University of Glasgow

ENG4052: Digital Communication 4 (2022-23)

Lab1: Digital Modulation and Demodulation

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Submission Date

1/25/2023

1 Introduction

Modulation and demodulation are keys in digital communication field. Digital modulation is the process of processing the coded information of signal source to make it suitable for transmission. Generally, a very high frequency relative to the baseband frequency sinusoidal signal, called carrier wave, is used to carry baseband signal. Then the modulated signal will be transmitted during communication. Modulation can change in amplitude, phase or frequency with the high frequency carrier according to the source signal changes. So, the three most basic digital modulation methods are ASK, FSK and PSK.

In this coding project, I will use Python3.10 in Visual Studio to implement and analyse two modulation and demodulation techniques, which are **Binary Phase Shift Keying** (BPSK or 2PSK) and **Quadrature Phase Shift Keying** (QPSK or 4PSK). Libraries NumPy1.23, SciPy1.9 are imported to implement advanced math operation. Library matplotlib3.6 is used to display graphics, which helps us to know about how signal changes after each processing.

2 BPSK modulation

2.1 Create original signal

In this lab, the transmitted information is student ID, a 7-digit decimal number. During transmission, digital signals need to be represented in binary, so the first thing is to convert the 7-digit decimal number to 24-digit binary number. My student ID is 2635088, and its binary number is 0010 1000 0011 0101 0101 0000. Method np.zfill(m) can fill zeros to high digits in a fixed m-digit binary number. Obviously, the first two zeros in this 24-digit binary number are filled by this way.

2.2 Modulation

Before modulation, the sample rate of signal source is initialised to 16, which means 1-bit digital signal has 16 sampling points. So, there will be 16*24 = 384 sample points for the original signal. Because of Nyquist limit, the normalized frequency of carrier wave is at least initialized to double sample rate, 1/8. There are two periods of carrier wave for one bit information during transmission. The coded information is shown in Fig. 2.1.

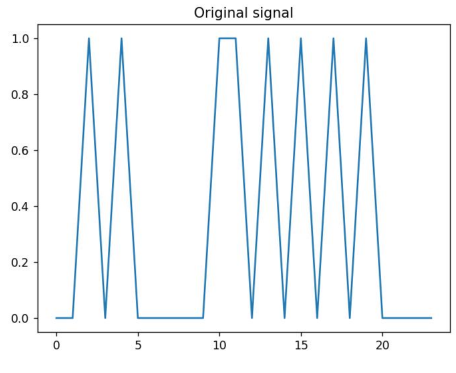


Figure 2.1 Original signal

A BPSK modulated signal can be expressed by following formular:

$$e_{2PSK}(t) = s(t)cos(2\pi f_c t)$$

In this expression, when original signal is 1, s(t) refers to 1; when signal is 0, s(t) refers to -1. In code, the expression 2*s[i]–1 can build the map of values from {0, 1} to {-1, 1}, corresponding to 180 degrees phase difference in the constellation diagram of binary code elements. And then a modulated signal of length 384 can be calculated with the 24 size of outer loop and the 16 size of inner loop. The modulated signal shows in the Fig. 2.2. The Fig. 2.3 is the frequency domain signal, where there is fundamental wave around 56 Hz.

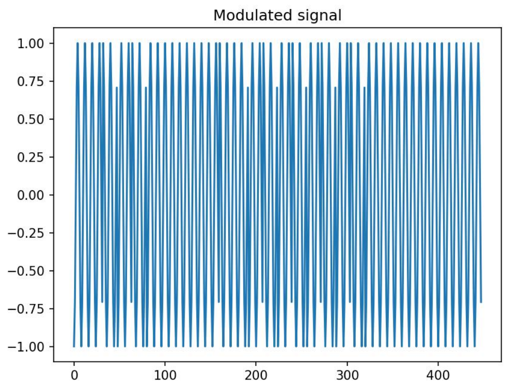


Figure 2.2 Modulated signal

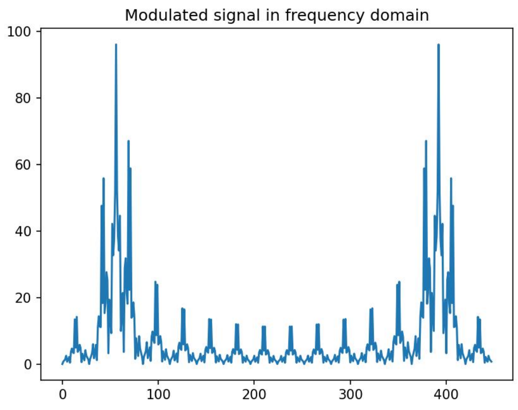


Figure 2.3 Modulated signal in frequency domain

We choose the first 6 periods of modulated signal to verify, corresponding to 001, as the Fig. 2.4 shows.

