Lab 4: Frame Synchronization and Frequency Offset Correction

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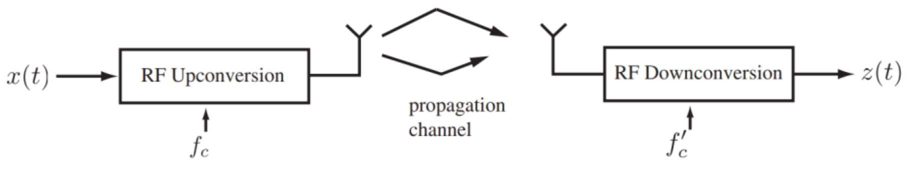
Introduction

Frame Synchronization and Frequency Offset Correction

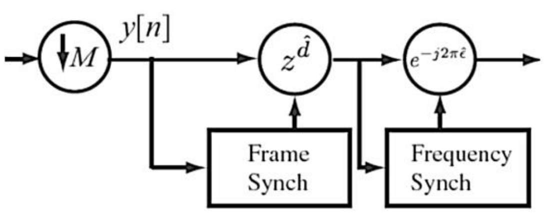
In the field of communication and computer science, the frame typically refers to a data block or packet in data transmission. It contains information about the transmission, such as the actual data, control information, synchronization details, and more.

Frame synchronization is a crucial aspect of communication systems, especially in scenarios where data is transmitted in frames or packets. In practice, due to propagation and signal processing delays, the location of the beginning of the frame is unknown. Therefore, the goal is to ensure that the receiver correctly identifies the boundaries of each frame and extracts the data accurately. Frames typically have a unique pattern or delimiter at the beginning or end, indicating the start or end of a frame. The synchronization process ensures that the receiver can properly interpret the transmitted frames, reducing the risk of errors in data extraction.

Frequency offset correction is essential when there is a mismatch in the carrier frequencies between the transmitter and the receiver. This mismatch can result from various factors, including oscillator inaccuracies and Doppler shifts. Once the frequency offset is determined, the receiver adjusts its local oscillator to compensate for the difference, ensuring that the received signal aligns with the intended carrier frequency. Correcting frequency offsets is crucial for maintaining the integrity of the received signal, as frequency deviations can lead to symbol misinterpretation and communication errors.

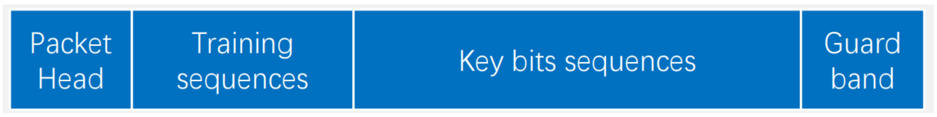


The system model is as below. The received signal should be processed by frame synchronization and then be processed through frequency synchronization.



Training Sequence Designing and principles of Frame Synchronization and Frequency Offset Correctio

The achievement of the above frame synchronization and frequency offset correction is mainly accomplished through a training sequence. The training sequence is a known sequence for both the transmitter and the receiver. The receiver can determine the frame position and frequency information of the signal by manipulating this training sequence. The format of a data packet is as follows, with the training sequence following the packet header and preceding the key bit sequence containing information. Therefore, by identifying the position of the training sequence, the frame position and frequency information can be determined.



Therefore, the design of training sequences is a critical step in digital communication systems, involving the transmission of specific sequences through the channel for training the receiver. Training sequences should possess sufficient uniqueness to enable accurate identification and discrimination by the receiver. This can be achieved by introducing distinctive patterns, encoding, or spectral features within the sequences. The spectral characteristics of training sequences are crucial for accurate estimation and compensation of frequency-selective fading in the channel. Appropriate spectral distribution enhances sensitivity to channel properties, aiding in precise adjustment of receiver parameters. And the length and complexity of training sequences depend on system requirements. Longer training sequences generally provide more accurate channel estimation but come with increased overhead. Complexity is contingent on system processing capabilities and complexity constraints. And the training sequences should possess two key characteristics: 1. It should have a strong autocorrection for frame detection. 2. It should have periodic structure for frequency correction.

Firstly, the training sequence requires strong autocorrelation but weak correlation with other sequences. In this way, the receiver can convolve the entire data packet with the same sequence, and the positions with strong correlation indicate the location of the training sequence, enabling frame synchronization. Many sequences exhibit such characteristics, and Barker codes are an example, as illustrated in the following diagram:

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

The correlation of two sequences can be represented as:

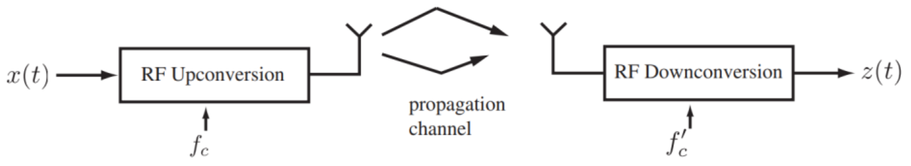
$$R[n] = \left| \sum_{k=0}^{N_t - 1} t^*[k] y[n+k] \right|^2$$

Then, the frame synchronization method is to find the location where the correlation is max, that is:

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

This algorithm above is also called as “the sliding correlation algorithm”.

Secondly, receiver can implement frequency offset correction using the periodic structure of the training sequence. The signal propagation process is that:



So the relationship among the transmitted signal x(t) and the received signal y(t) and he demodulated signal $\hat{y}$ are:

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

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

Because the training sequence is periodical, x(t) = x(t+N), so

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

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

One way to solve the frequency offset estimation problem is to formulate and solve a least-squares problem. Because f_0 appears in the exponent, we solve a modified least squares problem. Consider the squared error:

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

Using the concept of liner least squares, the coefficient a is:

$$\hat{a} = \frac{\sum_{l=L}^{N_t-1} y[l+N_t]y^*[l]}{\sum_{l=L}^{N_t-1} |y[l]|^2}$$

Since only the phase of aˆ is of interest, there is no need to compute the denominator. A simple estimate of the frequency offset is then:

$$\hat{\epsilon} = \frac{\text{phase} \sum_{l=L}^{N_t-1} y[l+N_t]y^*[l]}{2\pi N_t}$$

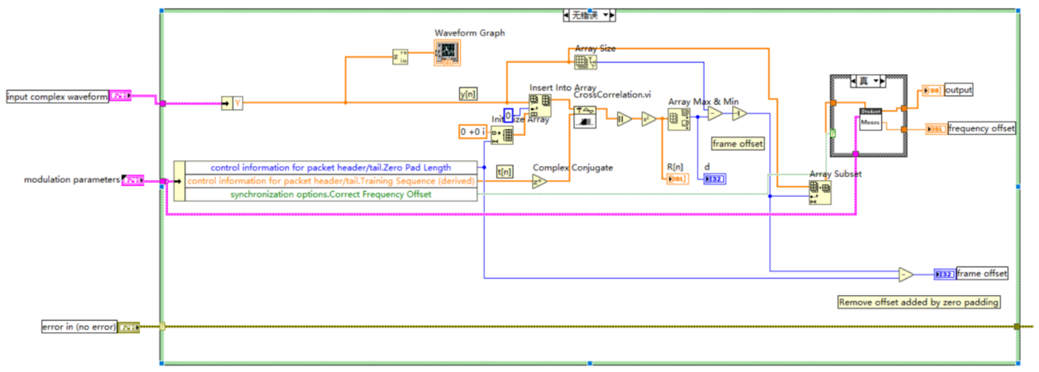
$$\hat{f}_e = \frac{\text{phase} \sum_{l=L}^{N_t-1} y[l+N_t]y^*[l]}{2\pi T N_t}$$

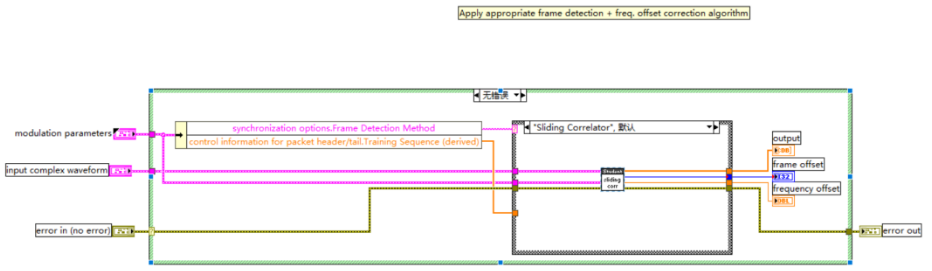
This algorithm is also called as “Moose algorithm”.

Lab results & Analysis:

2.1 Sliding Correlator Algorithm

2.1.1 Block Diagram



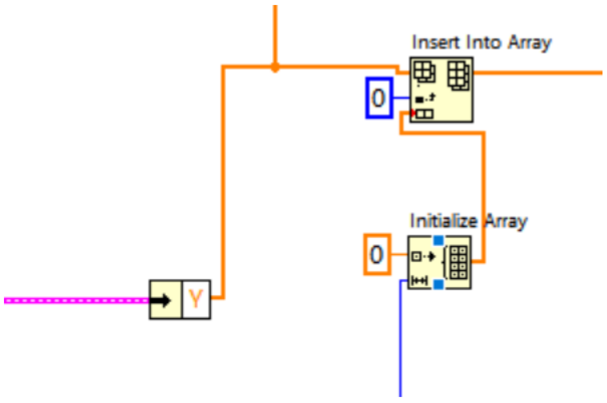


Apply appropriate frame detection + freq. offset correction algorithm
无错误
modulation parameters
synchronization options.Frame Detection Method
control information for packet header/tail.Training Sequence (derived)
"Sliding Correlator", 默认
input complex waveform
output
frame offset
frequency offset
error in (no error)
error out

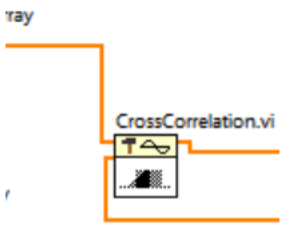
First graph is the block diagram in sliding correlator algorithm, and the second picture is the proof that I use my own block while simulation.

2.1.2 Program Process

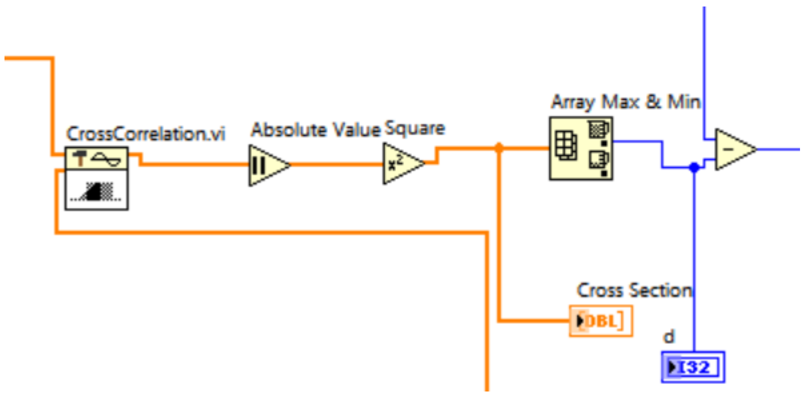
We can divide the into several parts, each part serves as a specific function.



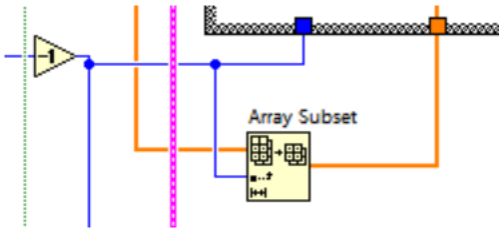
In this part, we want to assert zero into the original array, the number of zero equals to the zero-pad length in the modulation information.



This is the key step and key block. Just as what we said previously, we should generate the training sequence in the receiver side and then make a cross correlation. And the maximum value will be the sum of all the number's square.

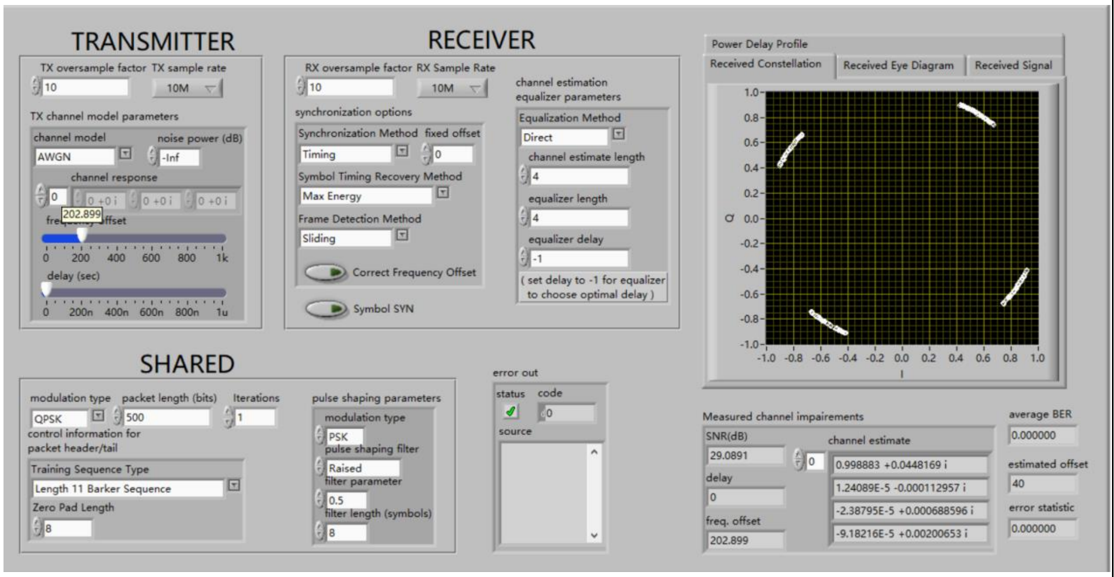


After cross correlation, we want to find out where is the largest energy, the blocks above provide this function. This is where the training sequence is.

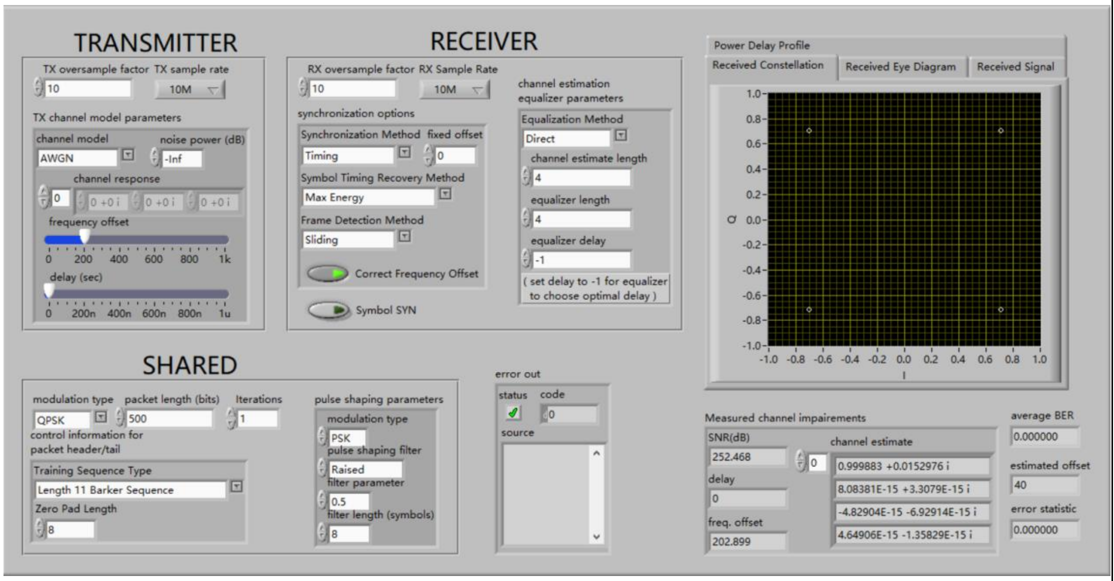


Last, we use Array Subset block to get the desired array, and input to a Moose.vi.

