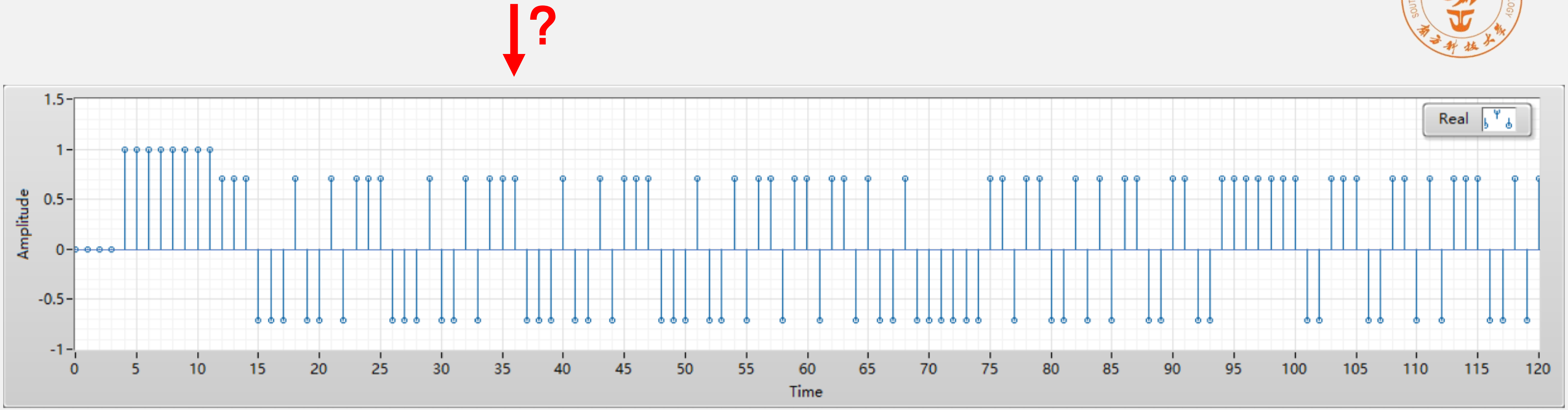
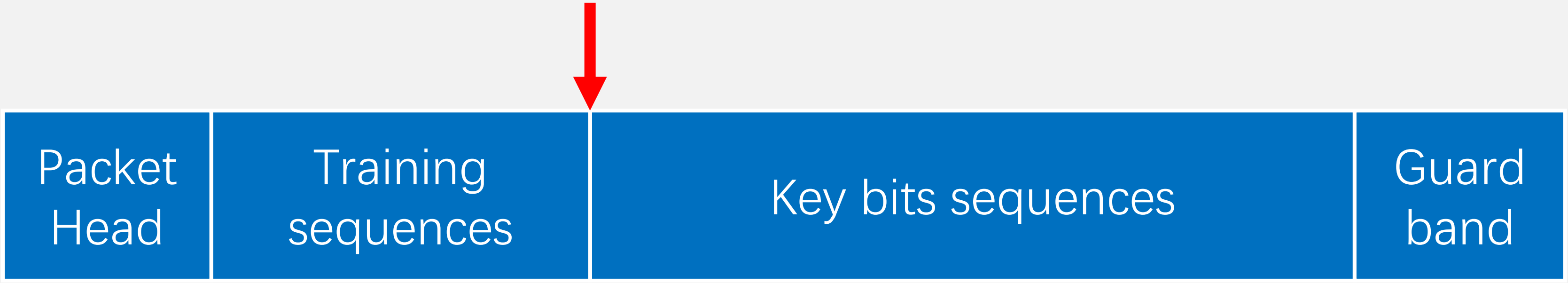
无线通信实验在线开放课程

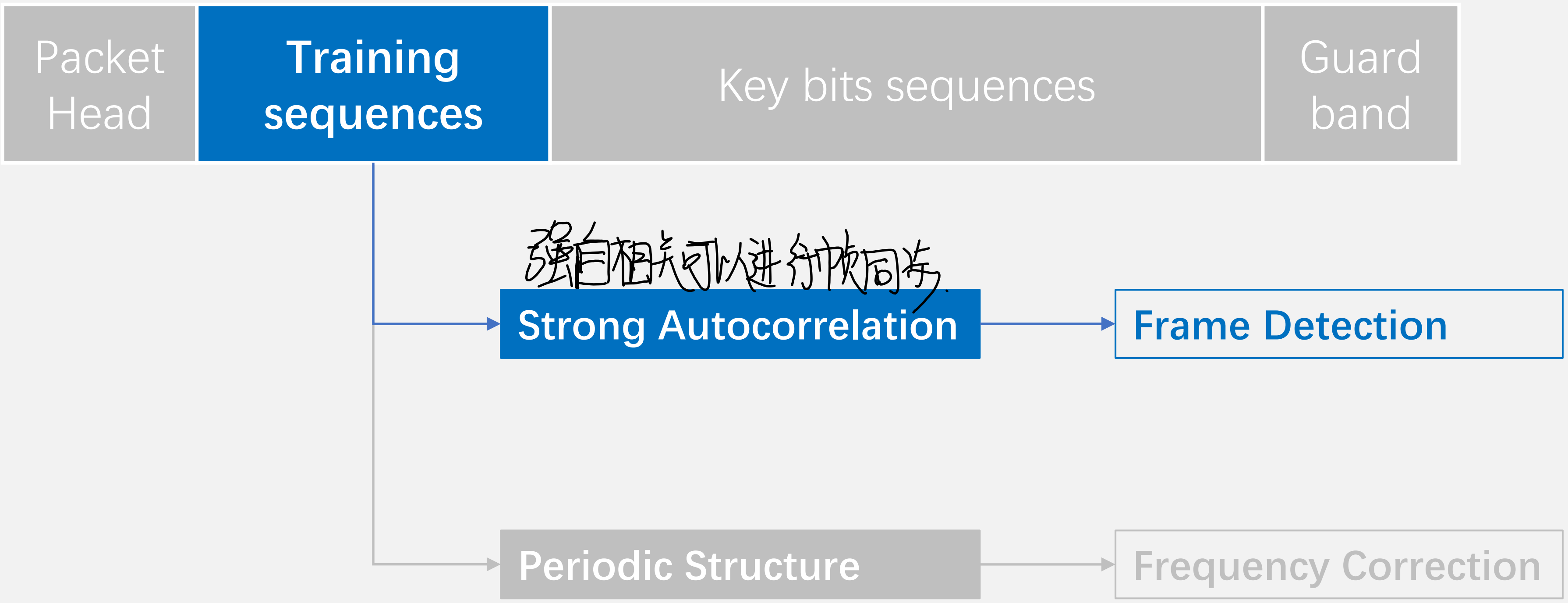
主讲人：吴光 博士

广东省教学质量工程建设项目


?
Amplitude
Time
Real


Packet Head
Training sequences
Key bits sequences
Guard band

Training sequences



Training sequences

Packet Head	**Training sequences**	Key bits sequences	Guard band

Training sequences → **Strong Autocorrelation** → Frame Detection

Training sequences → **Periodic Structure** → Frequency Correction

一个数据包的长度称为帧.

Lab 13 : Frame Detection and Frequency Correction

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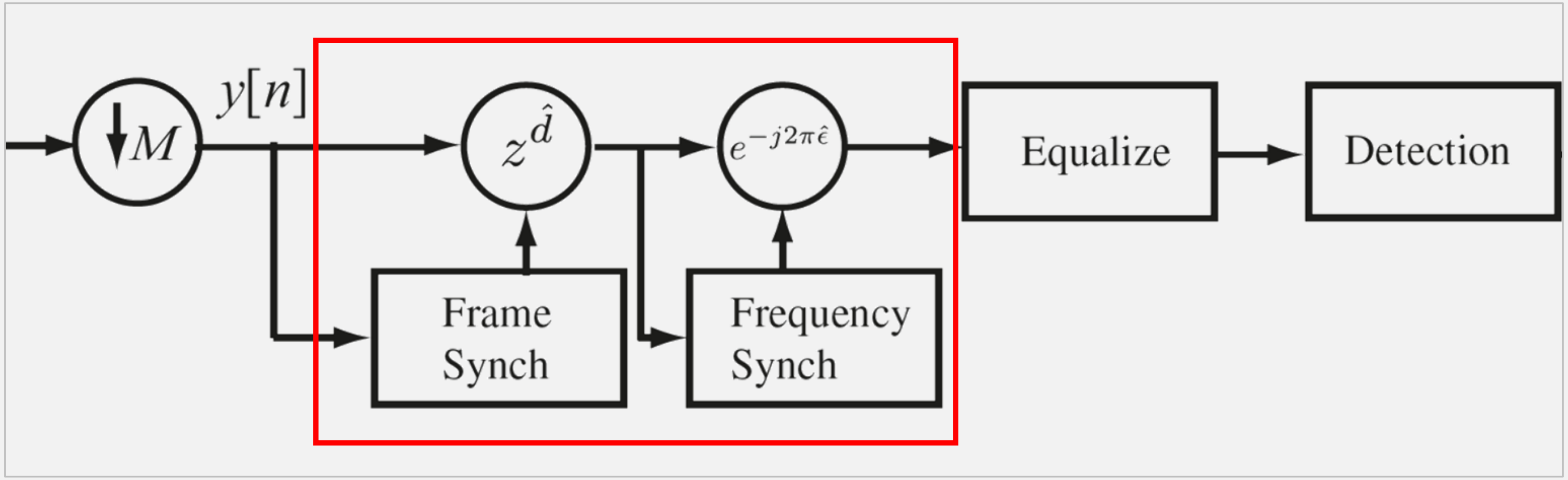
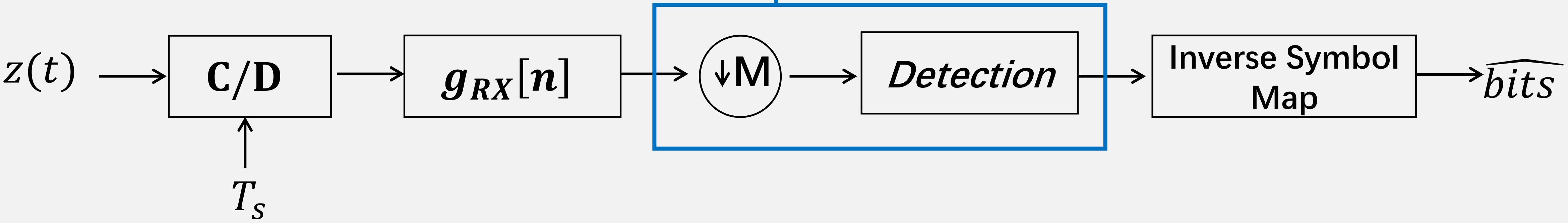


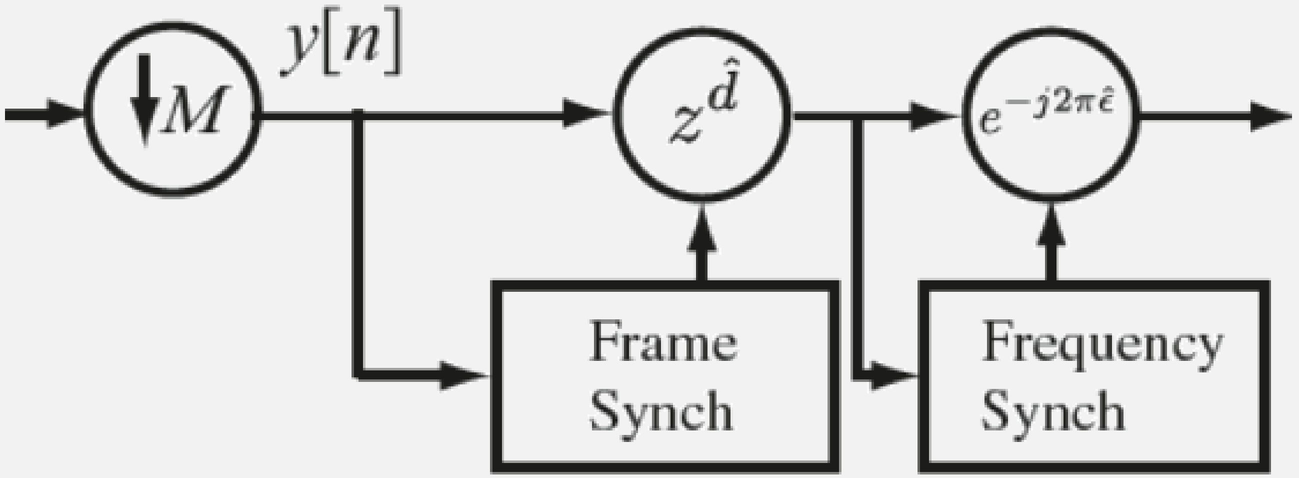
$y[n]$
$\downarrow M$
$z^{\hat{d}}$
$e^{-j2\pi\hat{\epsilon}}$
Equalize
Detection
Frame Synch
Frequency Synch

Receiver



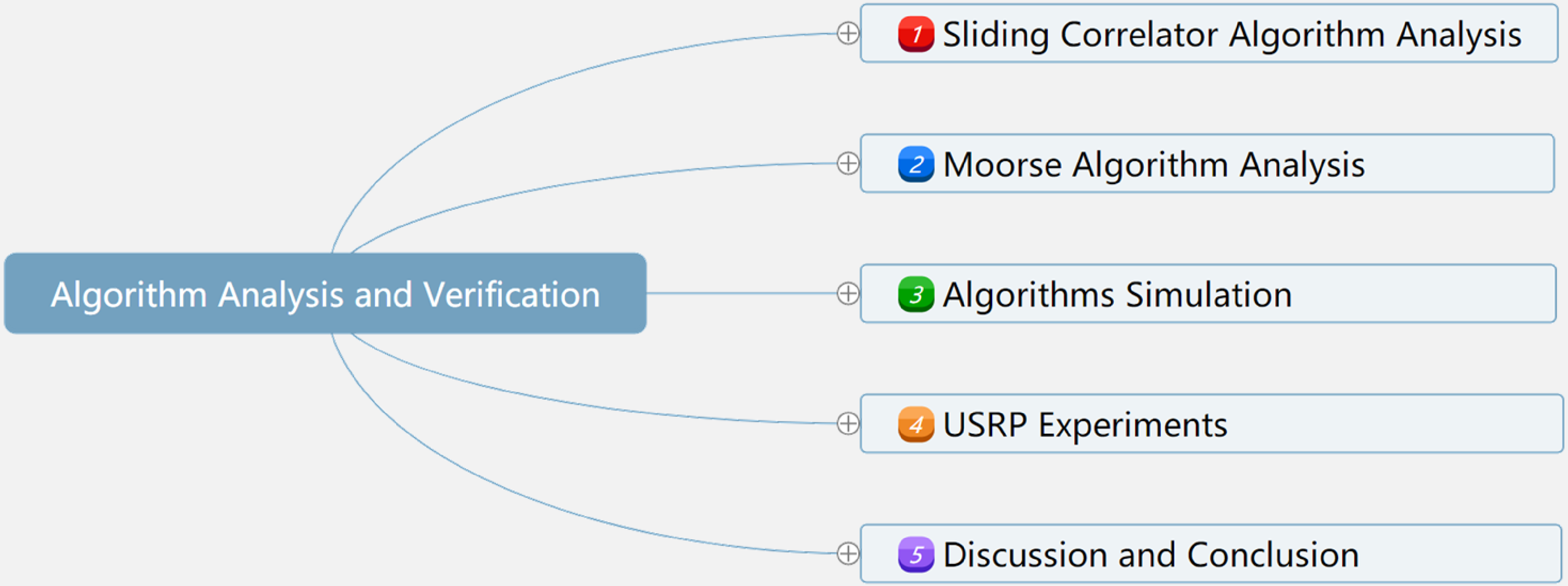
$z(t)$
C/D
T_s
$g_{RX}[n]$
↓M
Detection
Inverse Symbol Map
$\widehat{bits}$

