无线通信实验在线开放课程

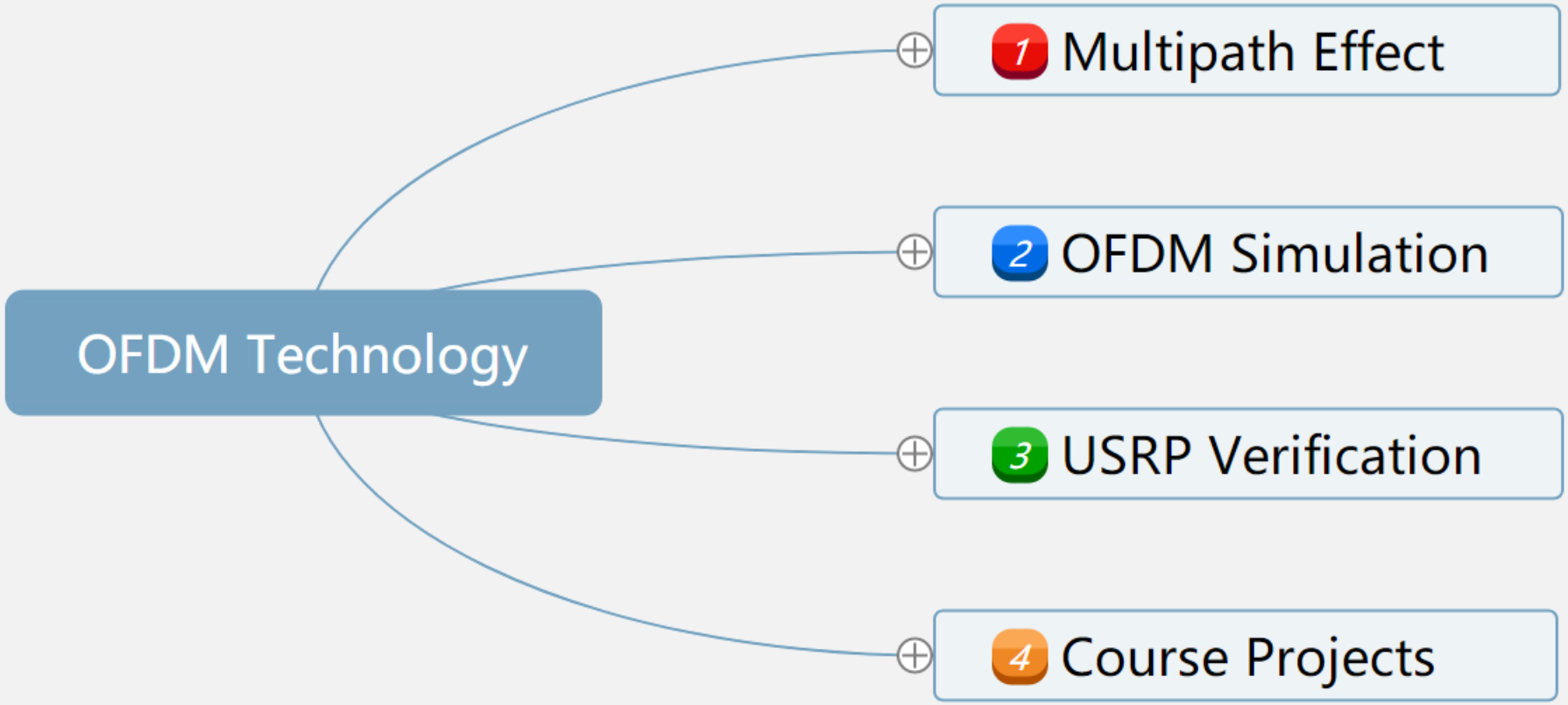
主讲人：吴光 博士

广东省教学质量工程建设项目

Lab 15: OFDM Technology

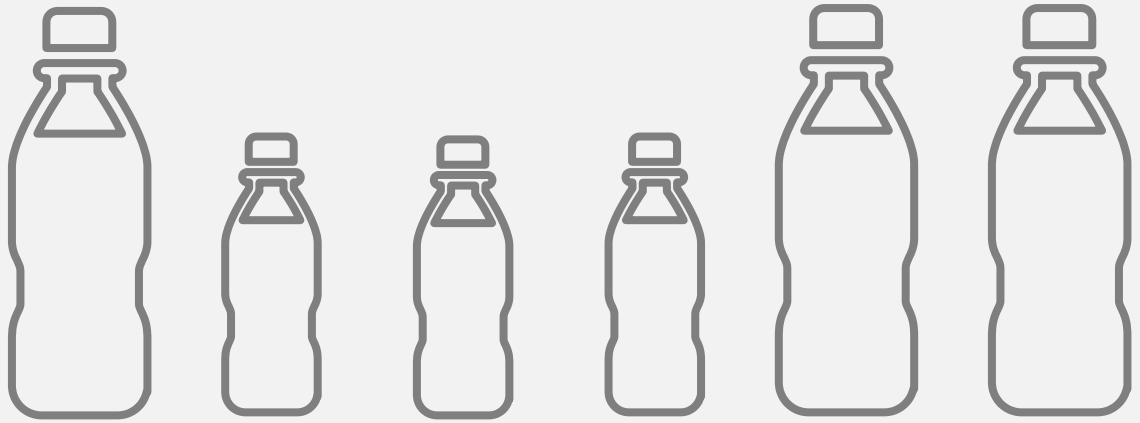
主讲人：吴光 博士
Email: wug@sustech.edu.cn

Demo: OFDM Technology


OFDM Technology
1 Multipath Effect
2 OFDM Simulation
3 USRP Verification
4 Course Projects


百事可乐
清柠
百事可乐

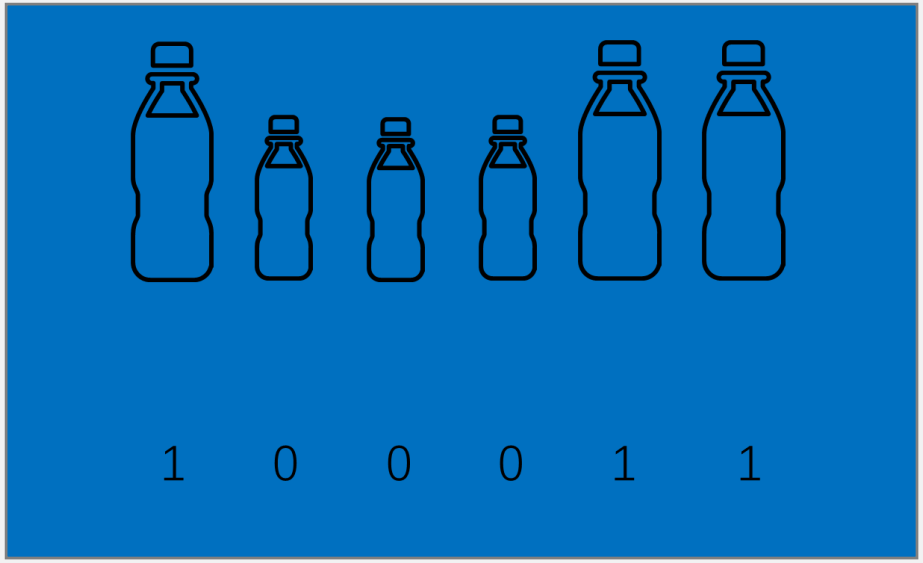
1　　0



1 0 0 0 1 1

营养成分表

项目	每100毫升	营养素参考值
能量	190千焦	2%
蛋白质	0克	0%
脂肪	0克	0%
-饱和脂肪酸	0克	0%
碳水化合物	11.2克	4%
-糖	11.2克	
钠	12毫克	1%



V.S.

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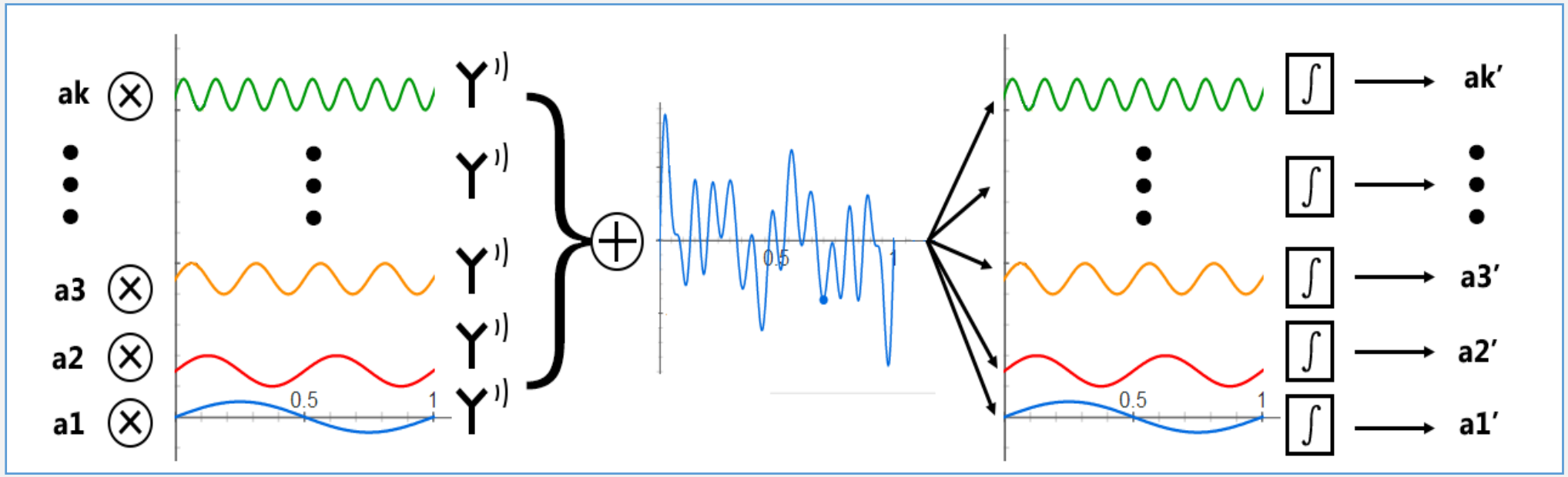
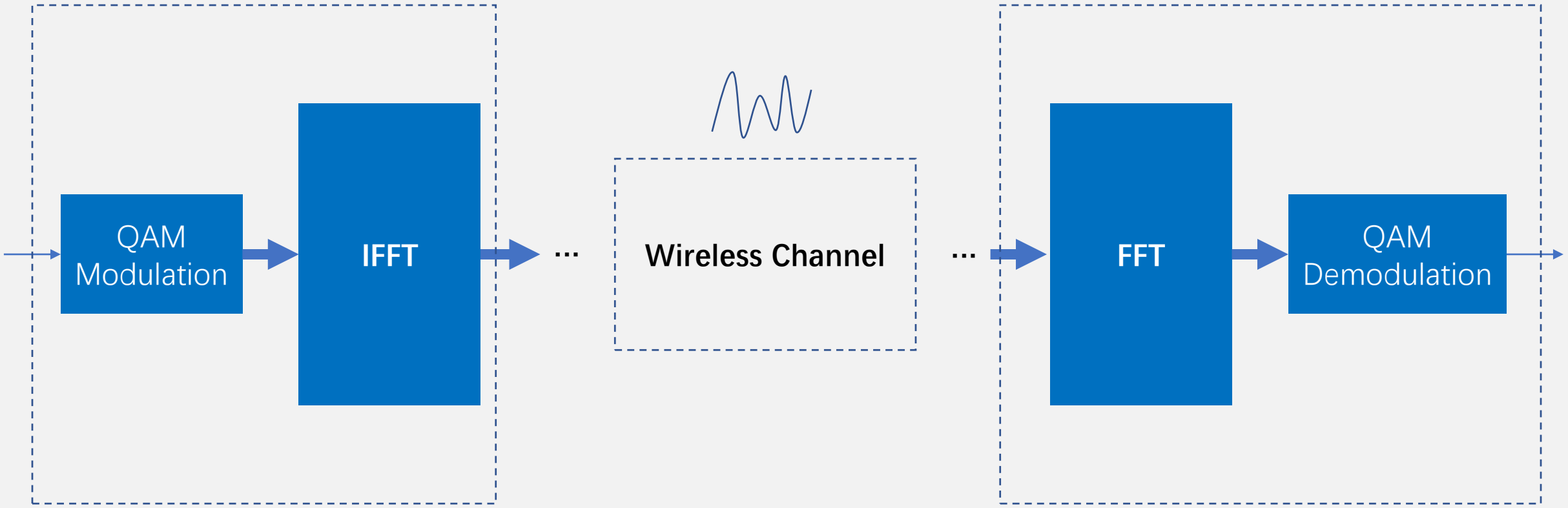