2.1.3 Simulation Result



TX oversample factor: 10 TX sample rate: 10M
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: 202.899
delay (sec)
RX oversample factor: 10 RX Sample Rate: 10M
synchronization options
Synchronization Method: Timing fixed offset: 0
Symbol Timing Recovery Method: Max Energy
Frame Detection Method: Sliding
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)
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
pulse shaping parameters
modulation type: PSK
pulse shaping filter: Raised
filter parameter: 0.5
filter length (symbols): 8
error out
status: ✓ code: 0
source
Measured channel impairements
SNR(dB): 29.0891
delay: 0
freq. offset: 202.899
channel estimate: 0
0.998883 +0.0448169 i
1.24089E-5 -0.000112957 i
-2.38795E-5 +0.000688596 i
-9.18216E-5 +0.00200653 i
average BER: 0.000000
estimated offset: 40
error statistic: 0.000000



TX oversample factor: 10 TX sample rate: 10M
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
delay (sec)
RX oversample factor: 10 RX Sample Rate: 10M
synchronization options
Synchronization Method: Timing fixed offset: 0
Symbol Timing Recovery Method: Max Energy
Frame Detection Method: Sliding
channel estimation equalizer parameters
Equalization Method: Direct
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equalizer delay: -1
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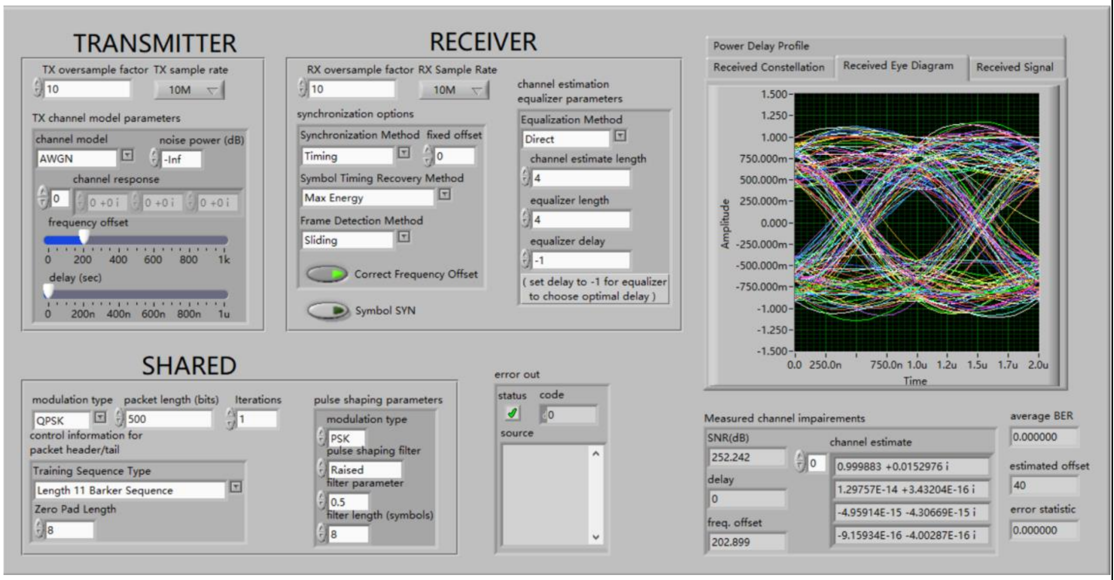
control information for packet header/tail
Training Sequence Type: Length 11 Barker Sequence
Zero Pad Length: 8
pulse shaping parameters
modulation type: PSK
pulse shaping filter: Raised
filter parameter: 0.5
filter length (symbols): 8
error out
status: ✓ code: 0
source
Measured channel impairements
SNR(dB): 252.468
delay: 0
freq. offset: 202.899
channel estimate: 0
0.999883 +0.0152976 i
8.08381E-15 +3.3079E-15 i
-4.82904E-15 -6.92914E-15 i
4.64906E-15 -1.35829E-15 i
average BER: 0.000000
estimated offset: 40
error statistic: 0.000000



TRANSMITTER

TX oversample factor: 10 | TX sample rate: 10M

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 | delay (sec)

RECEIVER

RX oversample factor: 10 | RX Sample Rate: 10M

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

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 | Iterations: 1

control information for packet header/tail: Training Sequence Type: Length 11 Barker Sequence | Zero Pad Length: 8

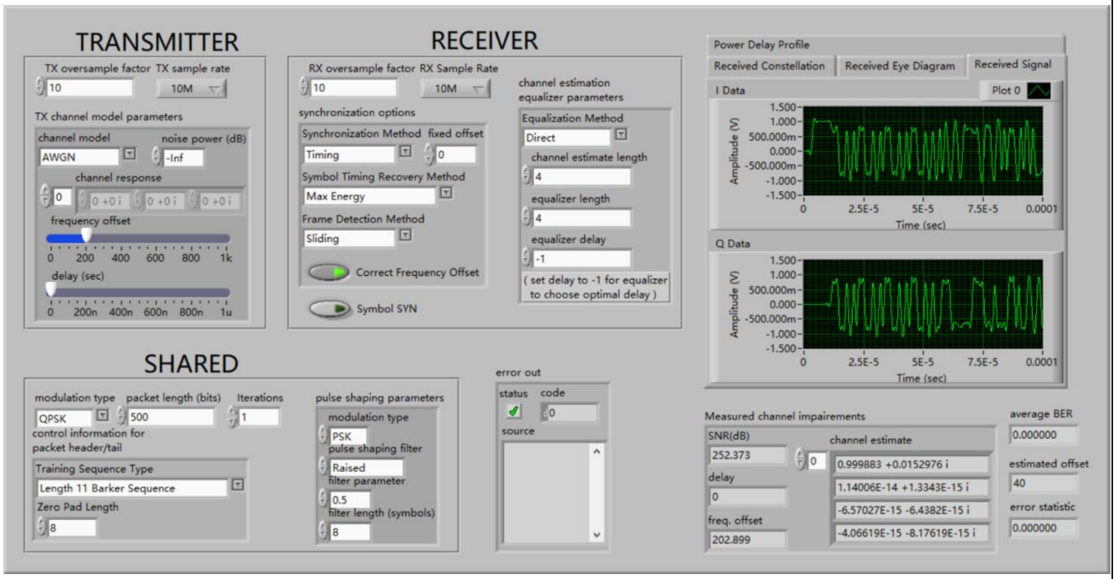
pulse shaping parameters: modulation type: PSK | pulse shaping filter: Raised | filter parameter: 0.5 | filter length (symbols): 8

error out: status ✓ | code: 0 | source

Measured channel impairements: SNR(dB): 252.242 | delay: 0 | freq. offset: 202.899

channel estimate: 0; 0.999883 +0.0152976 i; 1.29757E-14 +3.43204E-16 i; -4.95914E-15 -4.30669E-15 i; -9.15934E-16 -4.00287E-16 i

average BER: 0.000000 | estimated offset: 40 | error statistic: 0.000000



TRANSMITTER

TX oversample factor: 10 | TX sample rate: 10M

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 | delay (sec)

RECEIVER

RX oversample factor: 10 | RX Sample Rate: 10M

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

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 | Iterations: 1

control information for packet header/tail: 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

error out: status ✓ | code: 0 | source

Measured channel impairements: SNR(dB): 252.373 | delay: 0 | freq. offset: 202.899

channel estimate: 0; 0.999883 +0.0152976 i; 1.14006E-14 +1.3343E-15 i; -6.57027E-15 -6.4382E-15 i; -4.06619E-15 -8.17619E-15 i

average BER: 0.000000 | estimated offset: 40 | error statistic: 0.000000

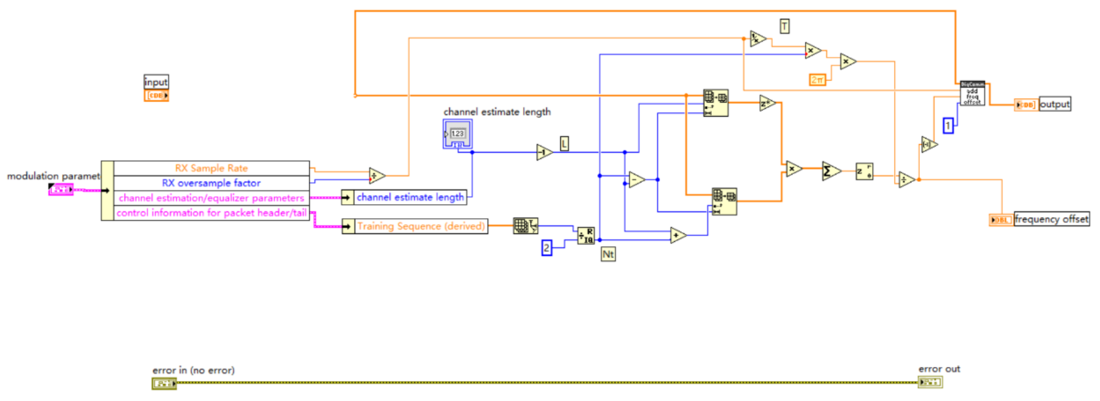
The first graph is the result without correlating frequency offset, we can see the frequency offset from the constellation

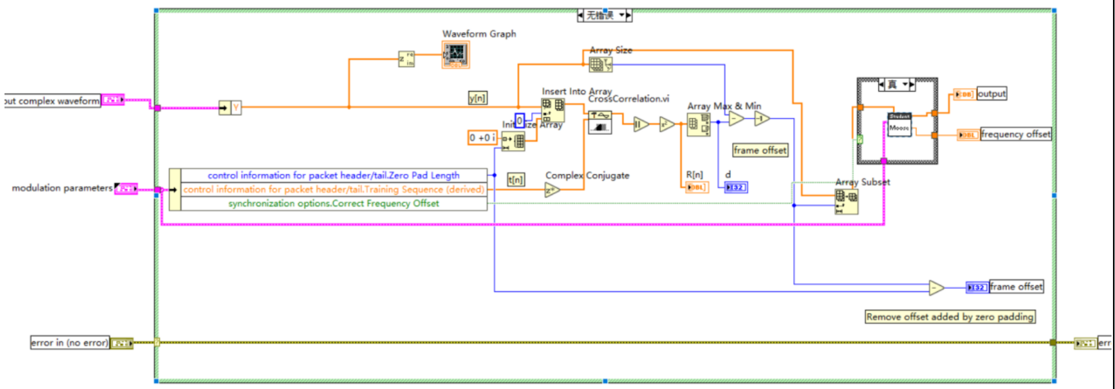
The second graph is the result after correlating, we can see obviously that there is a maximum point and the x coordinate corresponding to the length of the training sequence.

The next two graph shows that the signal was received properly and the proper eye diagram.

2.2 Moose Algorithm

2.2.1 Block Diagram

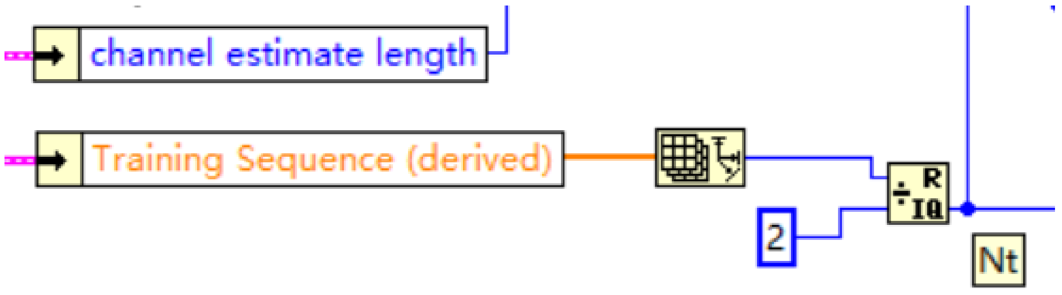




First graph is the block diagram in sliding correlator algorithm, and the second picture is the proof that I use my own block while simulation.

2.2.2 Program Process

Since the Moose algorithm splits the training sequence after four repetitions into two periodic sequences for frequency bias estimation. So we can get the N_t by divided 2 as below.

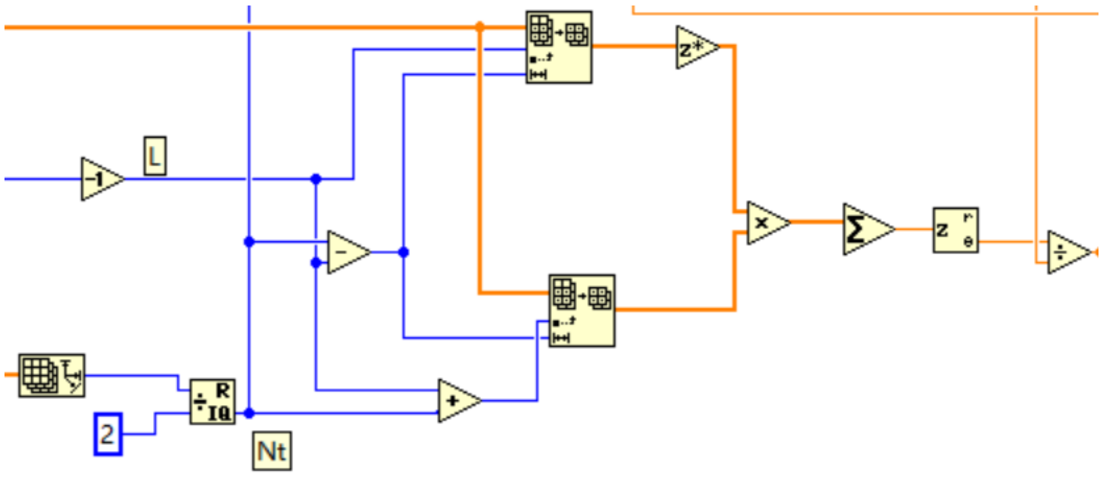


Then according to the equation:

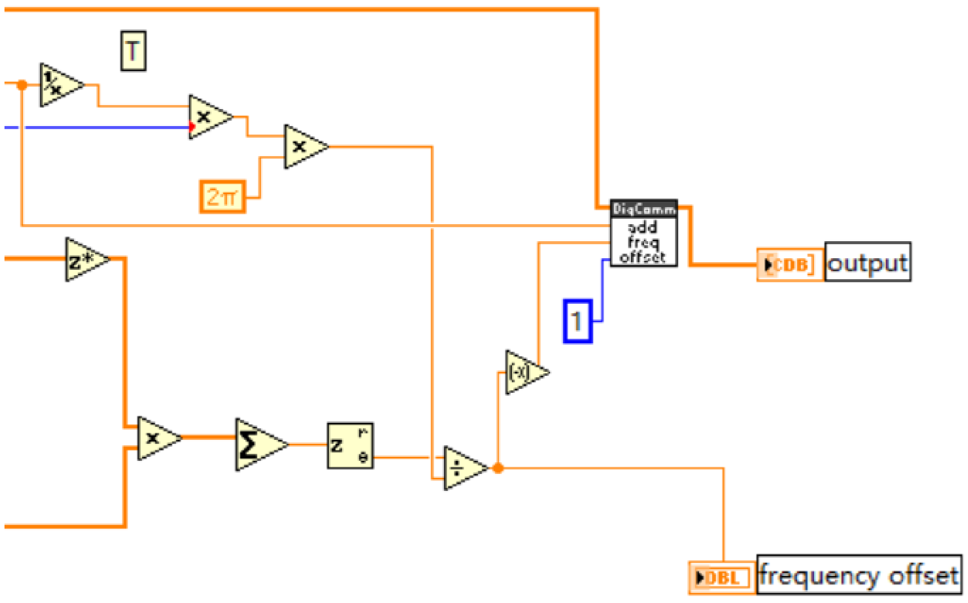
$$\hat{\epsilon} = \frac{\text{phase} \sum_{l=L}^{N_t-1} y[l+N_t]y^*[l]}{2\pi N_t}$$

$$\hat{f}_e = \frac{\text{phase} \sum_{l=L}^{N_t-1} y[l+N_t]y^*[l]}{2\pi T N_t},$$

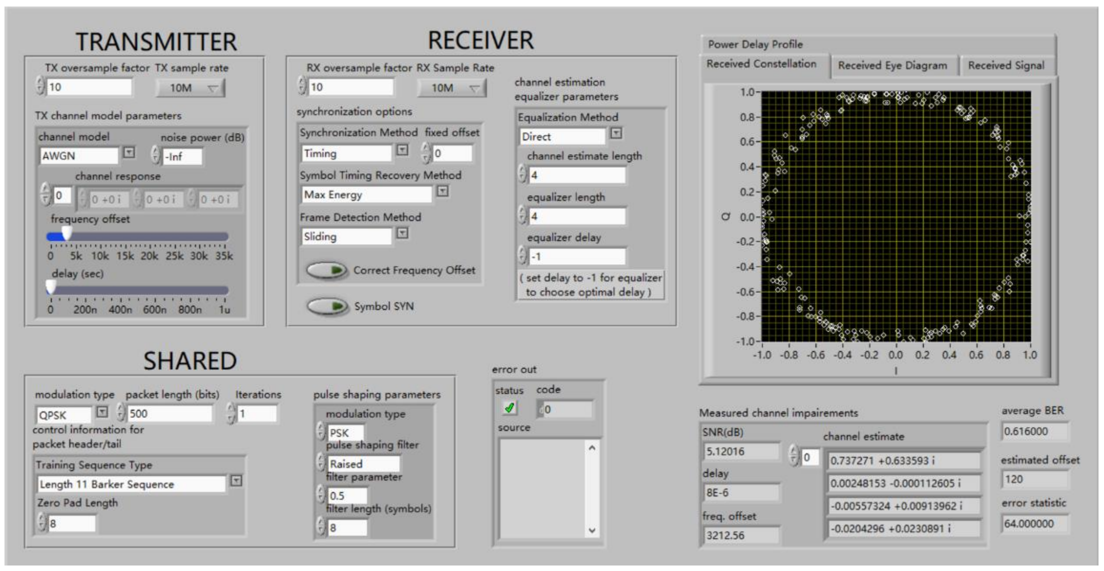
Take N_t as the interval and multiply it with its conjugate, and take the obtained result in phase. The above equation can be completed by dividing the training sequence into two arrays by Array Subset Vi. Then Conjugate one of the subarrays and multiply it with the other to find the sum.



According to the formula, the summation result is divided by 2 to obtain the frequency offset. Finally, the input is frequency shifted in the opposite direction to complete the frequency offset correction.



2.2.3 Simulation Result



TRANSMITTER

TX oversample factor: 10
TX sample rate: 10M

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, 5k, 10k, 15k, 20k, 25k, 30k, 35k)
delay (sec) (0, 200n, 400n, 600n, 800n, 1u)

RECEIVER

RX oversample factor: 10
RX Sample Rate: 10M

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

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
Iterations: 1
control information for packet header/tail
Training Sequence Type: Length 11 Barker Sequence
Zero Pad Length: 8

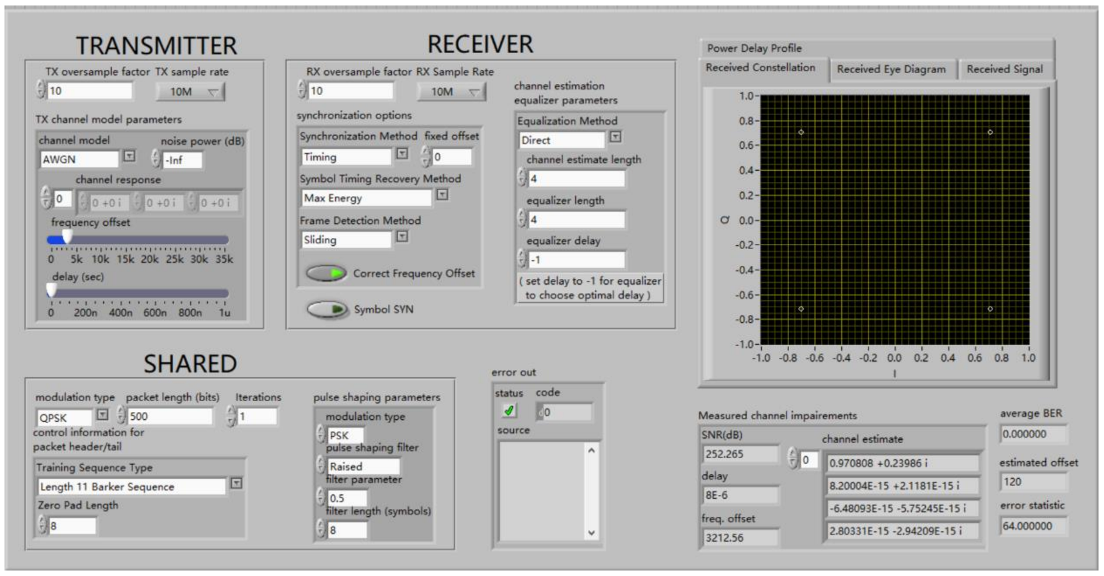
pulse shaping parameters
modulation type: PSK
pulse shaping filter: Raised
filter parameter: 0.5
filter length (symbols): 8

error out
status: ✓
code: 0
source

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

Measured channel impairements
SNR(dB): 5.12016
delay: 8E-6
freq. offset: 3212.56
channel estimate: 0
0.737271 +0.633593 i
0.00248153 -0.000112605 i
-0.00557324 +0.00913962 i
-0.0204296 +0.0230891 i

average BER: 0.616000
estimated offset: 120
error statistic: 64.000000



TRANSMITTER

TX oversample factor: 10
TX sample rate: 10M

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, 5k, 10k, 15k, 20k, 25k, 30k, 35k)
delay (sec) (0, 200n, 400n, 600n, 800n, 1u)

RECEIVER

RX oversample factor: 10
RX Sample Rate: 10M

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

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
Iterations: 1
control information for packet header/tail
Training Sequence Type: Length 11 Barker Sequence
Zero Pad Length: 8

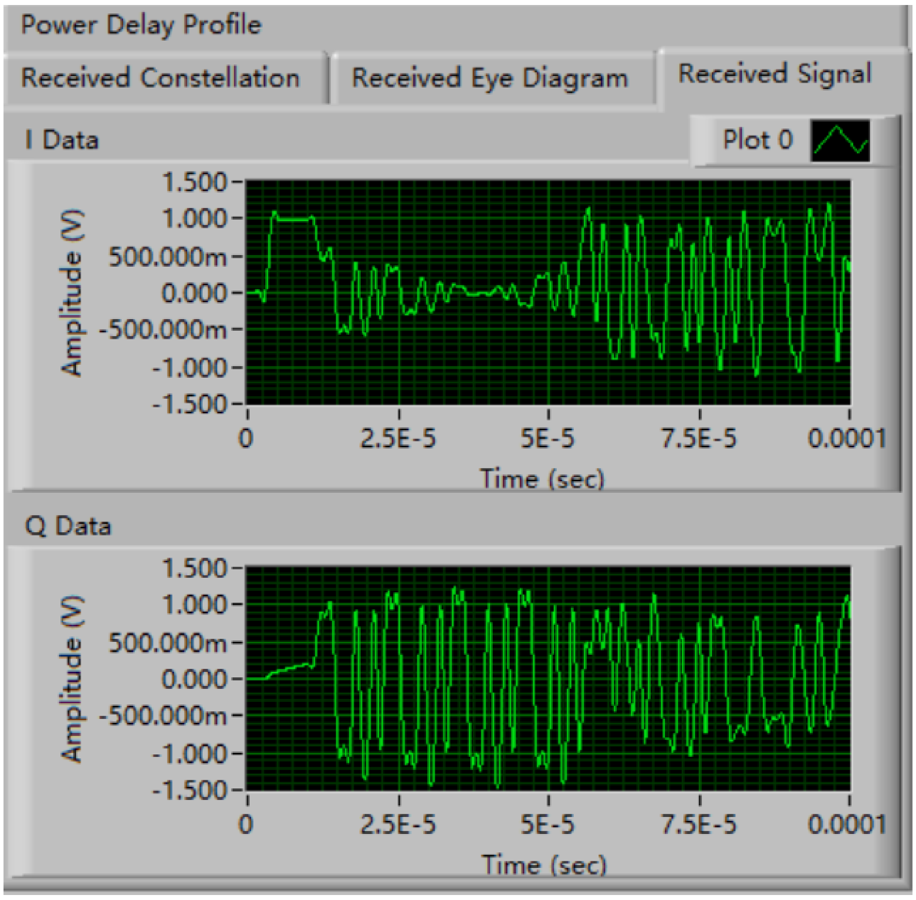
pulse shaping parameters
modulation type: PSK
pulse shaping filter: Raised
filter parameter: 0.5
filter length (symbols): 8

error out
status: ✓
code: 0
source

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

Measured channel impairements
SNR(dB): 252.265
delay: 8E-6
freq. offset: 3212.56
channel estimate: 0
0.970808 +0.23986 i
8.20004E-15 +2.1181E-15 i
-6.48093E-15 -5.75245E-15 i
2.80331E-15 -2.94209E-15 i

average BER: 0.000000
estimated offset: 120
error statistic: 64.000000



The first image does not use frequency bias correction, the second image does. By comparison, it can be seen that the frequency offset correction is successfully completed by the moose algorithm. The calculation result of frequency offset estimation in the lower right corner also agrees with the frequency offset of our setup. The signal was successfully recovered.

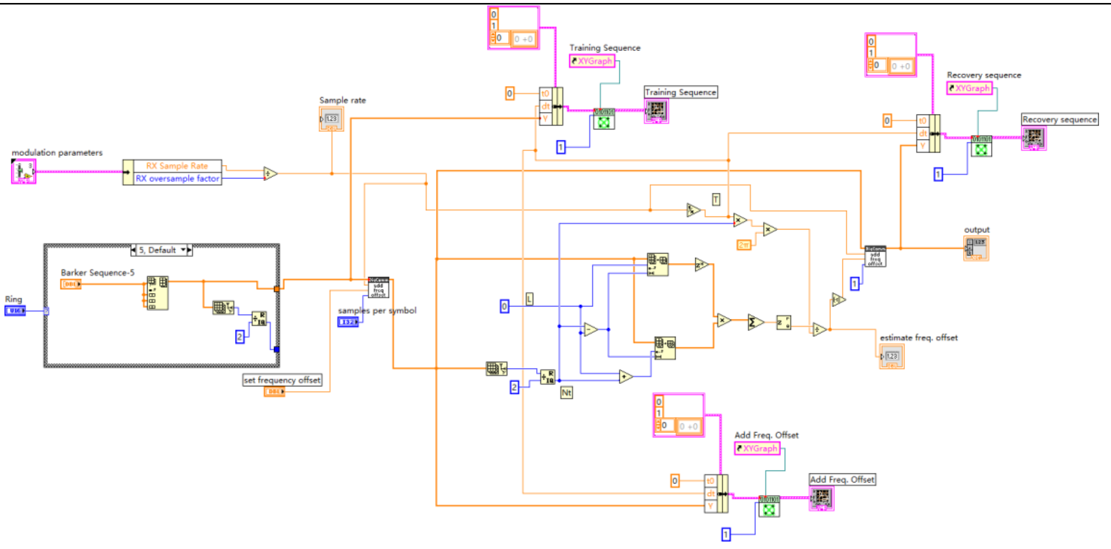
2.3 Analysis the performance of the Moose algorithm

According to the previous analysis, the frequency bias value f:

$$[-\frac{1}{2N_t T_s}, \frac{1}{2N_t T_s}]$$

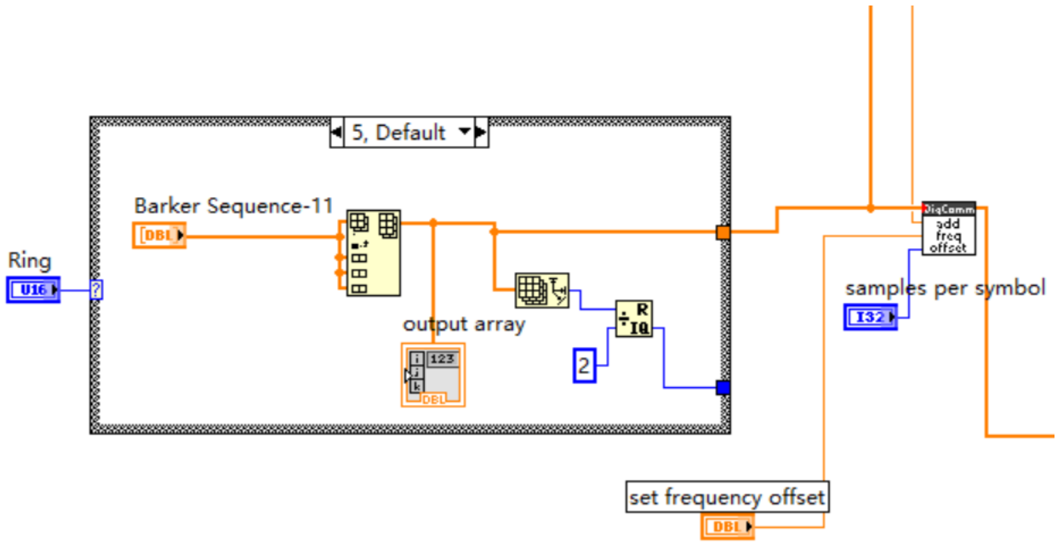
that can be accurately estimated when estimating frequency bias using the Moose algorithm, i.e., the estimation range, is limited by the symbol rate and the length of the training sequence. To verify this conclusion, we can generate a segment of data containing only the training sequence, add tunable frequency We can generate a piece of data containing only the training sequence, input it to the Moose algorithm for frequency bias estimation, and then verify the relationship between the estimated range and the symbol rate and the length of the training sequence. To verify the relationship between the estimated range and the symbol rate and the length of the training sequence.