System Model



Objective： I have an ability to

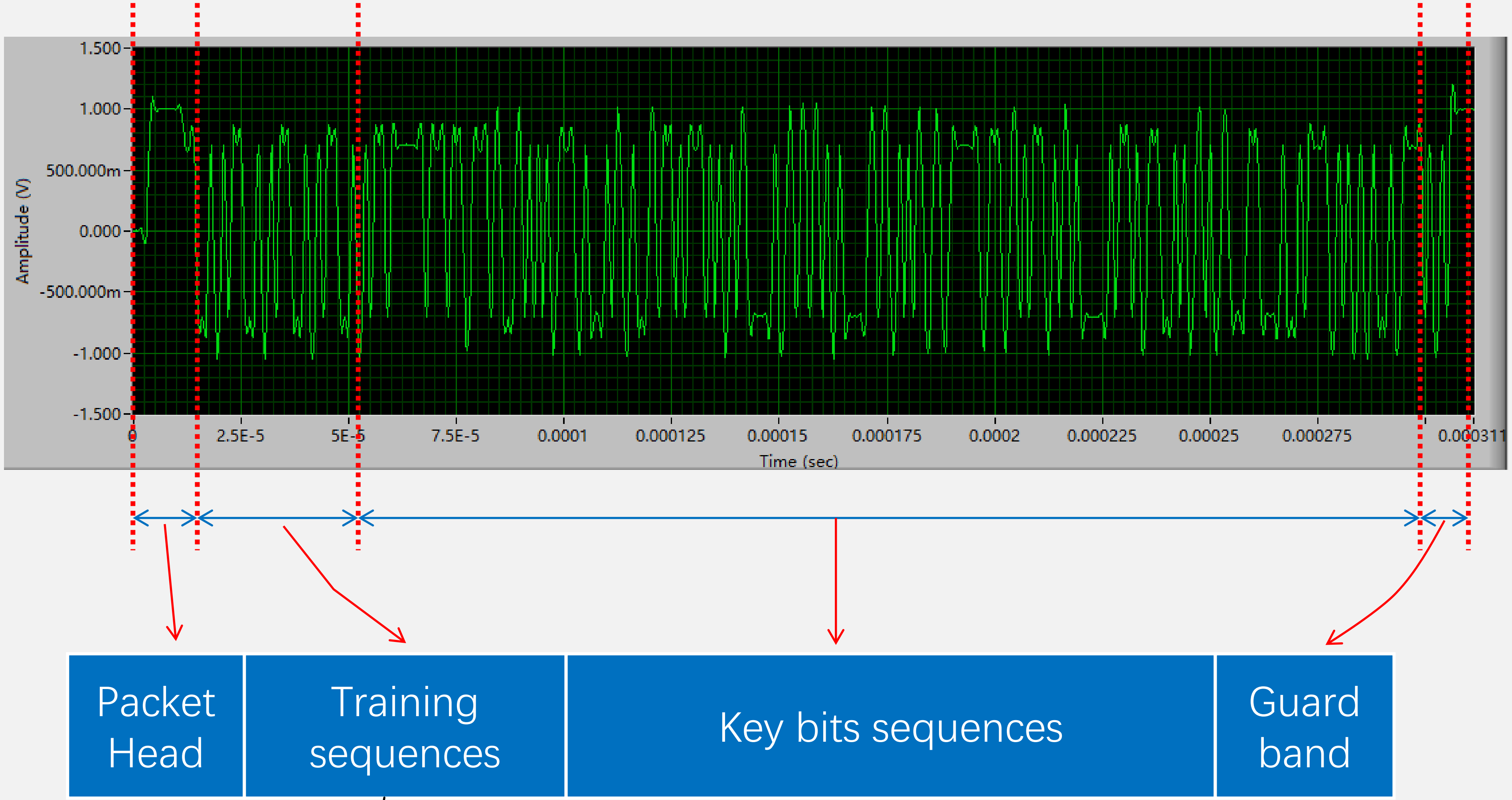
- ➢1. Understand the function of **training sequence**.
- ➢2. Understand the **frame synchronization** problem.
- ➢3. Design and implement frame synchronization algorithm: **sliding correlator**.
- ➢4. Understand the **frequency offset correction** problem.
- ➢5. Design and implement frequency offset correction algorithm: **Moose**.
- ➢6. Evaluate the performance of the algorithms by simulation and USRP.


Algorithm Analysis and Verification
1 Sliding Correlator Algorithm Analysis
2 Moorse Algorithm Analysis
3 Algorithms Simulation
4 USRP Experiments
5 Discussion and Conclusion

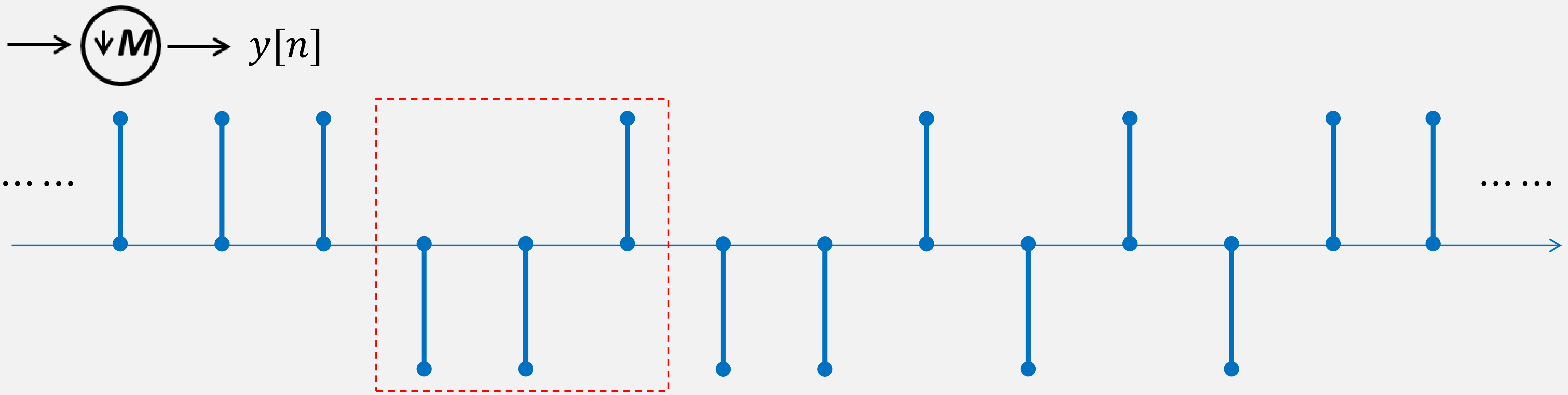
Demo: Training Sequence

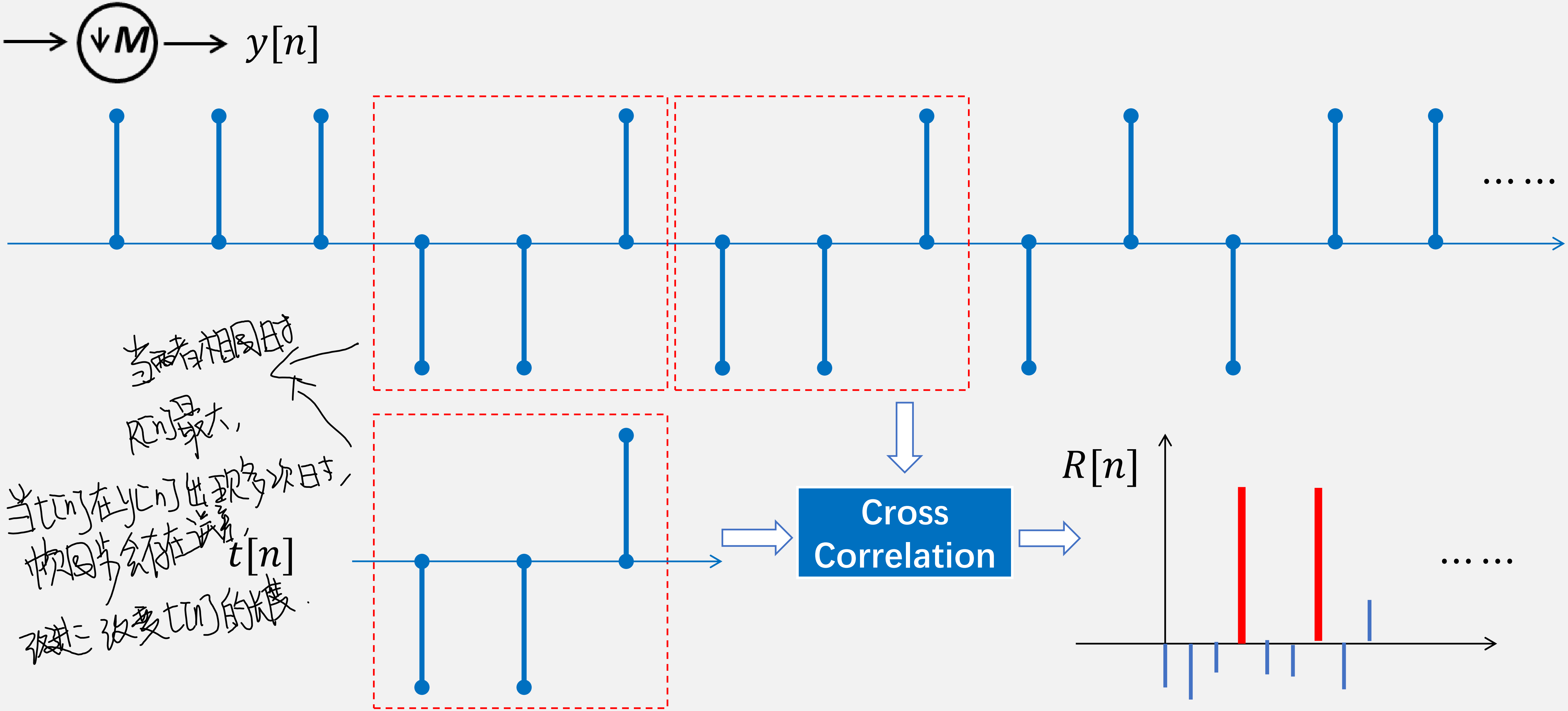
3、观察训练序列波形，帧同步原理

How to locate the training sequence ?



固定不变，收发双方都已知


↓M
y[n]



当两者相同时 $R[n]$ 最大，

当 $t[n]$ 在 $y[n]$ 出现多次时，帧同步会存在误差，

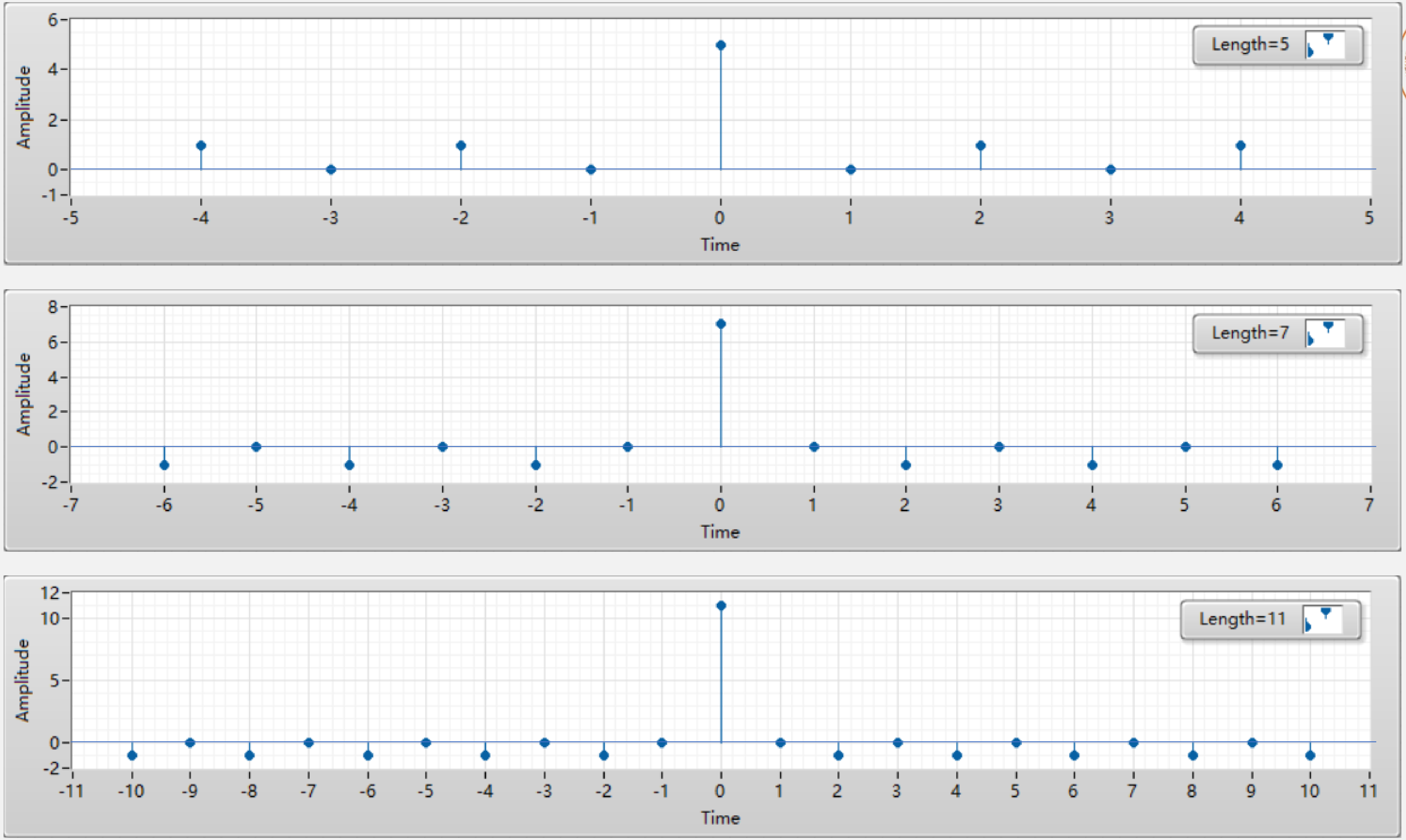
改进：改变 $t[n]$ 的长度.

barker序列满足的条件.

