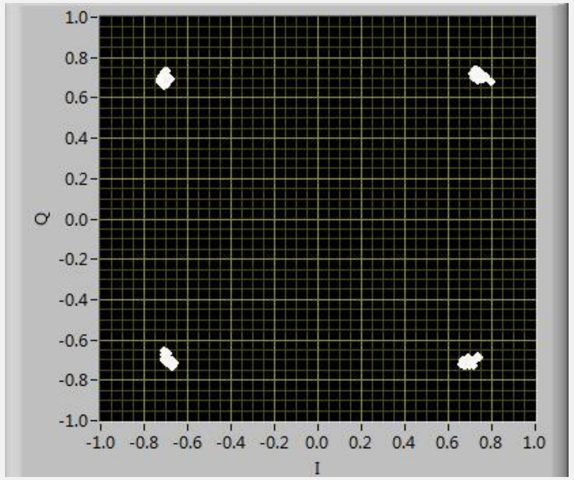
α =0

α =0.5

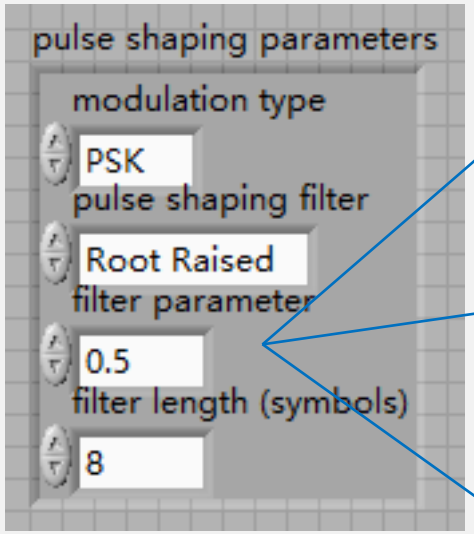
α = 1



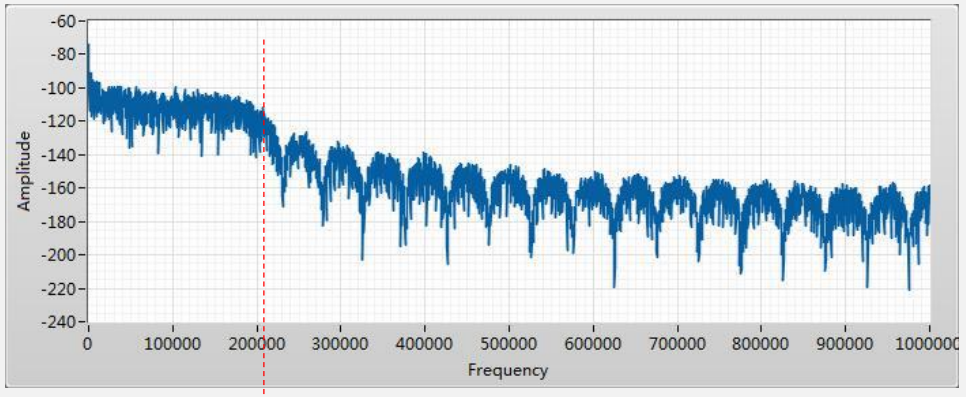




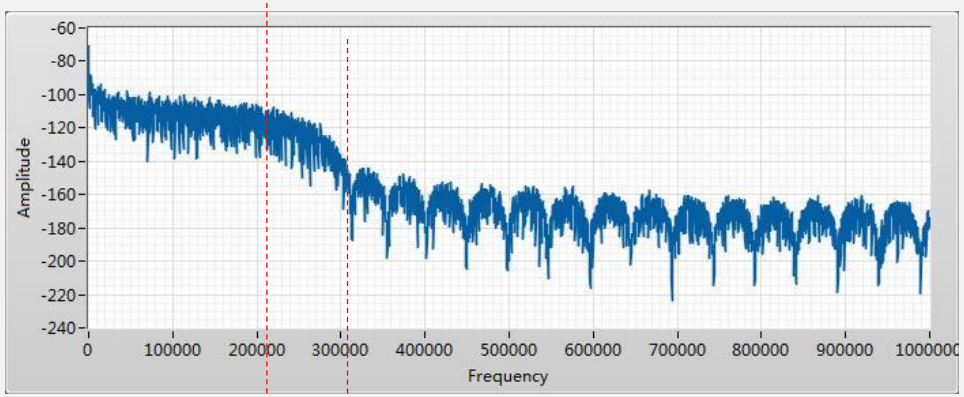
Bandwidth