Here is the block diagram of the program we tested.

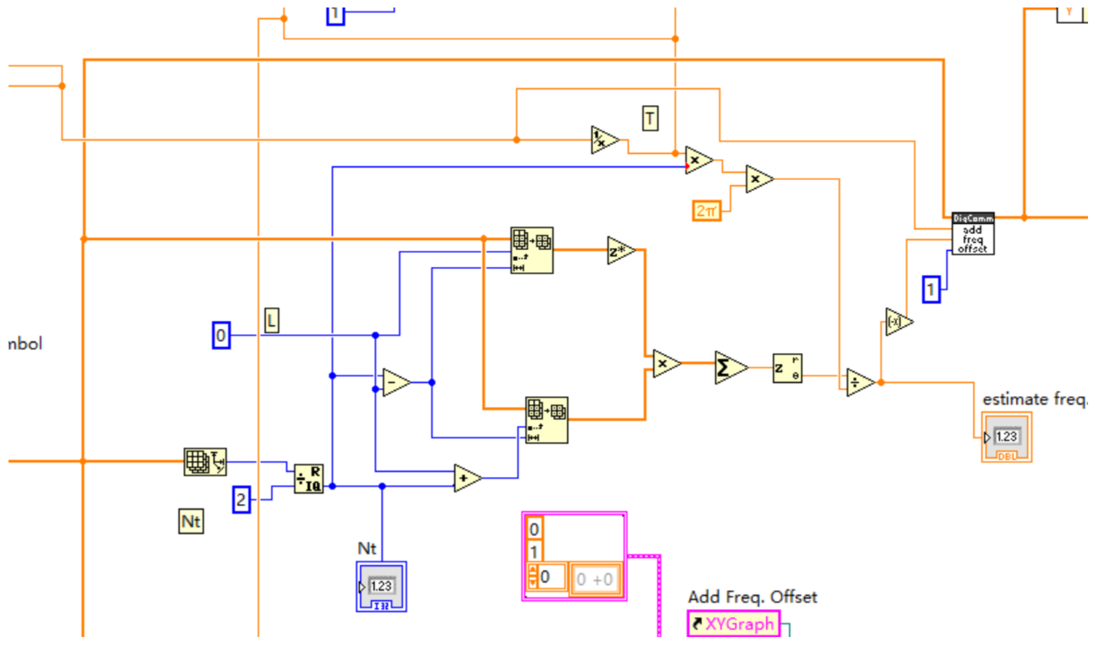


2.3.2 Program Process

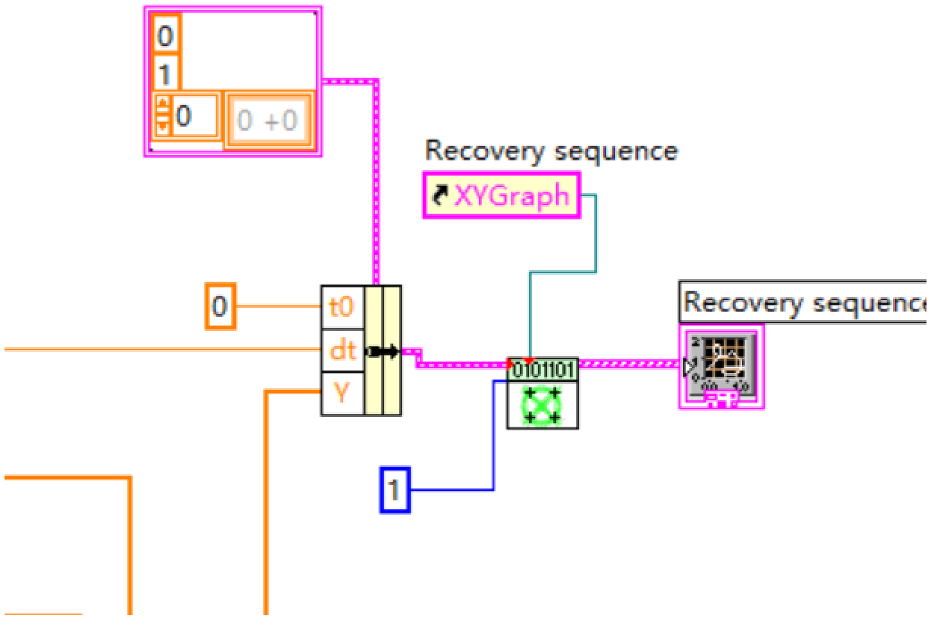
First, a training sequence is generated, and the 5-bit and 11-bit Barker code sequences are repeated four times as the training sequence. This is shown below. And add a frequency offset.



The frequency offset is calculated using the same block diagram of the moose algorithm as in 2.2

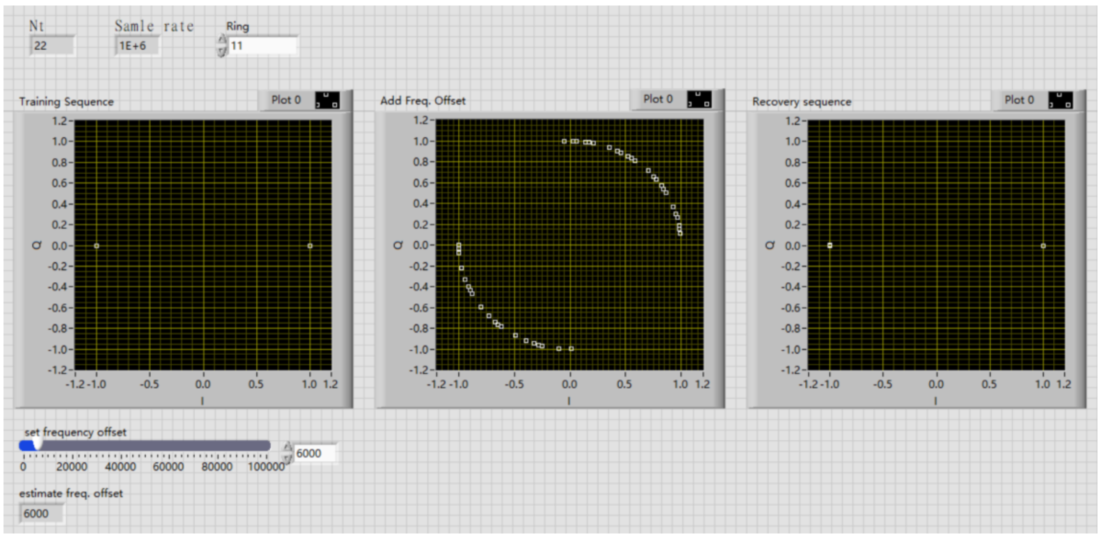


Use the following method to implement the display of the constellation chart.



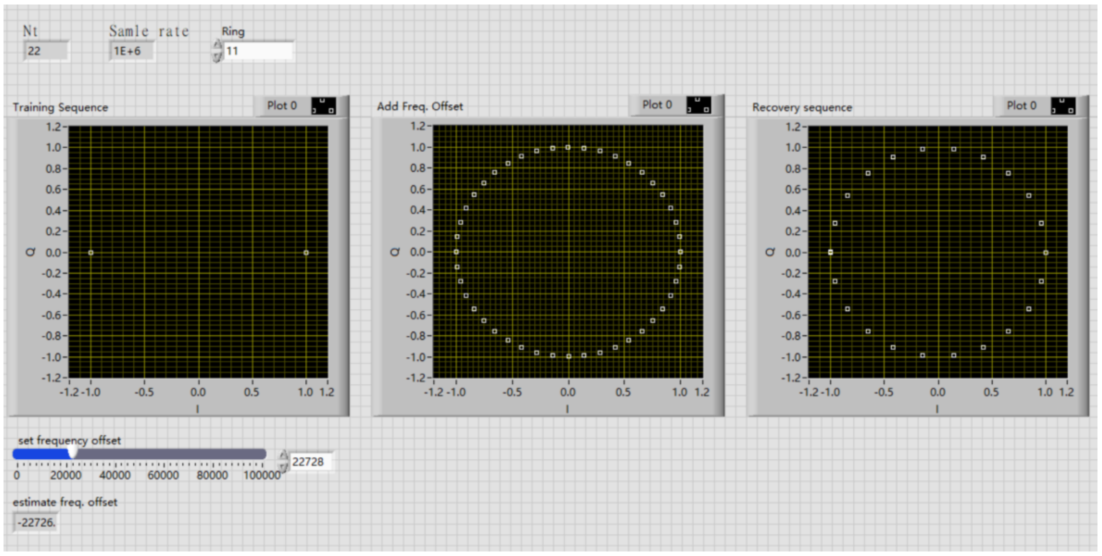
2.3.2 Analysis of relationship between frequency bias angle and frequency bias

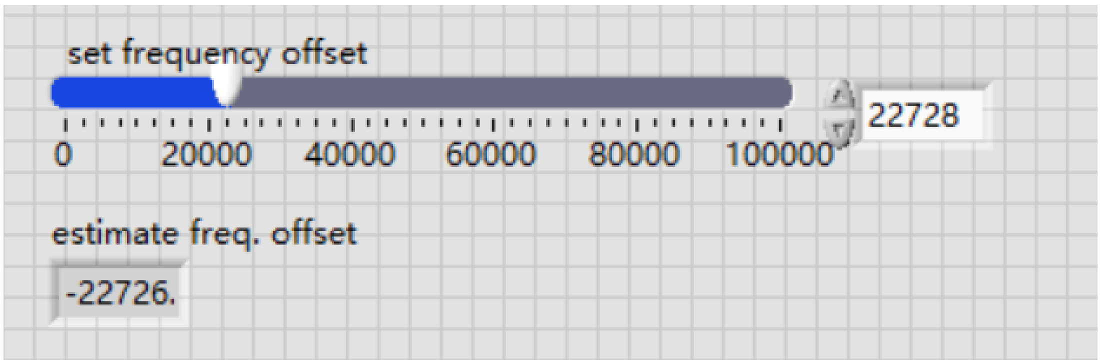
Before exploring the factors influencing the estimated range of frequency bias, it is necessary to use a set of benchmark parameters for the estimated frequency bias range to be tested. Here we set the symbol rate Ts= 1MHz and the training sequence uses 11-bit Barker codes. Since the Moose algorithm splits the training sequence after four repetitions into two periodic sequences for frequency bias estimation, the actual window length Nt = $\frac{11*4}{2}$ = 22.


Nt 22
Samle rate 1E+6
Ring 11
set frequency offset 6000
estimate freq. offset 6000

The three constellation plots are, in order, the original training sequence, the sequence after adding frequency bias, and the resultant plot recovered using the moose algorithm. We can see that the calculated frequency bias estimate is consistent with our settings, and the frequency bias correction is successful.

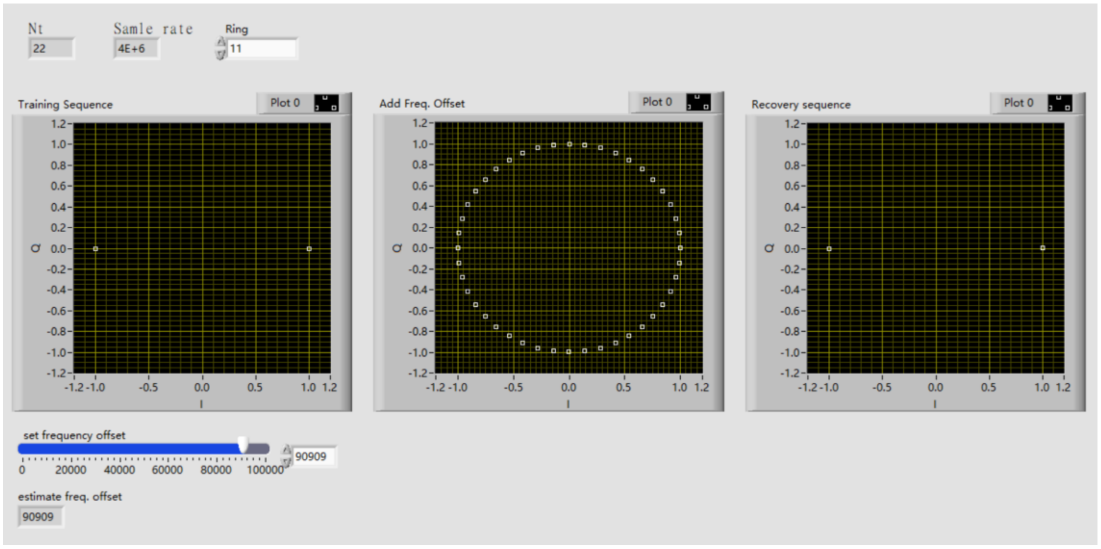
After testing, when the frequency bias f_0 = 22728Hz, the Moose algorithm can no longer estimate the frequency bias, and its output star diagram with the estimated results is shown below. (22728Hz is the Criticality)

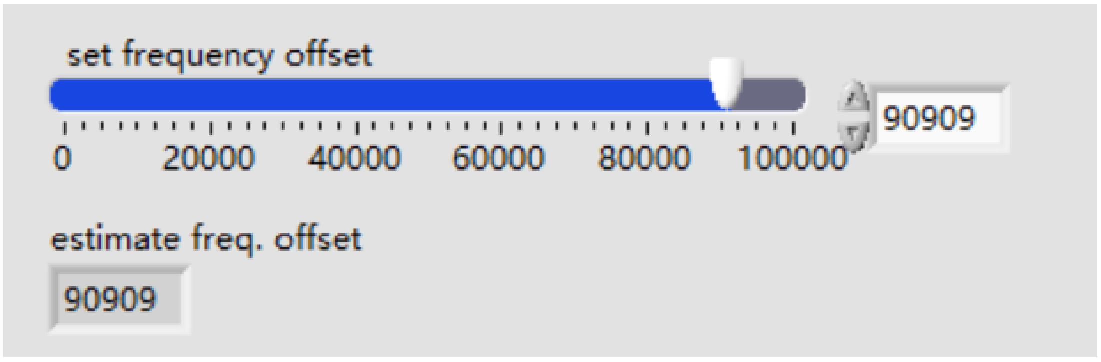

Nt 22
Samle rate 1E+6
Ring 11
set frequency offset 22728
estimate freq. offset -22726.