$$\left|\sum_{i=1}^{N_t-k} a_i a_{i+k}\right| \leq 1 \qquad 1 \leq k \leq N_t$$

$$\left|\sum_{i=1}^{N_t-k} a_i a_{i+k}\right| = N_t \qquad k = 0$$

Code Length	Barker Sequence
2	[−+, −−]
3	[− − +]
4	[− + −−, − + ++]
5	[− − − + −]
7	[− − − + + − +]
11	[− − − + + + − + + − +]
13	[− − − − − + + − − + − + −]



Autocorrelation of barker sequences

$$y[n] = hs[n-d] + v[n]$$

Training signal

Received signal

$$R[n] = \left| \sum_{k=0}^{N_t-1} t^*[k]\, y[n+k] \right|^2$$

Training signal

Received signal

$$R[n] = \left| \sum_{k=0}^{N_t - 1} t^*[k] y[n+k] \right|^2$$

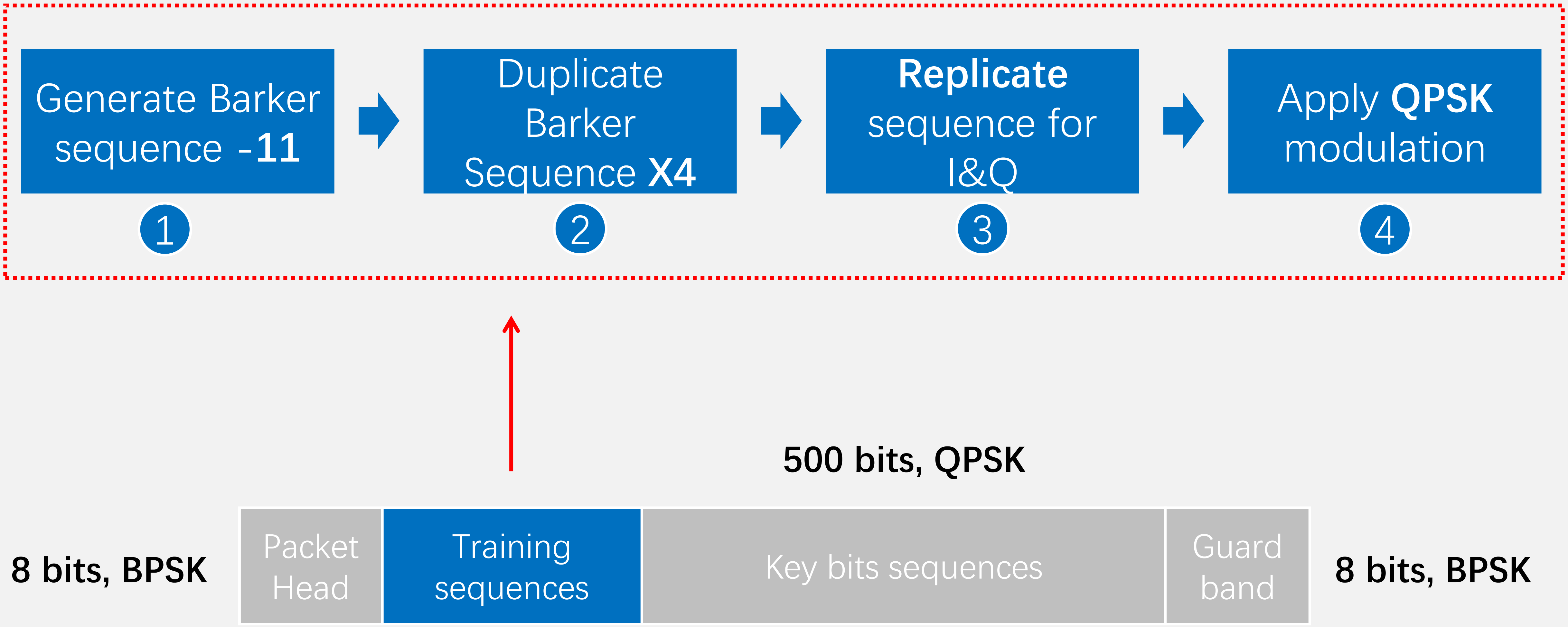
$$\hat{d} = \max_{n} R[n]$$

Algorithm Analysis

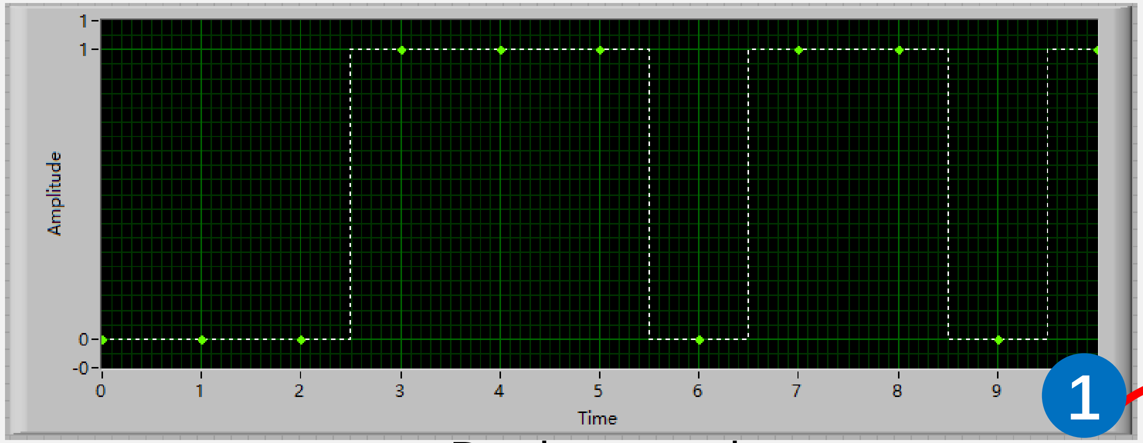
$$\hat{d} = \arg\max_{n} \sum_{p=0}^{P-1} \left| \sum_{k=0}^{N_{tr}-1} t^*[k]y[n+k+pN_{tot}] \right|$$

Algorithm Analysis and Verification

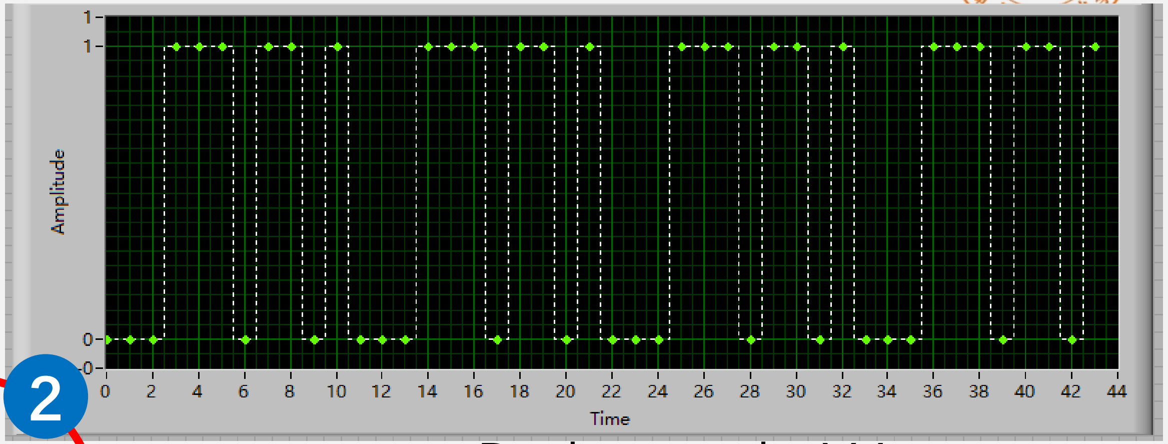
1. Sliding Correlator Algorithm Analysis
2. Moorse Algorithm Analysis
3. Algorithms Simulation
4. USRP Experiments
5. Discussion and Conclusion


Generate Barker sequence -11
1
Duplicate Barker Sequence X4
2
Replicate sequence for I&Q
3
Apply QPSK modulation
4
500 bits, QPSK
8 bits, BPSK
Packet Head
Training sequences
Key bits sequences
Guard band
8 bits, BPSK

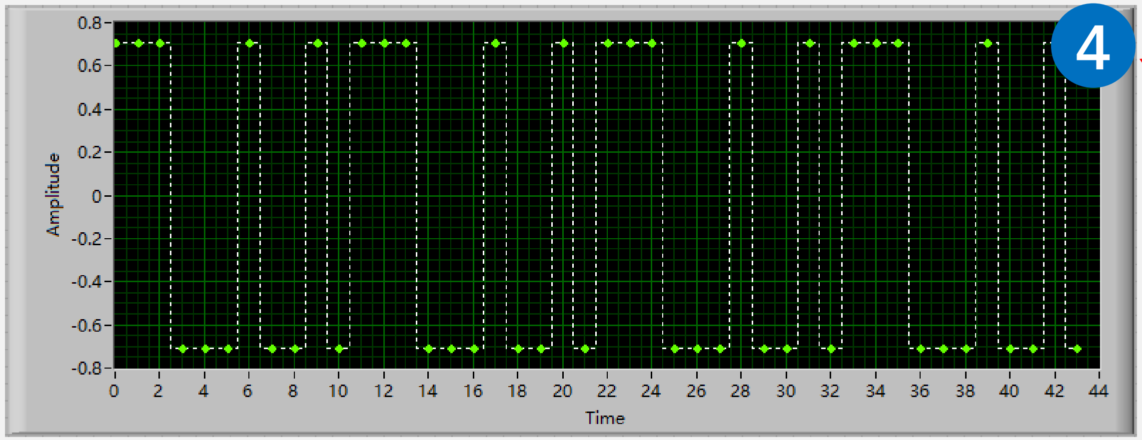
11	[− − − + + + − + + − +]