ak
a3
a2
a1
0.5
1
0.5
1
ak′
a3′
a2′
a1′


Wi Fi
TM

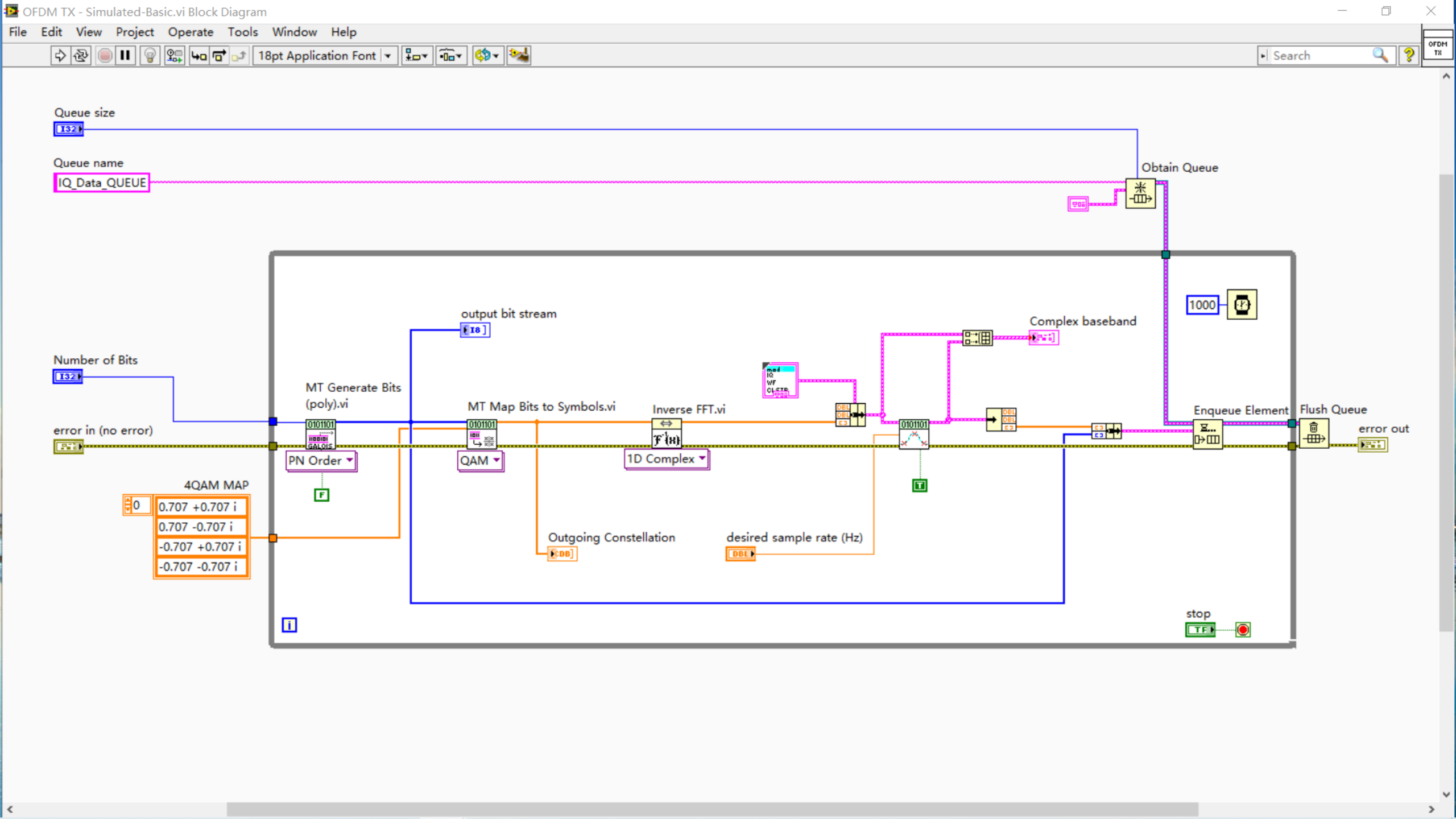

Lte
TM

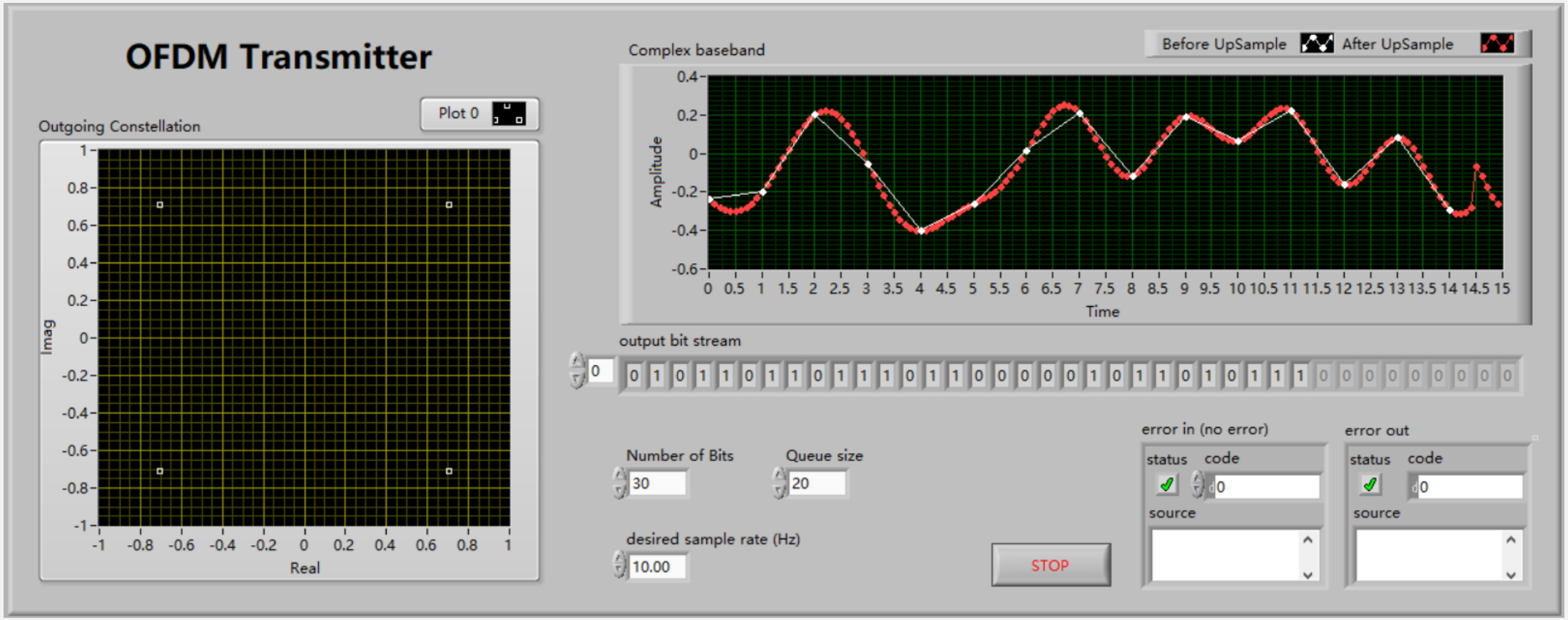

5G

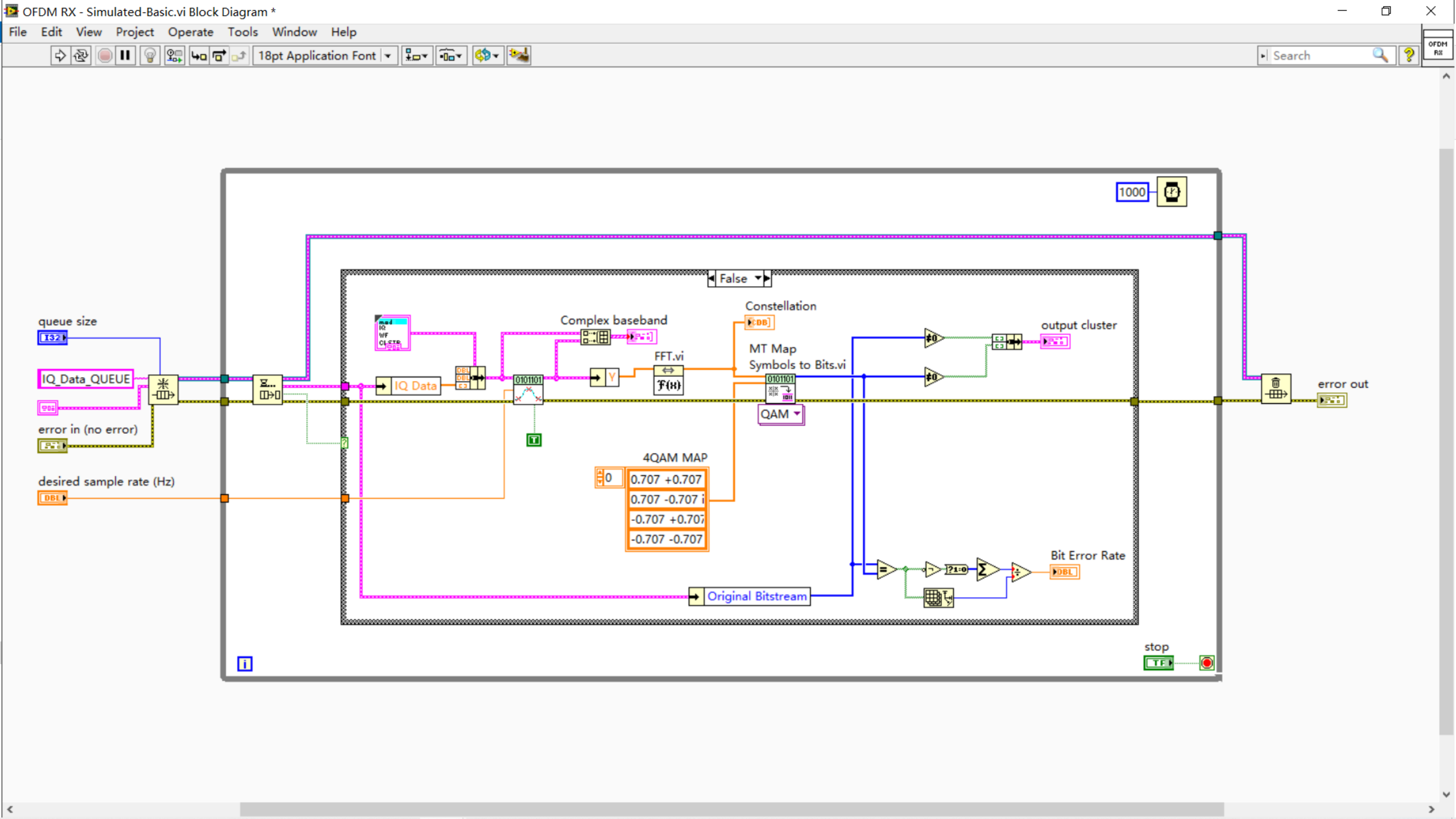


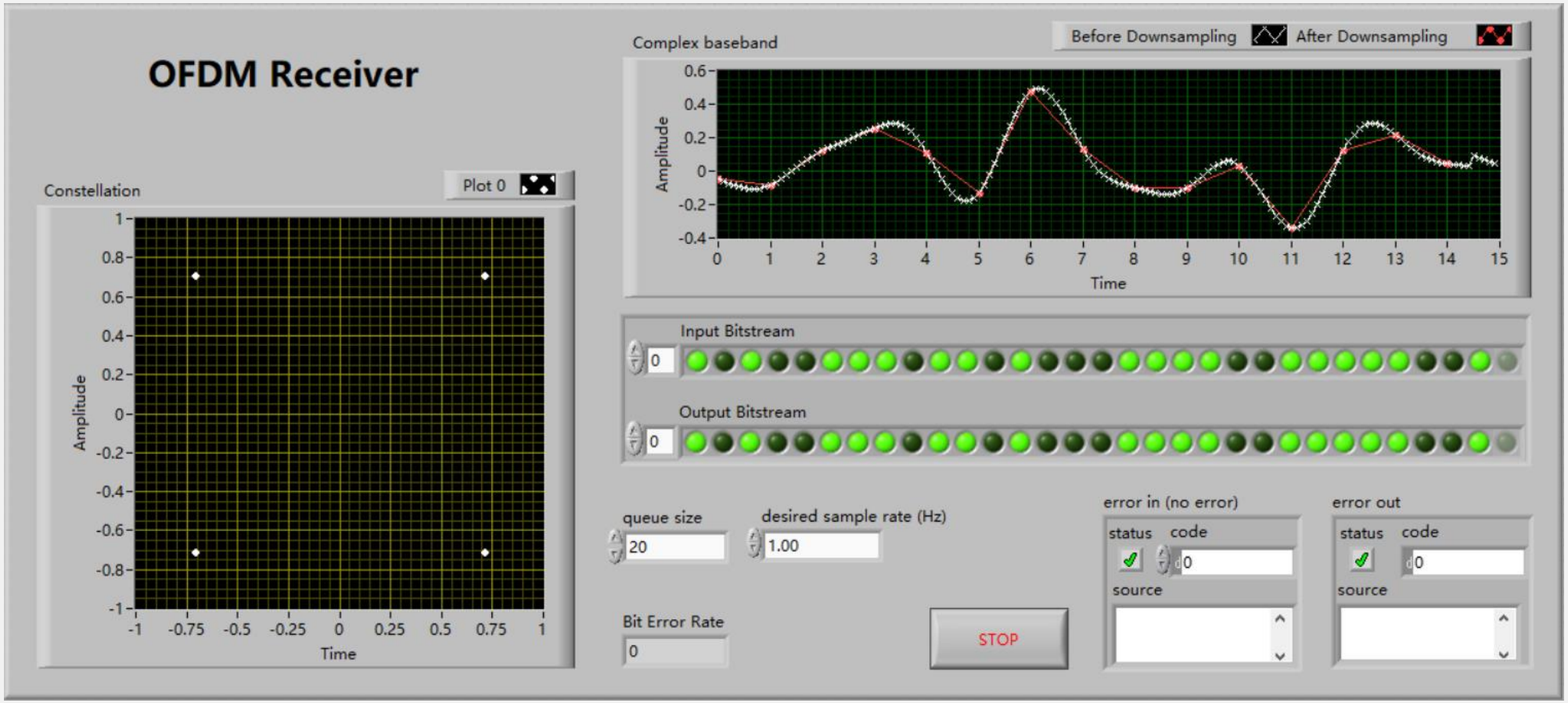
OFDM Transmitter

OFDM Receiver

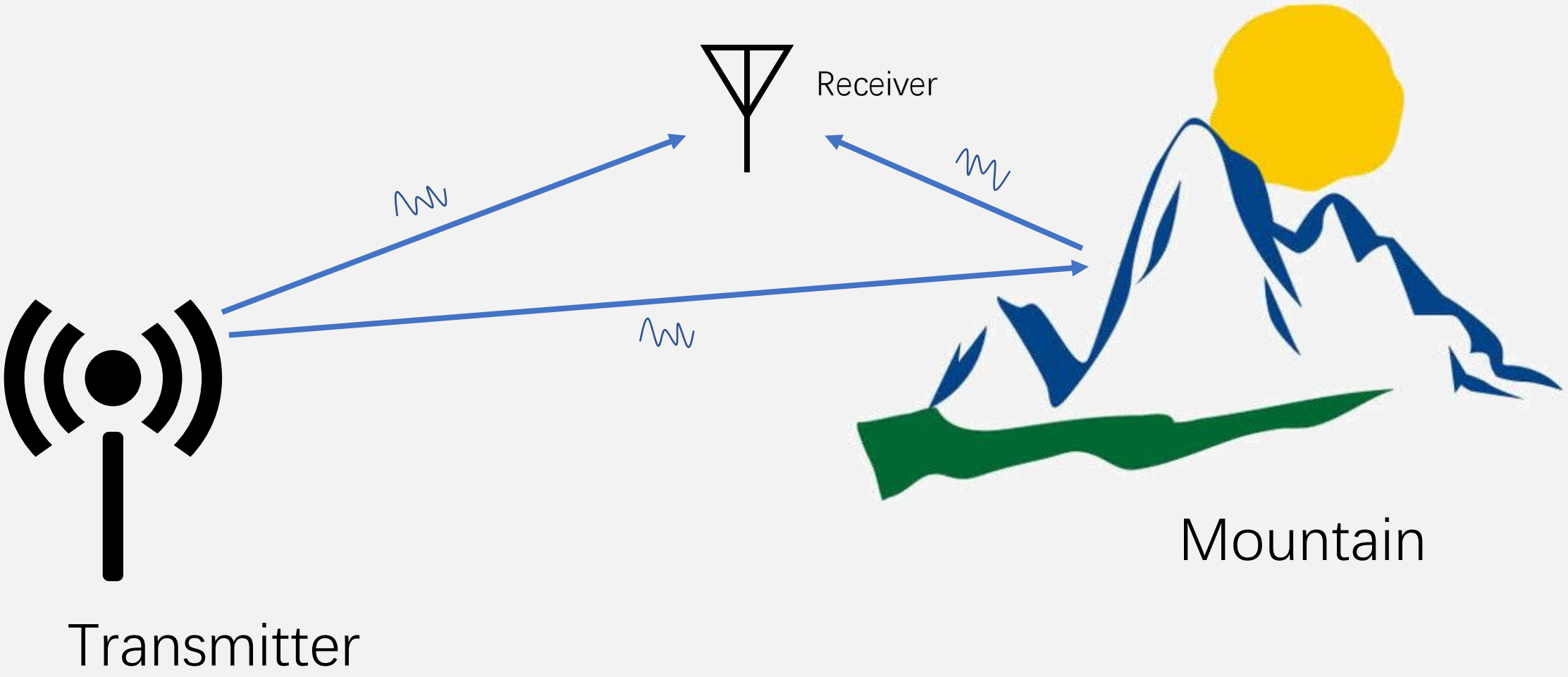

OFDM TX - Simulated-Basic.vi Block Diagram
File Edit View Project Operate Tools Window Help
18pt Application Font
Search
Queue size
I32
Queue name
IQ_Data_QUEUE
Obtain Queue
1000
output bit stream
I8
Complex baseband
Number of Bits
I32
MT Generate Bits (poly).vi
MT Map Bits to Symbols.vi
Inverse FFT.vi
Enqueue Element
Flush Queue
error out
error in (no error)
PN Order
QAM
1D Complex
4QAM MAP
0
0.707 +0.707 i
0.707 -0.707 i
-0.707 +0.707 i
-0.707 -0.707 i
Outgoing Constellation
desired sample rate (Hz)
stop
TF

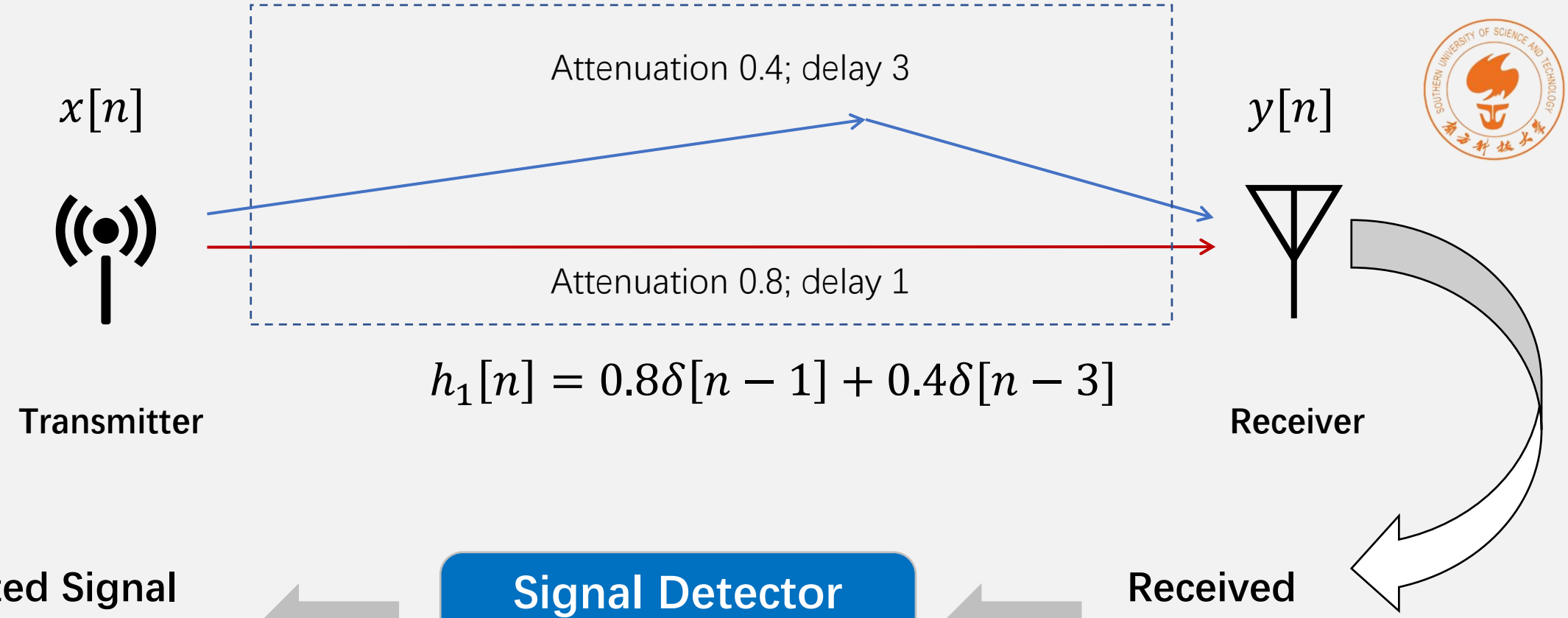

OFDM Transmitter
Outgoing Constellation
Plot 0
Imag
Real
Complex baseband
Before UpSample
After UpSample
Amplitude
Time
output bit stream
Number of Bits
30
Queue size
20
desired sample rate (Hz)
10.00
STOP
error in (no error)
status
code
source
error out
status
code
source


OFDM RX - Simulated-Basic.vi Block Diagram *
File Edit View Project Operate Tools Window Help
18pt Application Font
Search
1000
False
queue size
IQ_Data_QUEUE
error in (no error)
desired sample rate (Hz)
IQ Data
Complex baseband
Constellation
FFT.vi
MT Map
Symbols to Bits.vi
QAM
output cluster
error out
4QAM MAP
0.707 +0.707
0.707 -0.707 i
-0.707 +0.707
-0.707 -0.707
Original Bitstream
Bit Error Rate
stop


OFDM Receiver
Constellation
Plot 0
Amplitude
Time
Complex baseband
Before Downsampling
After Downsampling
Amplitude
Time
Input Bitstream
Output Bitstream
queue size
20
desired sample rate (Hz)
1.00
Bit Error Rate
0
STOP
error in (no error)
status
code
source
error out
status
code
source

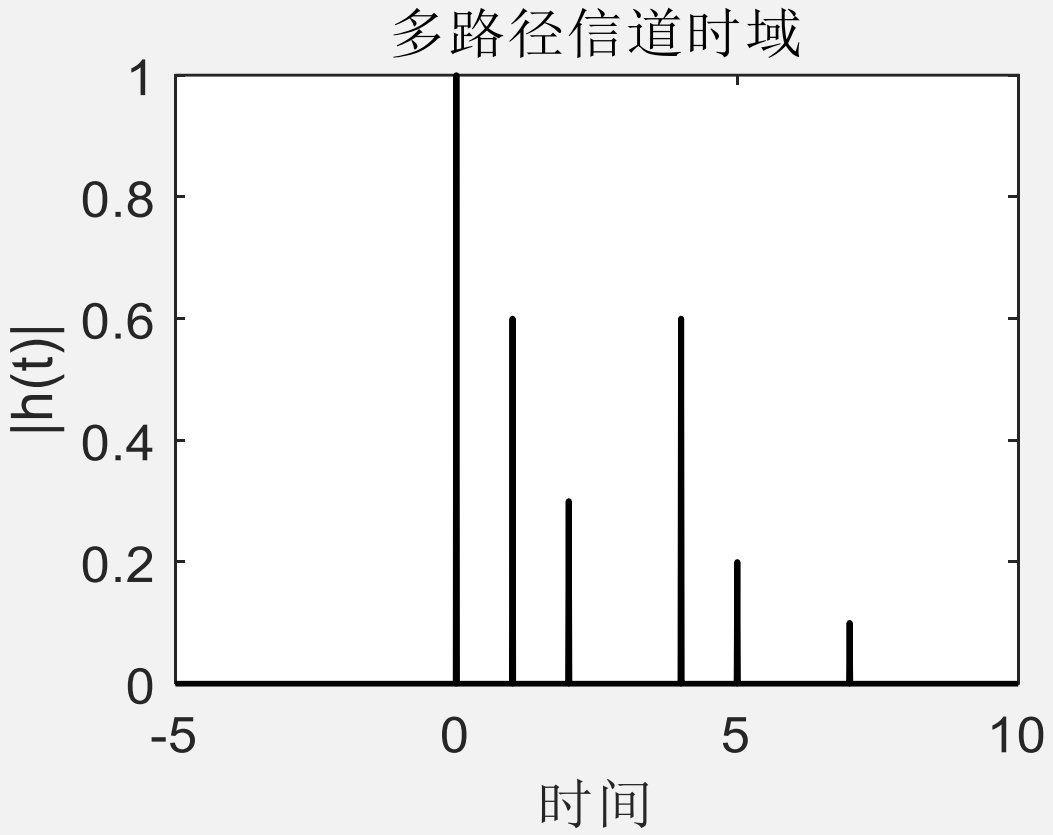
Multipath Propagation

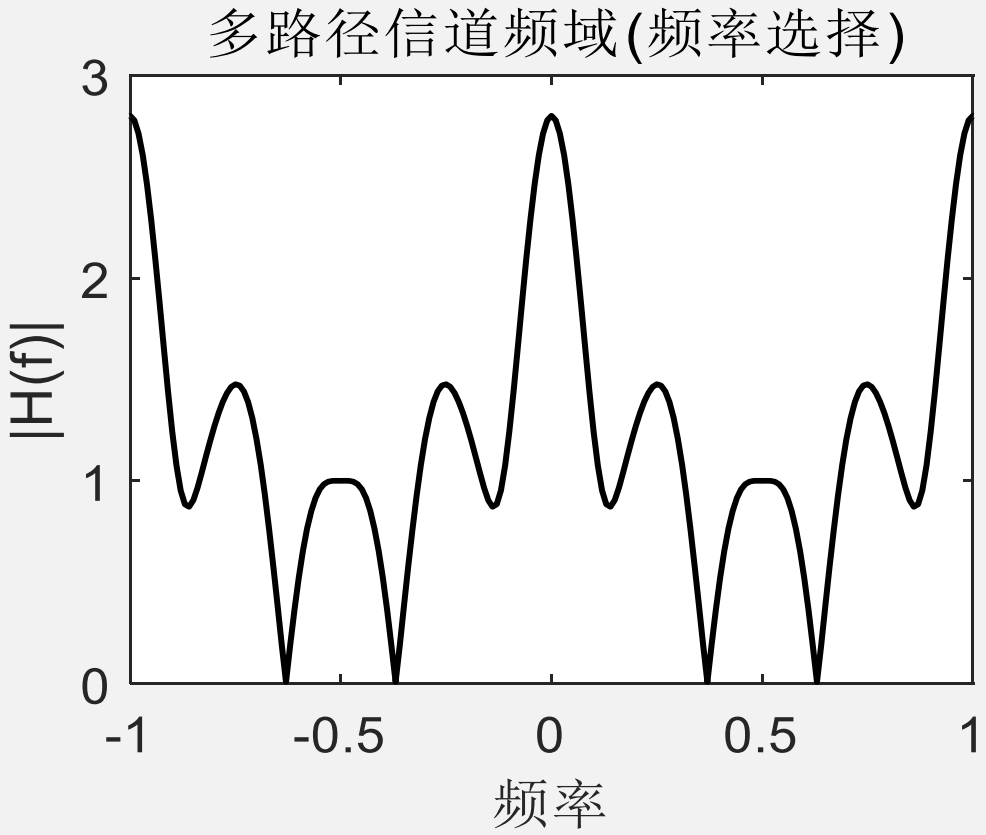




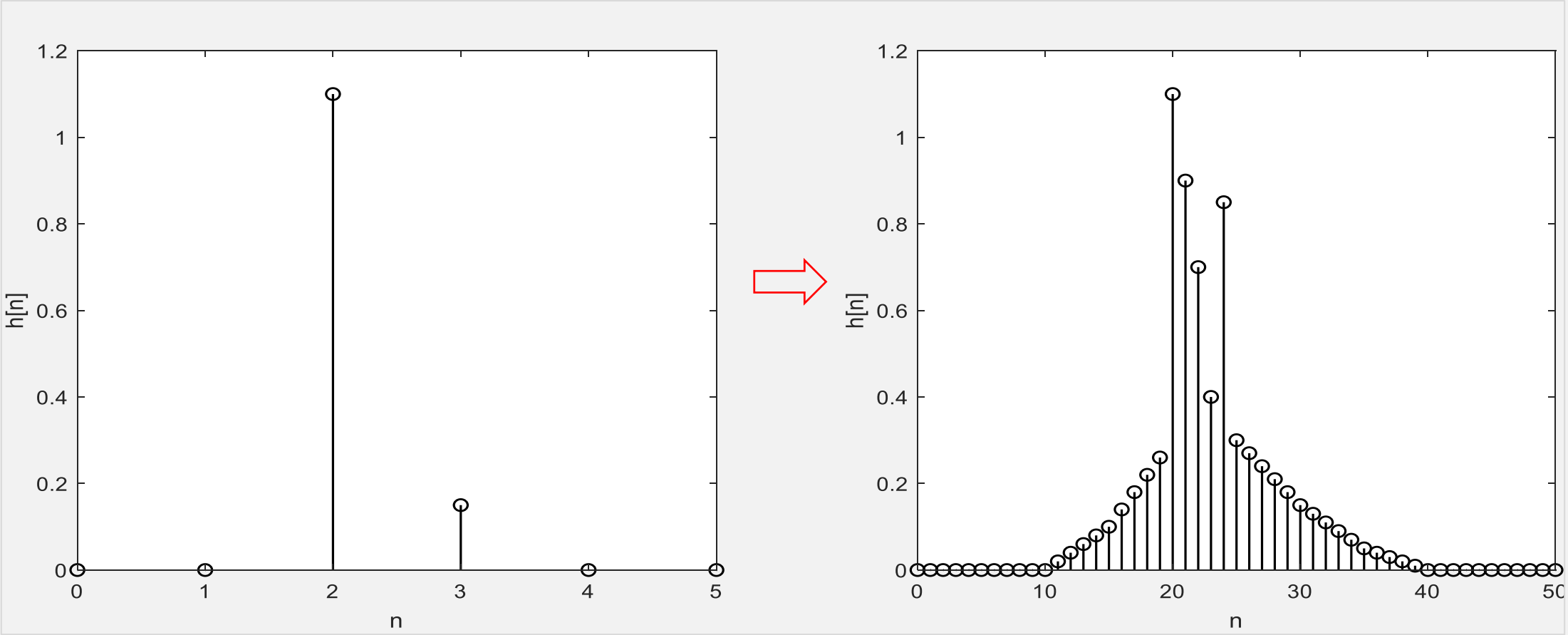
$$0.8h_2[n-1] + 0.4h_2[n-3] = \delta[n] \; or \; \delta[n-k]$$