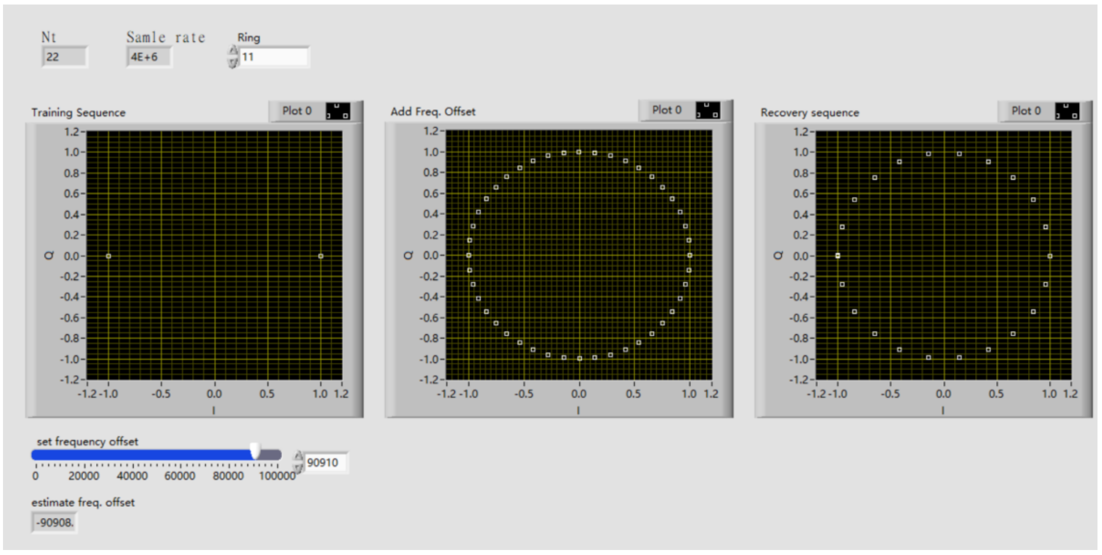

set frequency offset 22728
estimate freq. offset -22726.

Based on the above tests, we obtained the actual range of the frequency bias estimate as [-22727Hz, 22727Hz]. And substituting the benchmark parameters Ts = 1MHz, Nt = 22 into the theoretical range, the obtained theoretical estimate range of [-22727.27Hz, 22727.27Hz], which is consistent with the results of the benchmark test. Next we will further verify the relationship between the parameters and the estimated range by varying the input parameters.

2.3.2.1 After changing the symbol rate to 4MHz, which is 4 times the original rate of 1MHz, we then use the benchmark The effective range of frequency bias estimation was tested by gradually adjusting the frequency bias in the test, and the test results


Nt: 22
Samle rate: 4E+6
Ring: 11
set frequency offset: 90909
estimate freq. offset: 90909


set frequency offset: 90909
estimate freq. offset: 90909

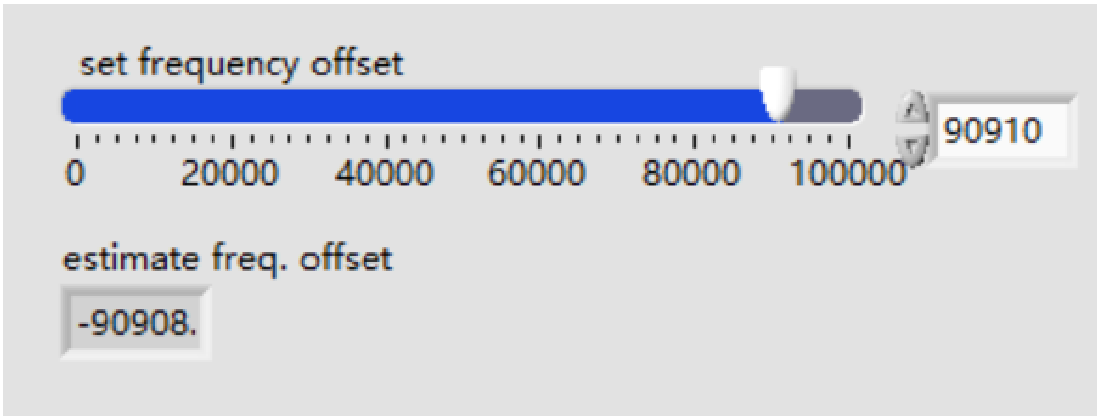

Nt 22

Samle rate 4E+6

Ring 11

set frequency offset 90910

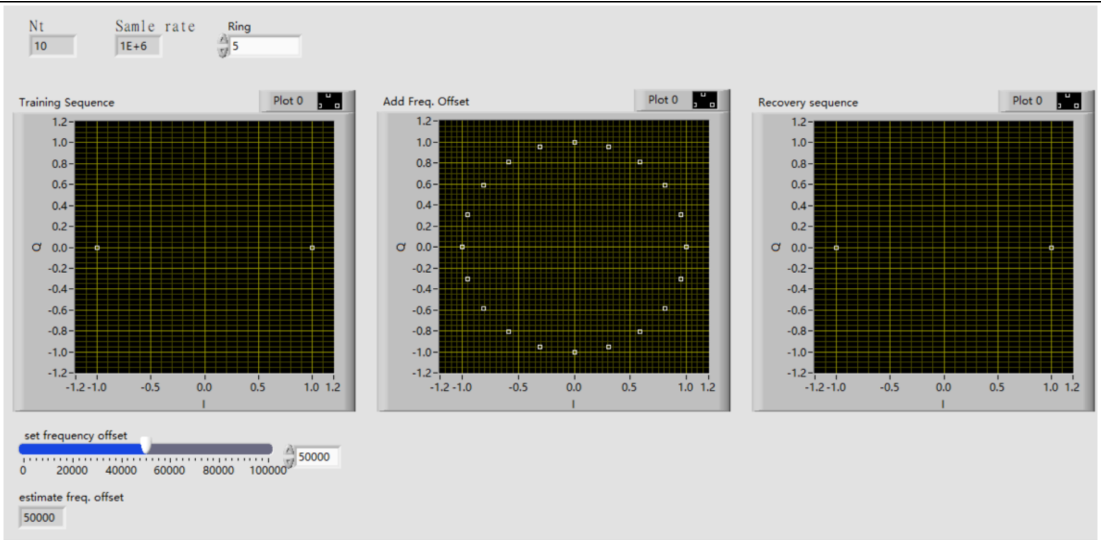
estimate freq. offset -90908.


set frequency offset 90910

estimate freq. offset -90908.

The left graph in Figure 4-32(b) shows the correction result when the frequency bias is 90909Hz, and the right graph shows the correction result when the frequency bias is The right graph shows the correction result when the frequency bias is 90910Hz. From the test results, it can be seen that the actual range of frequency bias estimation at this time is [-90909Hz, 90909Hz], which is the same as the calculated theoretical range [-90909.09Hz, 90909.09Hz] is basically essentially consistent, higher symbol rate increases the range of frequency bias estimation, and the symbol rate on the range of frequency bias estimation The effect of symbol rate on the range of frequency bias estimation is verified.

2.3.2.2 By changing the training sequence to a 5-bit Barker code sequence, the length of the comparison window of Moose's algorithm is reduced from 22 bits to 10 bits. We then use the method of gradually adjusting the frequency bias in the benchmark test to test the effective range of the frequency bias estimation. We then test the effective range of the bias estimation by gradually adjusting the frequency bias in the benchmark test

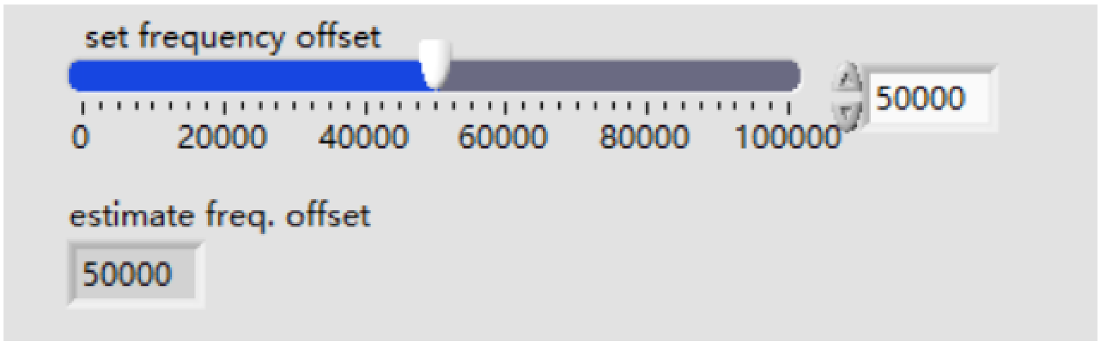

Nt: 10

Samle rate: 1E+6

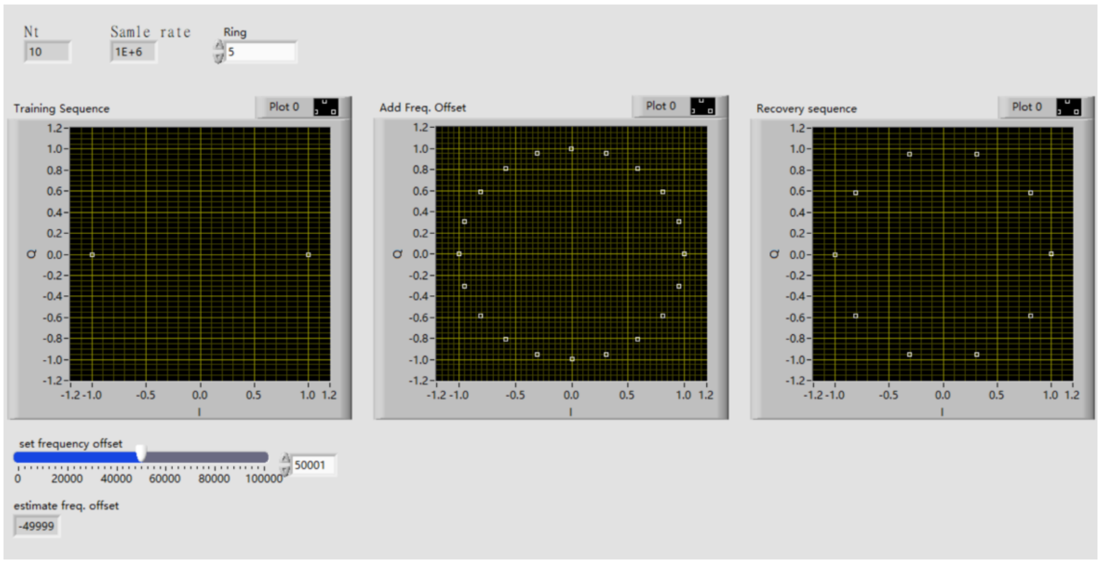
Ring: 5

set frequency offset: 50000

estimate freq. offset: 50000


set frequency offset: 50000

estimate freq. offset: 50000

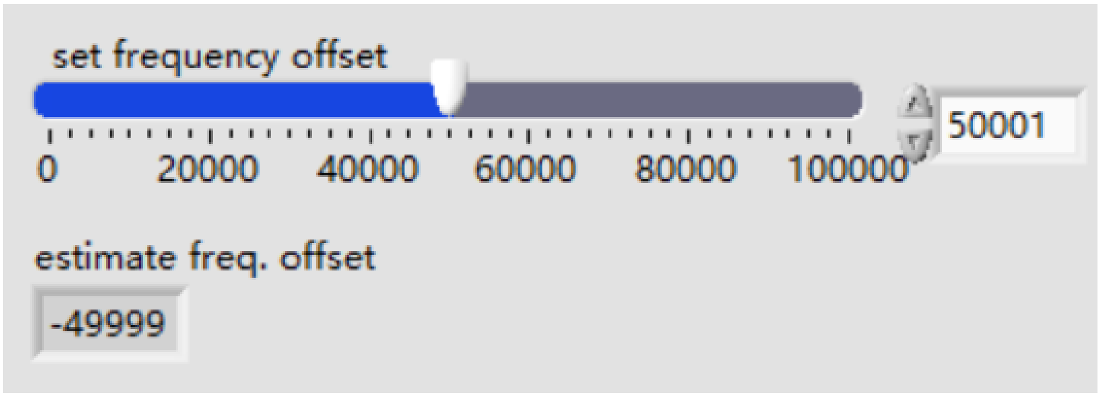

Nt: 10

Samle rate: 1E+6

Ring: 5

set frequency offset: 50001

estimate freq. offset: -49999



set frequency offset: 50001

estimate freq. offset: -49999

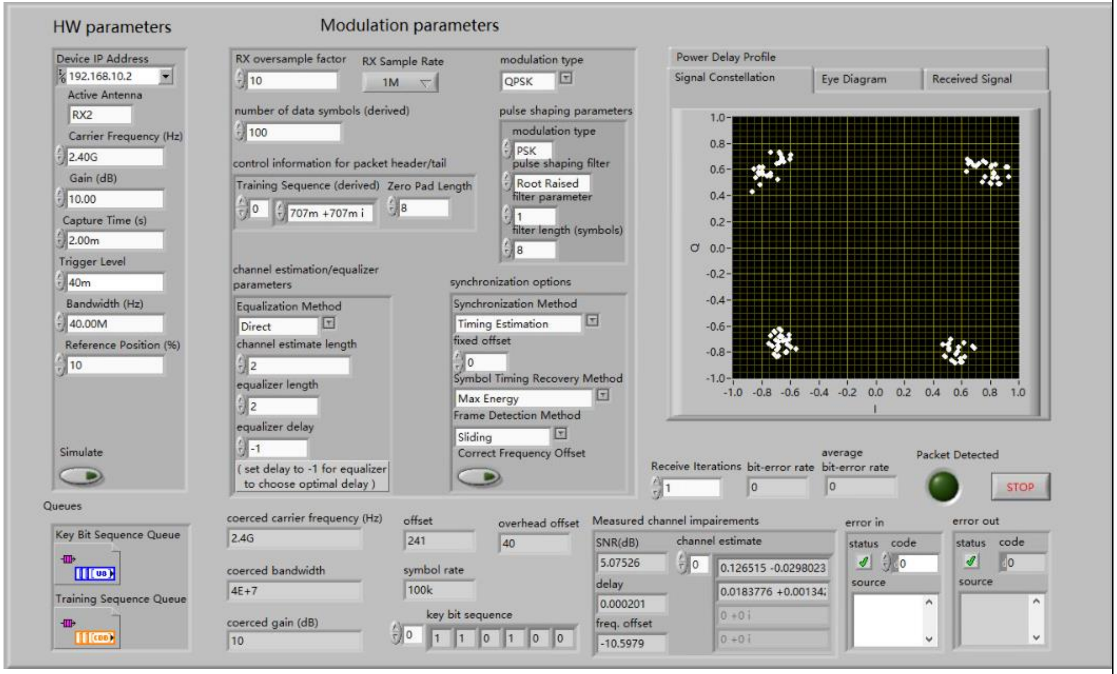
the left picture is the correction result when the frequency offset is 50000Hz, and the right picture is the correction result when the frequency offset is 50001Hz. By the test result, the scale of the frequency offset estimation for [- 50000 Hz, 50000 Hz], and into the theoretical scope of parameters are calculated. It can be seen that the longer the training sequence is, the smaller the range of frequency offset estimation is. The relationship between the length of the training sequence and the range of frequency offset estimation is further verified.
Through the above benchmark test and the test after adjusting parameters, we have successfully verified that the effective range of frequency offset estimation by Moose algorithm is:

$$[-\frac{1}{2N_tT_s},\frac{1}{2N_tT_s}]$$

2.4 USRP Verification

2.4.1 Frequency offset=0

First, we want to verify the correction of Sliding Correlator algorithm, so first we set the frequency offset=0, then we have the result:



HW parameters
Device IP Address: 192.168.10.2
Active Antenna: RX2
Carrier Frequency (Hz): 2.40G
Gain (dB): 10.00
Capture Time (s): 2.00m
Trigger Level: 40m
Bandwidth (Hz): 40.00M
Reference Position (%): 10