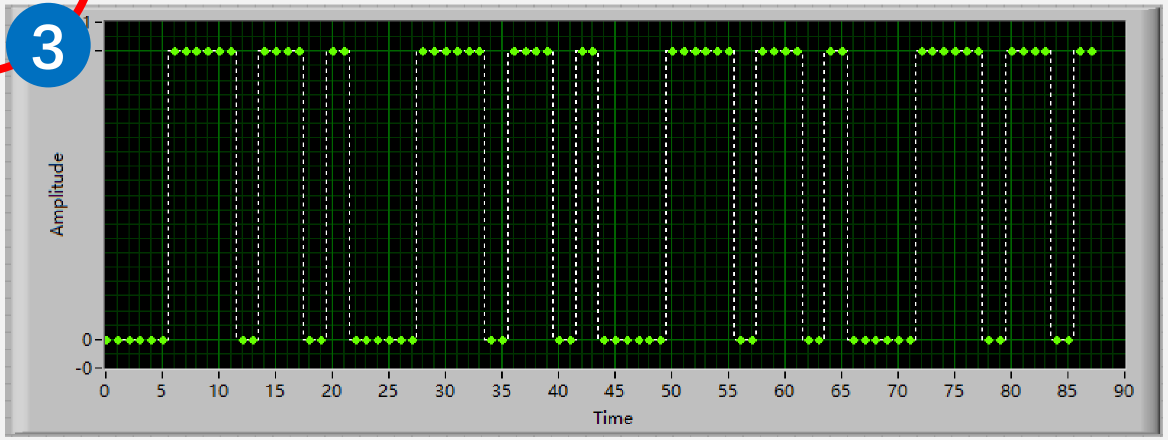
Barker code



Barker code X4

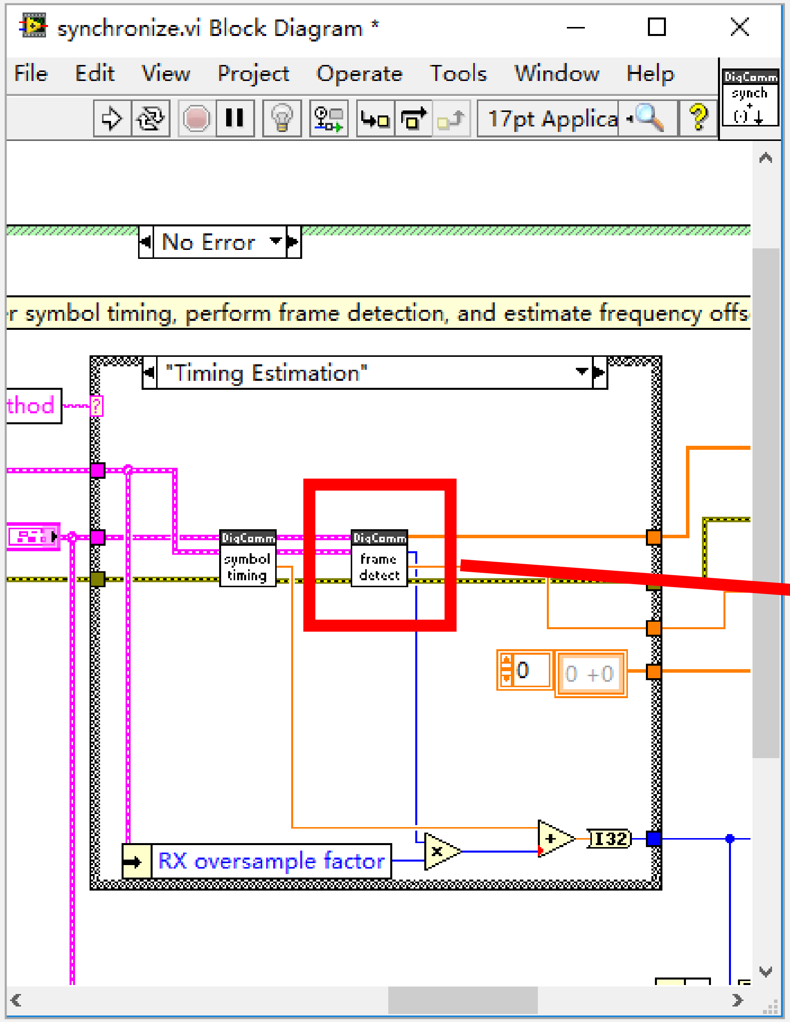


I/Q Barker sequence

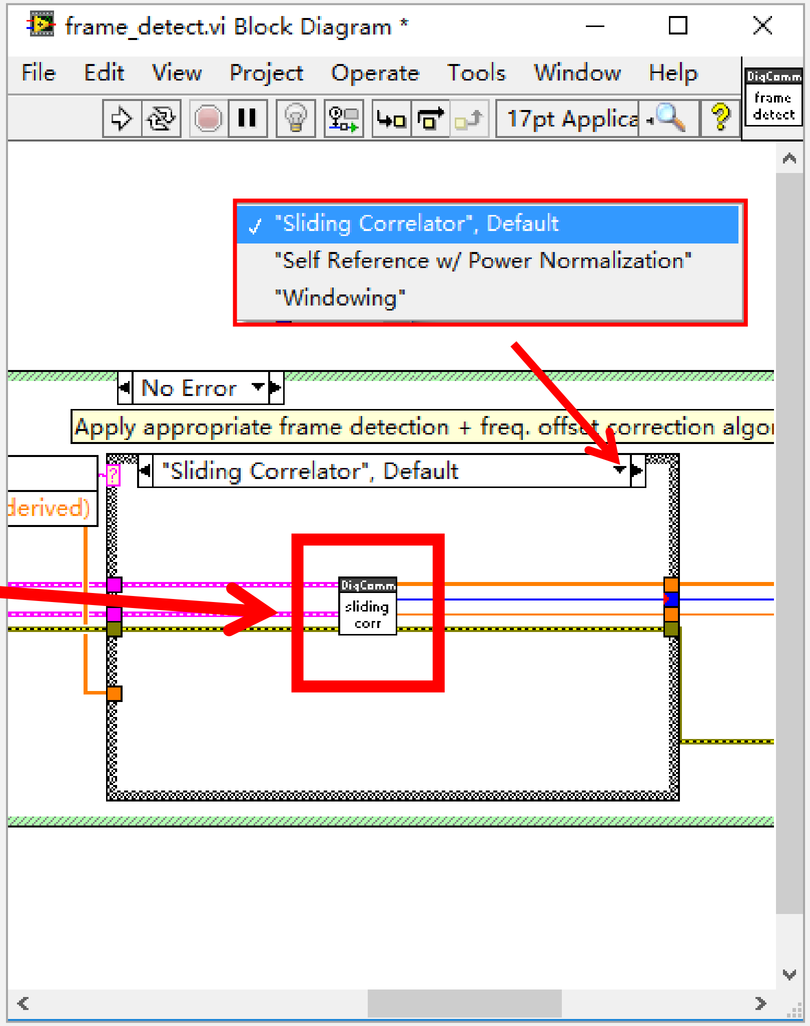


Replicate sequence

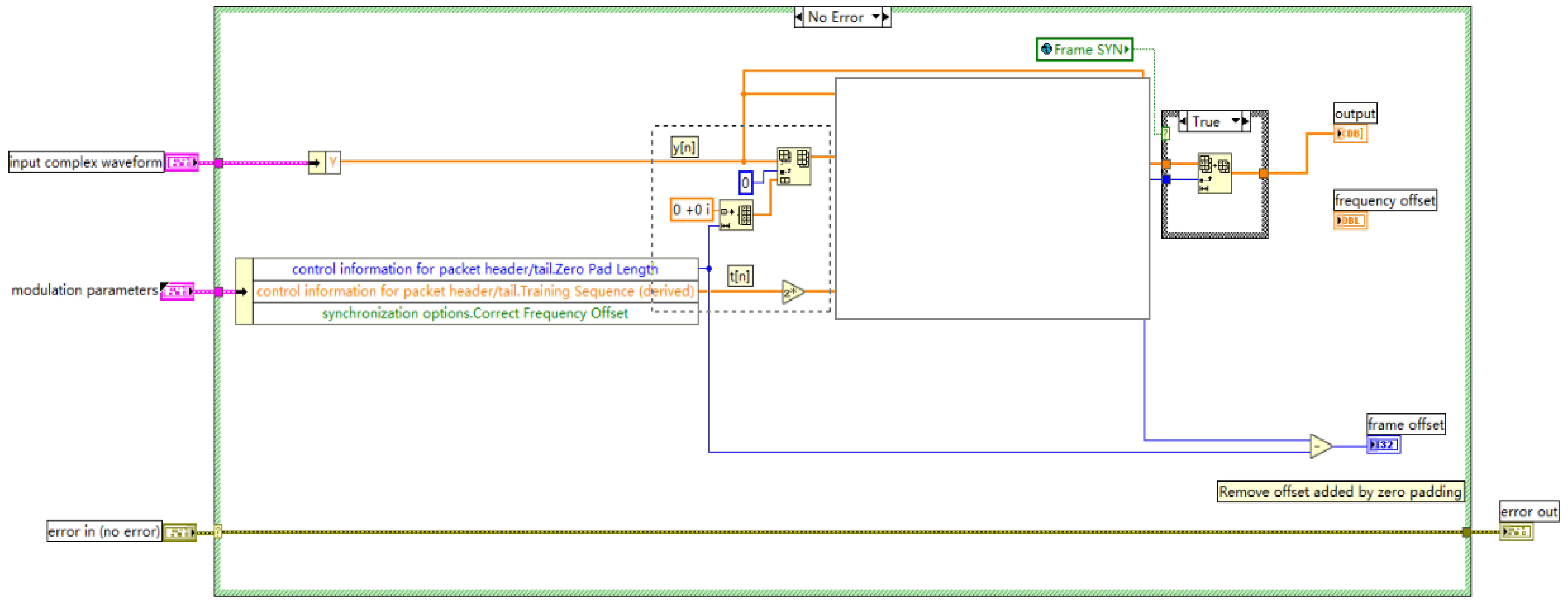
Frame Synchronization



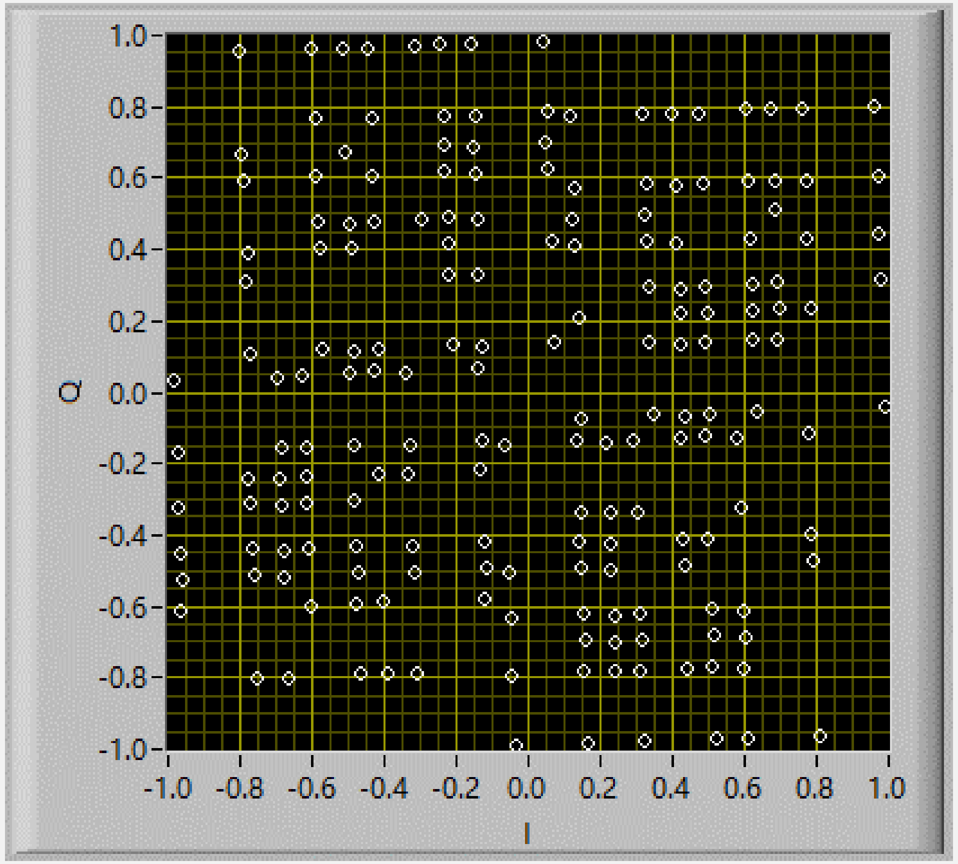
synchronize.vi Block Diagram *
File Edit View Project Operate Tools Window Help
17pt Applica
No Error
r symbol timing, perform frame detection, and estimate frequency offs
"Timing Estimation"
thod
DigComm symbol timing
DigComm frame detect
RX oversample factor
I32

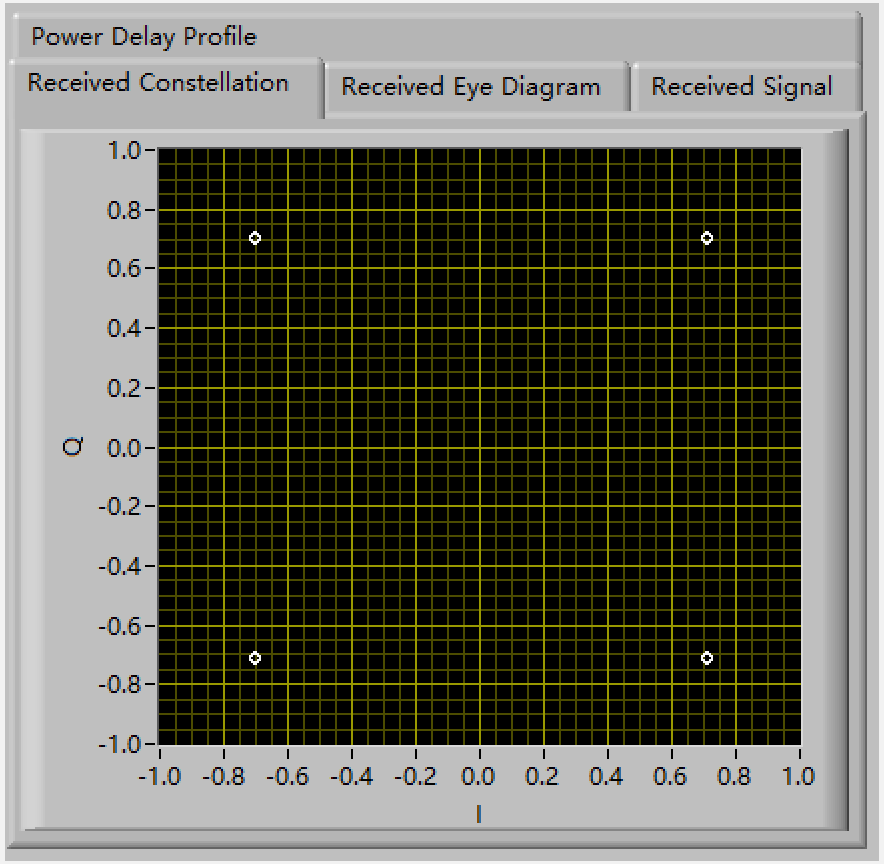


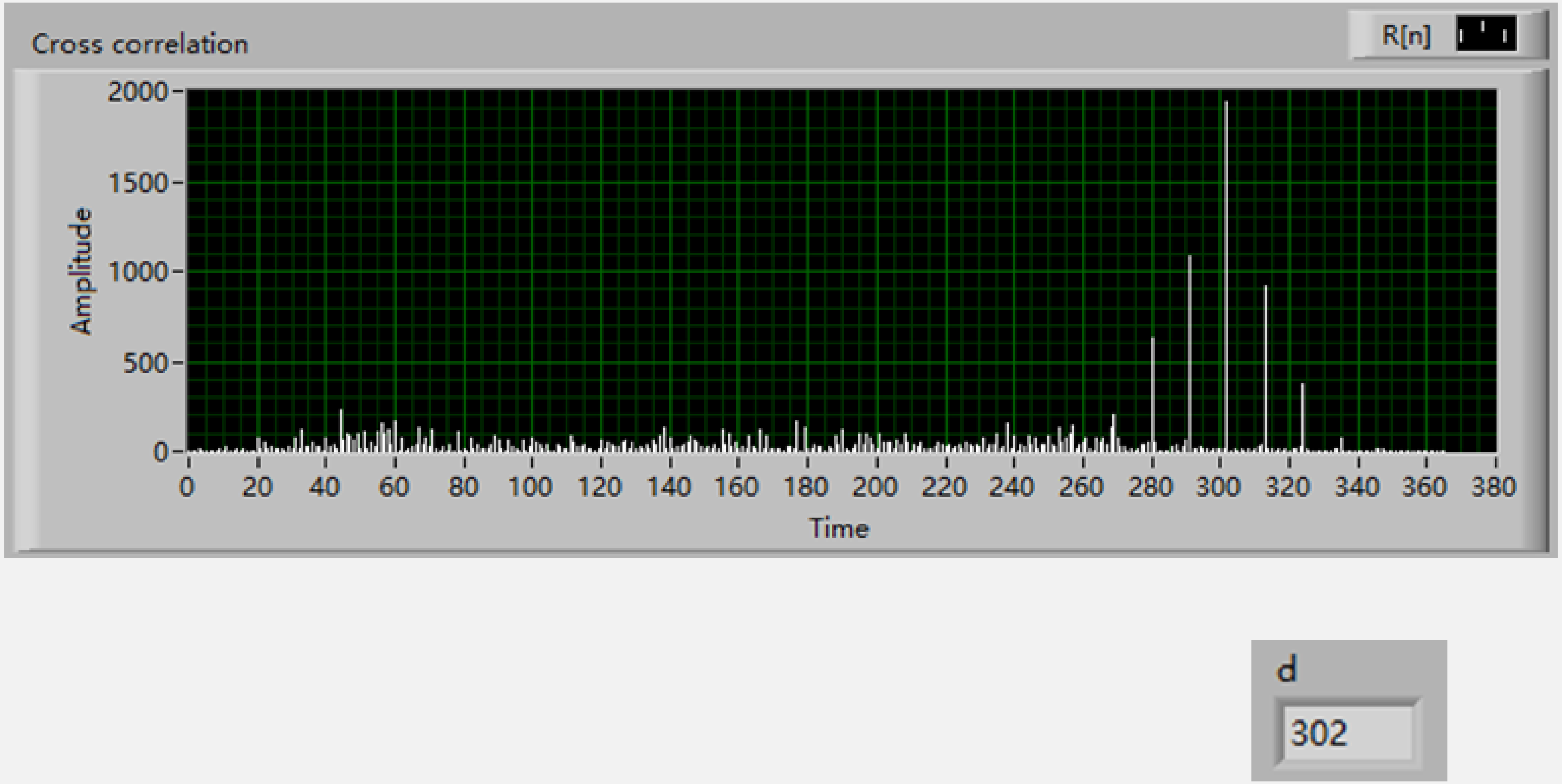
frame_detect.vi Block Diagram *
File Edit View Project Operate Tools Window Help
17pt Applica
"Sliding Correlator", Default
"Self Reference w/ Power Normalization"
"Windowing"
No Error
Apply appropriate frame detection + freq. offset correction algo
"Sliding Correlator", Default
derived)
DigComm sliding corr


No Error
Frame SYN
True
output
frequency offset
input complex waveform
y[n]
0
0 +0 i
t[n]
control information for packet header/tail.Zero Pad Length
control information for packet header/tail.Training Sequence (derived)
synchronization options.Correct Frequency Offset
modulation parameters
frame offset
Remove offset added by zero padding
error in (no error)
error out

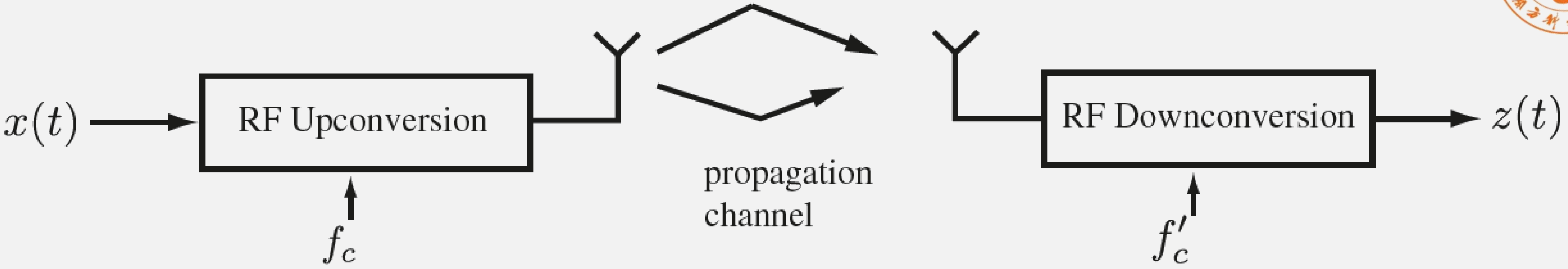
参数	设置值
调制类型	QPSK
训练序列类型	11位巴克码
Synchronization Method	Timing
下采样因子	10
Frame Detection Method	Sliding
发射接收端采样率 (Hz)	10M
包长度 (bits)	500