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


多路径信道时域
1
0.8
0.6
0.4
0.2
0
|h(t)|
-5
0
5
10
时间

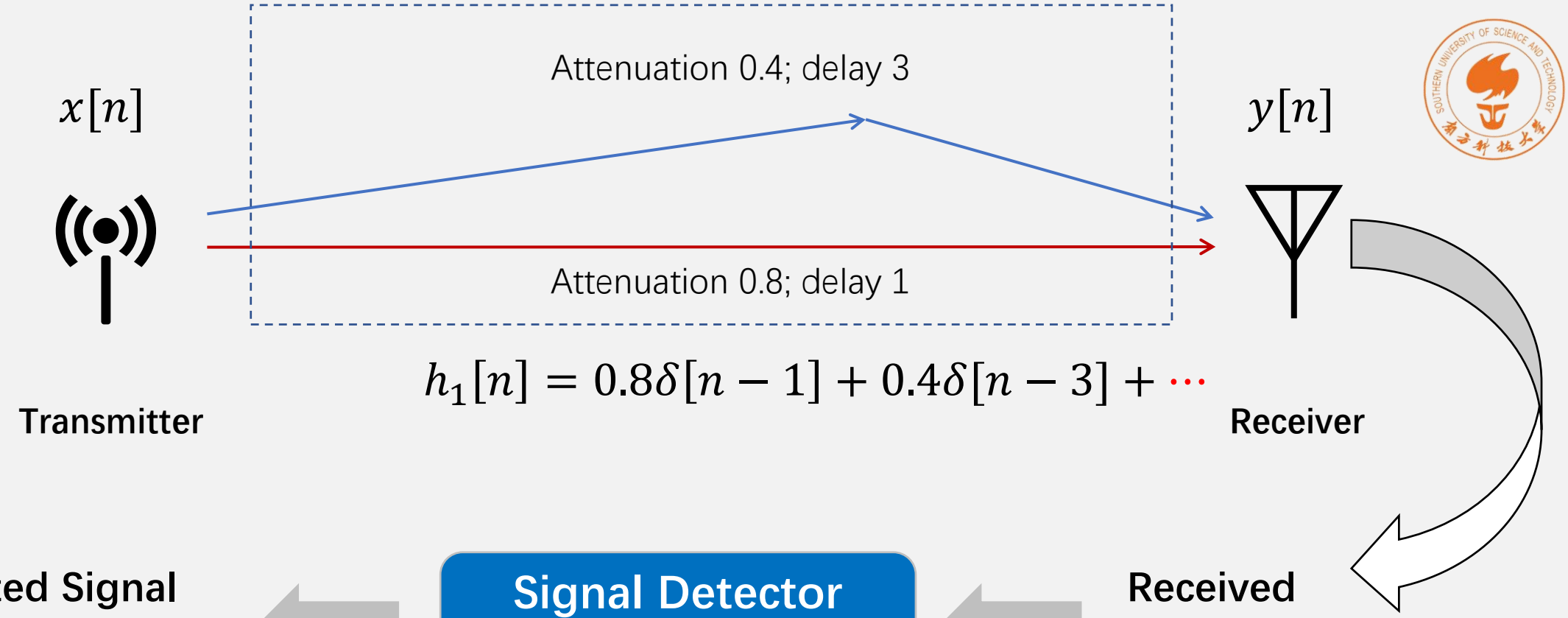

多路径信道频域(频率选择)
3
2
1
0
|H(f)|
-1
-0.5
0
0.5
1
频率

ISI ↑ as the Bandwidth ↑



Narrow-Band Channel

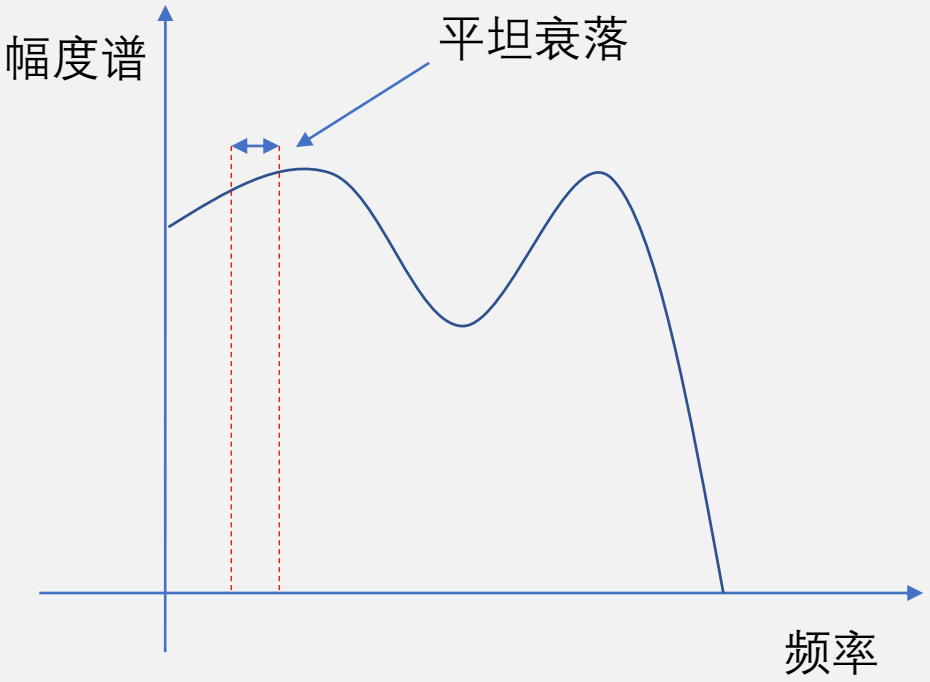
Wide-Band Channel

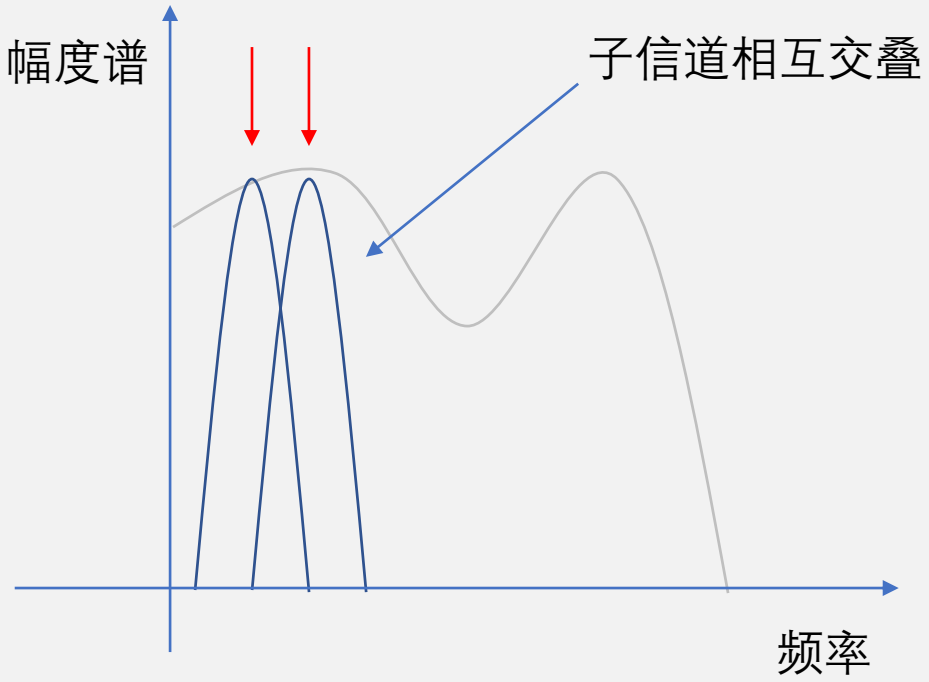


$$0.8h_2[n-1] + 0.4h_2[n-3] + \cdots = \delta[n] \; or \; \delta[n-k]$$

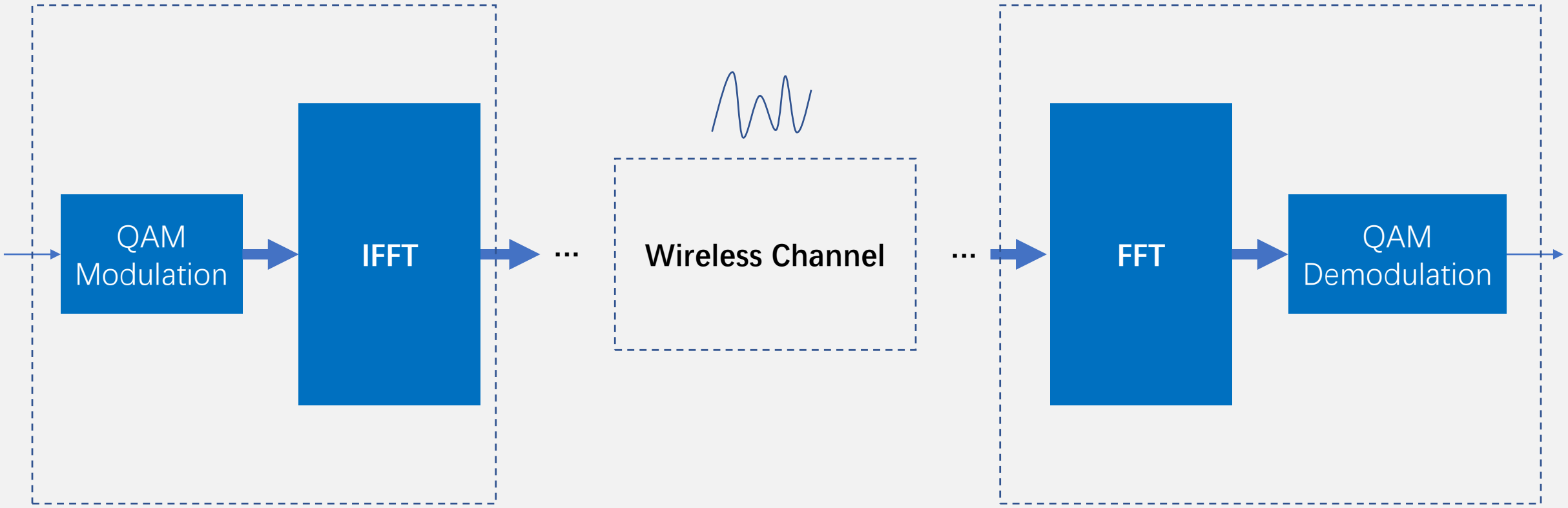
Impulse response: $h_2[n] * h_1[n] = \delta[n] \; or \; \delta[n-k]$

Understanding OFDM



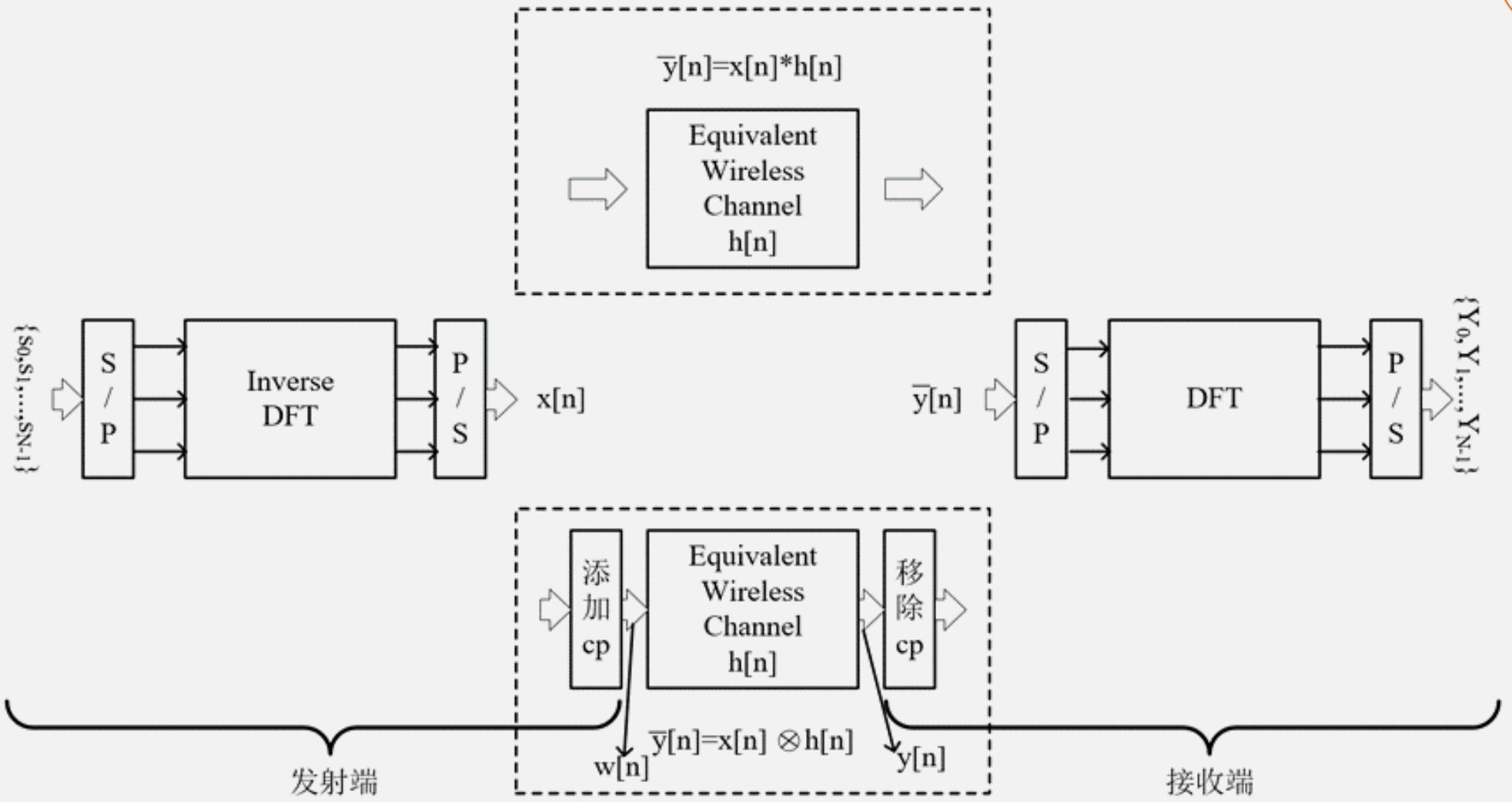


Exercise： Simple OFDM



OFDM Transmitter

OFDM Receiver


$\overline{y}[n]=x[n]*h[n]$
Equivalent Wireless Channel h[n]
$\{s_0,s_1,...,s_{N-1}\}$
S / P
Inverse DFT
P / S
x[n]
$\overline{y}[n]$
S / P
DFT
P / S
$\{Y_0,Y_1,...,Y_{N-1}\}$
添加 cp
Equivalent Wireless Channel h[n]
移除 cp
$\overline{y}[n]=x[n] \otimes h[n]$
w[n]
y[n]
发射端
接收端

$$\bar{y}[n] = x[n] * h[n]$$

$$\mathrm{DFT}[\bar{y}[n], N] = \mathrm{DFT}[x[n], N] \cdot \mathrm{DFT}[h[n], N]$$

$$\mathrm{DFT}[\bar{y}[n], N] = s[n] \cdot \mathrm{DFT}[h[n], N]$$

$$\bar{y}[n] = x[n] * h[n]$$

$$\mathrm{DFT}[\bar{y}[n], N] = \mathrm{DFT}[x[n], N] \cdot \mathrm{DFT}[h[n], N]$$

$$\mathrm{DFT}[\bar{y}[n], N] = s[n] \cdot \mathrm{DFT}[h[n], N]$$

$x[n] \longrightarrow x_{cp}[n]$ $\quad x_{cp}[n] = x[N-M], \cdots, x[N-1], x[0], x[1], \cdots, x[N-1]$

$$\bar{y}_{cp}[n] = x_{cp}[n] * h[n]$$

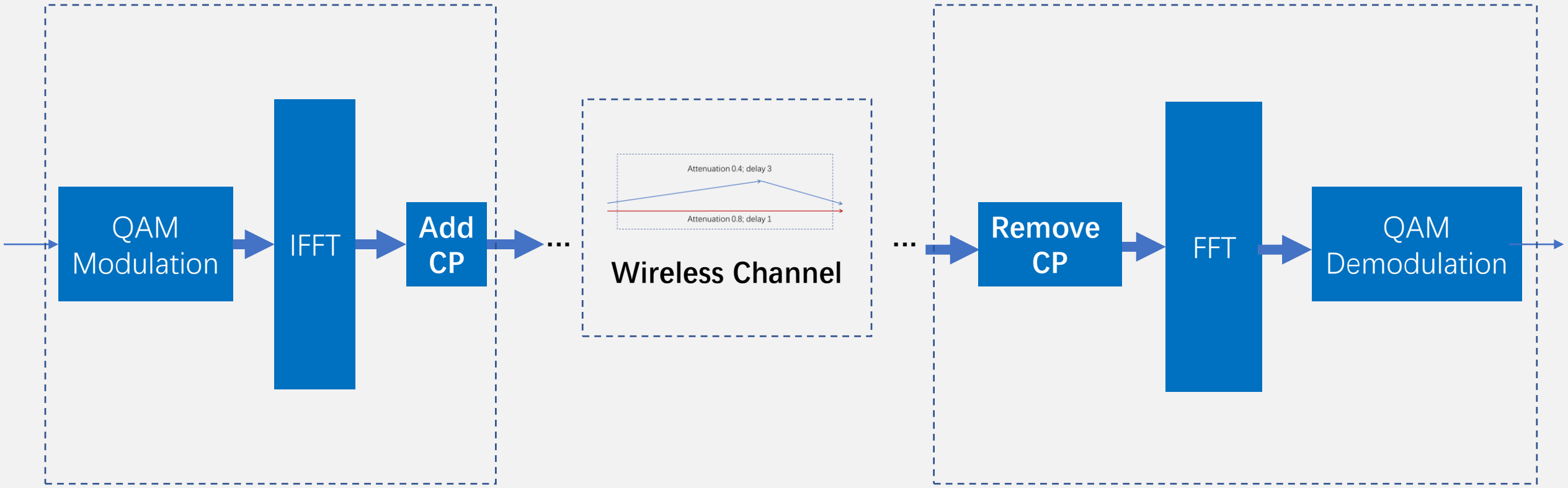
$\downarrow$

$\bar{y}_{cp}[n] \longrightarrow \bar{y}[n]$ 删除前M位，取中间的N位

$$\mathrm{DFT}[\bar{y}[n], N] = \mathrm{DFT}[x[n], N] \cdot \mathrm{DFT}[h[n], N]$$