Modulation parameters
RX oversample factor: 10
RX Sample Rate: 1M
modulation type: QPSK
number of data symbols (derived): 100
pulse shaping parameters
modulation type: PSK
pulse shaping filter: Root Raised
filter parameter: 1
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

Receive Iterations: 1
bit-error rate: 0
average bit-error rate: 0

coerced carrier frequency (Hz): 2.4G
coerced bandwidth: 4E+7
coerced gain (dB): 10
offset: 241
symbol rate: 100k
overhead offset: 40
key bit sequence: 0 | 1 1 0 1 0 0

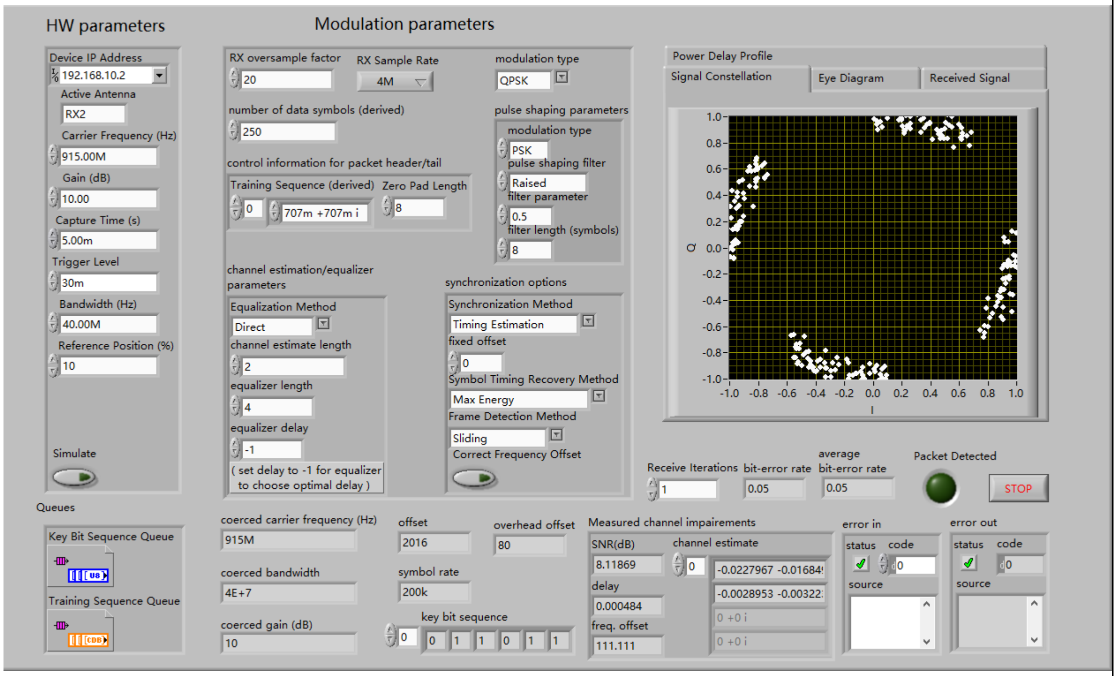
Measured channel impairements
SNR(dB): 5.07526
delay: 0.000201
freq. offset: -10.5979
channel estimate: 0 | 0.126515 -0.0298023 | 0.0183776 +0.00134; | 0 +0 i | 0 +0 i

error in: status ✓ code 0 source
error out: status ✓ code 0 source

From the result, we can see that when the frequency offset=0, we can correctly get four points in the constellation graph, indicating that we the sliding correlator algorithm is right.

2.4.2 Frequency offset=100

When we do not use frequency correction:



HW parameters
Device IP Address: 192.168.10.2
Active Antenna: RX2
Carrier Frequency (Hz): 915.00M
Gain (dB): 10.00
Capture Time (s): 5.00m
Trigger Level: 30m
Bandwidth (Hz): 40.00M
Reference Position (%): 10
Simulate

Modulation parameters
RX oversample factor: 20
RX Sample Rate: 4M
modulation type: QPSK
number of data symbols (derived): 250
pulse shaping parameters
modulation type: PSK
pulse shaping filter: 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: 4
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

Receive Iterations: 1
bit-error rate: 0.05
average bit-error rate: 0.05
Packet Detected
STOP

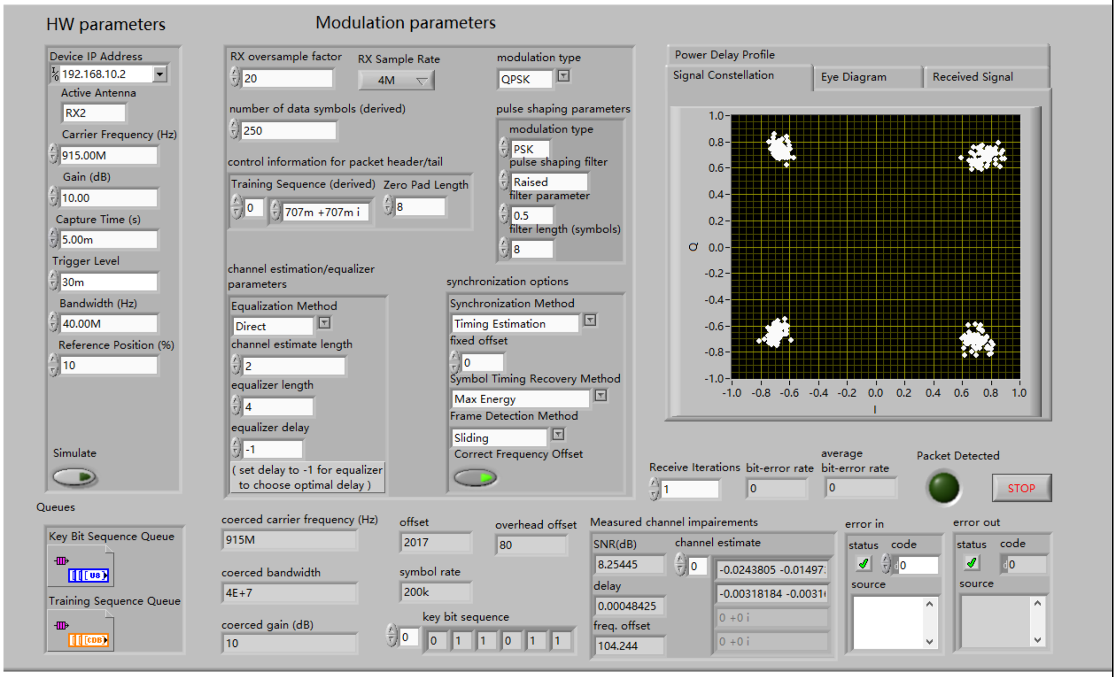
Queues
Key Bit Sequence Queue
Training Sequence Queue

coerced carrier frequency (Hz): 915M
offset: 2016
overhead offset: 80
coerced bandwidth: 4E+7
symbol rate: 200k
coerced gain (dB): 10
key bit sequence: 0 | 0 1 1 0 1 1

Measured channel impairements
SNR(dB): 8.11869
delay: 0.000484
freq. offset: 111.111
channel estimate: 0 | -0.0227967 -0.01684 | -0.0028953 -0.00322 | 0 +0 i | 0 +0 i

error in: status ✓, code 0, source
error out: status ✓, code 0, source

When we use frequency correction:



HW parameters
Device IP Address: 192.168.10.2
Active Antenna: RX2
Carrier Frequency (Hz): 915.00M
Gain (dB): 10.00
Capture Time (s): 5.00m
Trigger Level: 30m
Bandwidth (Hz): 40.00M
Reference Position (%): 10
Simulate

Modulation parameters
RX oversample factor: 20
RX Sample Rate: 4M
modulation type: QPSK
number of data symbols (derived): 250
pulse shaping parameters
modulation type: PSK
pulse shaping filter: 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: 4
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

Receive Iterations: 1
bit-error rate: 0
average bit-error rate: 0
Packet Detected
STOP

Queues
Key Bit Sequence Queue
Training Sequence Queue

coerced carrier frequency (Hz): 915M
offset: 2017
overhead offset: 80
coerced bandwidth: 4E+7
symbol rate: 200k
coerced gain (dB): 10
key bit sequence: 0 | 0 1 1 0 1 1

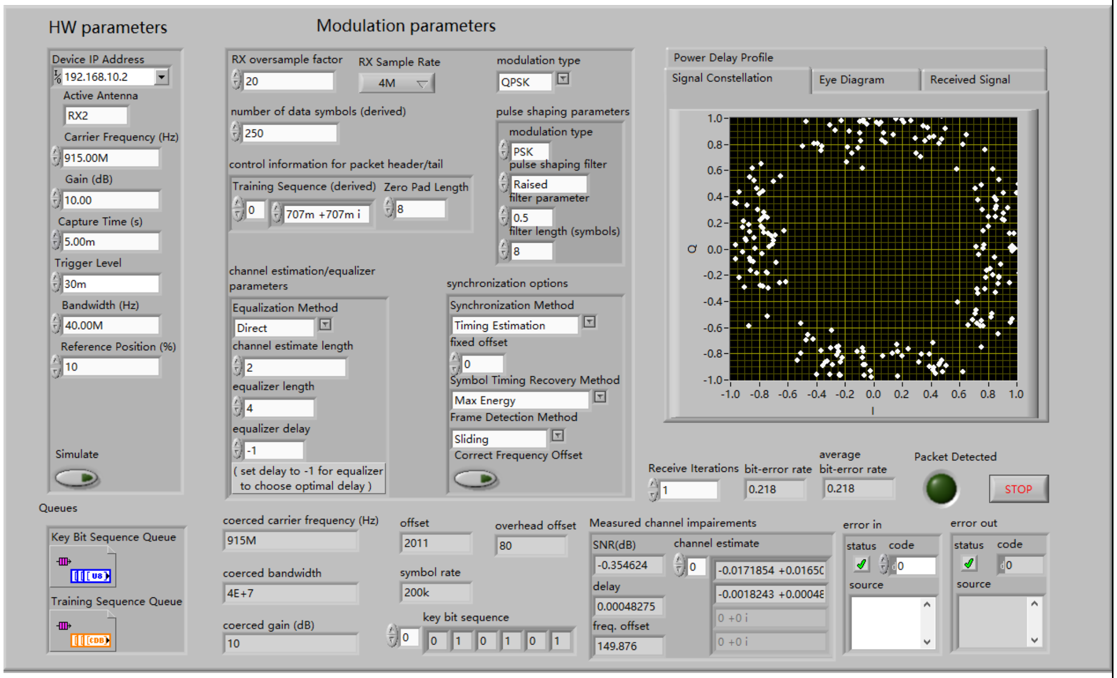
Measured channel impairements
SNR(dB): 8.25445
delay: 0.00048425
freq. offset: 104.244
channel estimate: 0 | -0.0243805 -0.01497 | -0.00318184 -0.0031 | 0 +0 i | 0 +0 i

error in: status ✓, code 0, source
error out: status ✓, code 0, source

From the results, we can see that the frequency offset makes the shift of the points in the constellation graph, here when we set the frequency as 100, the tail of each point will be long. However, if we use Moose algorithm, we still get bit error rate=0.

2.4.3 Frequency offset=150

When we do not use the frequency correction:


HW parameters

Device IP Address: 192.168.10.2
Active Antenna: RX2
Carrier Frequency (Hz): 915.00M
Gain (dB): 10.00
Capture Time (s): 5.00m
Trigger Level: 30m
Bandwidth (Hz): 40.00M
Reference Position (%): 10
Simulate

Queues
Key Bit Sequence Queue
Training Sequence Queue

Modulation parameters

RX oversample factor: 20
RX Sample Rate: 4M
modulation type: QPSK
number of data symbols (derived): 250
pulse shaping parameters
modulation type: PSK
pulse shaping filter: 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: 4
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

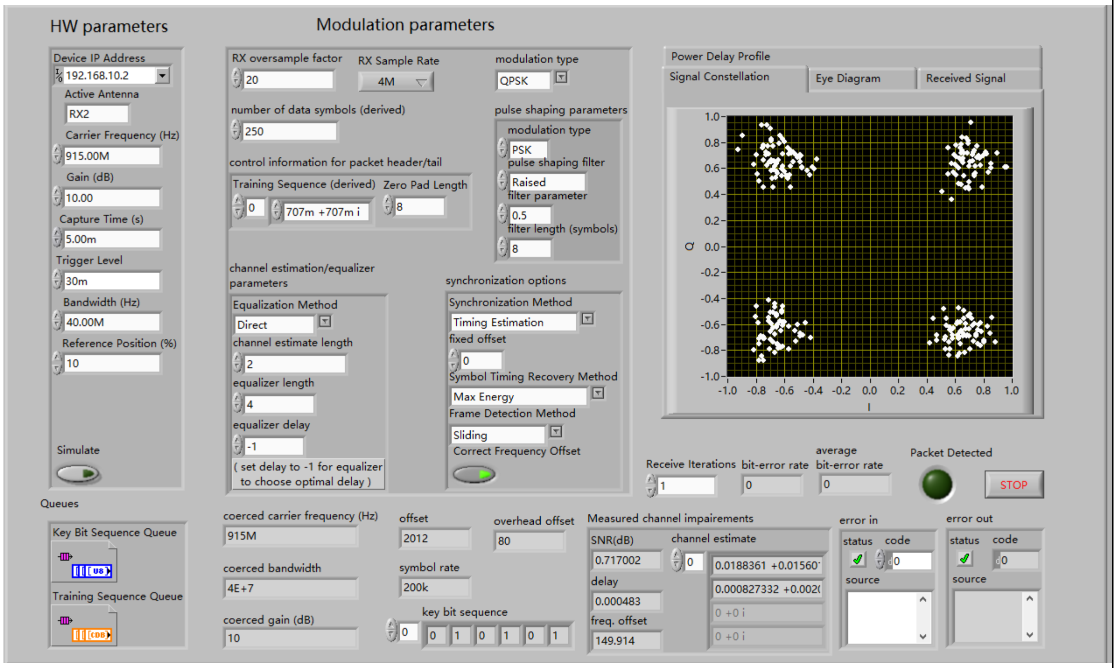
Receive Iterations: 1
bit-error rate: 0.218
average bit-error rate: 0.218
Packet Detected
STOP

coerced carrier frequency (Hz): 915M
offset: 2011
overhead offset: 80
coerced bandwidth: 4E+7
symbol rate: 200k
coerced gain (dB): 10
key bit sequence: 0 | 0 1 0 1 0 1

Measured channel impairements
SNR(dB): -0.354624
delay: 0.00048275
freq. offset: 149.876
channel estimate: 0
-0.0171854 +0.0165C
-0.0018243 +0.0004E
0 +0 i
0 +0 i

error in: status ✓ code 0 source
error out: status ✓ code 0 source

When we use frequency offset:


HW parameters

Device IP Address: 192.168.10.2
Active Antenna: RX2
Carrier Frequency (Hz): 915.00M
Gain (dB): 10.00
Capture Time (s): 5.00m
Trigger Level: 30m
Bandwidth (Hz): 40.00M
Reference Position (%): 10
Simulate