1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Q
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0
I


Power Delay Profile
Received Constellation
Received Eye Diagram
Received Signal
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Q
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0
I


Cross correlation
R[n]
2000
1500
1000
500
0
Amplitude
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
Time
d
302

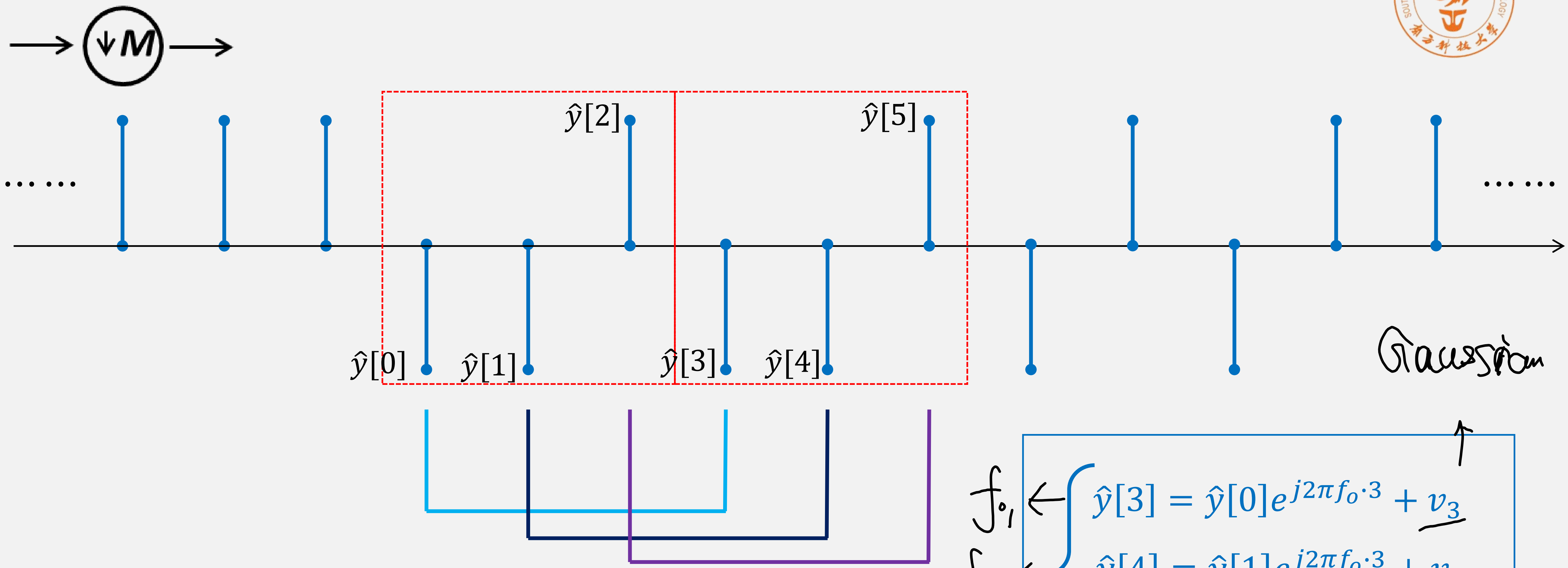
Demo: Frequency Correction



Frequency offset: $\boxed{f_o = f_c - f'_c}$

相干解调，if $f_c = f'$,

$$\boxed{z(t) = x(t)e^{j2\pi f_c t} \cdot e^{-j2\pi f' t} = x(t)e^{j2\pi(f_c - f')t} = x(t)e^{j2\pi f_o t}}$$



Gaussian

$$\frac{f_{o_1}+f_{o_2}+f_{o_3}}{3}$$

$$\begin{aligned}
f_{o_1} &\leftarrow \hat{y}[3] = \hat{y}[0]e^{j2\pi f_o\cdot 3} + \underline{v_3} \\
f_{o_2} &\leftarrow \hat{y}[4] = \hat{y}[1]e^{j2\pi f_o\cdot 3} + \underline{v_4} \\
f_{o_3} &\leftarrow \hat{y}[5] = \hat{y}[2]e^{j2\pi f_o\cdot 3} + \underline{v_5}
\end{aligned}$$

Moose Algorithm

- Step 1: to estimate $\epsilon = f_0 T$ with the training sequences $y[n]$,

$$
\begin{aligned}
y[n + \underbrace{N_t}_{\text{周期}}] &= e^{j2\pi\epsilon N_t} y[n] + v[n + N_t] \\
&\approx e^{j2\pi\epsilon N_t} y[n]
\end{aligned}
$$

$\min \| y[n+N_t] - e^{j2\pi\epsilon N_t} y[n] \|^2$

- Step 2: solve this problem by $\underbrace{\text{LLSE}}_{\text{最小均方}}$, 高斯噪声

$$J(a) = \sum_{l=L}^{N_t-1} \| y[l + N_t] - a y[l] \|^2$$

$$\boxed{\begin{aligned}
\hat{\epsilon} &= \frac{\text{phase} \sum_{l=L}^{N_t-1} y[l + N_t] y^*[l]}{2\pi N_t} \\
\hat{f}_e &= \frac{\text{phase} \sum_{l=L}^{N_t-1} y[l + N_t] y^*[l]}{2\pi T N_t}
\end{aligned}}$$

- Step 3: Frequency offset correction by: $\boxed{\tilde{y}[n] = e^{-j2\pi\epsilon n} y[n]}$

Algorithm Analysis

- Let $\hat{y}(t)$ denotes the demodulated signal,

$$y(t) = x(t)e^{j2\pi f_c t}$$

$$\hat{y}(t) = x(t)e^{j2\pi f_c t} \cdot e^{-j2\pi f' t} = x(t)e^{j2\pi (f_c - f')t} = x(t)e^{j2\pi f_o t}$$

- If the $x(t) = x(t+N)$ is periodical,

$$\hat{y}(t+N) = x(t+N)e^{j2\pi f_o (t+N)}$$

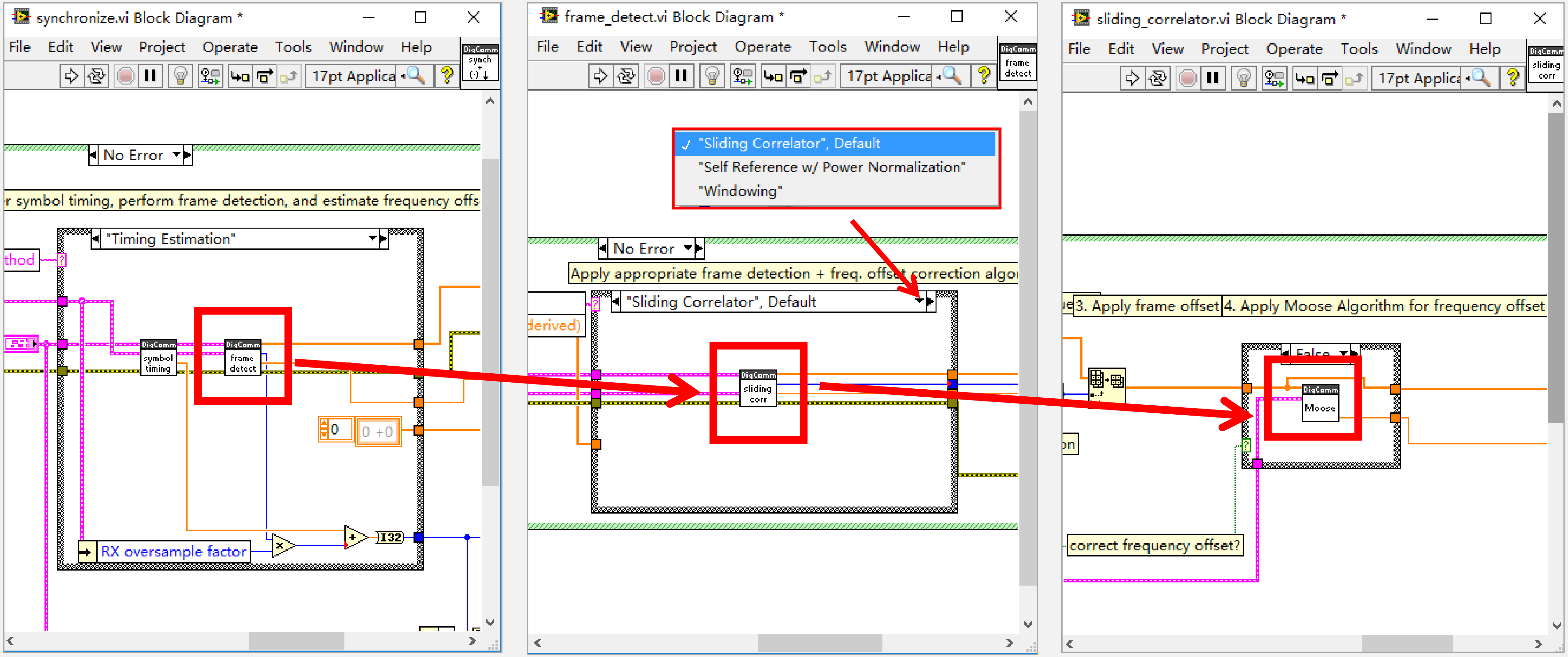
$$\boxed{\hat{y}(t+N) = x(t)e^{j2\pi f_o (t+N)} = x(t)e^{j2\pi f_o t} \cdot e^{j2\pi f_o N} = \hat{y}(t)e^{j2\pi f_o N}}$$

Accuracy

$$\hat{f}_e \in \left[-\frac{1}{2T_sN_t}, \frac{1}{2T_sN_t}\right]$$

Frequency Offset Correction

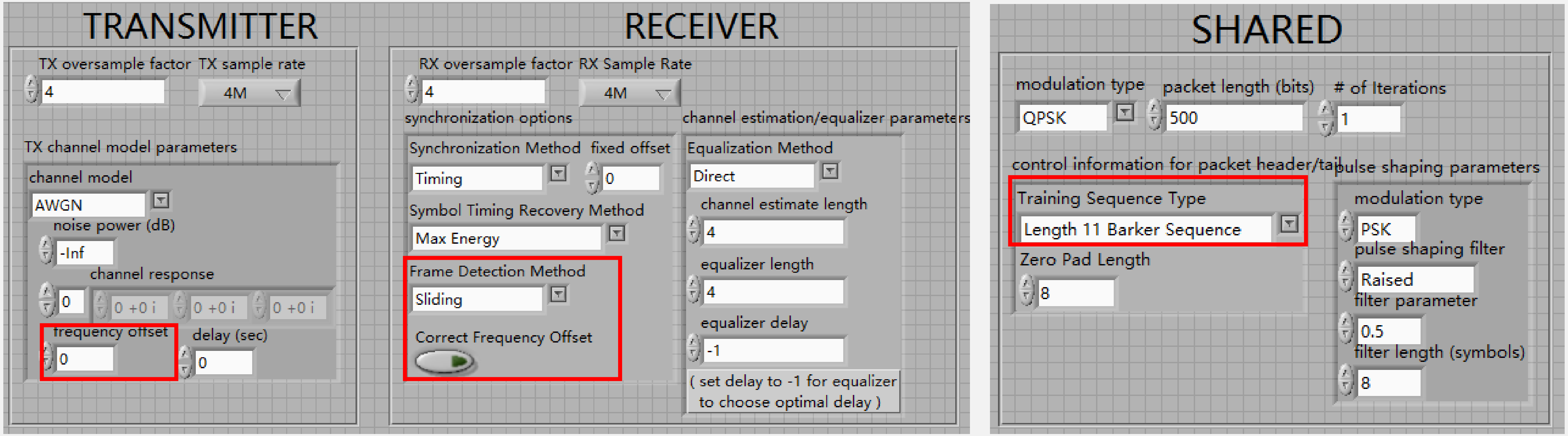
Replace moose.vi

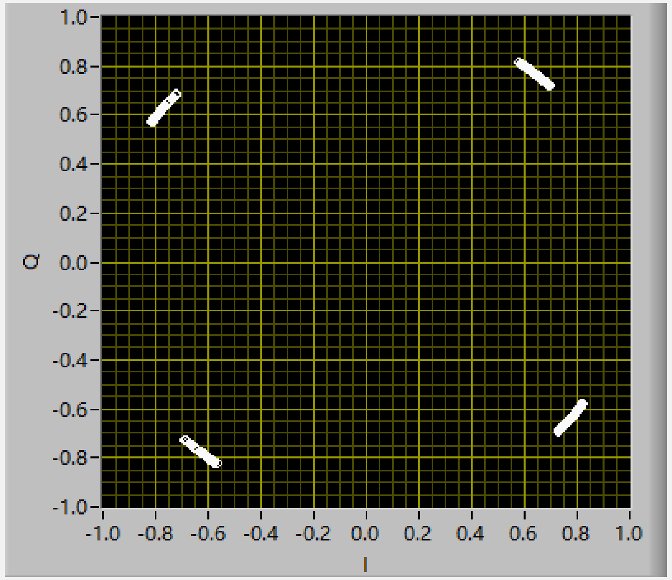


Steps

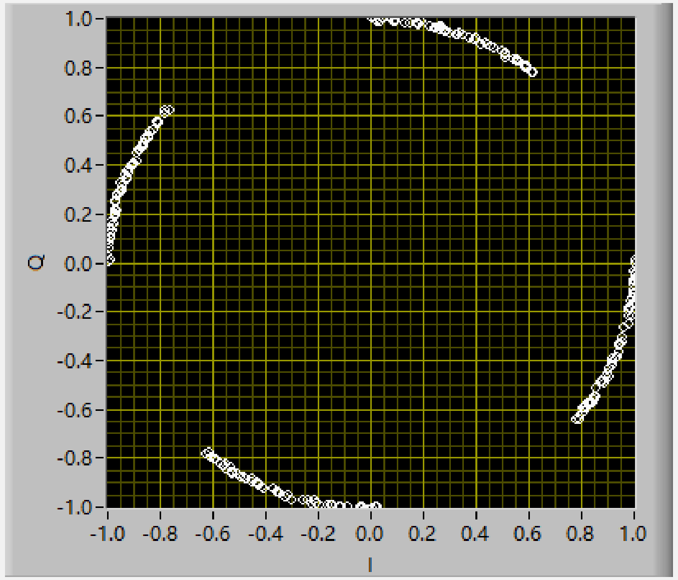
$$\widehat{f_e} = \frac{phase\sum_{l=L}^{N_t-1} y[l+N_t]y^*[l]}{2\pi T N_t}$$