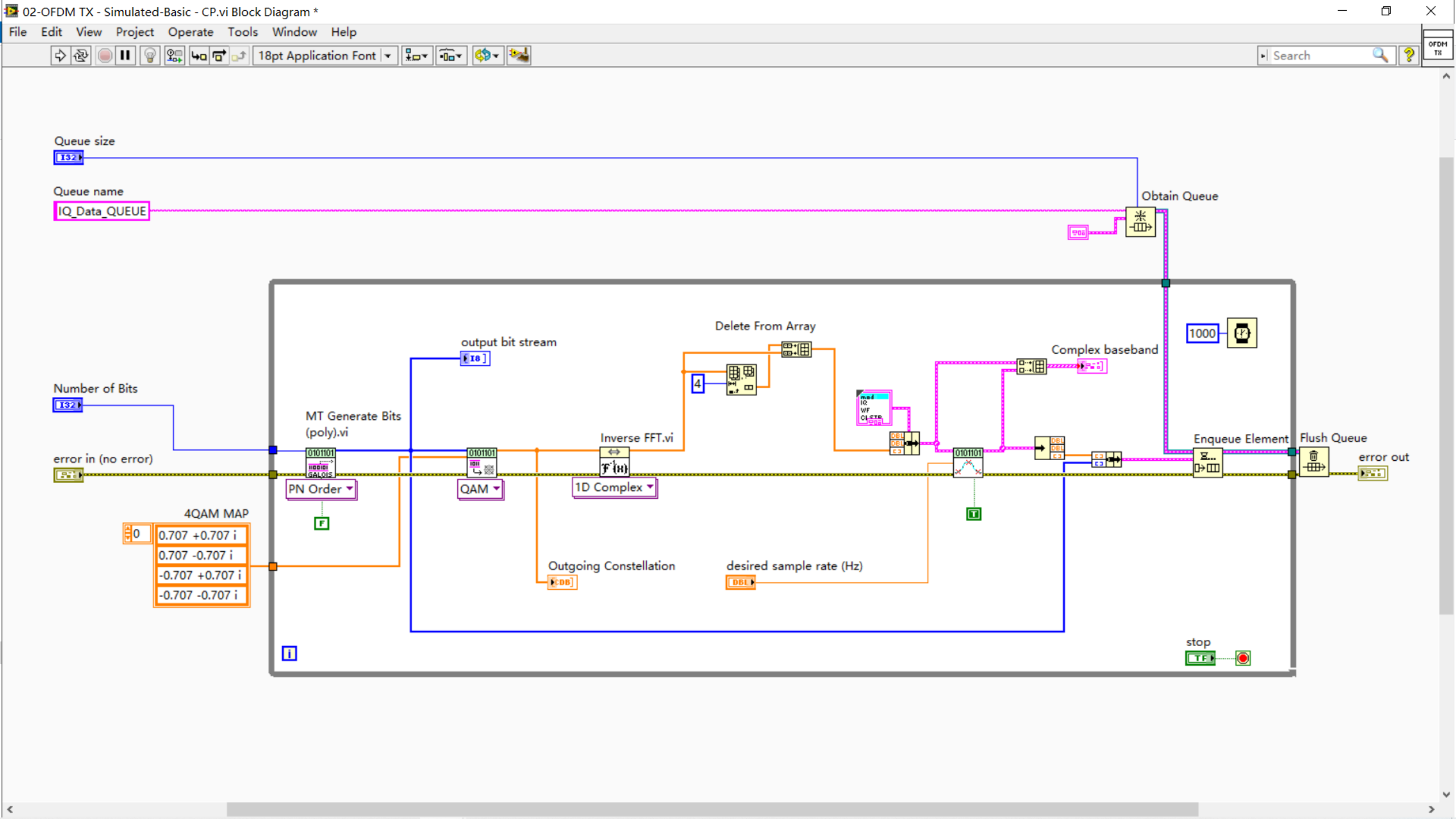
$\downarrow$

$$\mathrm{DFT}[\bar{y}[n], N] = s[n] \cdot \mathrm{DFT}[h[n], N]$$

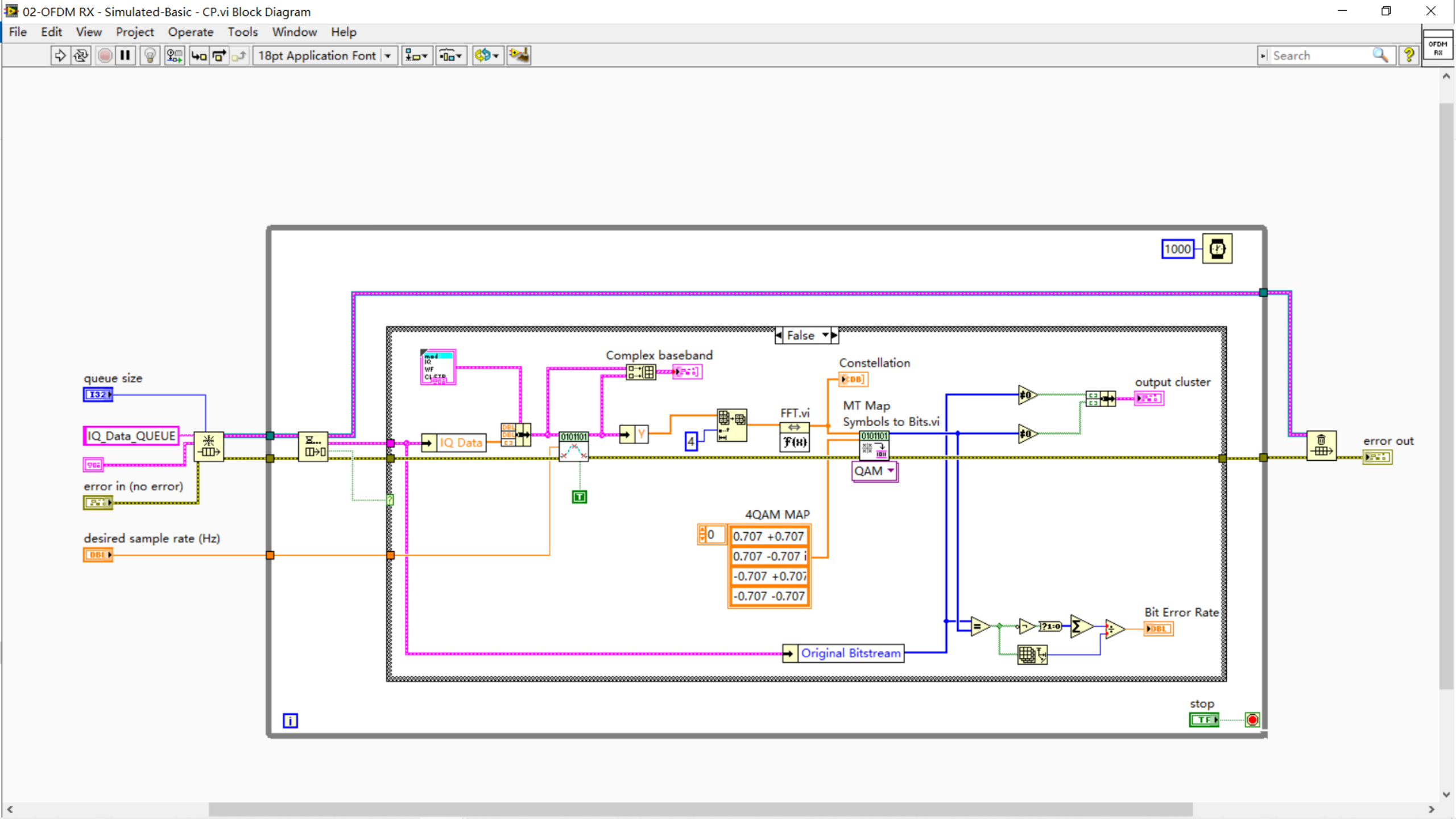


OFDM Transmitter

OFDM Receiver


02-OFDM TX - Simulated-Basic - CP.vi Block Diagram *
File Edit View Project Operate Tools Window Help
18pt Application Font
Search
Queue size
I32
Queue name
IQ_Data_QUEUE
Obtain Queue
Number of Bits
I32
error in (no error)
MT Generate Bits (poly).vi
PN Order
F
output bit stream
I8
QAM
Inverse FFT.vi
1D Complex
Delete From Array
4
Complex baseband
1000
Enqueue Element
Flush Queue
error out
4QAM MAP
0
0.707 +0.707 i
0.707 -0.707 i
-0.707 +0.707 i
-0.707 -0.707 i
Outgoing Constellation
CDB
desired sample rate (Hz)
DBL
T
i
stop
TF


0.4
0.2
0
-0.2
-0.4
Amplitude
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Time


02-OFDM RX - Simulated-Basic - CP.vi Block Diagram
File Edit View Project Operate Tools Window Help
18pt Application Font
Search
1000
False
queue size
IQ_Data_QUEUE
error in (no error)
desired sample rate (Hz)
IQ Data
Complex baseband
FFT.vi
Constellation
MT Map
Symbols to Bits.vi
QAM
output cluster
error out
4QAM MAP
0.707 +0.707
0.707 -0.707 i
-0.707 +0.707
-0.707 -0.707
Original Bitstream
Bit Error Rate
stop

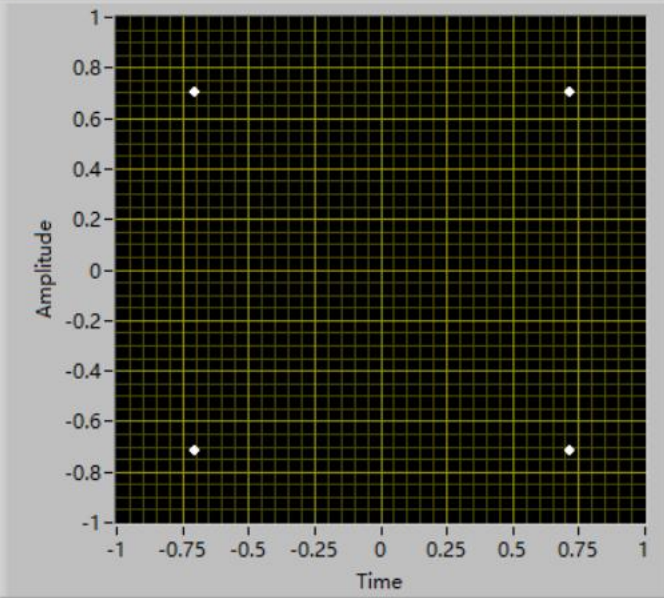
02-OFDM RX - Simulated-Basic - CP.vi

File Edit View Project Operate Tools Window Help

OFDM Receiver

Constellation

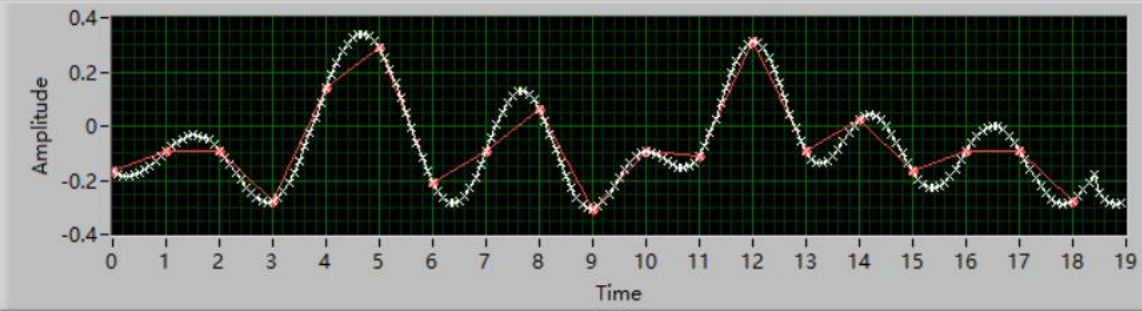
Plot 0



Complex baseband

Before Downsampling

After Downsampling



Input Bitstream

0

Output Bitstream

0

queue size

20

desired sample rate (Hz)

1.00

Bit Error Rate

0

STOP

error in (no error)

status code

0

source

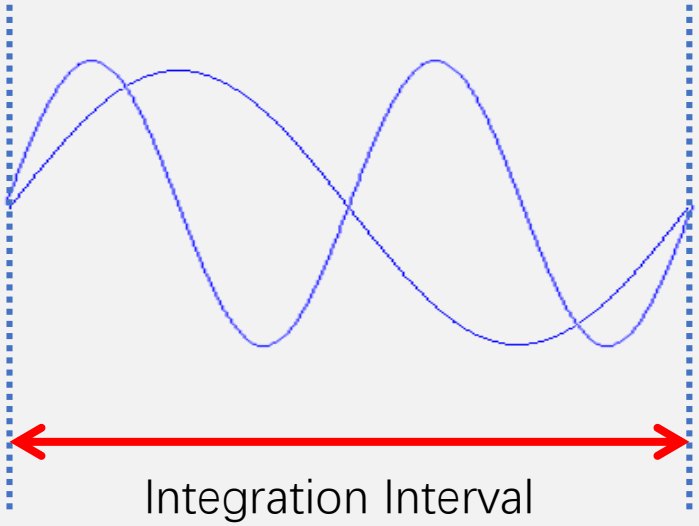
error out

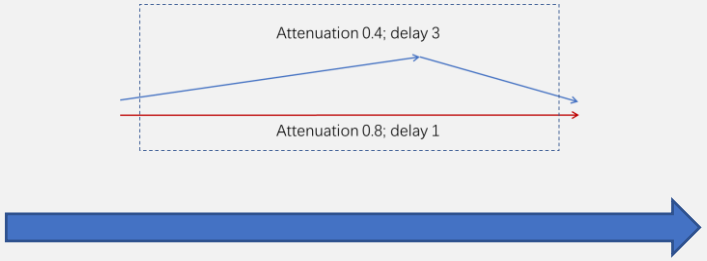
status code

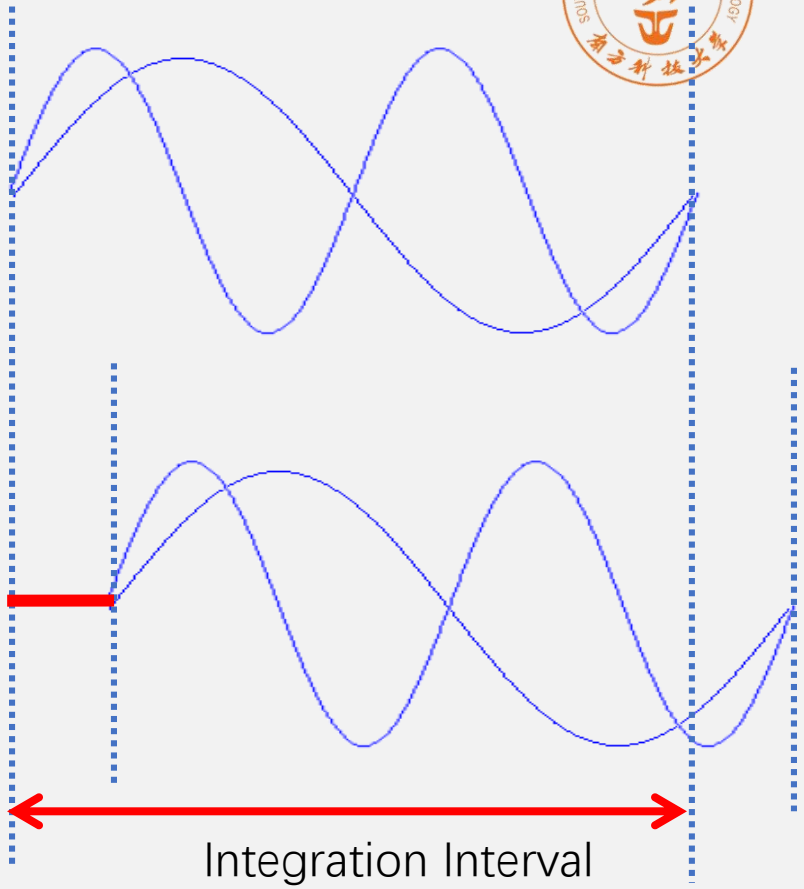
0

source

Orthogonality between subcarriers





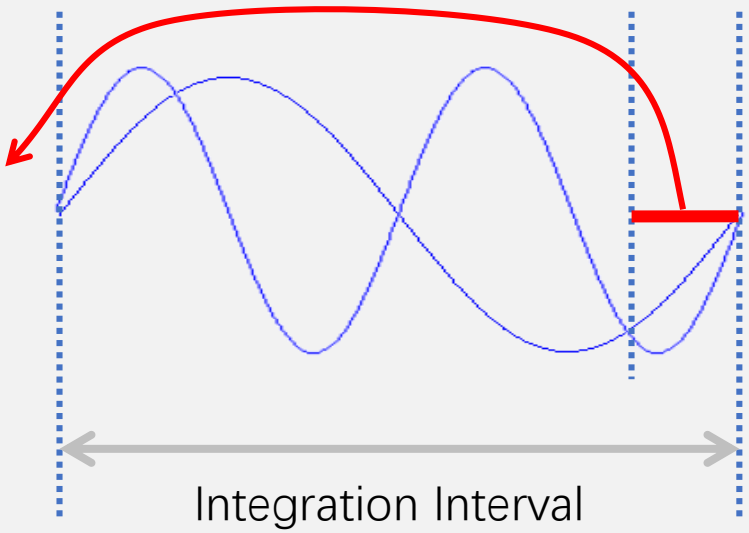


OFDM symbol

Multipath Channel

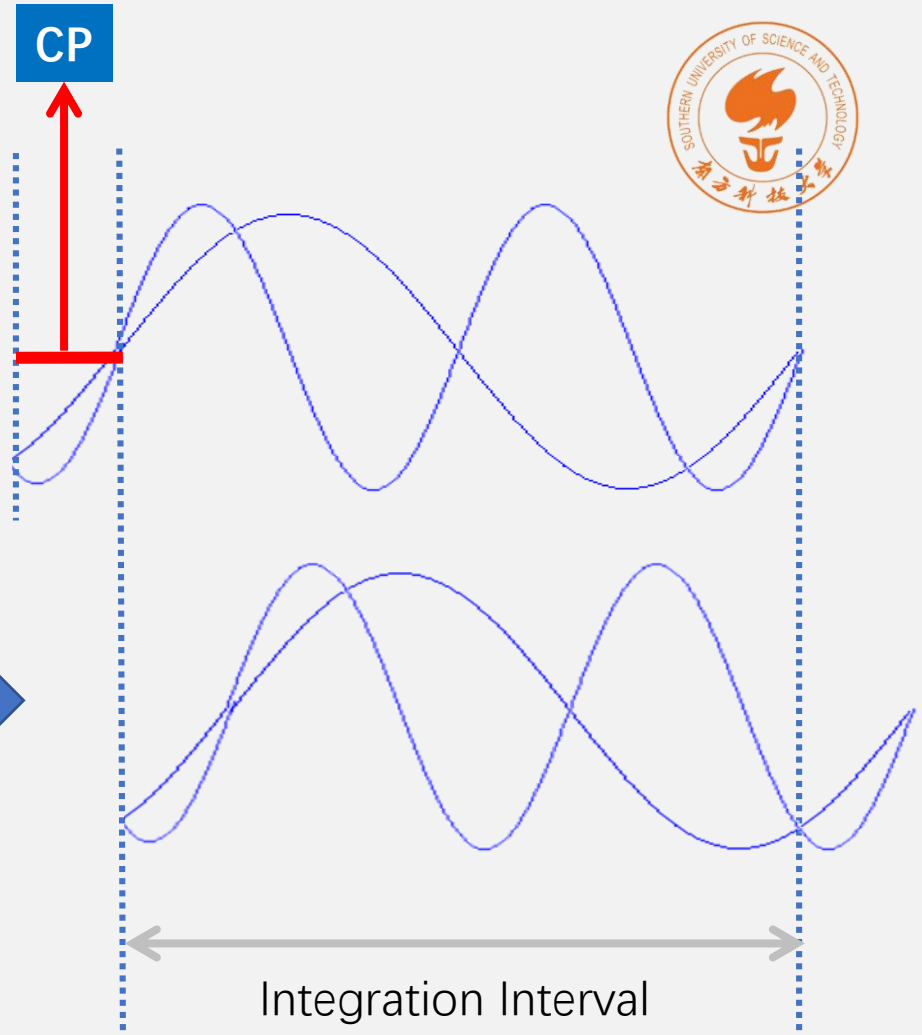
Output Waveform

2、Add Cyclic Prefix (CP)



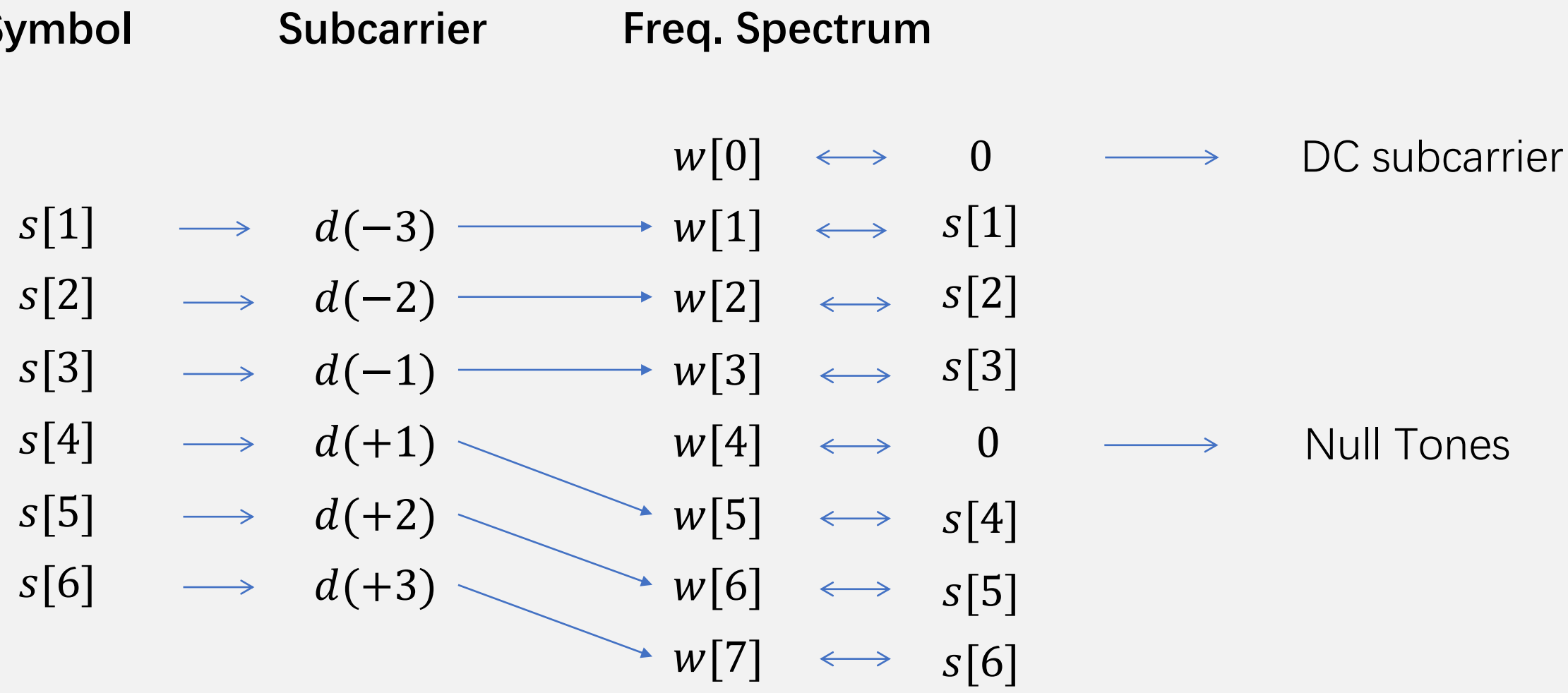
OFDM symbol

Add Cyclic Prefix (CP)