Queues
Key Bit Sequence Queue
Training Sequence Queue

Modulation parameters

RX oversample factor: 20
RX Sample Rate: 4M
modulation type: QPSK
number of data symbols (derived): 250
pulse shaping parameters
modulation type: PSK
pulse shaping filter: 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: 4
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

Receive Iterations: 1
bit-error rate: 0
average bit-error rate: 0
Packet Detected
STOP

coerced carrier frequency (Hz): 915M
offset: 2012
overhead offset: 80
coerced bandwidth: 4E+7
symbol rate: 200k
coerced gain (dB): 10
key bit sequence: 0 | 0 1 0 1 0 1

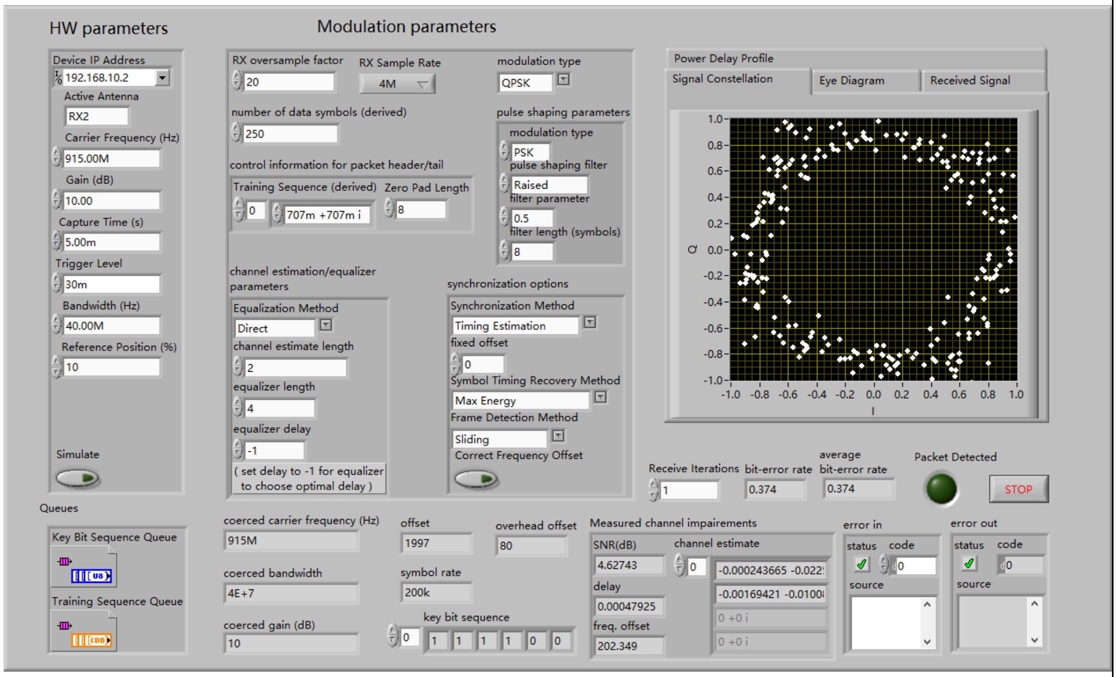
Measured channel impairements
SNR(dB): 0.717002
delay: 0.000483
freq. offset: 149.914
channel estimate: 0
0.0188361 +0.01560
0.000827332 +0.002(
0 +0 i
0 +0 i

error in: status ✓ code 0 source
error out: status ✓ code 0 source

From the results, we can see that the frequency offset makes the shift of the points in the constellation graph, here when we set the frequency as 150, the tail of each point has cover a lot of space in the plane. However, if we use Moose algorithm, we still get bit error rate=0.

2.4.4 Frequency offset=200

When we do not use the frequency correction:


HW parameters

Device IP Address: 192.168.10.2
Active Antenna: RX2
Carrier Frequency (Hz): 915.00M
Gain (dB): 10.00
Capture Time (s): 5.00m
Trigger Level: 30m
Bandwidth (Hz): 40.00M
Reference Position (%): 10
Simulate

Modulation parameters

RX oversample factor: 20
RX Sample Rate: 4M
modulation type: QPSK
number of data symbols (derived): 250
control information for packet header/tail
Training Sequence (derived): 0, 707m +707m i
Zero Pad Length: 8
pulse shaping parameters
modulation type: PSK
pulse shaping filter: Raised
filter parameter: 0.5
filter length (symbols): 8
channel estimation/equalizer parameters
Equalization Method: Direct
channel estimate length: 2
equalizer length: 4
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

Receive Iterations: 1
bit-error rate: 0.374
average bit-error rate: 0.374
Packet Detected
STOP

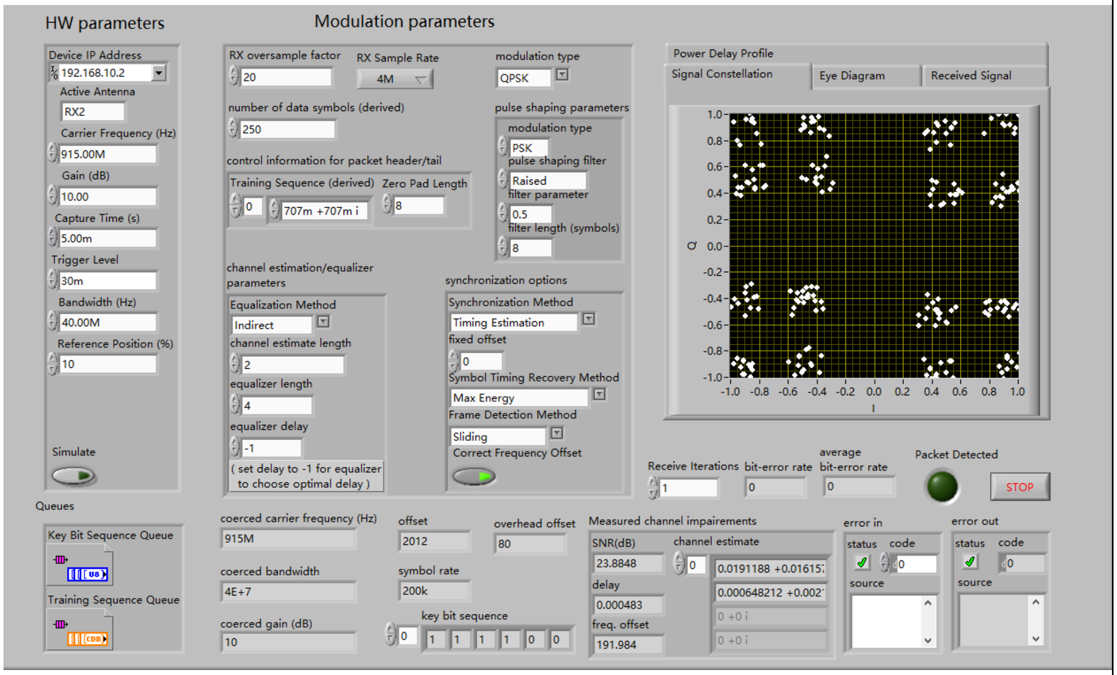
Queues
Key Bit Sequence Queue
Training Sequence Queue

coerced carrier frequency (Hz): 915M
offset: 1997
overhead offset: 80
coerced bandwidth: 4E+7
symbol rate: 200k
coerced gain (dB): 10
key bit sequence: 0 | 1 1 1 1 0 0

Measured channel impairements
SNR(dB): 4.62743
delay: 0.00047925
freq. offset: 202.349
channel estimate: 0 | -0.000243665 -0.022 | -0.00169421 -0.0100 | 0 +0 i | 0 +0 i

error in: status ✓ code 0 source
error out: status ✓ code 0 source

When we use frequency offset:


HW parameters

Device IP Address: 192.168.10.2
Active Antenna: RX2
Carrier Frequency (Hz): 915.00M
Gain (dB): 10.00
Capture Time (s): 5.00m
Trigger Level: 30m
Bandwidth (Hz): 40.00M
Reference Position (%): 10
Simulate

Modulation parameters

RX oversample factor: 20
RX Sample Rate: 4M
modulation type: QPSK
number of data symbols (derived): 250
control information for packet header/tail
Training Sequence (derived): 0, 707m +707m i
Zero Pad Length: 8
pulse shaping parameters
modulation type: PSK
pulse shaping filter: Raised
filter parameter: 0.5
filter length (symbols): 8
channel estimation/equalizer parameters
Equalization Method: Indirect
channel estimate length: 2
equalizer length: 4
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

Receive Iterations: 1
bit-error rate: 0
average bit-error rate: 0
Packet Detected
STOP

Queues
Key Bit Sequence Queue
Training Sequence Queue

coerced carrier frequency (Hz): 915M
offset: 2012
overhead offset: 80
coerced bandwidth: 4E+7
symbol rate: 200k
coerced gain (dB): 10
key bit sequence: 0 | 1 1 1 1 0 0

Measured channel impairements
SNR(dB): 23.8848
delay: 0.000483
freq. offset: 191.984
channel estimate: 0 | 0.0191188 +0.01615 | 0.000648212 +0.002 | 0 +0 i | 0 +0 i

error in: status ✓ code 0 source
error out: status ✓ code 0 source

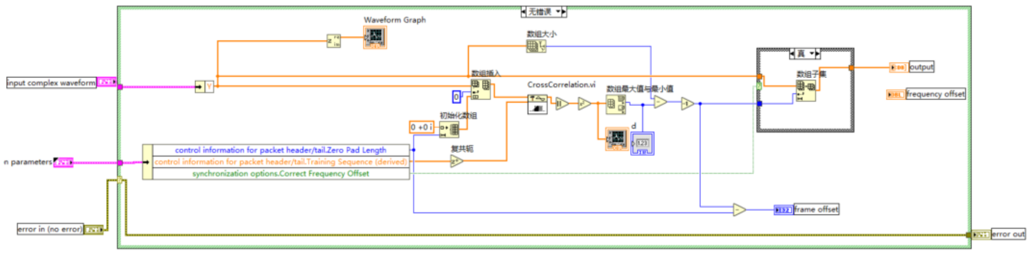
From the results, we can see that the frequency offset makes the shift of the points in the constellation graph, here when we set the frequency as 150, the tail of each point has cover all the space in the plane. However, if we use Moose algorithm, we still get bit error rate=0.

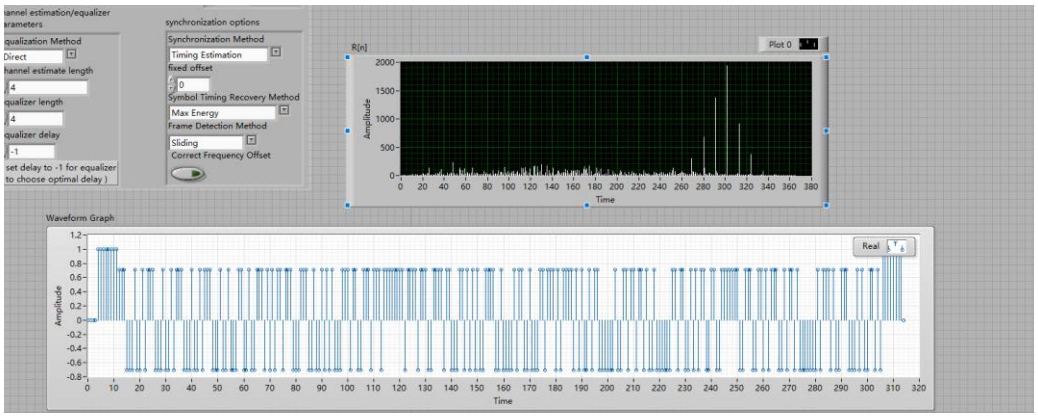
2.4.5 Comparison between different frequency offset

From the above result we can see that while the frequency offset becomes larger, the deviation angles also become large, we can see when the frequency offset=200, there is almost a circle in the constellation graph.

Experience

1.Screen shot on course:




annel estimation/equalizer arameters

qualization Method: Direct

hannel estimate length: 4

qualizer length: 4

qualizer delay: -1

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

synchronization options

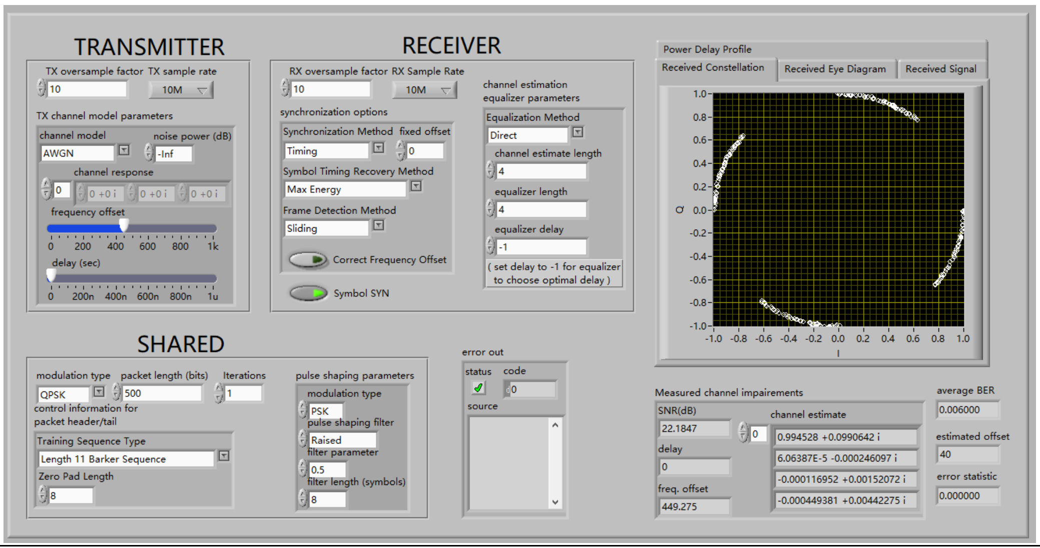
Synchronization Method: Timing Estimation

fixed offset: 0

Symbol Timing Recovery Method: Max Energy

Frame Detection Method: Sliding

Correct Frequency Offset


TRANSMITTER

TX oversample factor: 10

TX sample rate: 10M

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

delay (sec)