Simulation Results

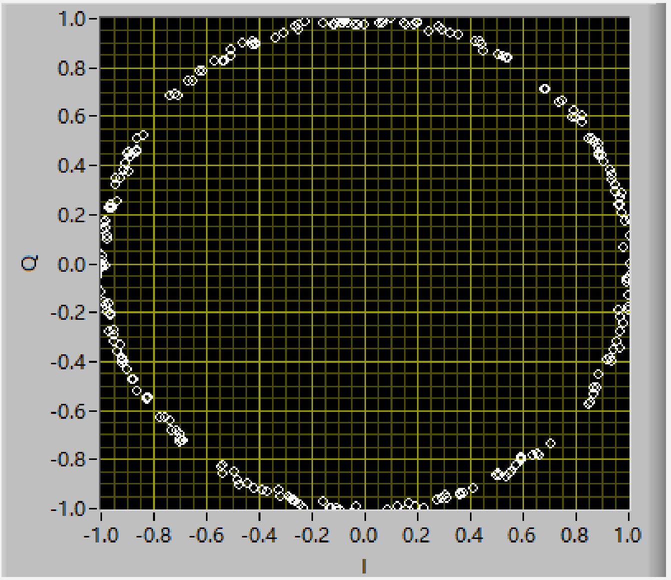

TRANSMITTER
TX oversample factor
4
TX sample rate
4M
TX channel model parameters
channel model
AWGN
noise power (dB)
-Inf
channel response
0
0 +0 i
0 +0 i
0 +0 i
frequency offset
0
delay (sec)
0
RECEIVER
RX oversample factor
4
RX Sample Rate
4M
synchronization options
Synchronization Method
Timing
fixed 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)
SHARED
modulation type
QPSK
packet length (bits)
500
# of Iterations
1
control information for packet header/tai
Training Sequence Type
Length 11 Barker Sequence
Zero Pad Length
8
pulse shaping parameters
modulation type
PSK
pulse shaping filter
Raised
filter parameter
0.5
filter length (symbols)
8



$f_o = 100Hz$



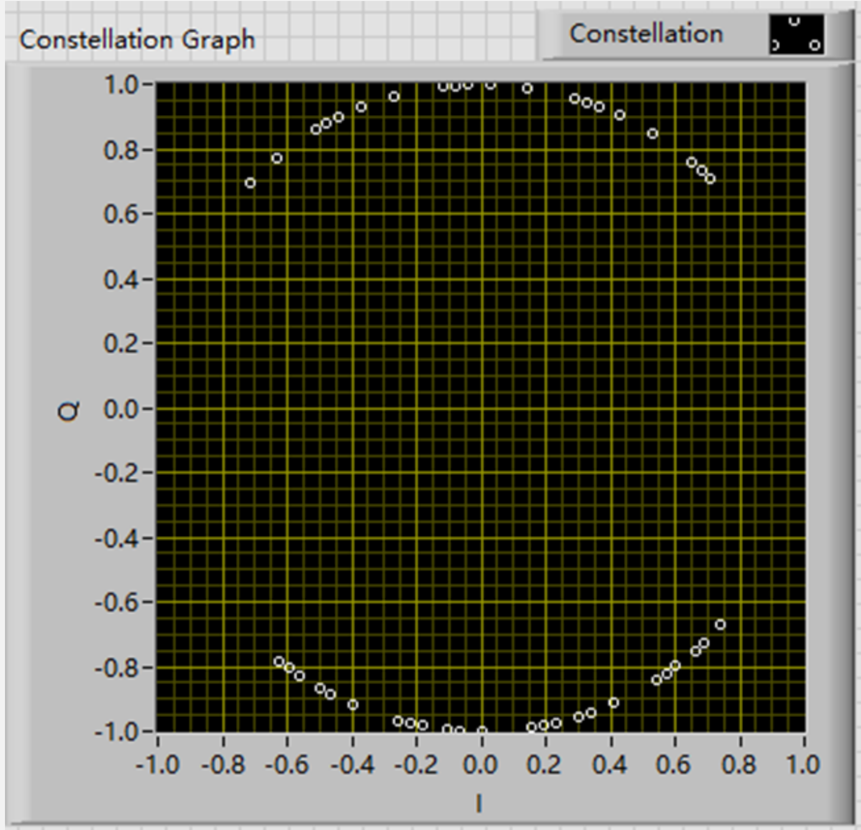
$f_o = 450Hz$

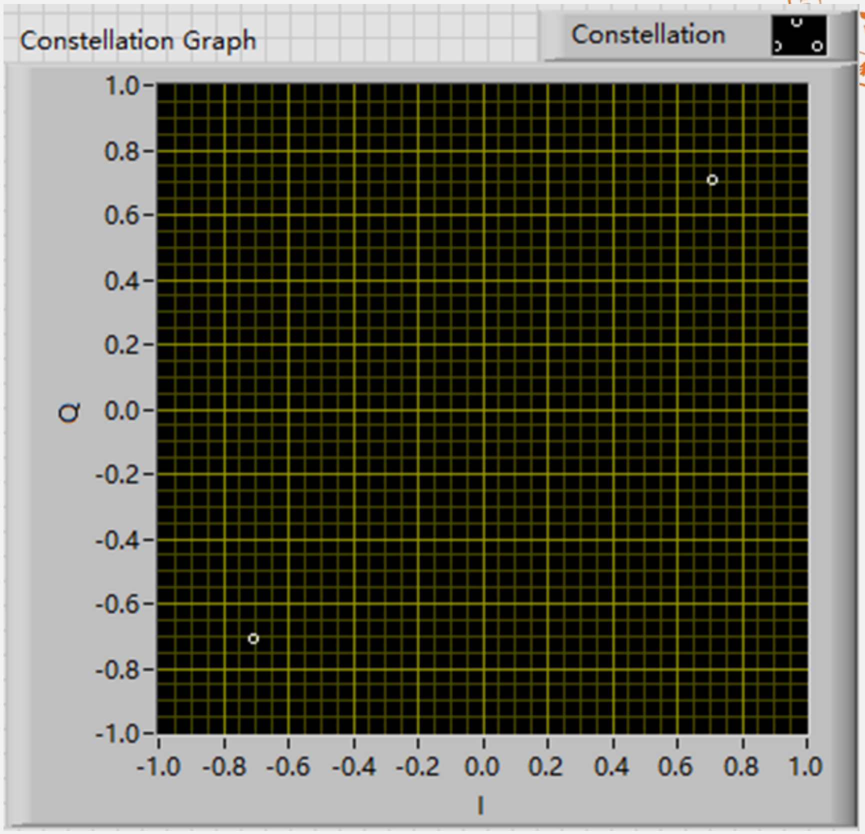


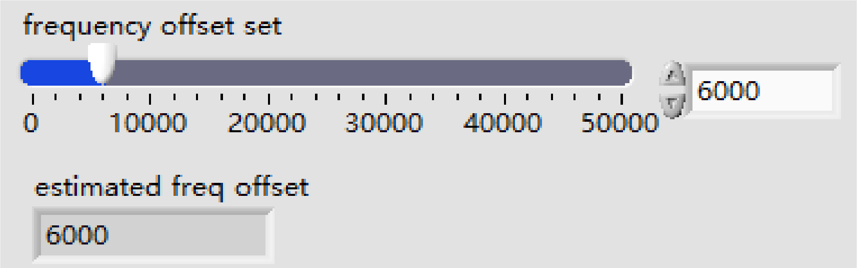
$f_o = 900Hz$

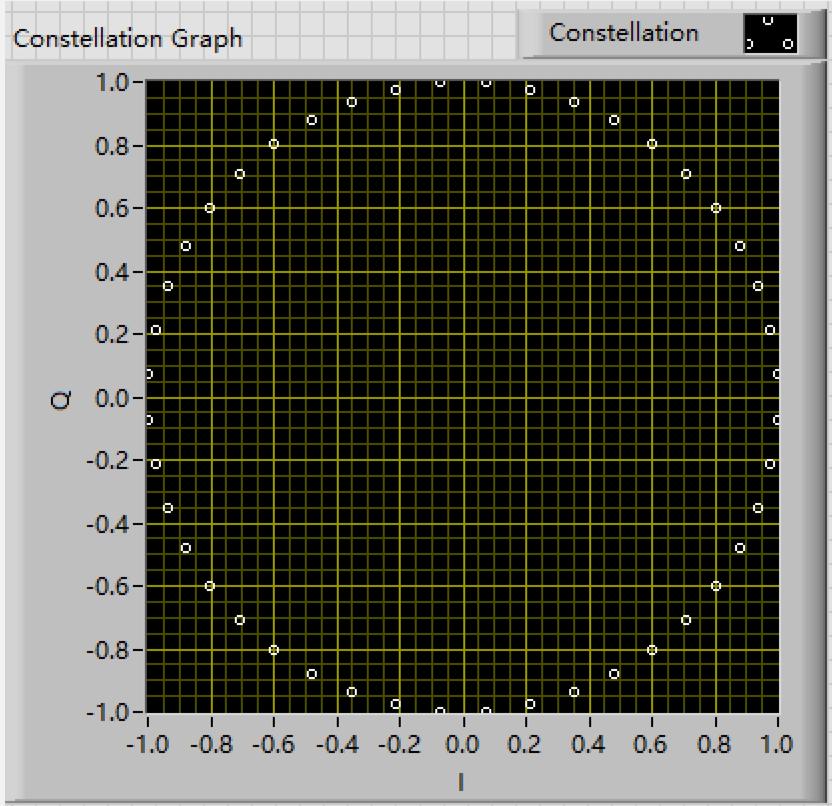
$$Phase\ deg. = 2 \cdot 180^{\circ} \cdot f_o \cdot n_{max} \cdot \frac{1}{f_s}, \qquad n_{max} = 299, f_s = 1M/s$$

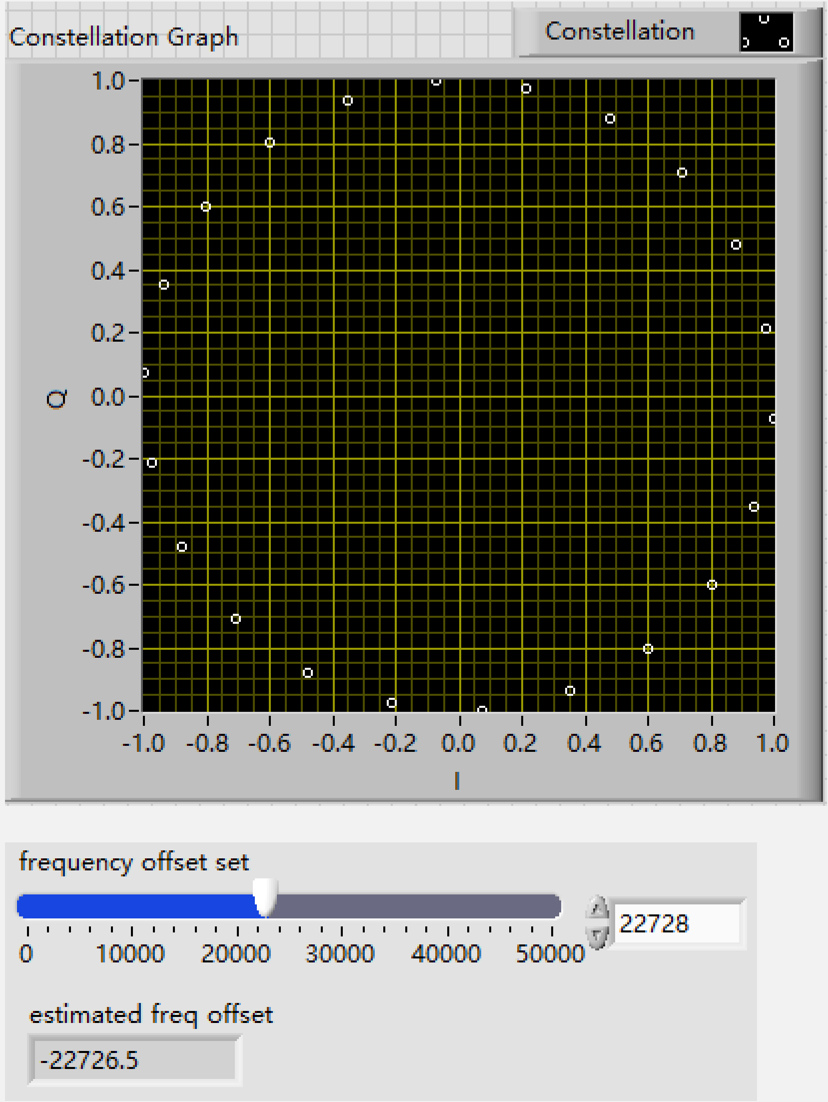
Performance Analysis

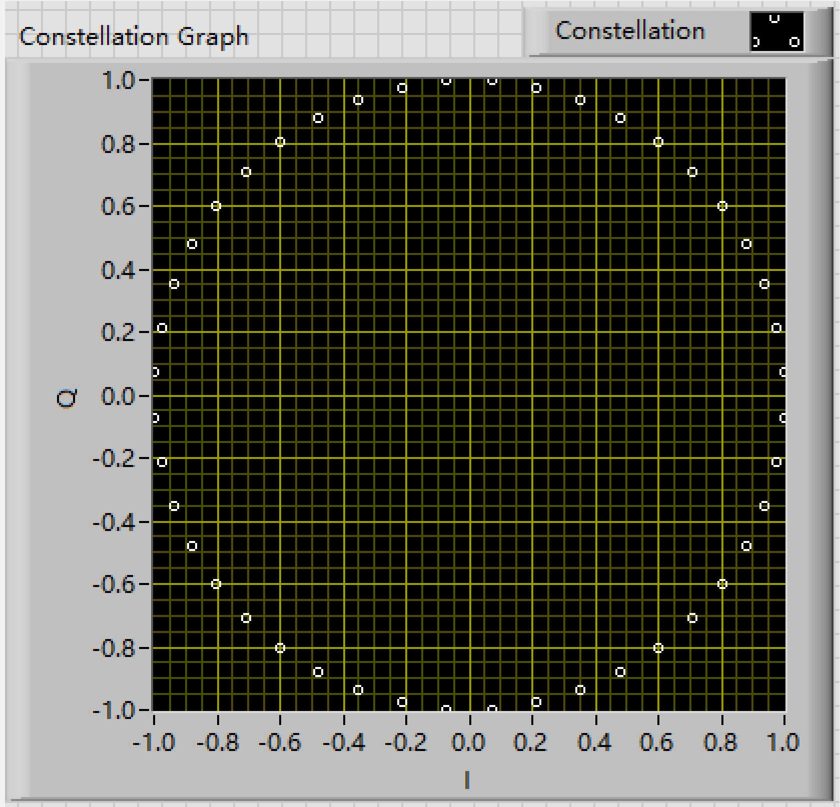

Constellation Graph
Constellation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Q
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0
I