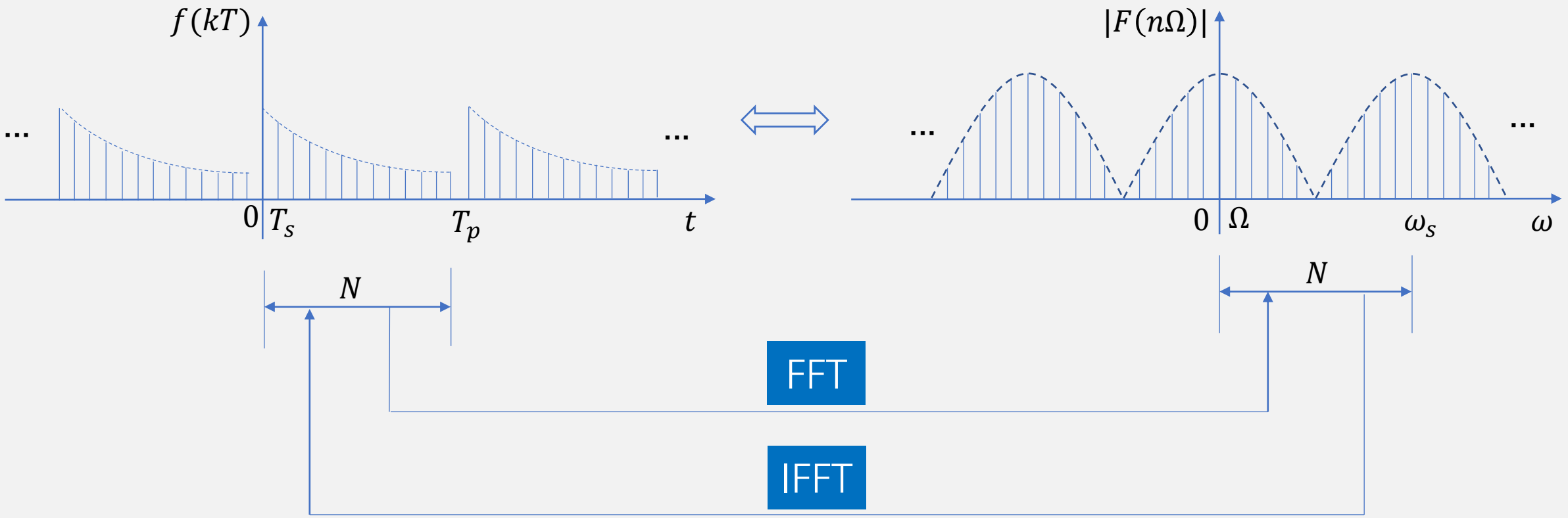


Output Waveform

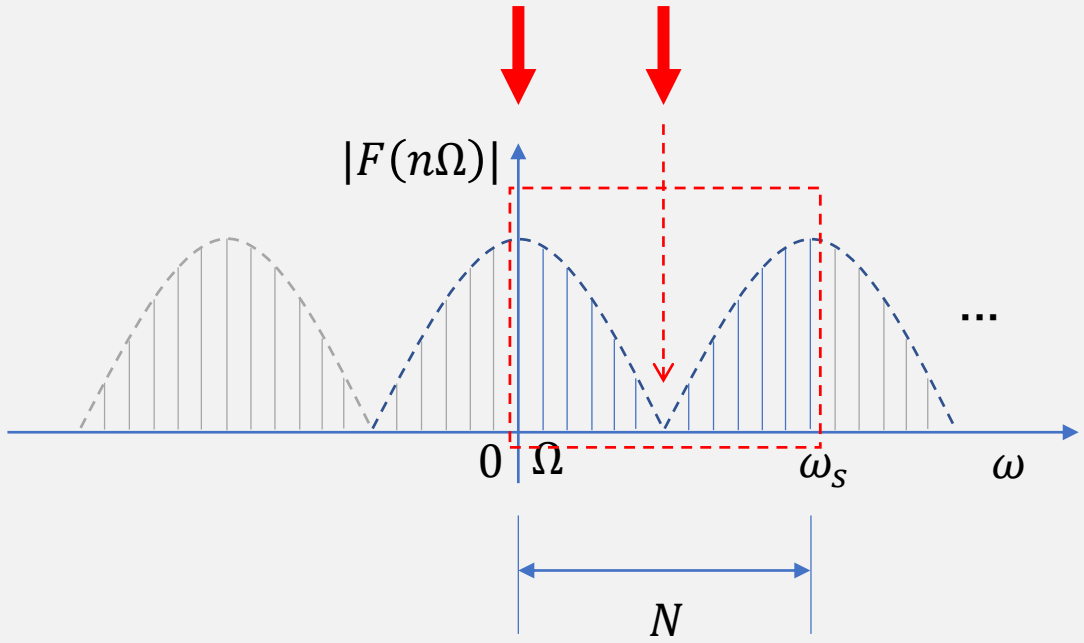
3、Subcarrier mapping for OFDM

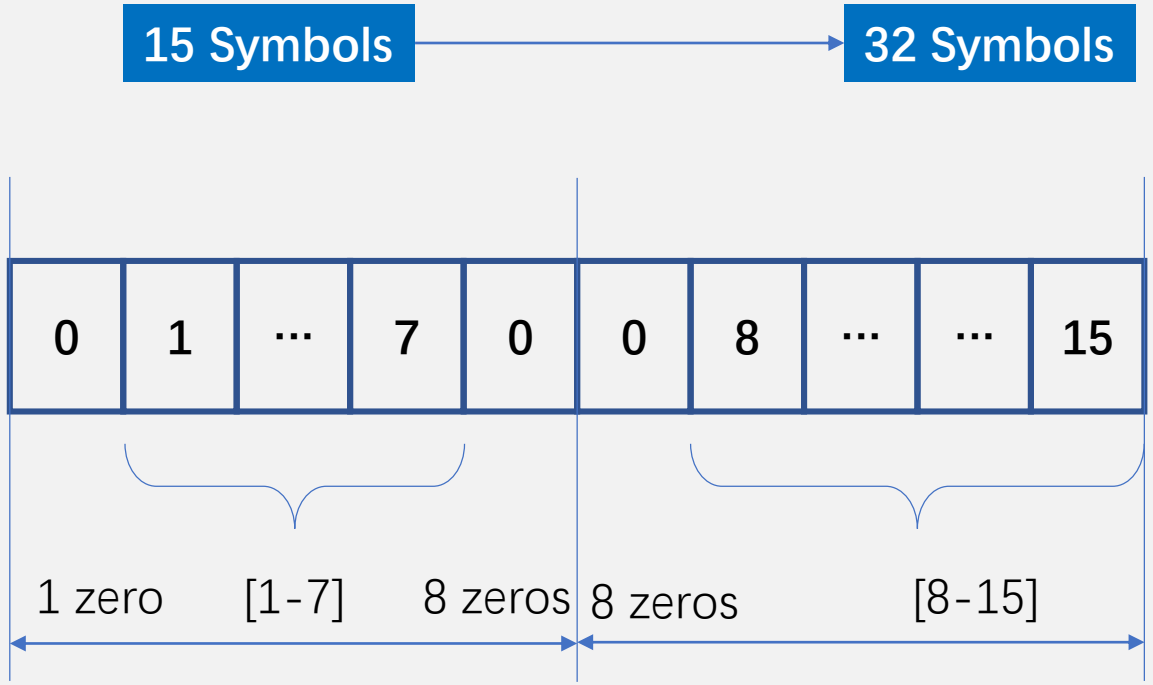


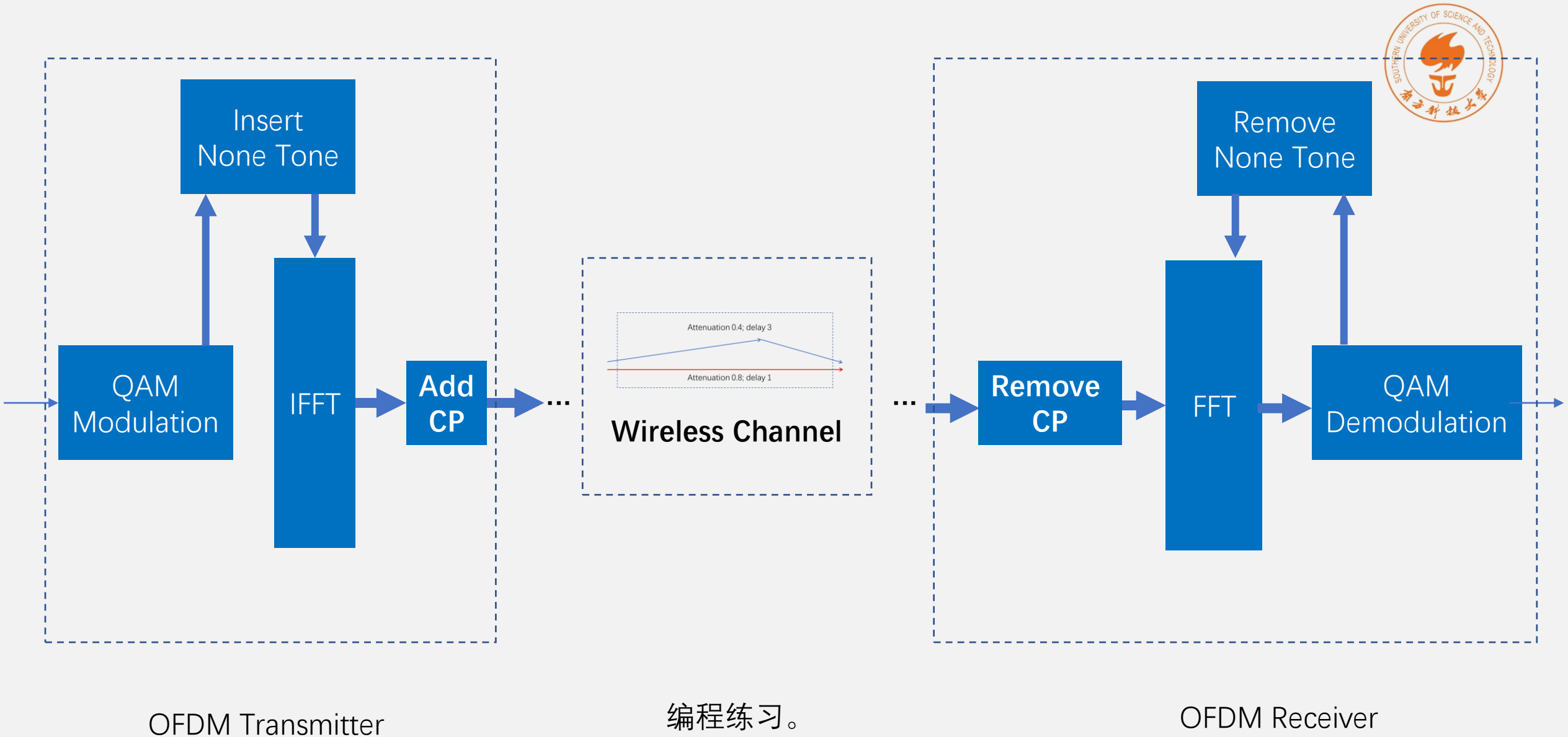
About FFT and IFFT



Insert None Tone



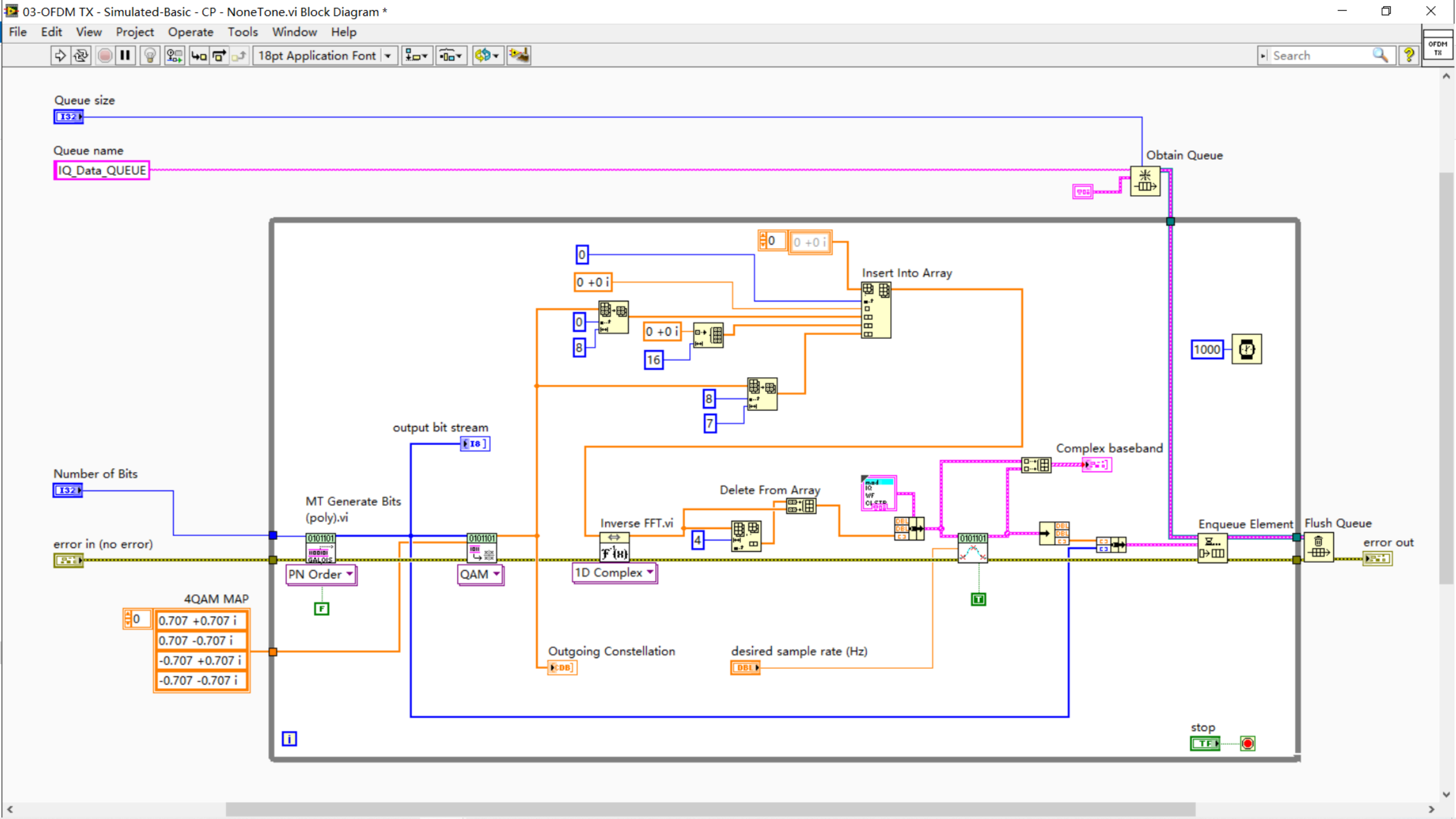


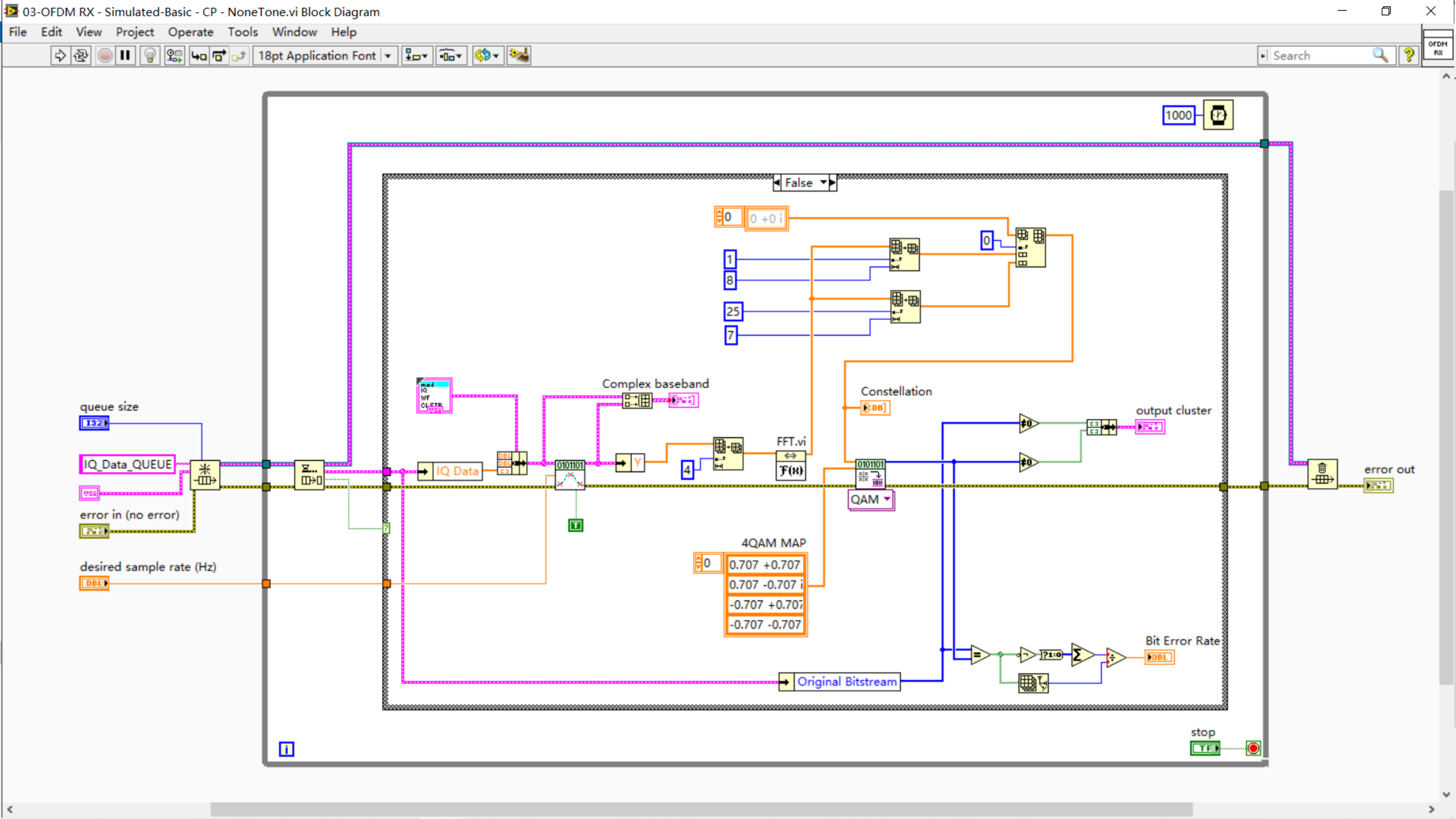


OFDM Transmitter

编程练习。

OFDM Receiver


03-OFDM TX - Simulated-Basic - CP - NoneTone.vi Block Diagram *
File Edit View Project Operate Tools Window Help
18pt Application Font
Search
Queue size
I32
Queue name
IQ_Data_QUEUE
Obtain Queue
Insert Into Array
1000
output bit stream
I8
Number of Bits
I32
error in (no error)
MT Generate Bits (poly).vi
PN Order
F
QAM
Inverse FFT.vi
1D Complex
Delete From Array
Complex baseband
Enqueue Element
Flush Queue
error out
4QAM MAP
0
0.707 +0.707 i
0.707 -0.707 i
-0.707 +0.707 i
-0.707 -0.707 i
Outgoing Constellation
DBL
desired sample rate (Hz)
DBL
stop
TF


03-OFDM RX - Simulated-Basic - CP - NoneTone.vi Block Diagram
File Edit View Project Operate Tools Window Help
18pt Application Font
Search
1000
False
0
0 +0 i
1
8
25
7
0
Complex baseband
Constellation
output cluster
FFT.vi
queue size
IQ_Data_QUEUE
error in (no error)
desired sample rate (Hz)
IQ Data
4
QAM
4QAM MAP
0.707 +0.707
0.707 -0.707 i
-0.707 +0.707
-0.707 -0.707
Bit Error Rate
Original Bitstream
error out
stop

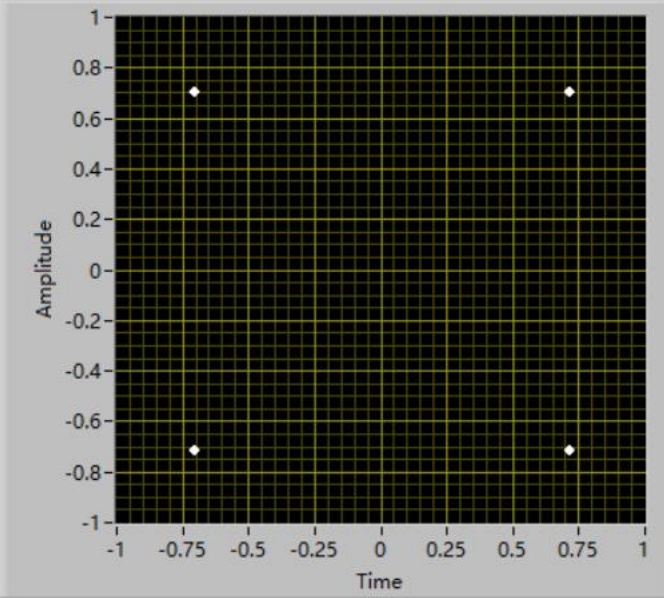
03-OFDM RX - Simulated-Basic - CP - NoneTone.vi

File Edit View Project Operate Tools Window Help

OFDM Receiver

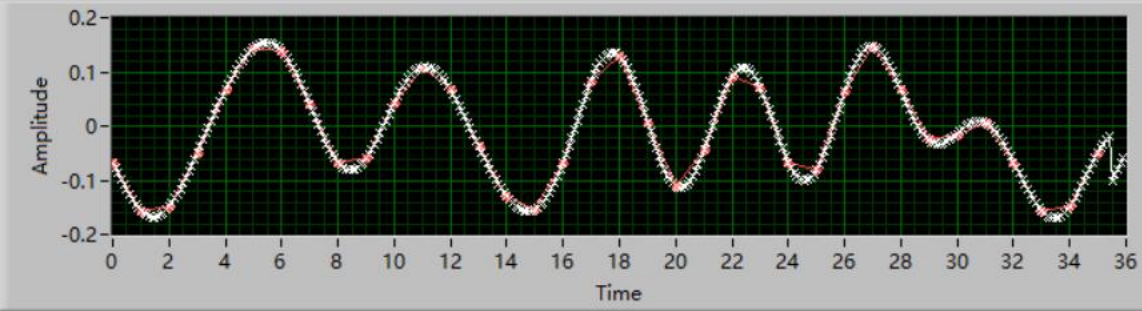
Constellation

Plot 0



Complex baseband

Before Downsampling After Downsampling



Input Bitstream

0

Output Bitstream

0

queue size

20

desired sample rate (Hz)