RECEIVER

RX oversample factor: 10

RX Sample Rate: 10M

synchronization options

Synchronization Method: Timing

fixed offset: 0

Symbol Timing Recovery Method: Max Energy

Frame Detection Method: Sliding

Correct Frequency Offset

Symbol SYN

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

Iterations: 1

control information for packet header/tail

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

error out

status: ✓

code: 0

source

Measured channel impairements

SNR(dB): 22.1847

delay: 0

freq. offset: 449.275

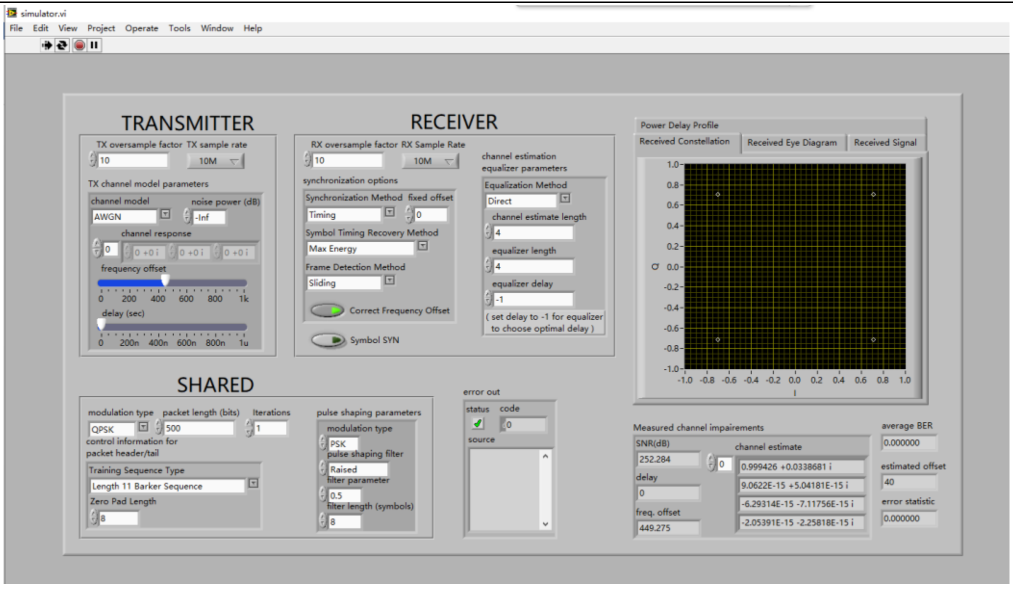
channel estimate: 0

0.994528 +0.0990642 i
6.06387E-5 -0.000246097 i
-0.000116952 +0.00152072 i
-0.000449381 +0.00442275 i

average BER: 0.006000

estimated offset: 40

error statistic: 0.000000



TRANSMITTER

TX oversample factor: 10
TX sample rate: 10M
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: 0 200 400 600 800 1k
delay (sec): 0 200n 400n 600n 800n 1u

RECEIVER

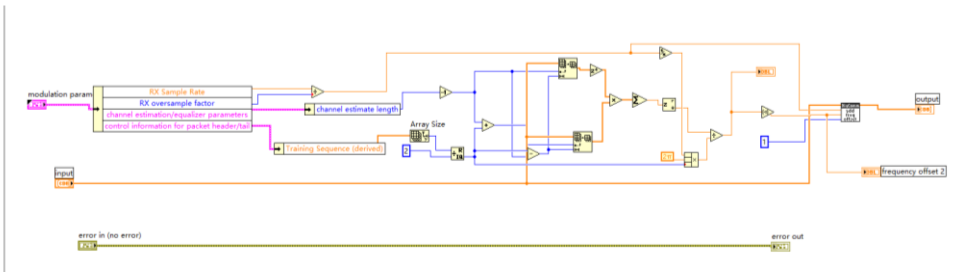
RX oversample factor: 10
RX Sample Rate: 10M
synchronization options
Synchronization Method: Timing
fixed offset: 0
Symbol Timing Recovery Method: Max Energy
Frame Detection Method: Sliding
Correct Frequency Offset
Symbol SYN
channel estimation equalizer parameters
Equalization Method: Direct
channel 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
Iterations: 1
control information for packet header/tail
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

error out
status: ✓
code: 0
source

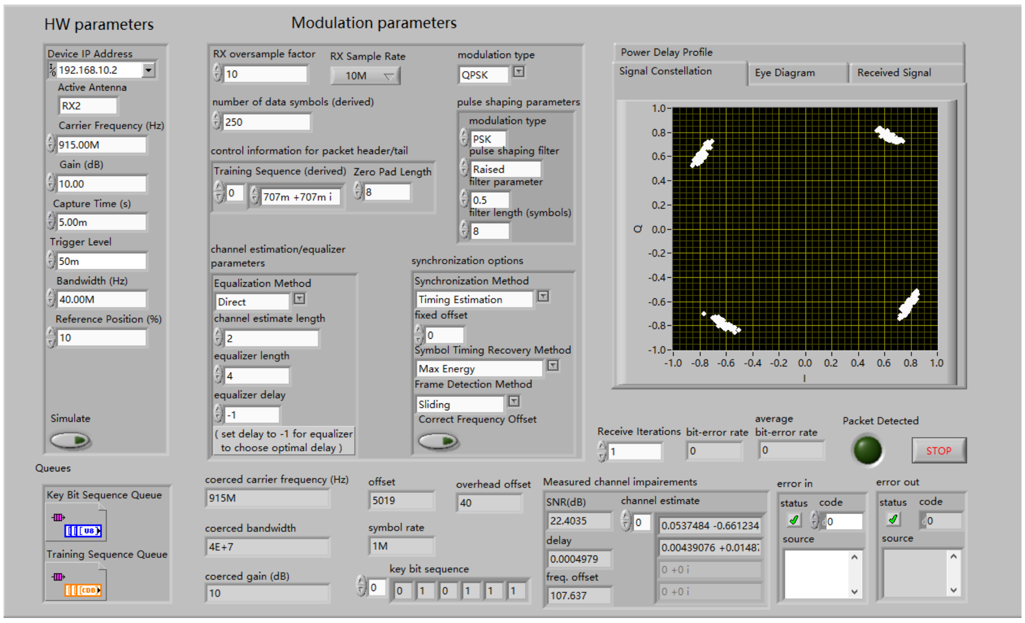
Measured channel impairements
SNR(dB): 252.284
delay: 0
freq. offset: 449.275
channel estimate: 0
0.999426 +0.0338681 i
9.0622E-15 +5.04181E-15 i
-6.29314E-15 -7.11756E-15 i
-2.05391E-15 -2.25818E-15 i
average BER: 0.000000
estimated offset: 40
error statistic: 0.000000



2.Problems we meet and experience

When we use usrp to verify the moose algorithm, we found that the constellation point shift is too small by increasing frequency from 100Hz to 200Hz.

100Hz:



HW parameters

Device IP Address: 192.168.10.2
Active Antenna: RX2
Carrier Frequency (Hz): 915.00M
Gain (dB): 10.00
Capture Time (s): 5.00m
Trigger Level: 50m
Bandwidth (Hz): 40.00M
Reference Position (%): 10
Simulate

Modulation parameters

RX oversample factor: 10
RX Sample Rate: 10M
number of data symbols (derived): 250
control information for packet header/tail
Training Sequence (derived): 0 | 707m +707m i
Zero Pad Length: 8
modulation type: QPSK
pulse shaping parameters
modulation type: PSK
pulse shaping filter: Raised
filter parameter: 0.5
filter length (symbols): 8
channel estimation/equalizer parameters
Equalization Method: Direct
channel estimate length: 2
equalizer length: 4
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

Receive Iterations: 1
bit-error rate: 0
average bit-error rate: 0
Packet Detected

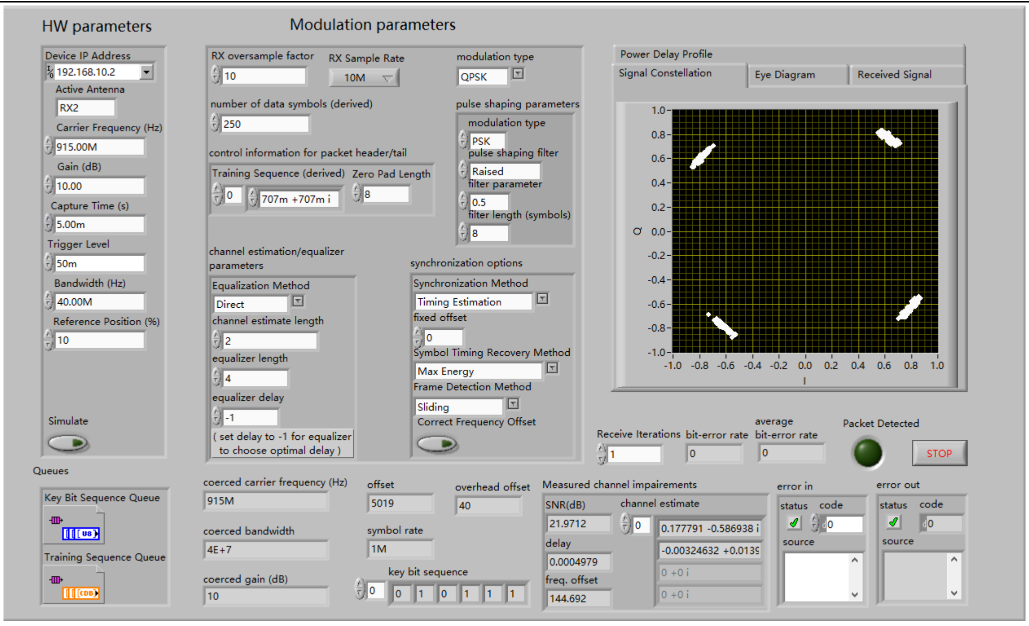
Queues
Key Bit Sequence Queue
Training Sequence Queue
coerced carrier frequency (Hz): 915M
coerced bandwidth: 4E+7
coerced gain (dB): 10
offset: 5019
symbol rate: 1M
overhead offset: 40
key bit sequence: 0 | 0 1 0 1 1 1

Measured channel impairements
SNR(dB): 22.4035
delay: 0.0004979
freq. offset: 107.637
channel estimate: 0
0.0537484 -0.661234
0.00439076 +0.0148
0 +0 i
0 +0 i

error in
status: ✓
code: 0
source

error out
status: ✓
code: 0
source

150Hz:

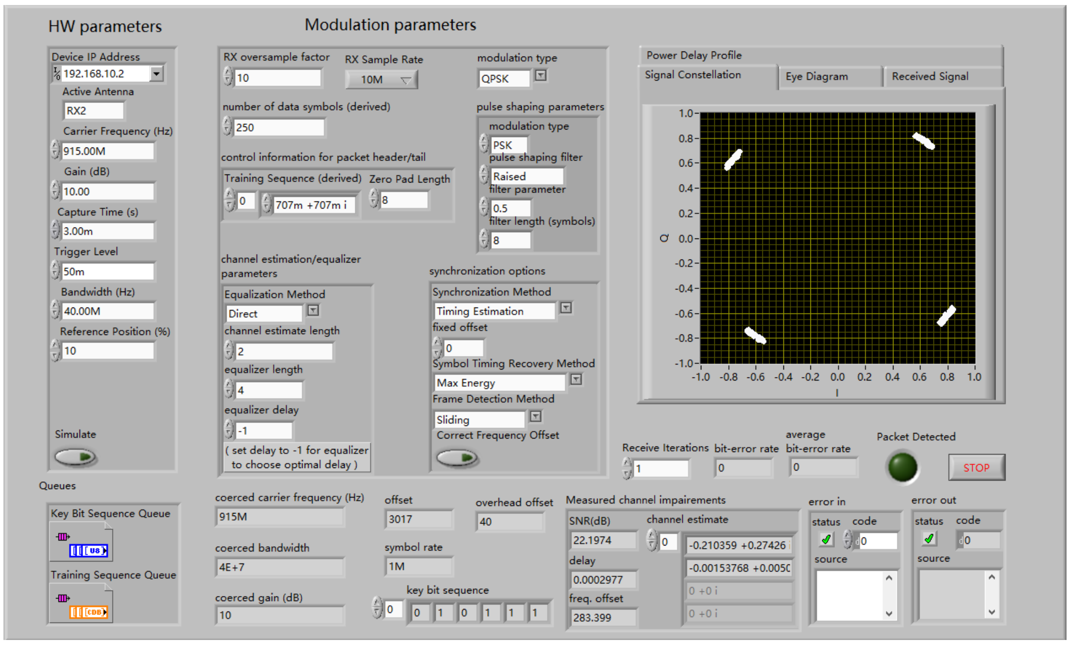

HW parameters
Device IP Address: 192.168.10.2
Active Antenna: RX2
Carrier Frequency (Hz): 915.00M
Gain (dB): 10.00
Capture Time (s): 5.00m
Trigger Level: 50m
Bandwidth (Hz): 40.00M
Reference Position (%): 10
Simulate

Modulation parameters
RX oversample factor: 10
RX Sample Rate: 10M
modulation type: QPSK
number of data symbols (derived): 250
pulse shaping parameters: modulation type: PSK; pulse shaping filter: 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: 4; 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

Queues: Key Bit Sequence Queue; Training Sequence Queue
coerced carrier frequency (Hz): 915M
coerced bandwidth: 4E+7
coerced gain (dB): 10
offset: 5019
symbol rate: 1M
overhead offset: 40
key bit sequence: 0 | 0 1 0 1 1 1

Receive Iterations: 1
bit-error rate: 0
average bit-error rate: 0
Packet Detected
STOP
Measured channel impairements: SNR(dB): 21.9712; delay: 0.0004979; freq. offset: 144.692
channel estimate: 0 | 0.177791 -0.586938 i; -0.00324632 +0.0139; 0 +0 i; 0 +0 i
error in: status ✓ code 0 source
error out: status ✓ code 0 source

200Hz:


HW parameters
Device IP Address: 192.168.10.2
Active Antenna: RX2
Carrier Frequency (Hz): 915.00M
Gain (dB): 10.00
Capture Time (s): 3.00m
Trigger Level: 50m
Bandwidth (Hz): 40.00M
Reference Position (%): 10
Simulate

Modulation parameters
RX oversample factor: 10
RX Sample Rate: 10M
modulation type: QPSK
number of data symbols (derived): 250
pulse shaping parameters: modulation type: PSK; pulse shaping filter: 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: 4; 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

Queues: Key Bit Sequence Queue; Training Sequence Queue
coerced carrier frequency (Hz): 915M
coerced bandwidth: 4E+7
coerced gain (dB): 10
offset: 3017
symbol rate: 1M
overhead offset: 40
key bit sequence: 0 | 0 1 0 1 1 1

Receive Iterations: 1
bit-error rate: 0
average bit-error rate: 0
Packet Detected
STOP
Measured channel impairements: SNR(dB): 22.1974; delay: 0.0002977; freq. offset: 283.399
channel estimate: 0 | -0.210359 +0.27426; -0.00153768 +0.005C; 0 +0 i; 0 +0 i
error in: status ✓ code 0 source
error out: status ✓ code 0 source

According to the formula of phase degree, it is obviously to find that f_s should be smaller to make difference dramatically.

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

So, we choose 20 as sample factor, 4MHz as sample rate. And we get better diagram in the section 2.4 USRP Verification.

In addition, through this experiment, we deepened our understanding of frame synchronization and frequency offset issues in digital communication. We mastered the sliding correlation algorithm for addressing frame synchronization problems and the Moorse algorithm for mitigating frequency offset issues. We are also capable of implementing these processes in LabVIEW and conducting prototype verification using USRP. Our major takeaway is that while

the principles of these algorithms are relatively simple and easy to comprehend and learn, the task becomes more challenging when it comes to programming implementation in LabVIEW. There are many details to consider, and the overall framework is quite complex. Therefore, our ability to translate algorithms into programming code is an area where we need to enhance our skills. **3.Contribution distribution** We two finish the whole LabVIEW program together. Song Yihang complete procedure design including sliding correlation and Moose algorithm, performance analysis of Moose algorithm, and validate the effectiveness of the sliding correlation algorithm and the moose algorithm using USRP. The introduction of basic principle of frame synchronization and frequency offset correction, and the principle and details of sliding correlation and Moose algorithm were elaborated by Zhang Haodong.	
Score	98