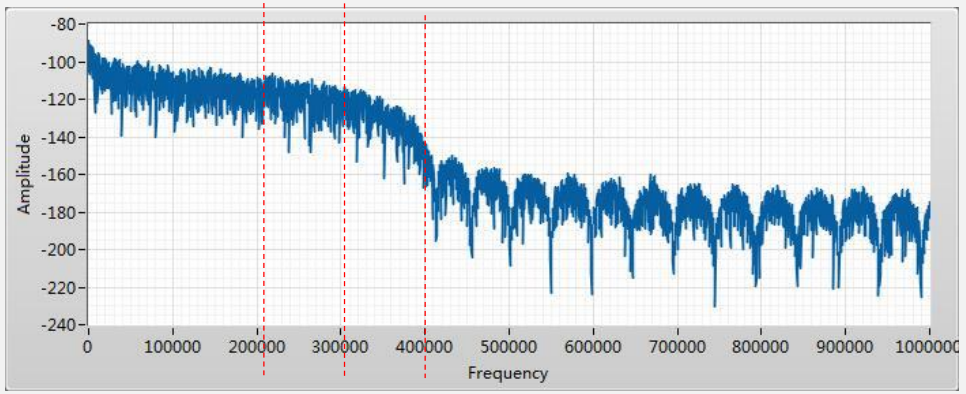
$\alpha = 0$ →

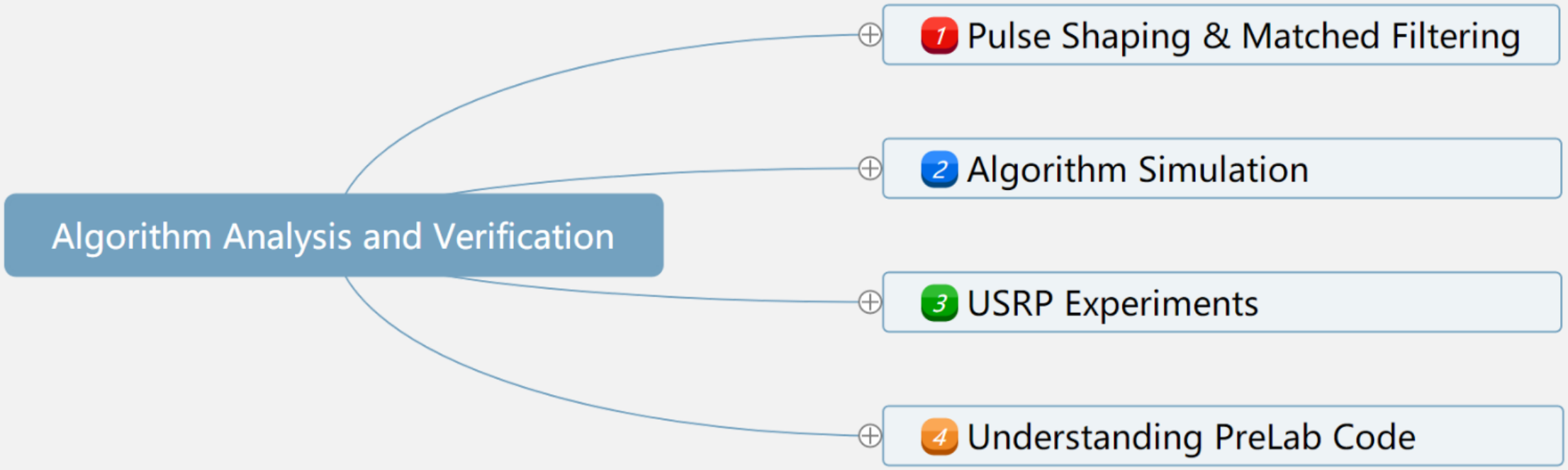


$\alpha = 0.5$ →



$\alpha = 1$ →

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- Question ?