1.00

Bit Error Rate

0

STOP

error in (no error)

status code

0

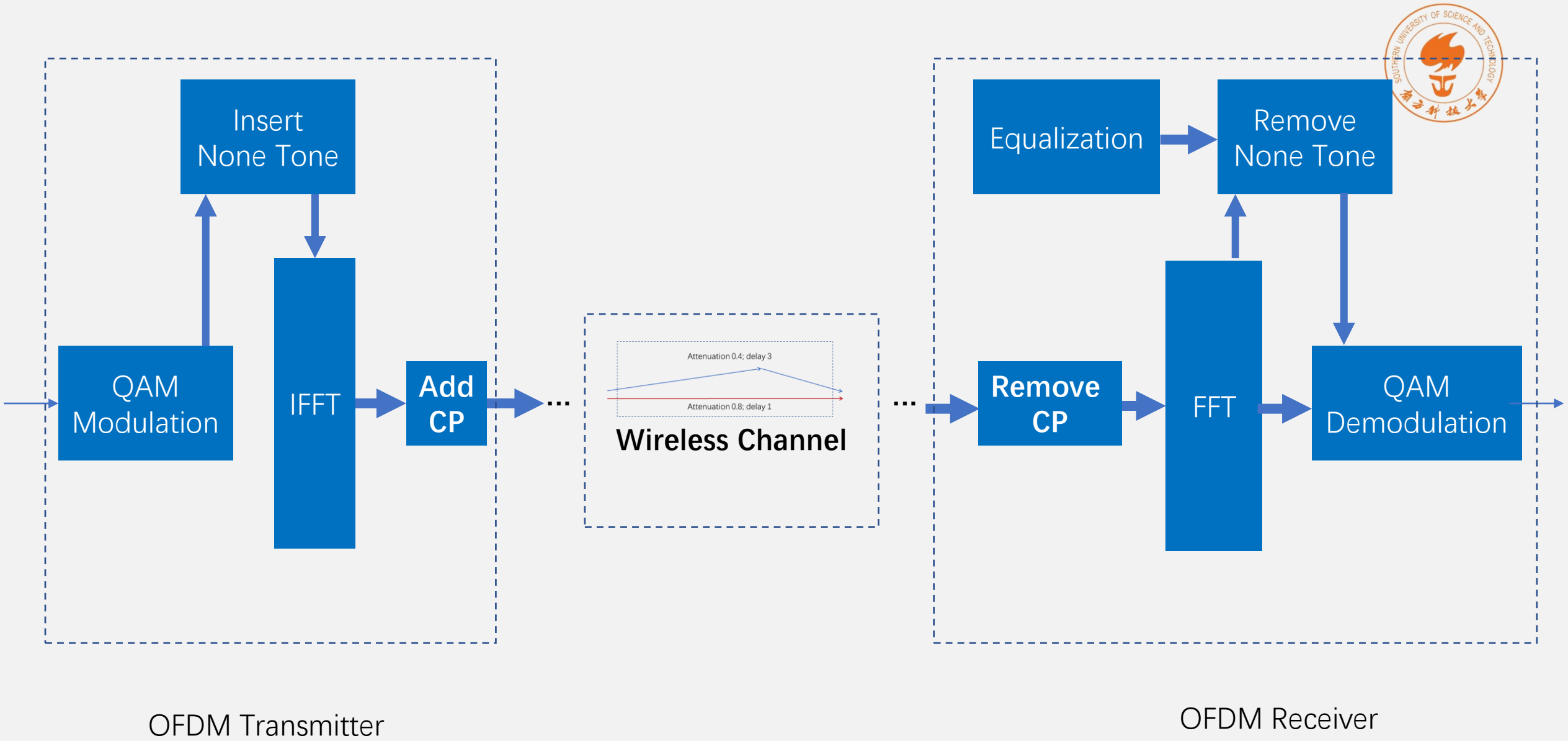
source

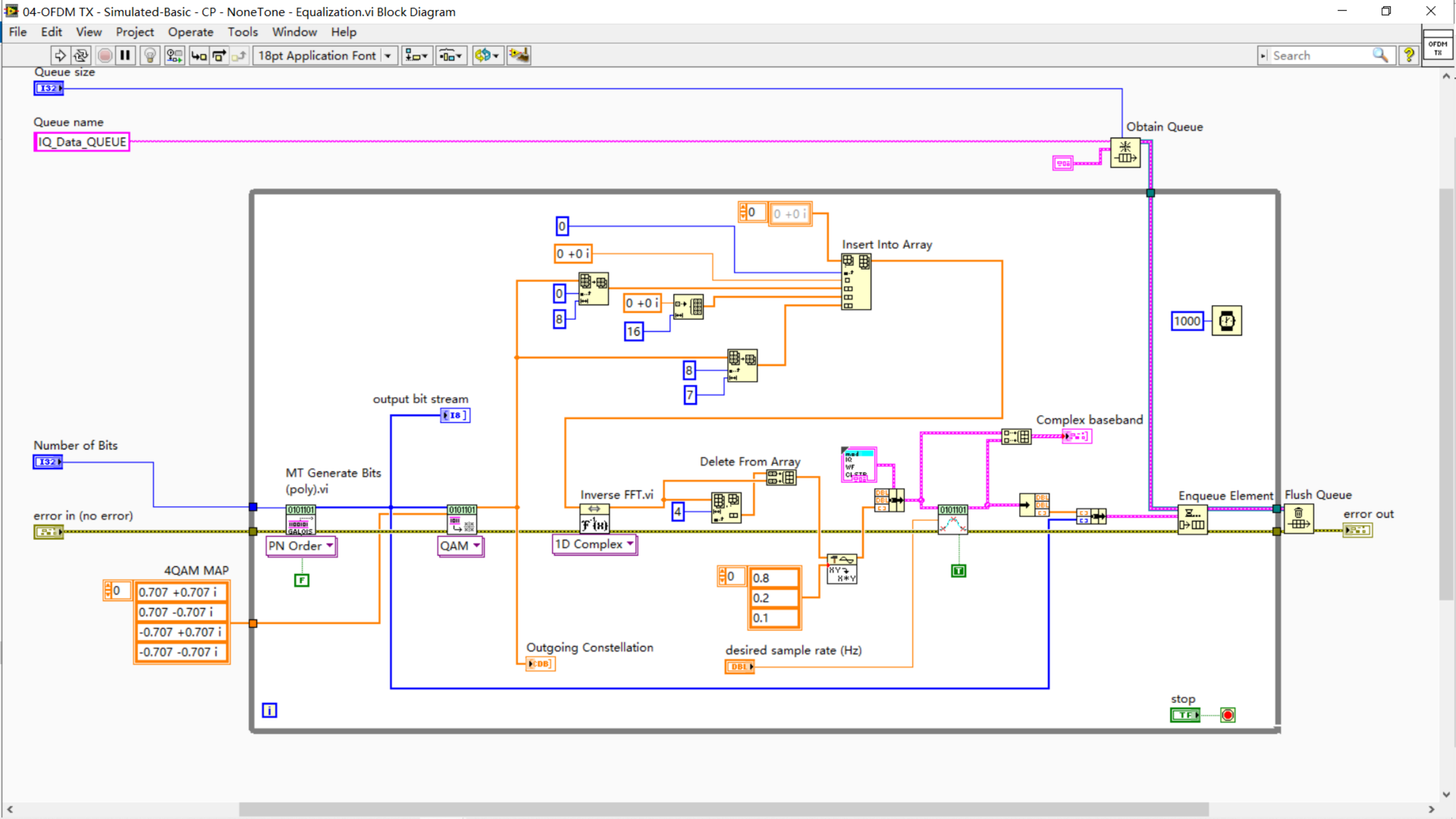
error out

status code

0

source


Insert
None Tone
QAM
Modulation
IFFT
Add
CP
...
Attenuation 0.4; delay 3
Attenuation 0.8; delay 1
Wireless Channel
...
Equalization
Remove
None Tone
Remove
CP
FFT
QAM
Demodulation
OFDM Transmitter
OFDM Receiver


04-OFDM TX - Simulated-Basic - CP - NoneTone - Equalization.vi Block Diagram
File Edit View Project Operate Tools Window Help
18pt Application Font
Search
Queue size
Queue name
IQ_Data_QUEUE
Obtain Queue
Insert Into Array
1000
output bit stream
Number of Bits
MT Generate Bits (poly).vi
Delete From Array
Complex baseband
Inverse FFT.vi
Enqueue Element
Flush Queue
error out
error in (no error)
PN Order
QAM
1D Complex
4QAM MAP
0.707 +0.707 i
0.707 -0.707 i
-0.707 +0.707 i
-0.707 -0.707 i
Outgoing Constellation
desired sample rate (Hz)
stop

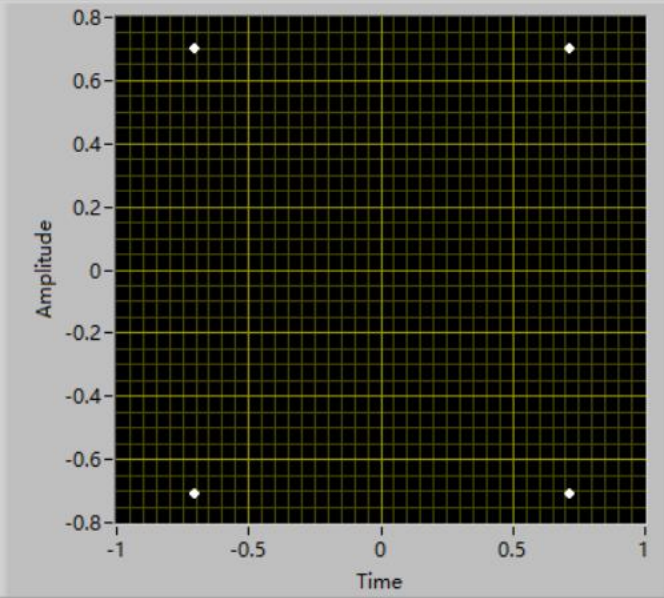
04-OFDM RX - Simulated-Basic - CP - NoneTone - Equalization.vi

File Edit View Project Operate Tools Window Help

OFDM Receiver

Constellation

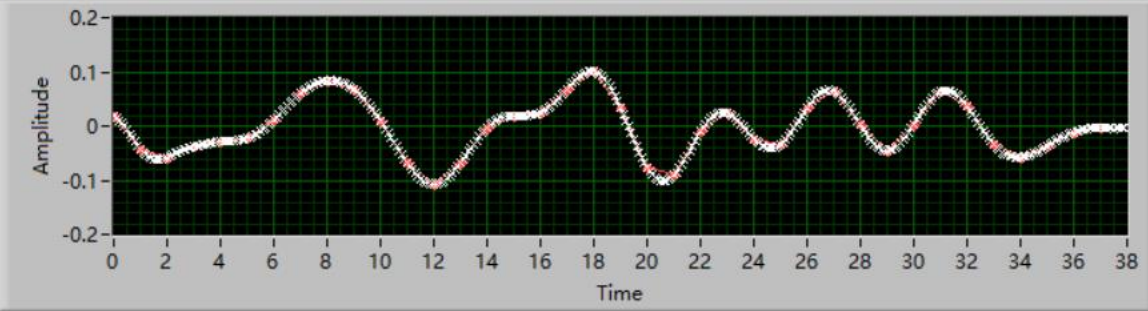
Plot 0



Complex baseband

Before Downsampling

After Downsampling



Input Bitstream

0

Output Bitstream

0

queue size

20

desired sample rate (Hz)

1.00

Bit Error Rate

0

STOP

error in (no error)

status code

0

source

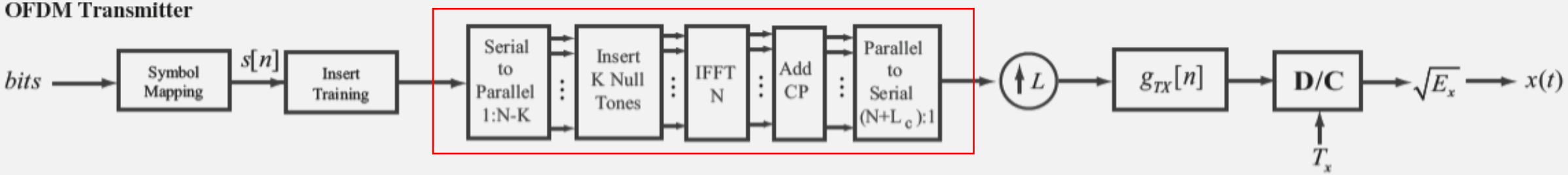
error out

status code

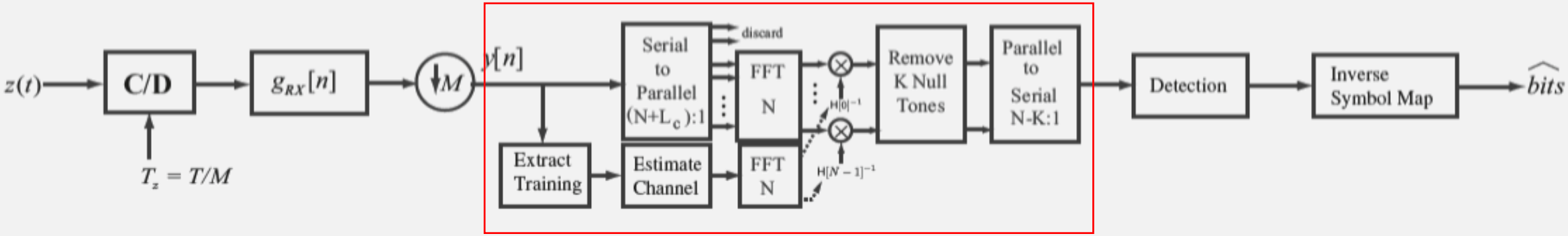
0

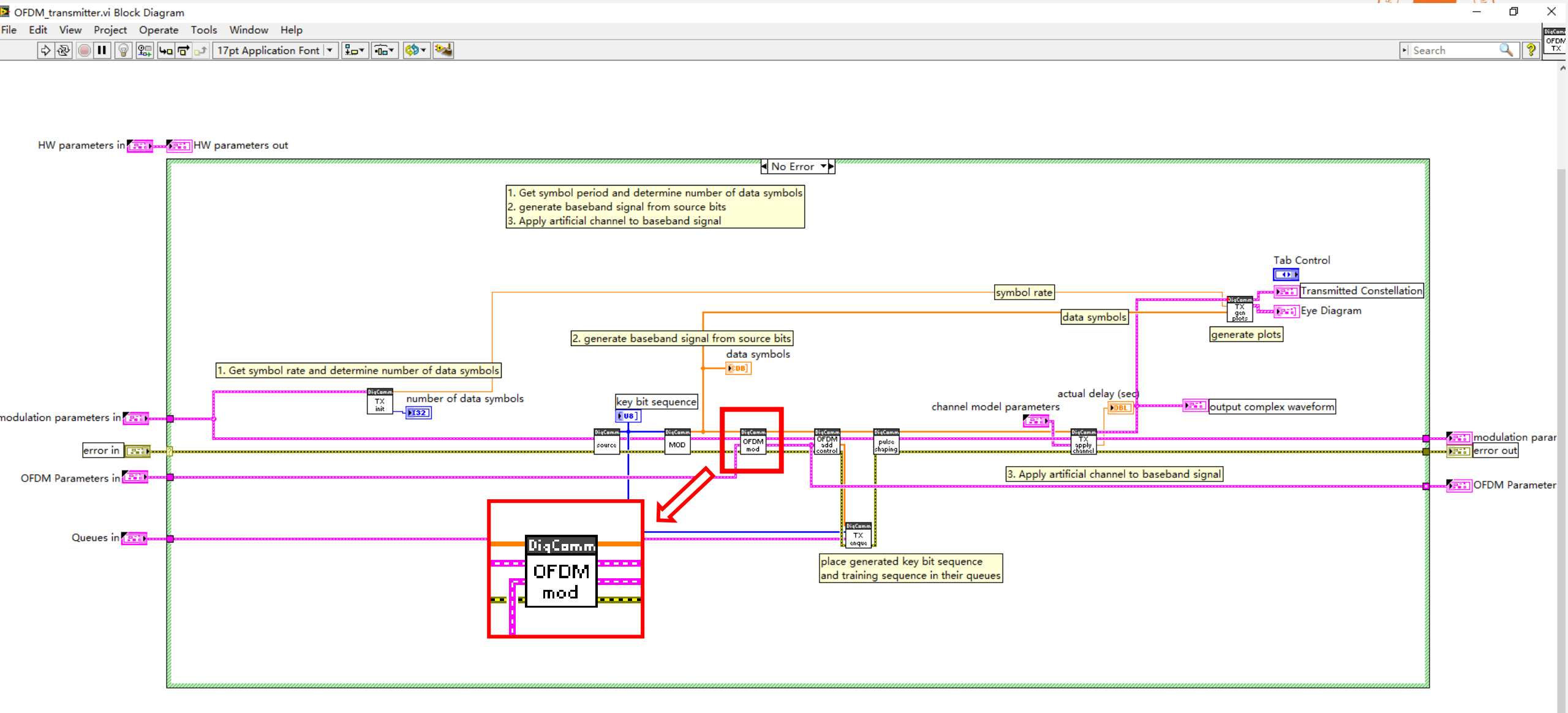
source

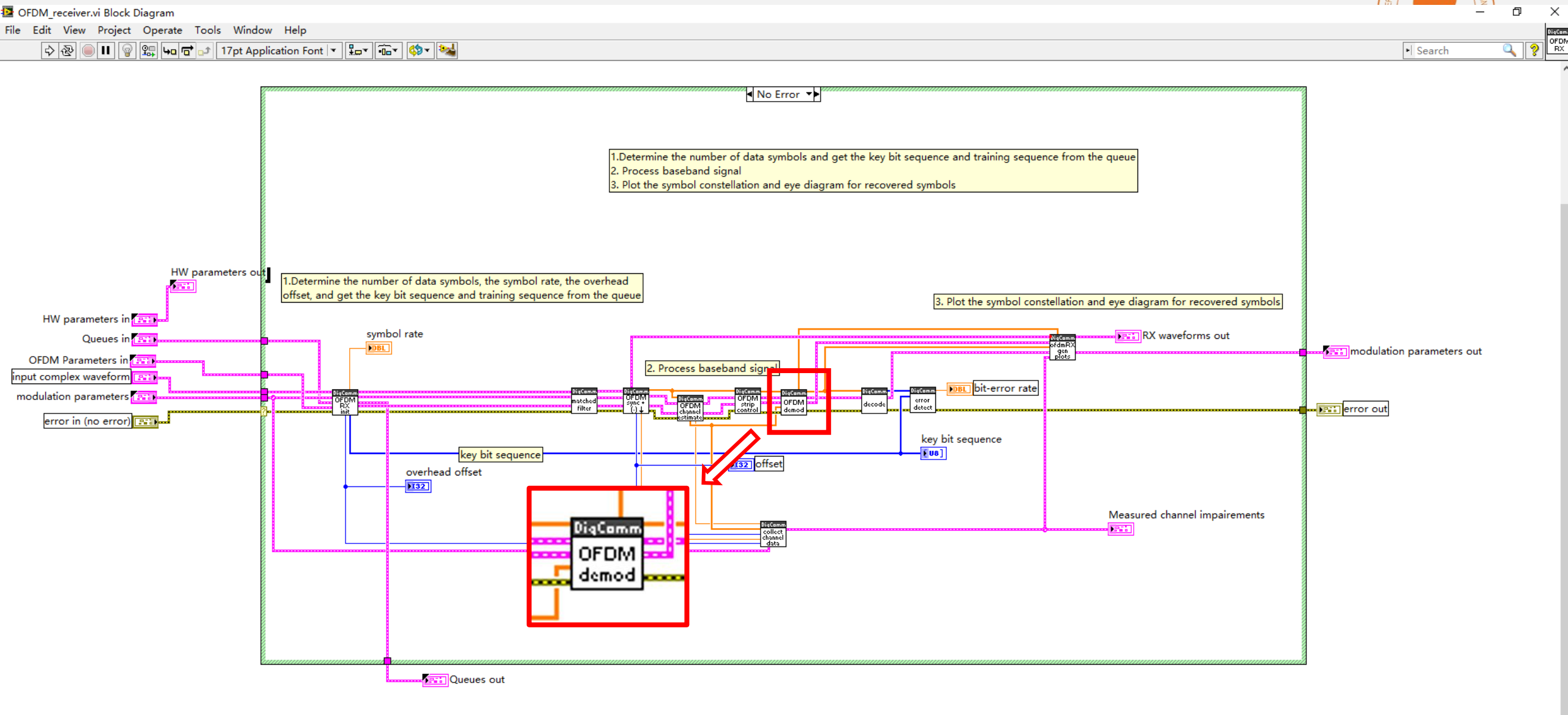
OFDM Transmitter



OFDM Receiver




OFDM_transmitter.vi Block Diagram
File Edit View Project Operate Tools Window Help
17pt Application Font
Search
HW parameters in
HW parameters out
No Error
1. Get symbol period and determine number of data symbols
2. generate baseband signal from source bits
3. Apply artificial channel to baseband signal
Tab Control
Transmitted Constellation
Eye Diagram
generate plots
symbol rate
data symbols
2. generate baseband signal from source bits
data symbols
1. Get symbol rate and determine number of data symbols
number of data symbols
key bit sequence
actual delay (sec)
channel model parameters
output complex waveform
modulation parameters in
error in
OFDM Parameters in
Queues in
3. Apply artificial channel to baseband signal
modulation parar
error out
OFDM Parameter
DigComm
OFDM
mod
place generated key bit sequence
and training sequence in their queues


OFDM_receiver.vi Block Diagram
File Edit View Project Operate Tools Window Help
17pt Application Font
Search
No Error
1.Determine the number of data symbols and get the key bit sequence and training sequence from the queue
2. Process baseband signal
3. Plot the symbol constellation and eye diagram for recovered symbols
HW parameters out
1.Determine the number of data symbols, the symbol rate, the overhead offset, and get the key bit sequence and training sequence from the queue
3. Plot the symbol constellation and eye diagram for recovered symbols
HW parameters in
Queues in
OFDM Parameters in
input complex waveform
modulation parameters
error in (no error)
symbol rate
2. Process baseband signal
RX waveforms out
modulation parameters out
bit-error rate
error out
key bit sequence
offset
overhead offset
Measured channel impairements
Queues out
DiqComm
OFDM
demod

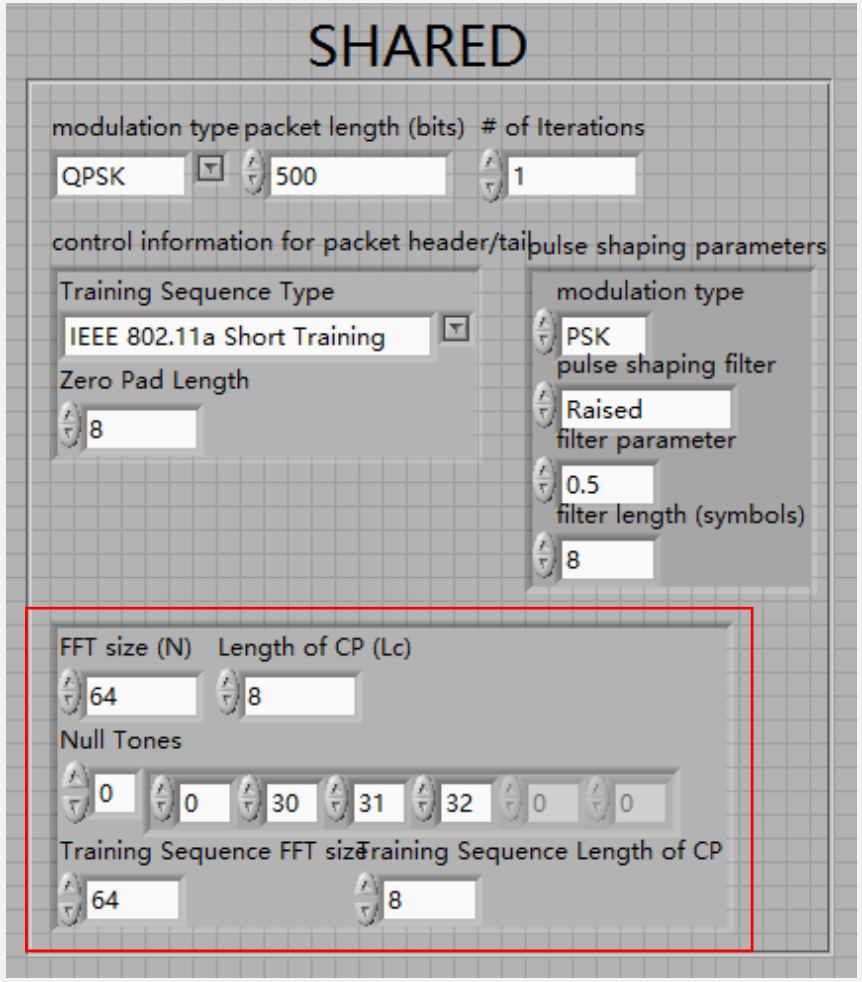
项目设计

- **Basic：**
  1、Task 1：Programming for OFDM Transceiver.（30 Points）
  1、Task 2：Frequency Selectivity of Wireless Channels.（15 Points）
  2、Task 3：Sensitivity to Frequency Offsets.（15 Points）