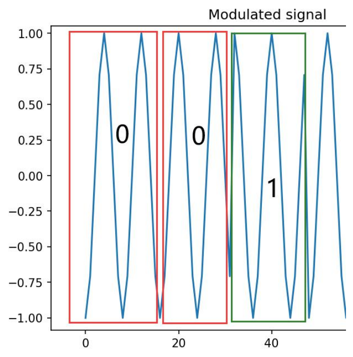


Figure 2.4 Verify modulated signal

2.3 Demodulation

Demodulation is the inverse process of modulation. After demodulation, the original signal will be recovery from demodulated signal. The code implements coherent demodulation method, which means a reference signal, the same frequency and phase as the carrier wave, is multiplied with the modulated signal. The Fig. 2.5 shows the processing of coherent demodulation.

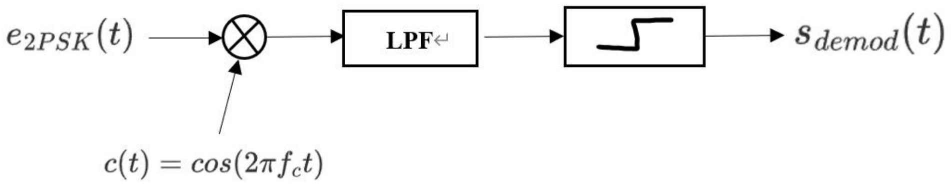


Figure 2.5 Processing of coherent demodulation

The first thing is that 384 modulated signals need to do the multiplication with reference sinusoidal wave in time order as the following expression shows.

$$e_{2PSK}(t)c(t) = s(t)cos(\omega_c t)cos(\omega_c t) = s(t)cos^2(\omega_c t)$$

The Fig. 2.6 shows the signal after multiplication. The Fig. 2.7 shows the signal in frequency domain with FFT, where there is secondary harmonic around 112 Hz.

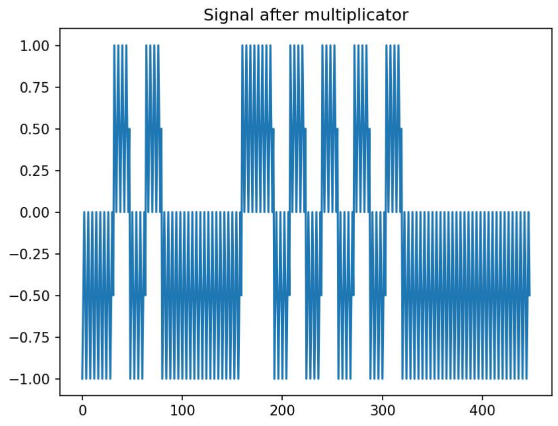


Figure 2.6 Signal after multiplicator

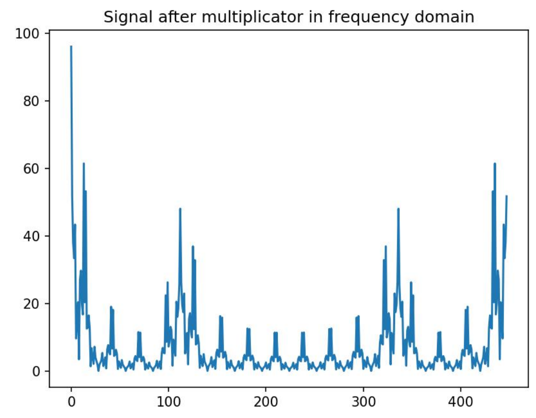


Figure 2.7 Signal after multiplicator in frequency domain

Mathematically, according to trigonometric identity transformation, the multiplier result can be expressed as following.

$$e_{2PSK}(t)c(t) = \frac{1}{2}s(t)(1 + cos(2\omega_c t))$$

The Fig. 2.8 shows the signal after low pass filter, and the Fig. 2.9 shows the filtered signal in frequency domain, where there is only low frequency information left. The secondary harmonics has been filtered by LPF compared with Fig. 2.7.