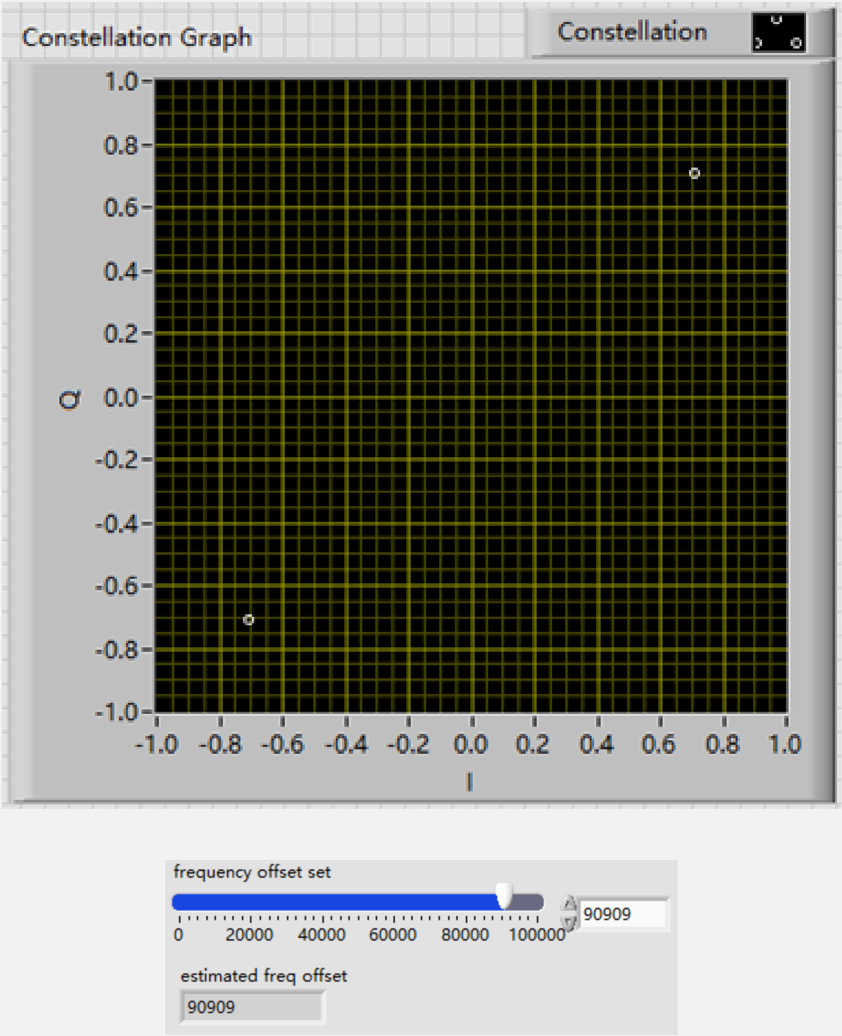

Constellation Graph
Constellation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Q
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0
I


frequency offset set
0 10000 20000 30000 40000 50000
6000
estimated freq offset
6000

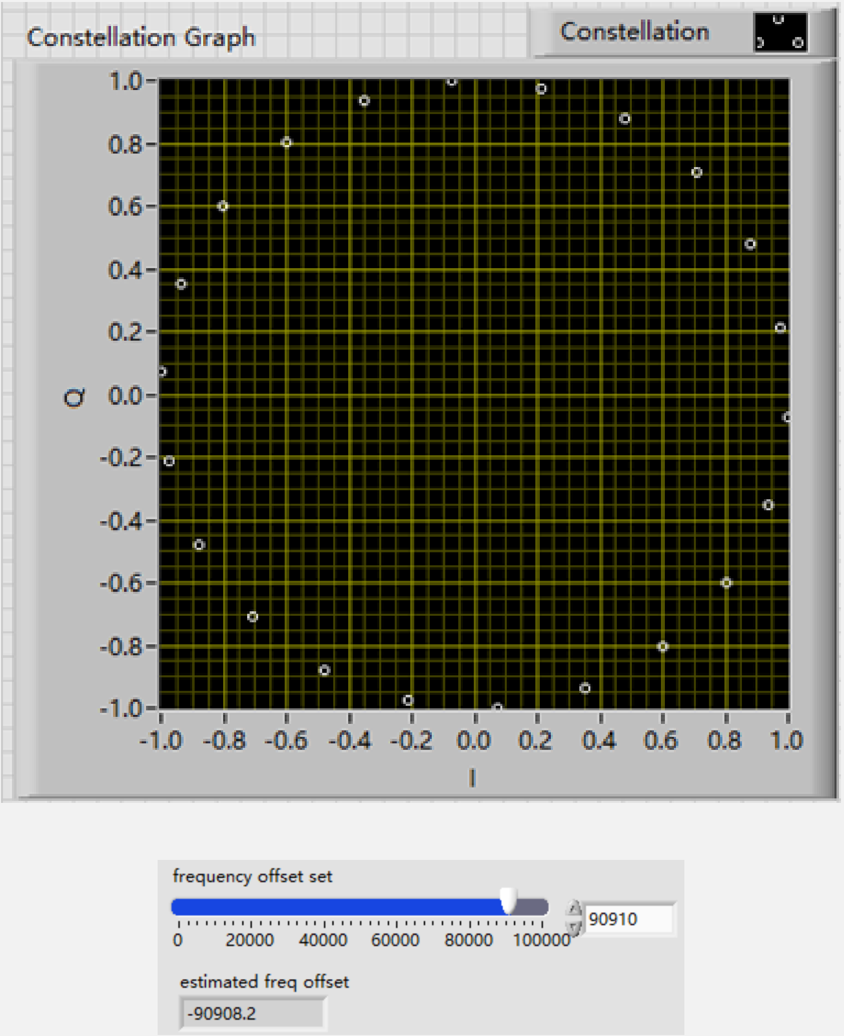

Constellation Graph
Constellation
Q
I
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0


Constellation Graph
Constellation
Q
I
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0
frequency offset set
0 10000 20000 30000 40000 50000
22728
estimated freq offset
-22726.5

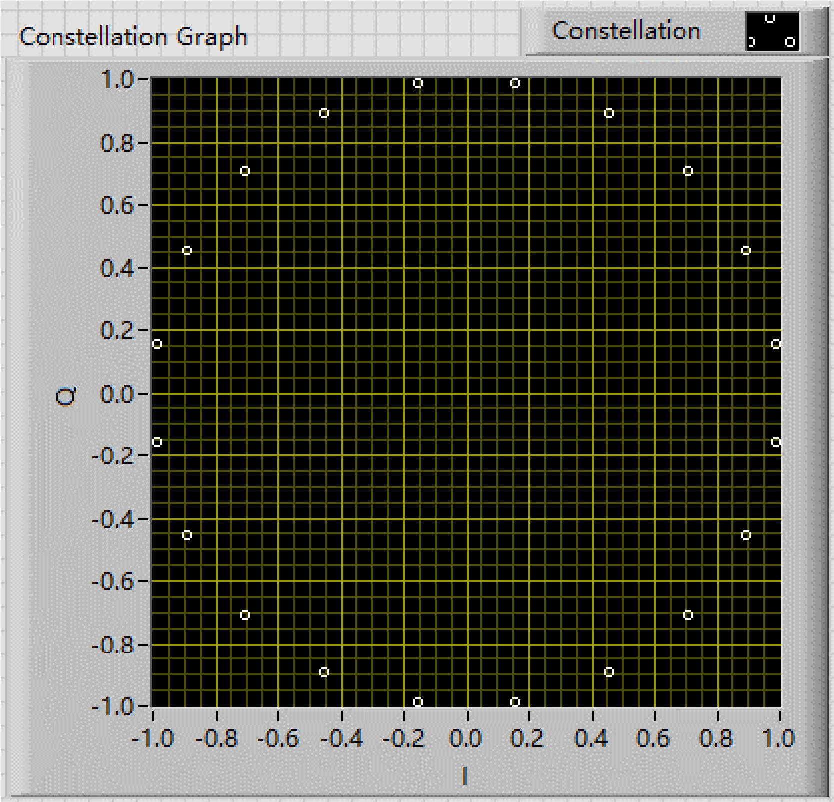

Constellation Graph
Constellation
Q
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0
I

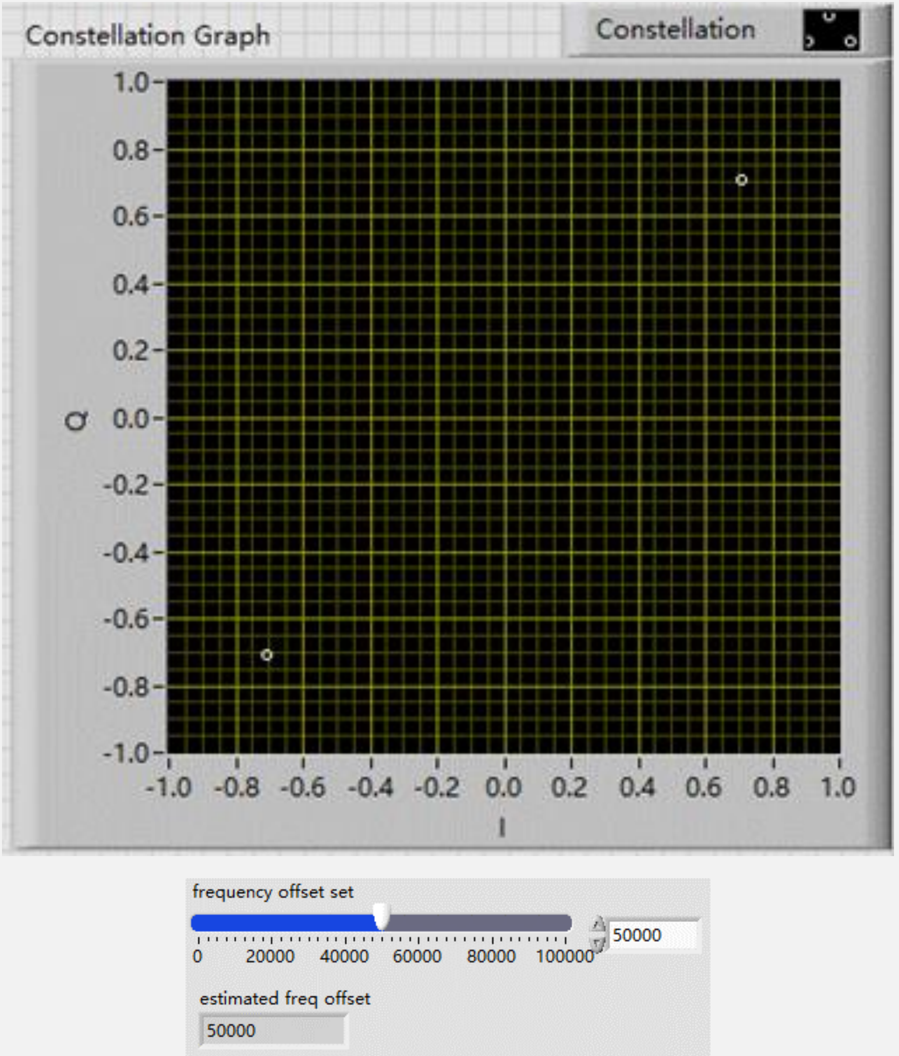


Constellation Graph
Constellation
Q
I
frequency offset set
90909
estimated freq offset
90909

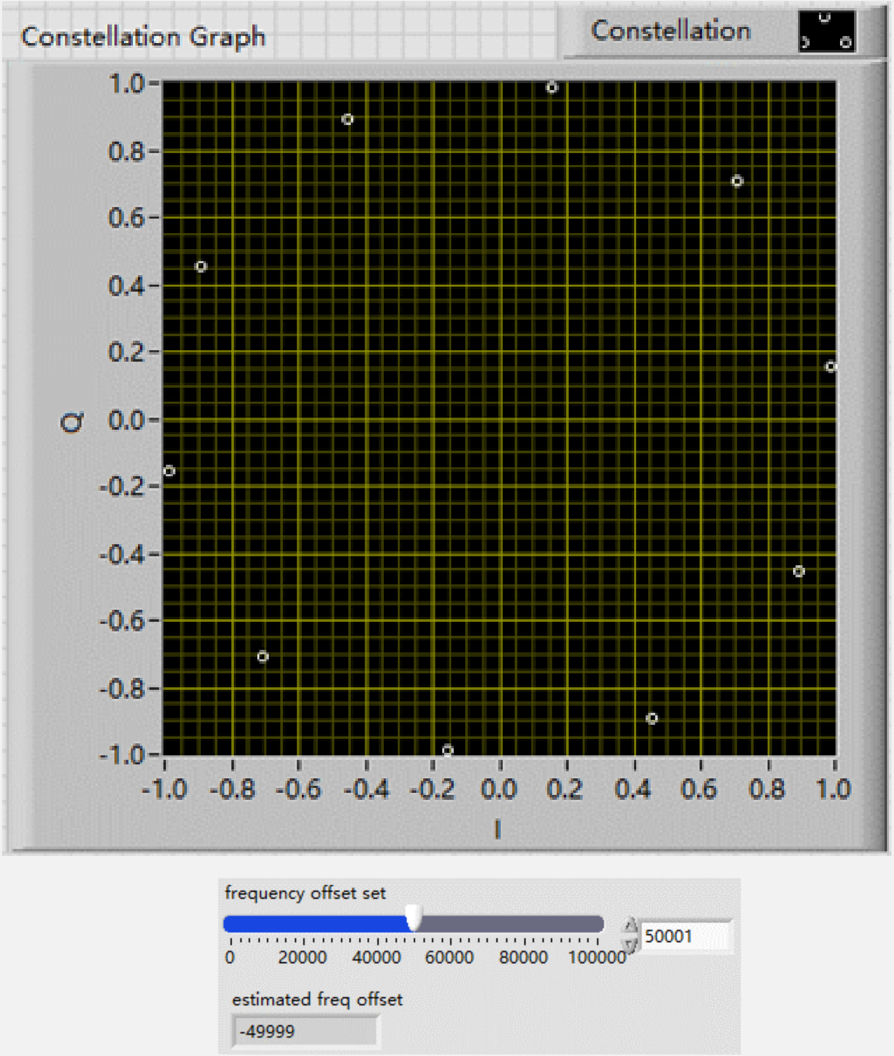


Constellation Graph
Constellation
Q
I
frequency offset set
90910
estimated freq offset
-90908.2


Constellation Graph
Constellation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Q
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0
I



Constellation Graph
Constellation
Q
I
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
frequency offset set
0
20000
40000
60000
80000
100000
50000
estimated freq offset
50000