- **Advanced：**
  1、Task 1：High-order Modulation of Subcarrier.（20 Points）
  2、Task 2：Image/Video Transmission with OFDM.（20 Points）

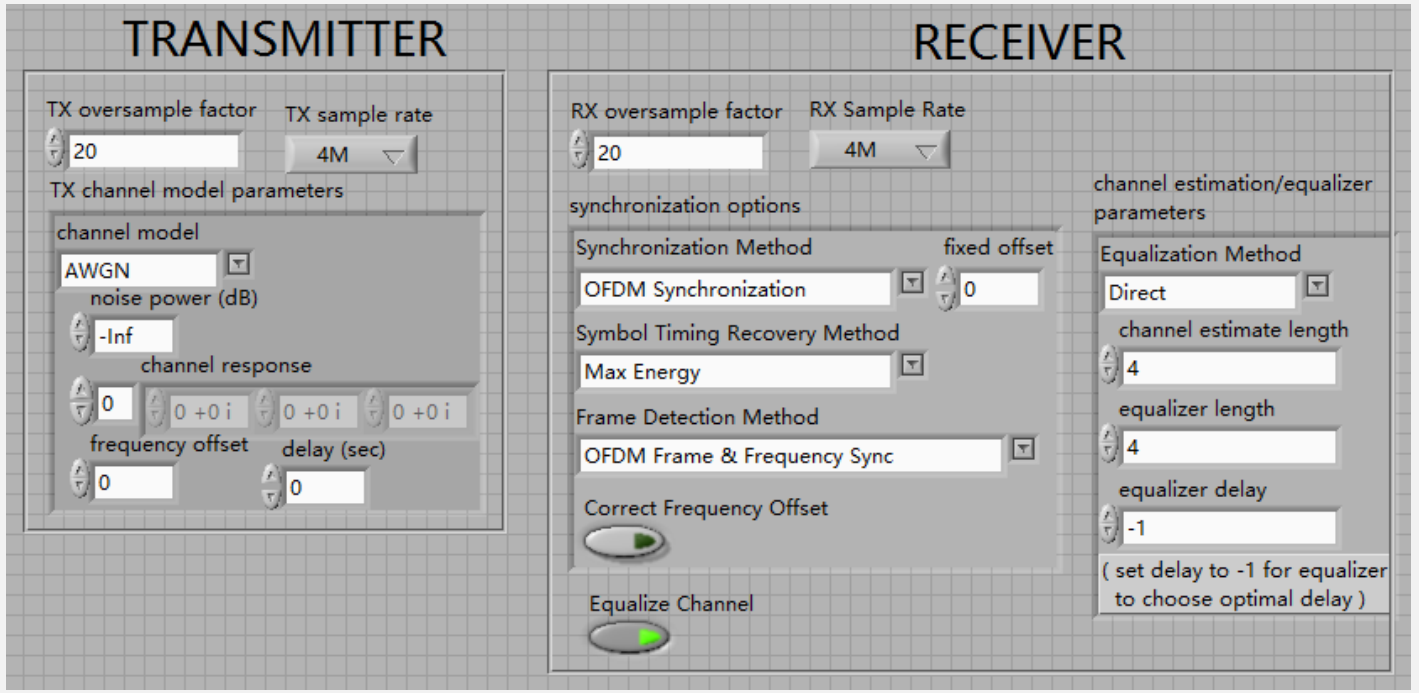
Task1: Frequency Selectivity of Wireless Channels

- Packet length = 500 bits
- Modulation type = QPSK
- Channel estimate length = 4
- FFT size (N) = 64
- Length of CP (L_c) = 8
- Null tones = {0, 31, 32, 33}



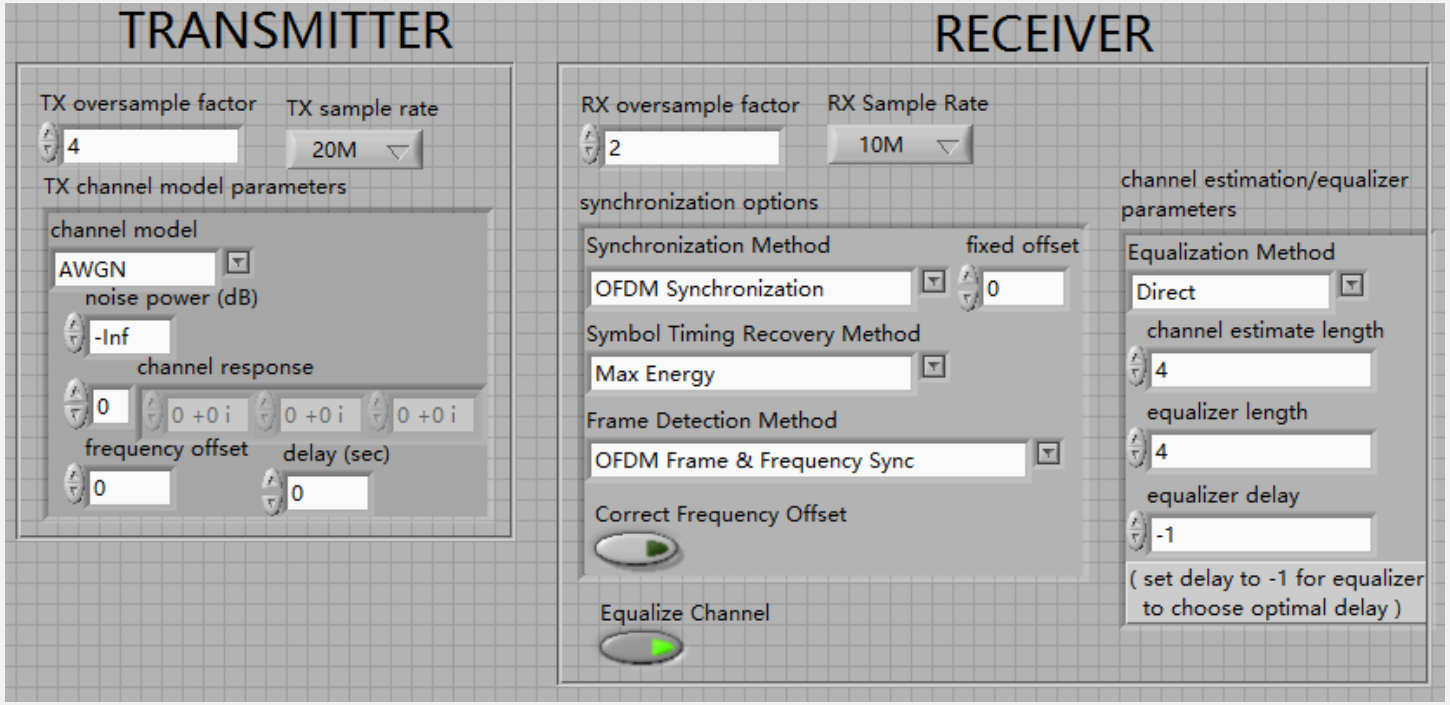
Task1: Frequency Selectivity of Wireless Channels

- TX sample rate = 4 MSamp/sec
- TX oversample factor = 20
- RX sample rate = 4 MSamp/sec
- RX oversample factor = 20
- Capture time = 2.4 msec

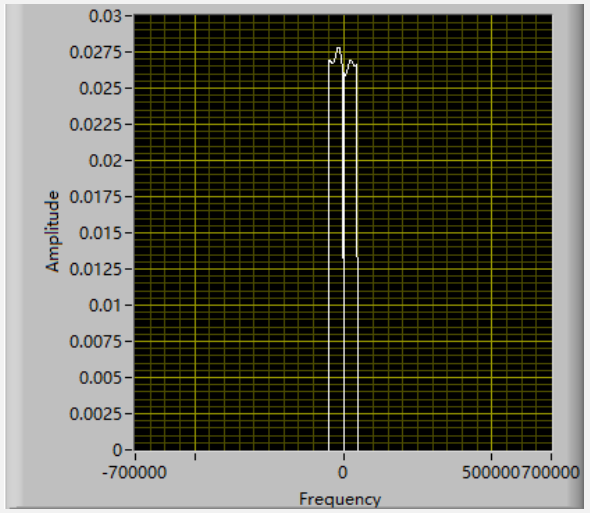


Task1: Frequency Selectivity of Wireless Channels

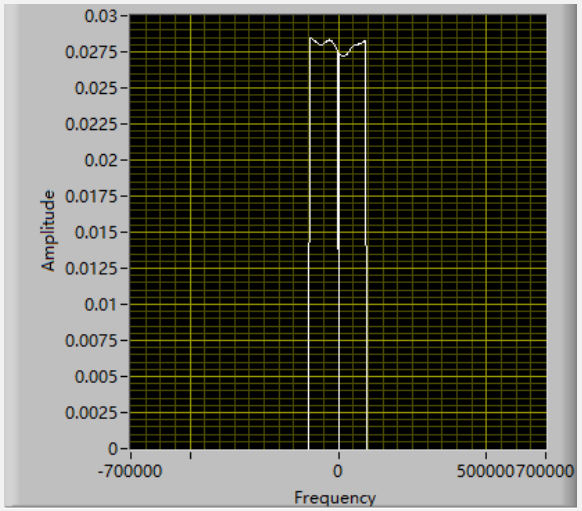
- TX sample rate = 20 MSamp/sec
- TX oversample factor = 4
- RX sample rate = 10 MSamp/sec
- RX oversample factor = 2
- Capture time = 100 μsec



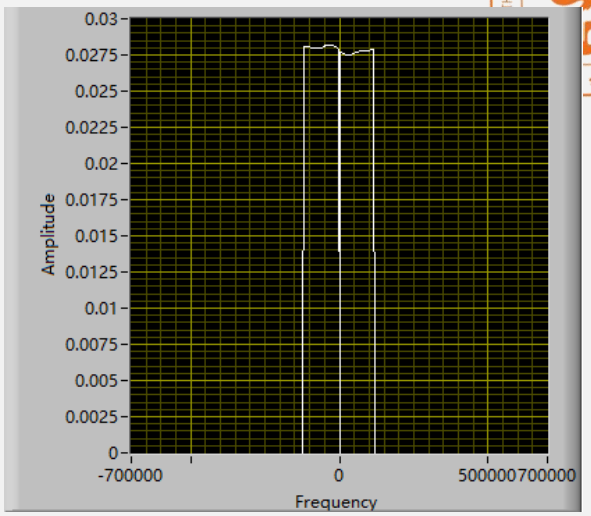
提示任务1：子载波数N=64，循环前缀Lc=8，射频载波fc=915MHz，上采样因子OFactor=4