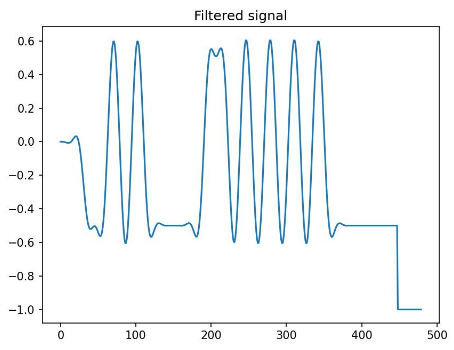


Figure 2.8 Filtered signal

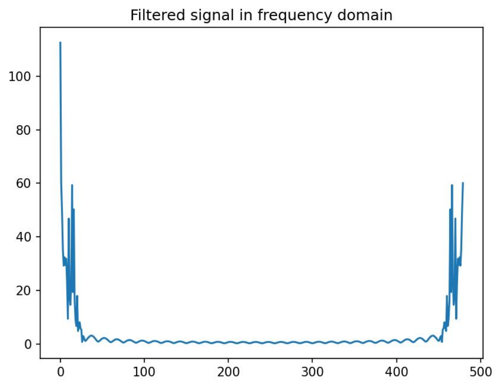


Figure 2.9 Filtered signal in frequency domain

Finally, after sample judgement of filtered signal, we can get demodulated signal, which should be the same as original signal. We can also verify the demodulated signal by comparing the Fig. 2.10

with the Fig. 2.1.

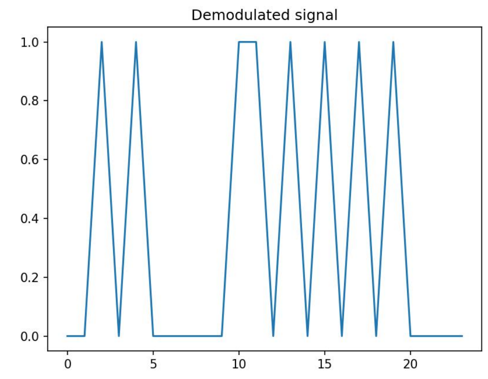


Figure 2.10 Demodulated signal

3 QPSK modulation

QPSK can be shown as two phases dependent BPSK where there is 90 degrees each other.

3.1 Modulation

Using the same original signal in BPSK, like the processing of BPSK modulation, QPSK modulation involves in-phase (I component) and quadrature (Q component). With the same formular of BPSK, I component need to multiply with cos wave, and Q component need to multiply by sin wave. The two wave have the same frequency and phase. The modulated signal is shown as following Fig. 3.1. And the Fig. 3.2 shows the modulated signal in frequency domain.

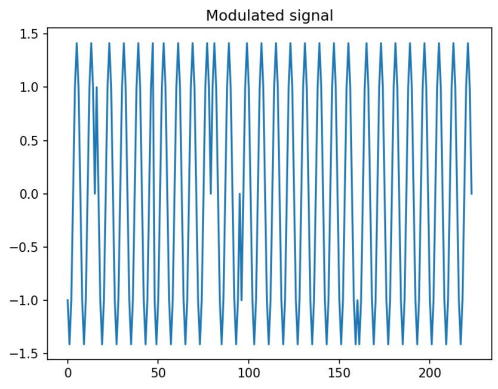


Figure 3.1 Modulated signal

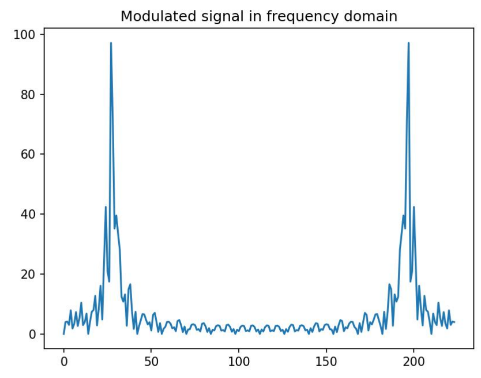


Figure 3.2 Modulated signal in frequency domain

3.2 Demodulation

When QPSK demodulation, IQ components also pass through separately in time order like processing of BPSK's demodulation. The two filtered signal are shown in the Fig. 3.3.