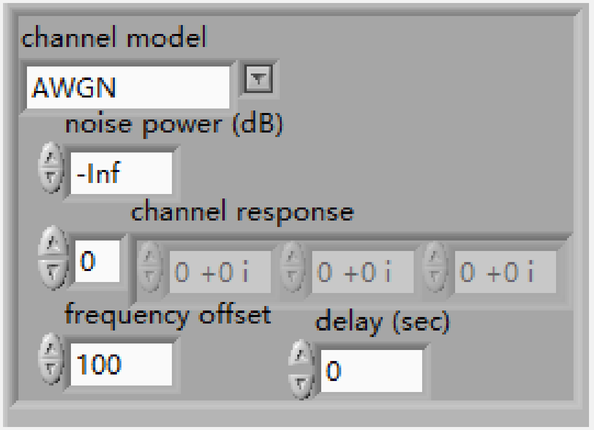


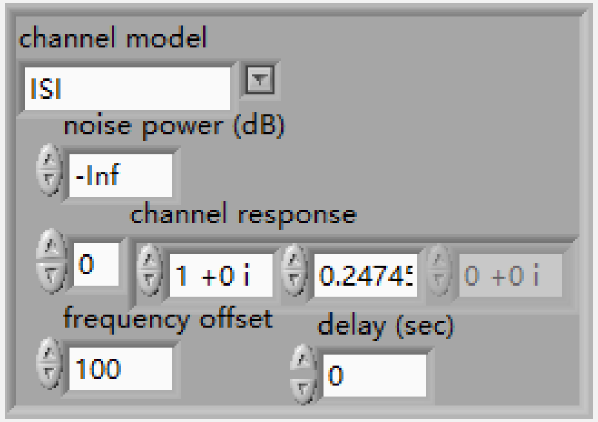
Constellation Graph
Constellation
Q
I
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
frequency offset set
0
20000
40000
60000
80000
100000
50001
estimated freq offset
-49999

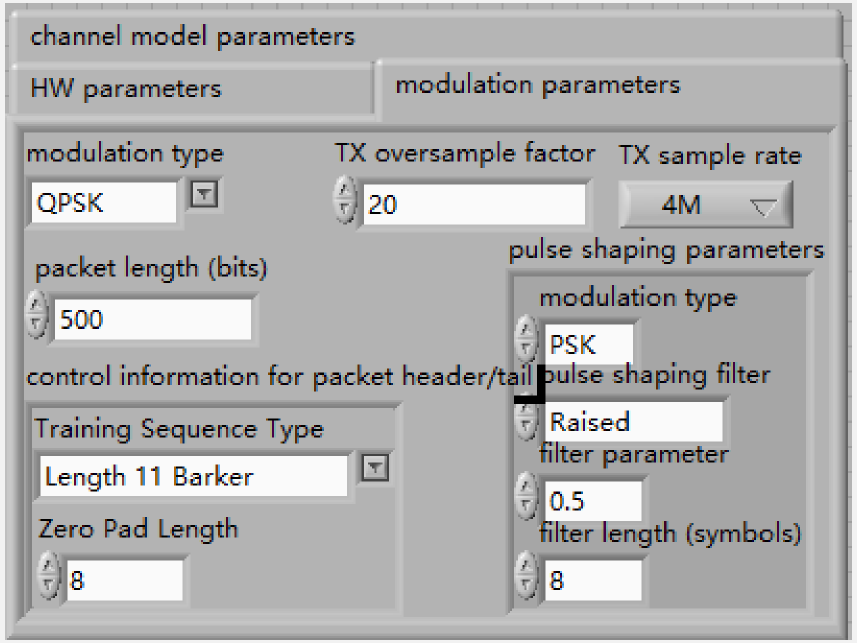
Algorithm Analysis and Verification

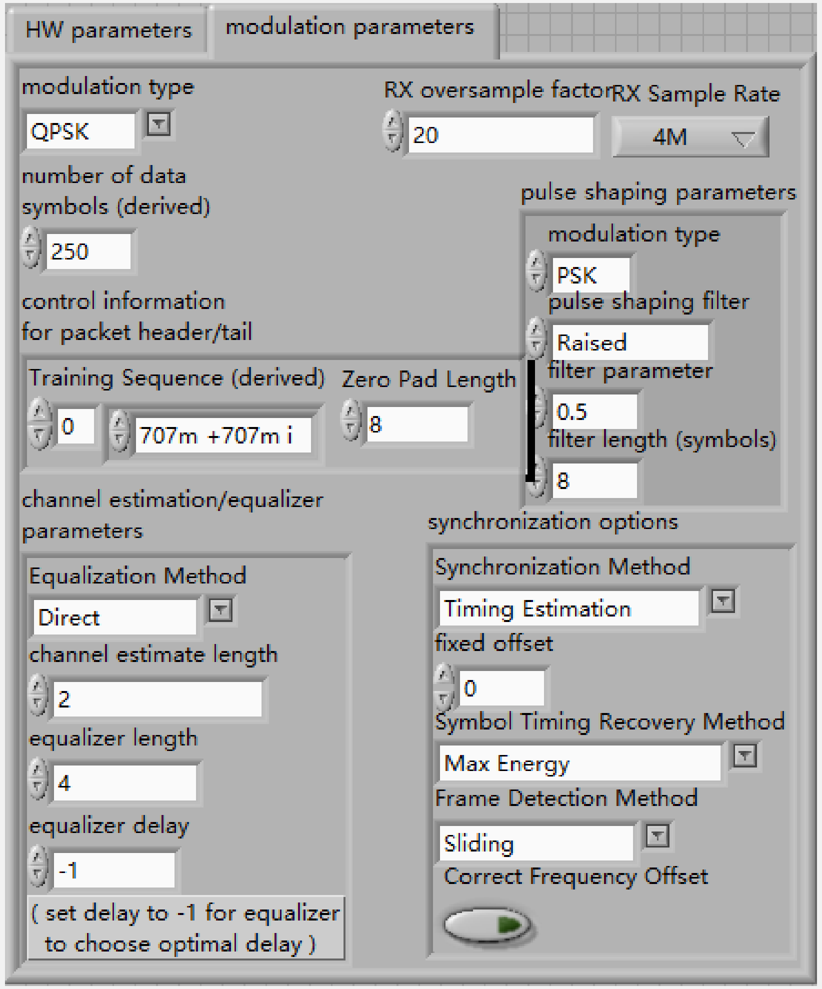
1. Sliding Correlator Algorithm Analysis
2. Moorse Algorithm Analysis
3. Algorithms Simulation
4. USRP Experiments
5. Discussion and Conclusion

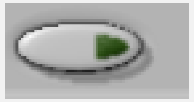
USRP Experiment Setup



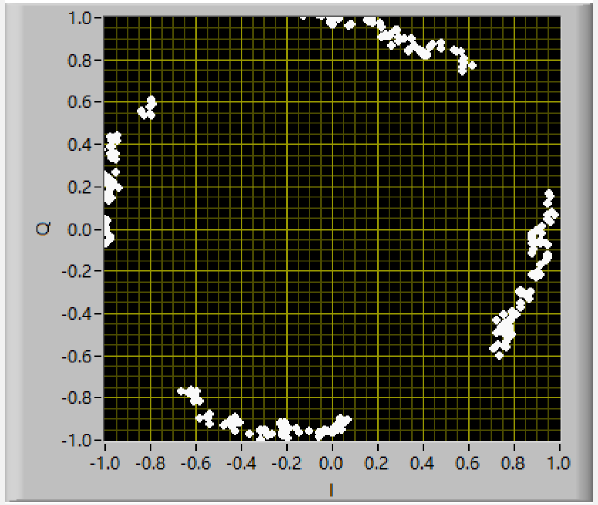


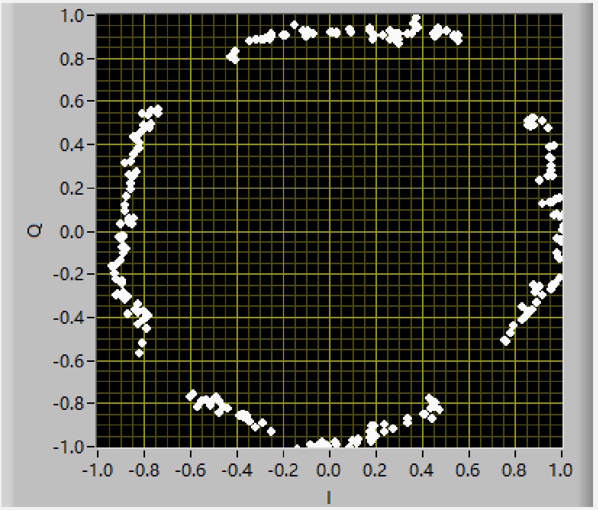


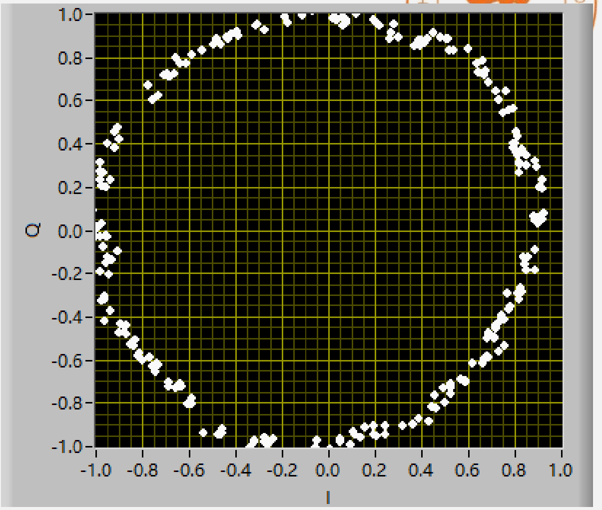




No Correction



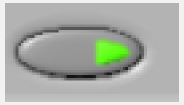




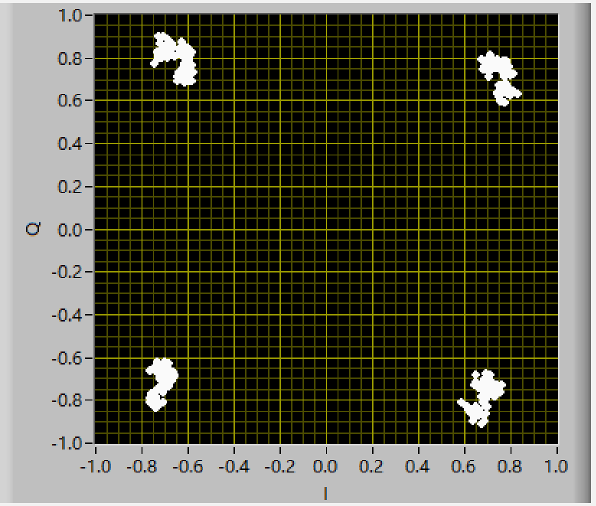
$f_o = 100Hz$

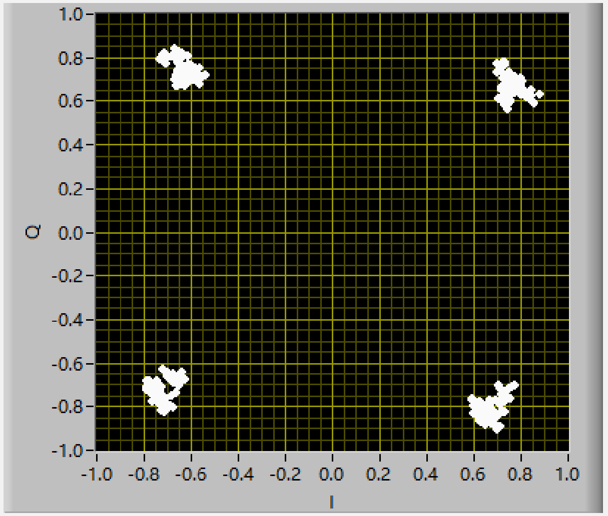
$f_o = 150Hz$

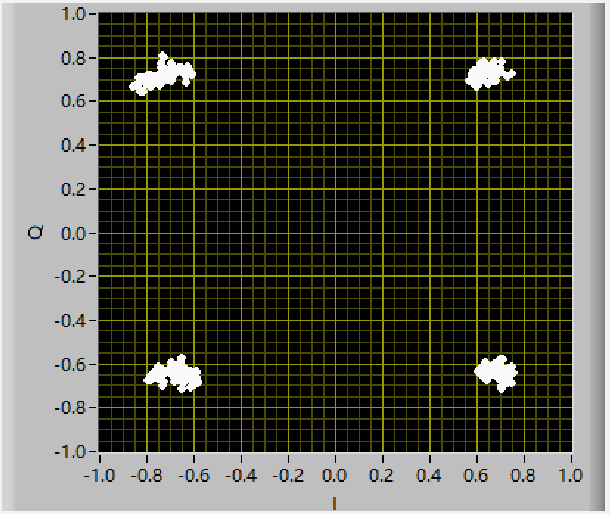
$f_o = 200Hz$

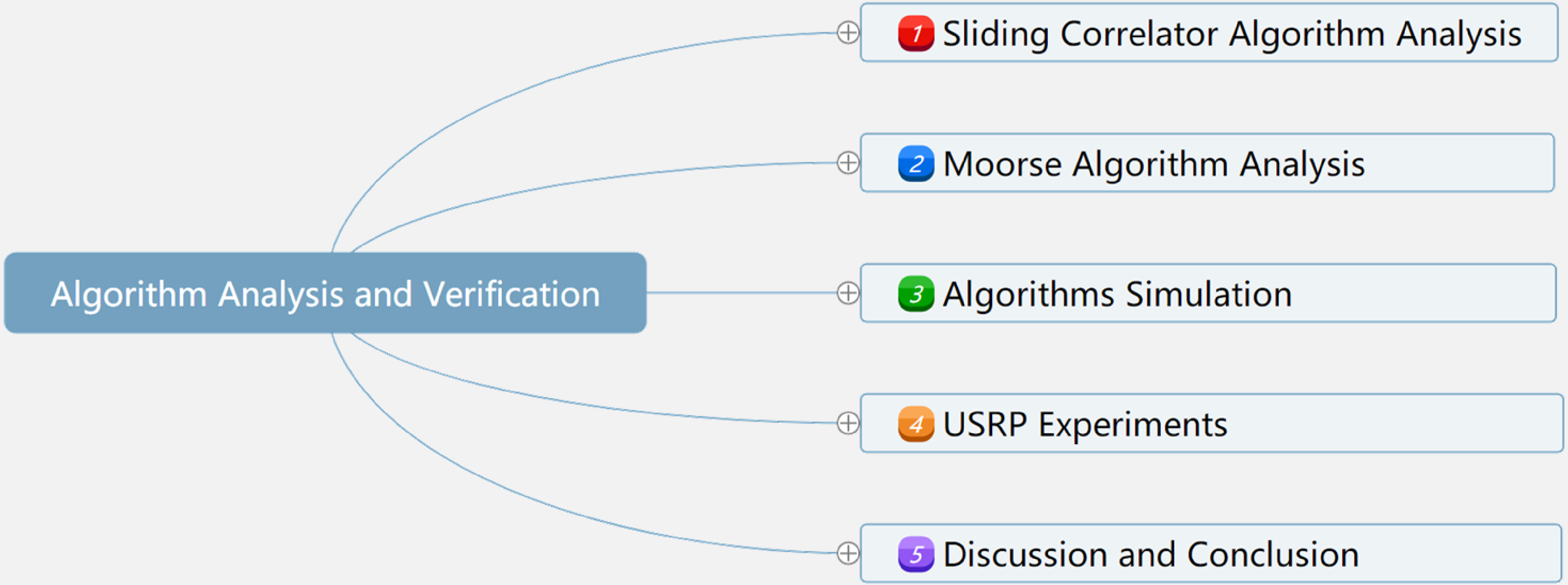


Correction








Algorithm Analysis and Verification
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- **Question ?**