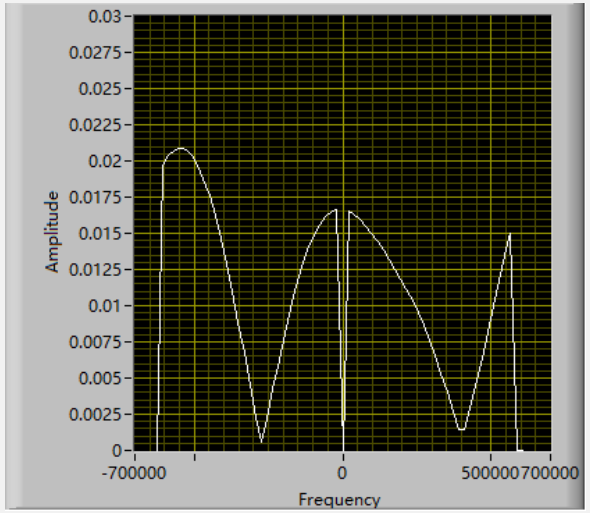
SampleRate=400KHz



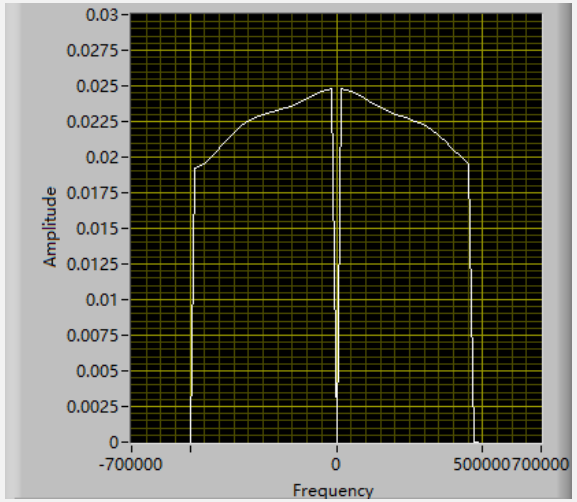
SampleRate=800KHz



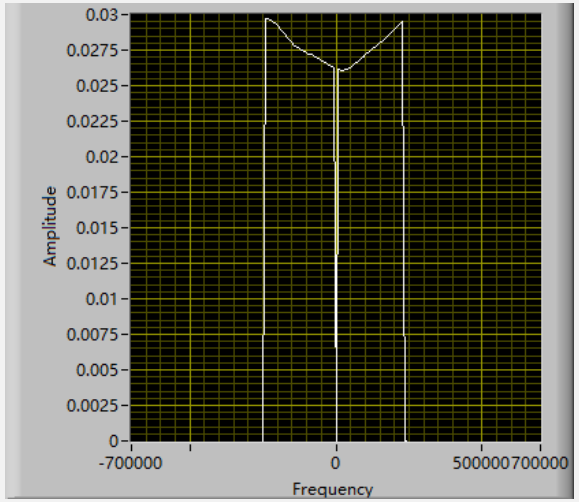
SampleRate=1MHz



SampleRate=5MHz

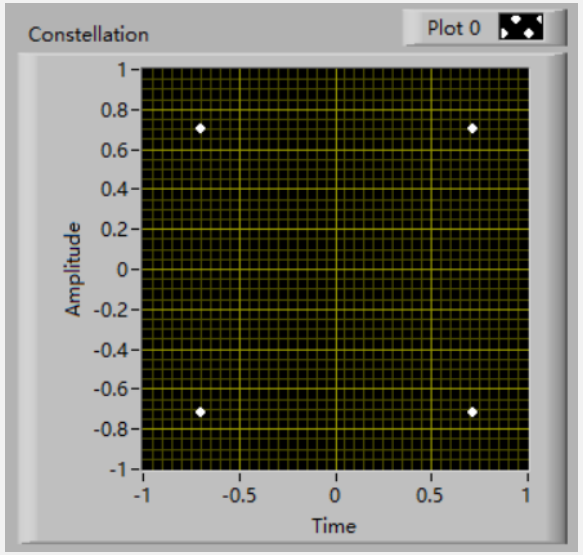


SampleRate=4MHz

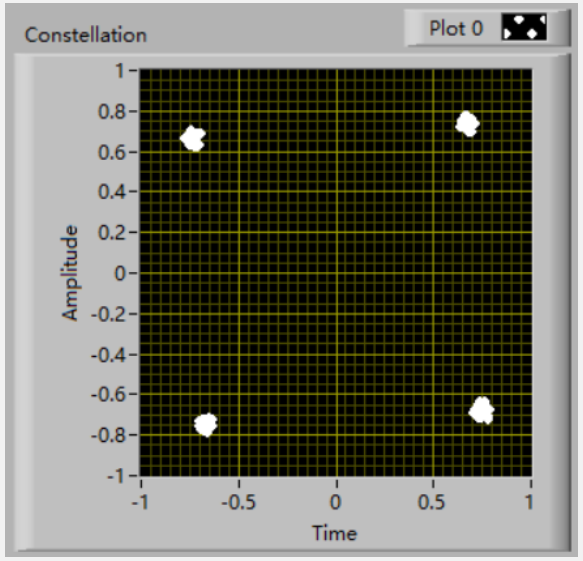


SampleRate=2MHz

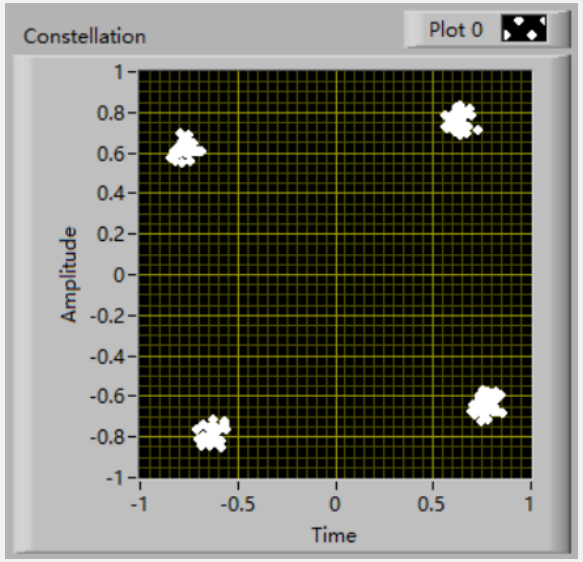
Task2: Frequency Offset



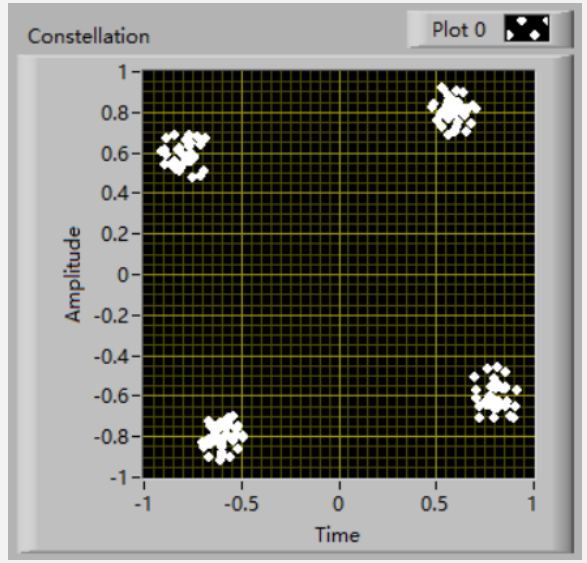
Frequency Offset: 0 Hz



Frequency Offset: 10 Hz



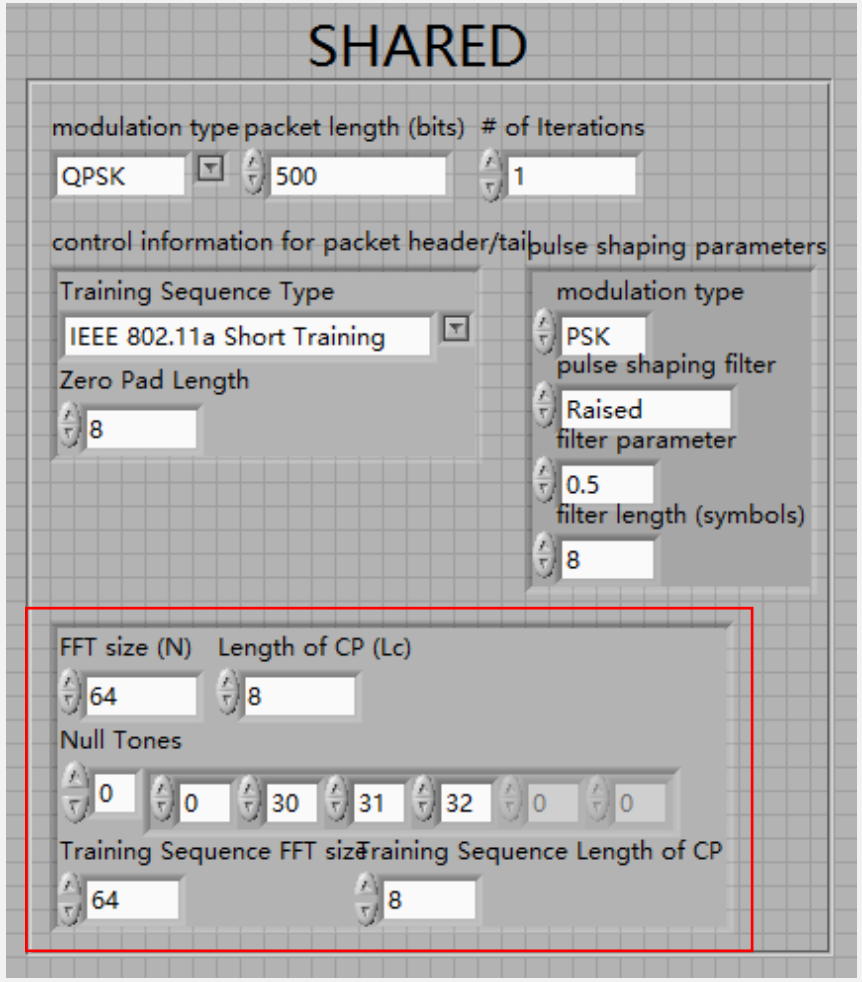
Frequency Offset: 20 Hz



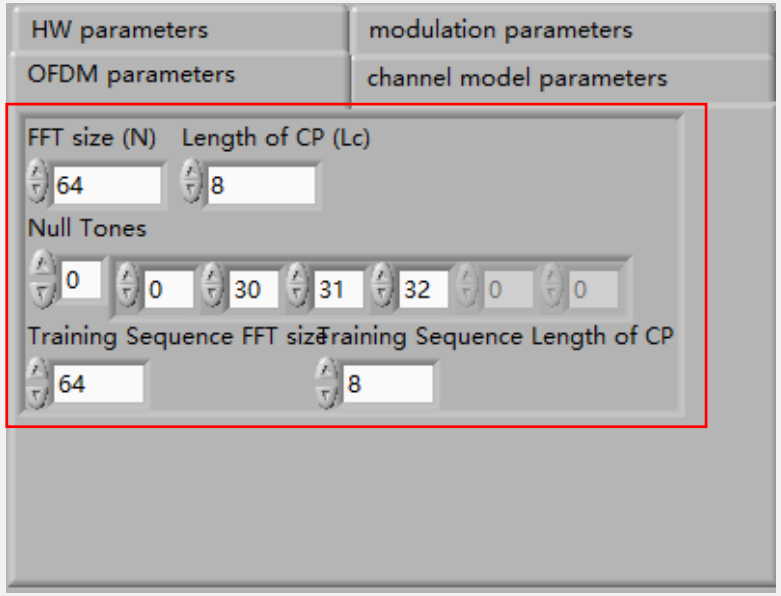
Frequency Offset: 30 Hz

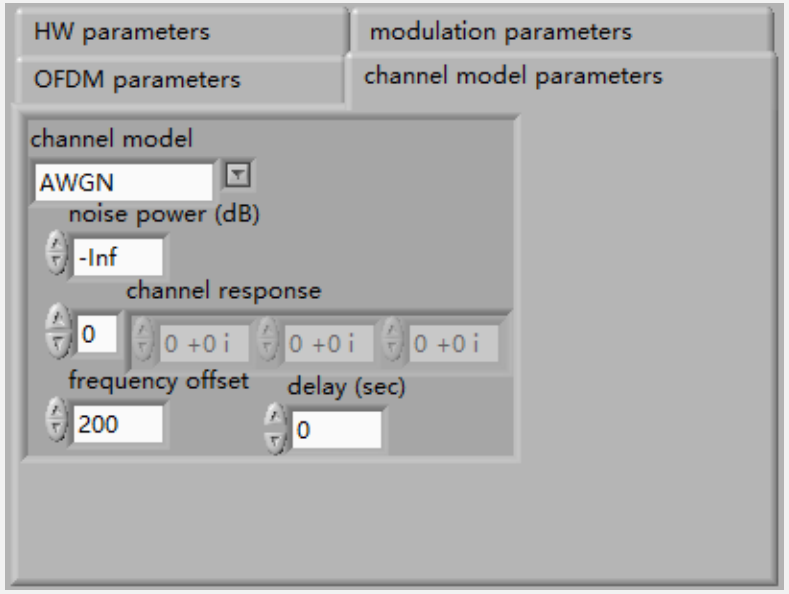
Task2: Sensitivity to Frequency Offsets

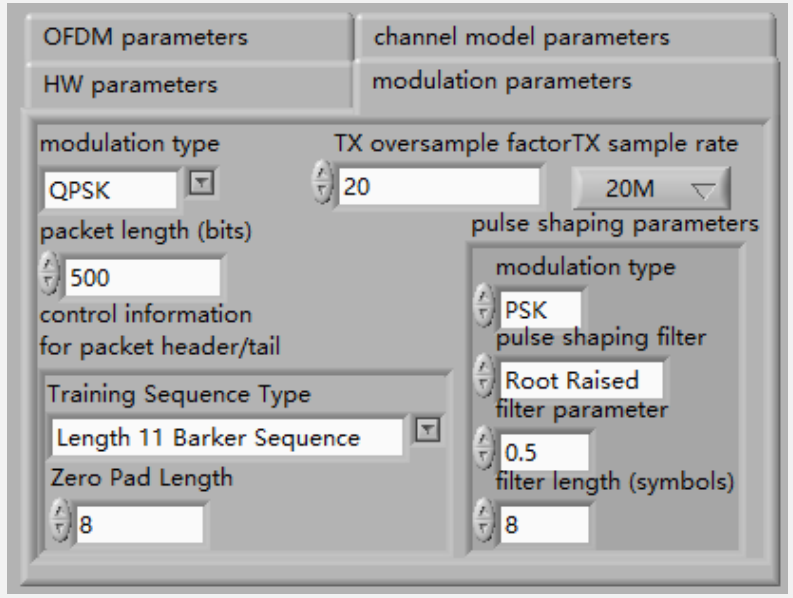
- TX sample rate = 20 MSamp/sec
- TX oversample factor = 20
- RX sample rate = 4 MSamp/sec
- RX oversample factor = 4
- Capture time = 500 μsec
- Frequency offset (Hz) = 200 Hz



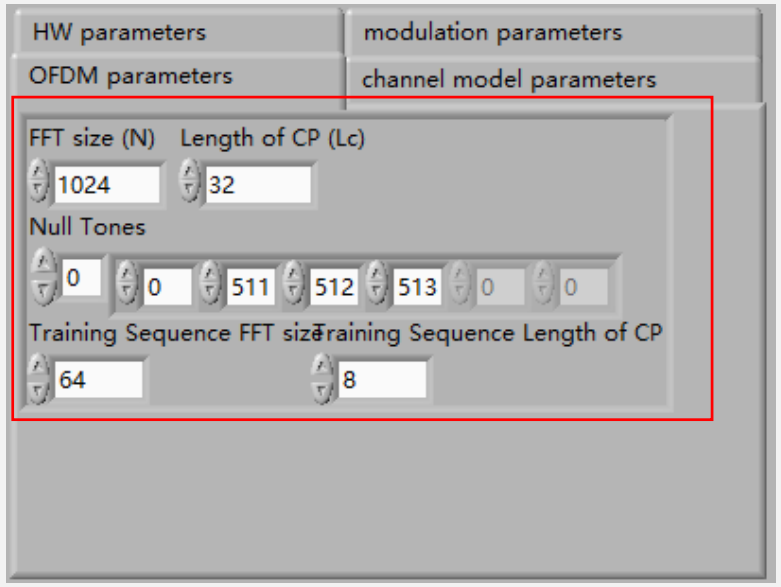
Task2: Sensitivity to Frequency Offsets

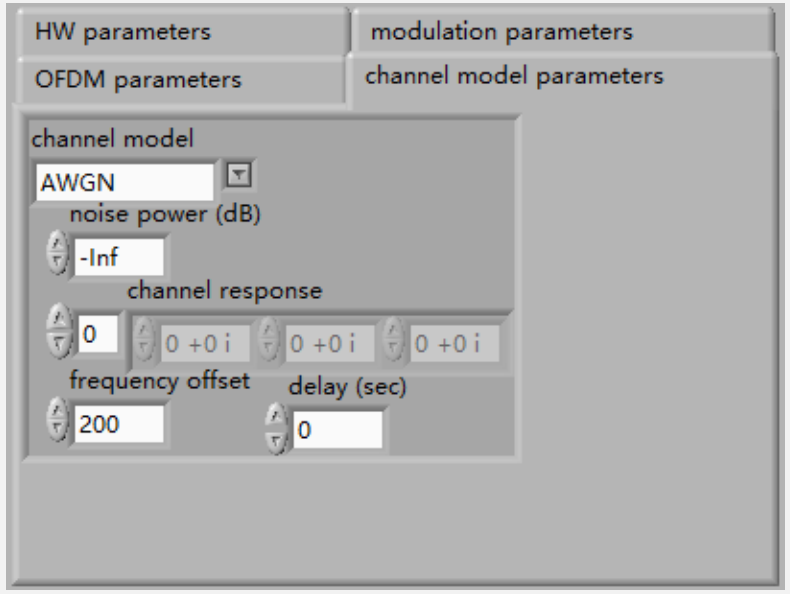


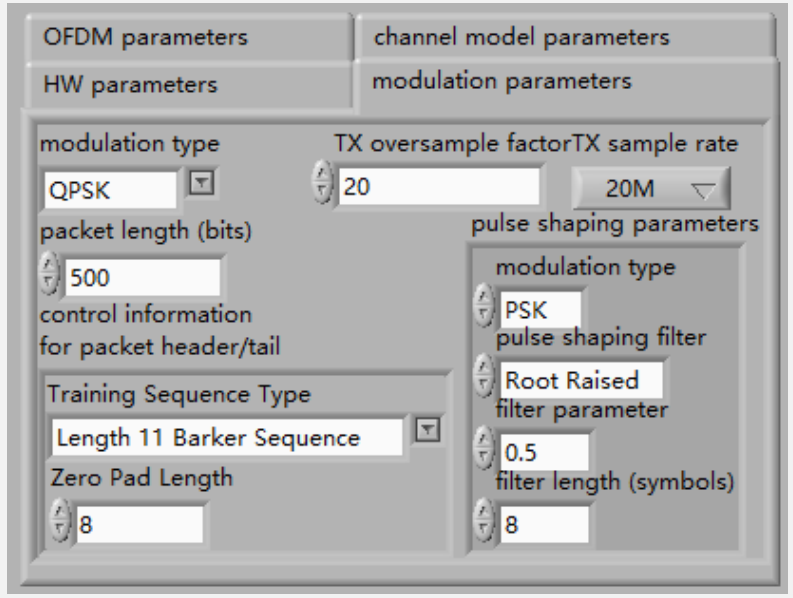


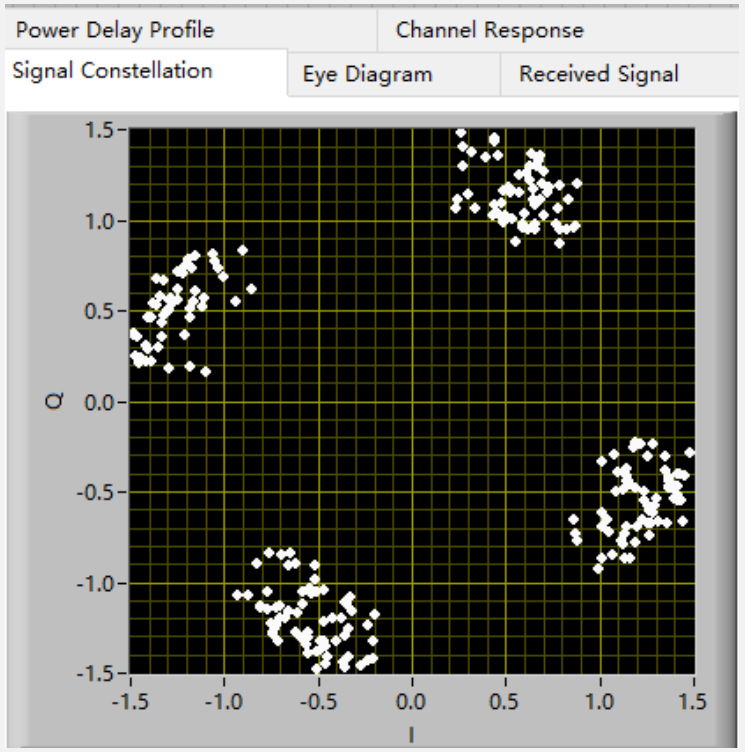


Task2: Sensitivity to Frequency Offsets

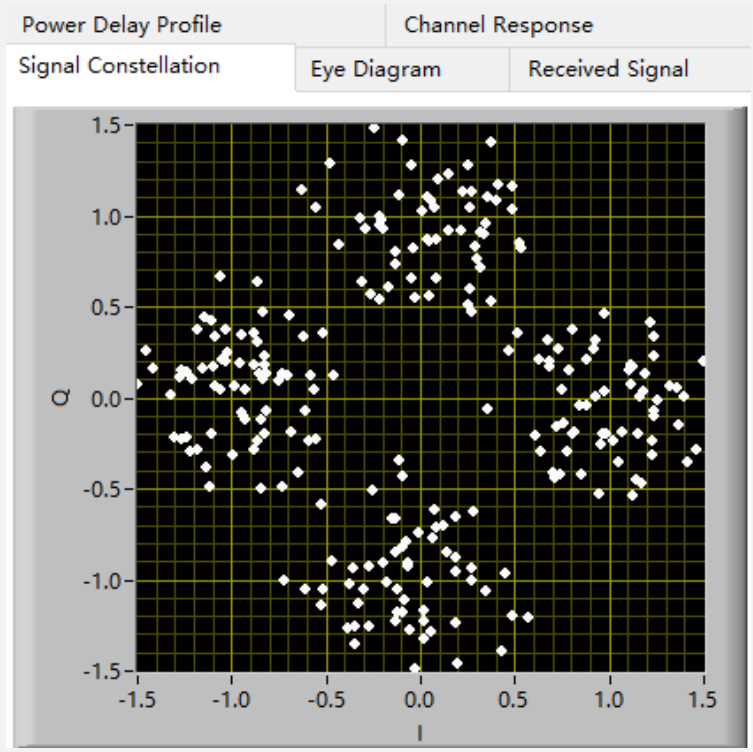




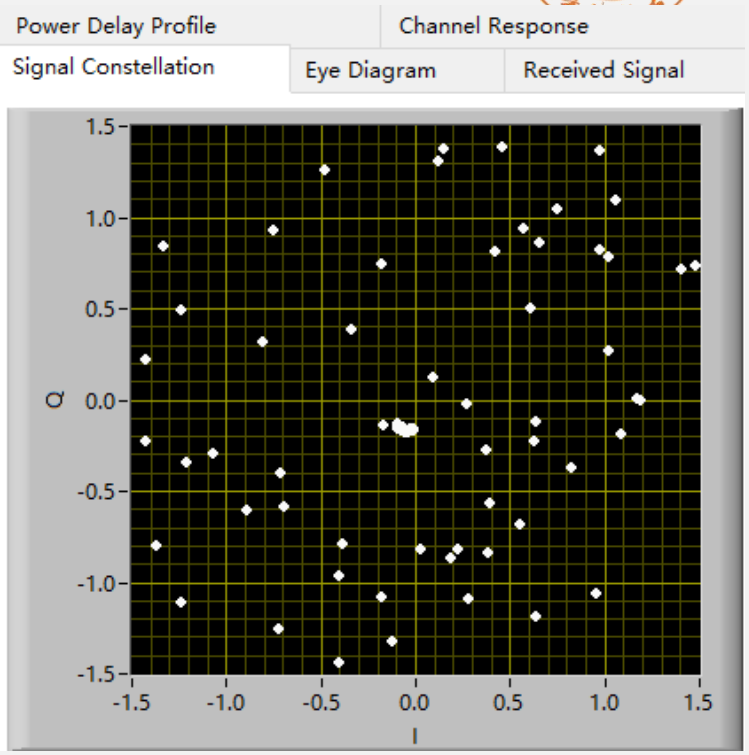




[20,20,4,4] N=64



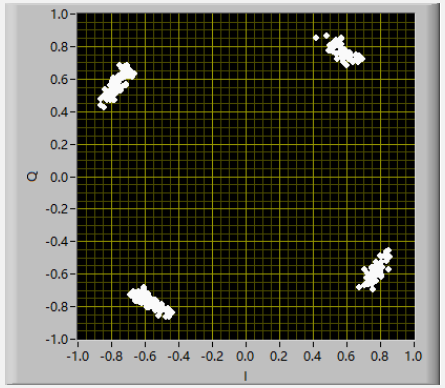
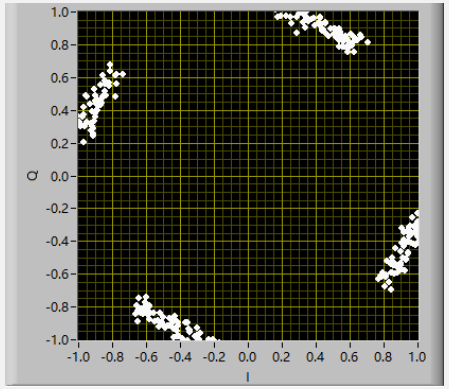
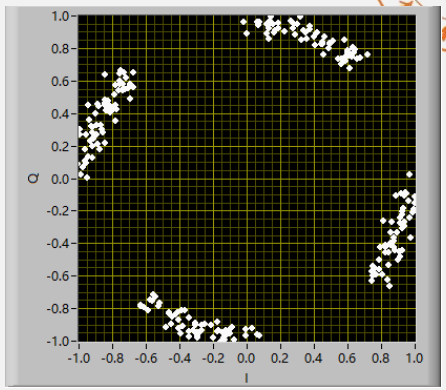
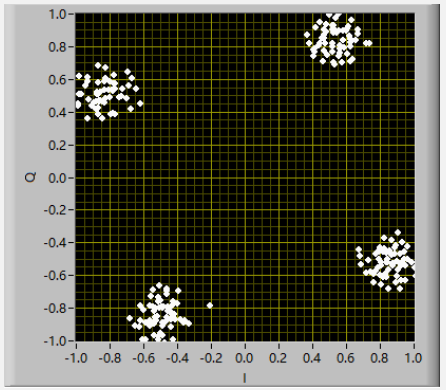
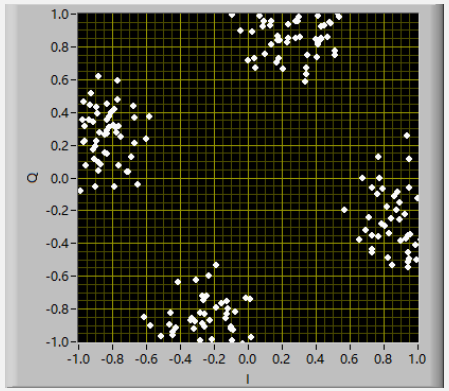
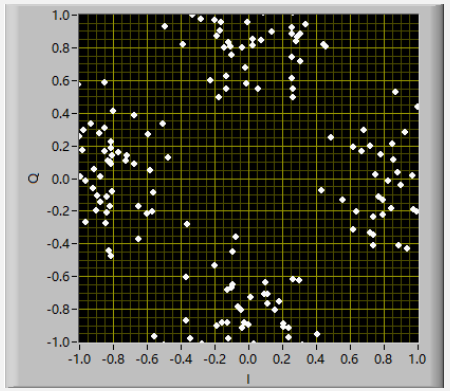
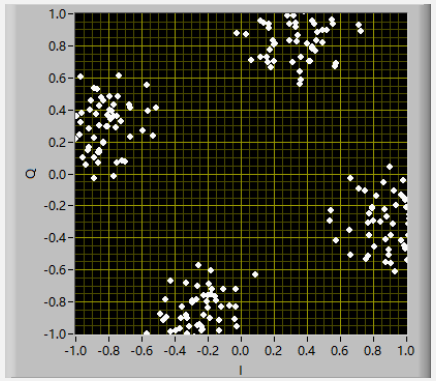
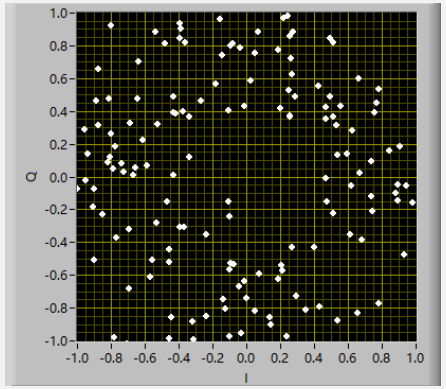
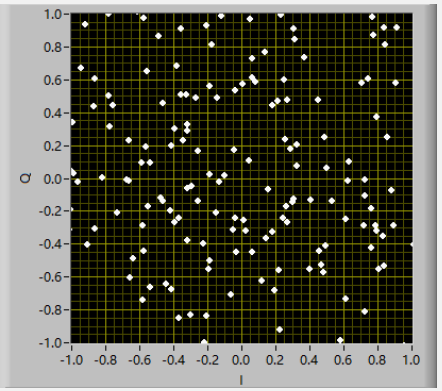
[4,4,4,4] N=1024

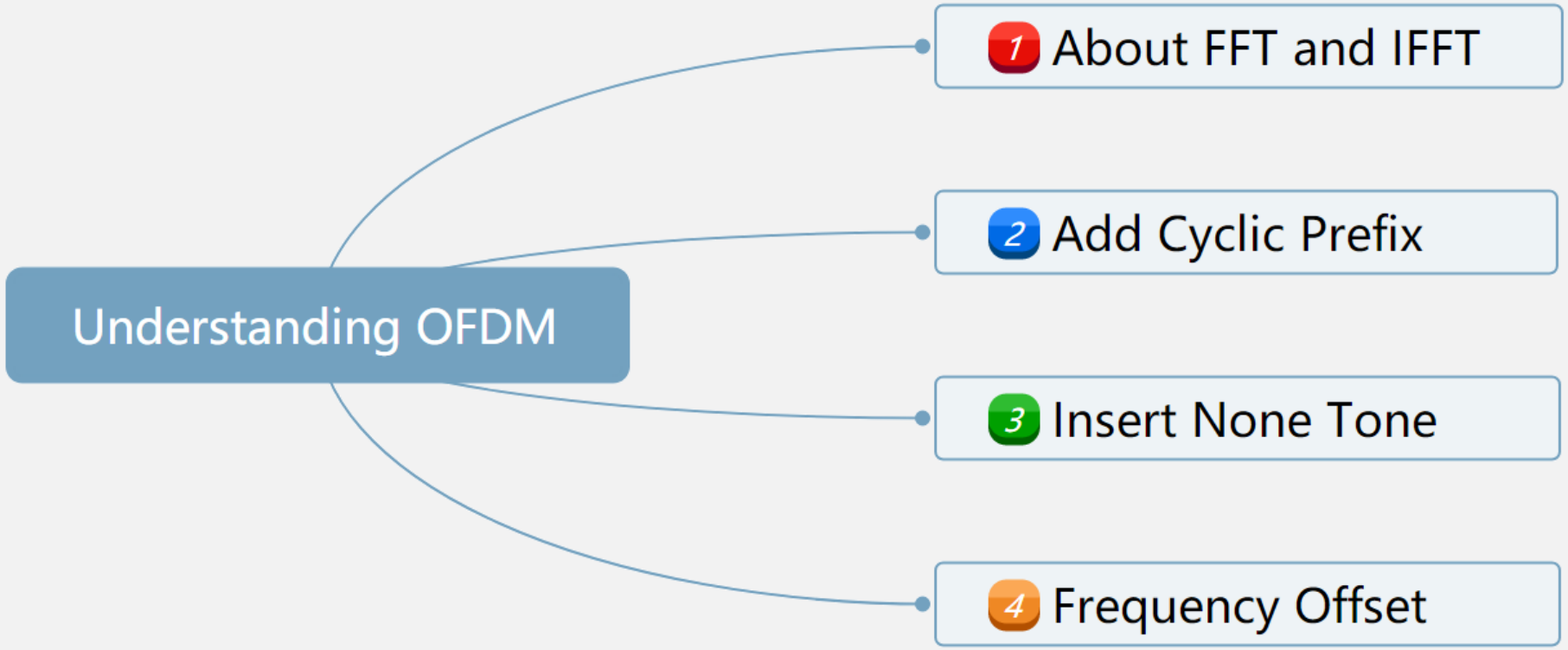


[20,20,4,4] N=1024

[Sample Rate, Over sample factor]

提示任务2：子载波数N=64/512/1024，循环前缀Lc=8/16/32，上采样因子OFactor=10，采样率SampleRate=4MHz

	频偏 df=50Hz	频偏 df=100Hz	频偏 df=150Hz
N=64			
N=512			
N=1024			


Understanding OFDM
1 About FFT and IFFT
2 Add Cyclic Prefix
3 Insert None Tone
4 Frequency Offset

- Question ?