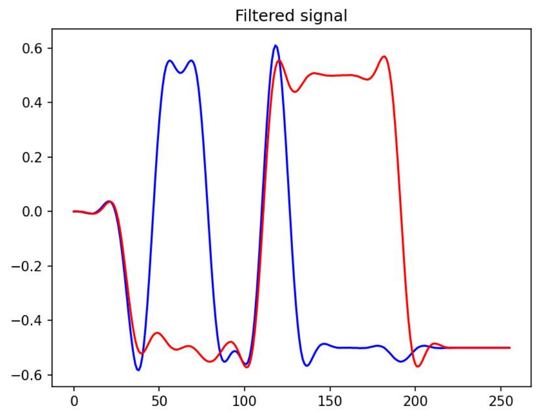


Figure 3.3 Filtered signal

Finally, we use sampling judgement methods to get the original signal as following Fig. 3.4, which is the same as Fig. 2.1.

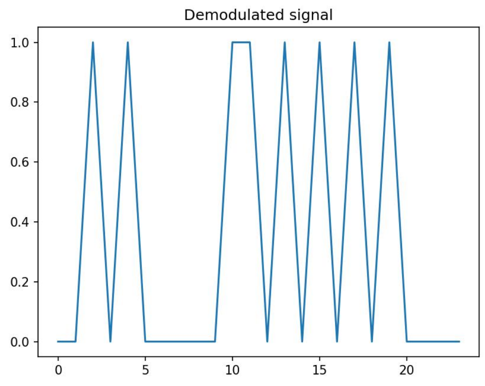


Figure 3.4 Filtered signal

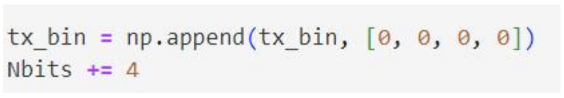
4 Conclusion

4.1 Filter delay

Because data stream passes through LPS filter, the result of LPS filter will generate the half of the number of taps. We need to append the same number of zeros after filtered data stream at the end separately.

4.2 Zeros fill after valid original signal

Although the transmitted signal has 24 bits, the edge effect will be generated when the low-pass filter does convolution during demodulation. Therefore, zero filling operation should be carried out at the end of the transmitted signal stream of BPSK and QPSK before modulation. Its noted that QPSK is a two-bit as one coded element, so the number of zero filling should be even. In the code, BPSK are filled with two zeros, and QPSK are filled with four zeros. The code are shown as following.



```python
tx_bin = np.append(tx_bin, [0, 0, 0, 0])
Nbits += 4
```

Appendix:

BPSK.py

```python
import numpy as np
from matplotlib import pyplot as plt
from scipy import fft
from scipy import signal

def bin_array(num, m):
    # Convert a positive integer num into an m-bit bit vector
    return np.array(list(np.binary_repr(num).zfill(m))).astype(np.bool)

# Decimal to binary
id_num = 2635088
Nbits = 24
tx_bin = bin_array(id_num, Nbits)
print(tx_bin)

plt.figure()
plt.title('Original signal')
plt.plot(tx_bin)
plt.show()

tx_bin = np.append(tx_bin, [0, 0])
Nbits += 2

# BPSK modulation
# initialisation
bit_len = 16 # 16 samples per bit, so sample rate = 1/16
fc = 0.125 # normalised carrier frequency because of Nyquist limit fc >= 2fs, so there will be 2 periods of carrier wave per bit
s = np.copy(tx_bin)
s_mod = np.empty(0)
t = 0
# based on IQ modulation
for i in range(Nbits):
    for j in range(bit_len):
        # BPSK s(t):{0, 1} => {-1, 1}
        s_mod = np.append(s_mod, (2*s[i] - 1) * np.cos(2*np.pi*fc*t))
        t += 1
```

```
plt.figure()
plt.title('Modulated signal')
plt.plot(s_mod)
plt.show()

plt.figure()
plt.title('Modulated signal in frequency domain')
plt.plot(np.abs(fft.fft(s_mod)))
plt.show()

# Demodulation(coherent detection method)
s_demod_multi = np.empty(0)
t = 0
for i in range(Nbits):
    for j in range(bit_len):
        s_demod_multi = np.append(s_demod_multi, s_mod[t] * np.cos(2*np.pi*fc*t))
        t += 1

plt.figure()
plt.title('Signal after multiplicator')
plt.plot(s_demod_multi)
plt.show()

plt.figure()
plt.title('Signal after multiplicator in frequency domain')
plt.plot(np.abs(fft.fft(s_demod_multi)))
plt.show()

# Do filter, try to change coeffients of fir filter
numtaps = 64 # 32
cutoff = 0.1
fir = signal.firwin(numtaps, cutoff)
s_demod_lpf = signal.lfilter(fir, 1, s_demod_multi)
s_demod_lpf = np.append(s_demod_lpf, -np.ones(numtaps//2))

plt.figure()
plt.title('Filtered signal')
plt.plot(s_demod_lpf)
plt.show()

plt.figure()
plt.title('Filtered signal in frequency domain')
plt.plot(np.abs(fft.fft(s_demod_lpf)))
plt.show()

# Sample judgement
s_demod_bin = np.empty(0)
for i in range(Nbits):
    t = (2*i+1)*bit_len//2 + numtaps // 2    # use median sample to judge original signal
    s_demod_bin = np.append(s_demod_bin, s_demod_lpf[t] > 0.0)
print(s_demod_bin[:24])

plt.figure()
plt.title('Demodulated signal')
plt.plot(s_demod_bin[:24])
plt.show()
```

QPSK.py

```
import numpy as np
from matplotlib import pyplot as plt
from scipy import fft
from scipy import signal

def bin_array(num, m):
    # Convert a positive integer num into an m-bit bit vector
    return np.array(list(np.binary_repr(num).zfill(m))).astype(np.bool)

id_num = 2635088
Nbits = 24
tx_bin = bin_array(id_num, Nbits)
print(tx_bin)

tx_bin = np.append(tx_bin, [0, 0, 0, 0])
Nbits += 4

plt.figure()
plt.title('Original signal')
plt.plot(tx_bin[:24])
plt.show()

# QPSK modulation
# initialise constants and variables
fc = 0.125
bit_len = 16
s = np.copy(tx_bin)
s_mod = np.empty(0)
```

```
t = 0

# based on IQ component, constellation diagram {45, 135, 225, 315}
# 4PSK, 1 Baud presents 2 bits, two bits into one group
for i in range(0, Nbits, 2):
    for j in range(bit_len):
        s_mod  =  np.append(s_mod,  (2*s[i]  -  1)  *  np.cos(2*np.pi*fc*t)  +  (2*s[i+1]  -  1)  *
np.sin(2*np.pi*fc*t))
        t += 1

# Show modulated signal
plt.figure()
plt.title('Modulated signal')
plt.plot(s_mod)
plt.show()

# Use fft to frequency analyse
plt.figure()
plt.title('Modulated signal in frequency domain')
plt.plot(np.abs(fft.fft(s_mod)))
plt.show()

# Demodulation, using coherent detection,
# First step: IQ components respectively multiply the carrier wave and qudrature carrier wave
s_demod_i = np.empty(0)
s_demod_q = np.empty(0)
t = 0

for i in range(0, Nbits, 2):
    for j in range(bit_len):
        s_demod_i = np.append(s_demod_i, s_mod[t]*np.cos(2*np.pi*fc*t))
        s_demod_q = np.append(s_demod_q, s_mod[t]*np.sin(2*np.pi*fc*t))
        t += 1

# Second step: use low-pass filter to filter harmonic wave
# initilise filter coefficients
numtaps = 64
fir = signal.firwin(numtaps, 0.1)

# IQ component do filter
s_filt_i = signal.lfilter(fir, 1, s_demod_i)
s_filt_i = np.append(s_filt_i, -np.ones(numtaps//2)/2)
s_filt_q = signal.lfilter(fir, 1, s_demod_q)
s_filt_q = np.append(s_filt_q, -np.ones(numtaps//2)/2)
```

```
plt.figure()
plt.title('Filtered signal')
plt.plot(s_filt_i, color = 'b')
plt.plot(s_filt_q, color = 'r')
plt.show()

# Sample judgement
# in fact, QPSK can be considered as two qudrature BPSK
s_demod_bin = np.empty(0)
for i in range(0, Nbits, 2):
    t = (i+1)*bit_len//2 + numtaps//2
    s_demod_bin = np.append(s_demod_bin, s_filt_i[t] > 0.0)
    s_demod_bin = np.append(s_demod_bin, s_filt_q[t] > 0.0)

s_demod_bin = s_demod_bin[:-1]
print(s_demod_bin)

plt.figure()
plt.title('Demodulated signal')
plt.plot(s_demod_bin[:24])
plt.show()
```