Communication System

Lab 4: OFDM Transmission Using USRP

B10901125 電機四 賴禹宏

B11901062 電機三 陳威齊

B11901110 電機三 陳璿吉

Part 1. A Successful Wi-Fi Based OFDM Transmission (Finished at 2024-11-22 20:03, modified at 2024-11-26 22:30)

A. Transmit a frame with 5 OFDM data symbols, modulated with 4-QAM. Plot the received frame in the time domain and mark the STS, LTS, and data symbols.

Figure 1 shows that received frame in time domain. The dotted vertical lines represent the onset of each symbol.

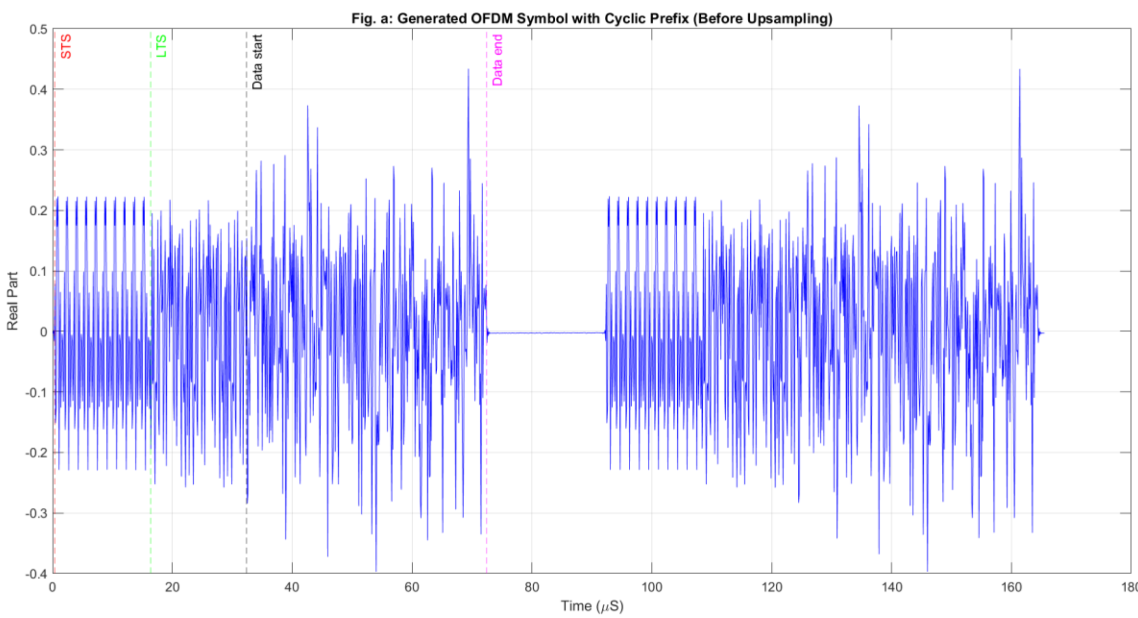

Figure 1. Received 5 OFDM Signal

B. Transmit a frame with 100 OFDM data symbols. Plot the OFDM symbol constellation before and after equalization side by side.

Figure 2.1 and Figure 2.2 depict the received OFDM symbol before equalization. Since the quality of channel varies in each simulation, we observe that Figure 2.1 and Figure 2.2 are very different. Such difference will influence the bit error rate.

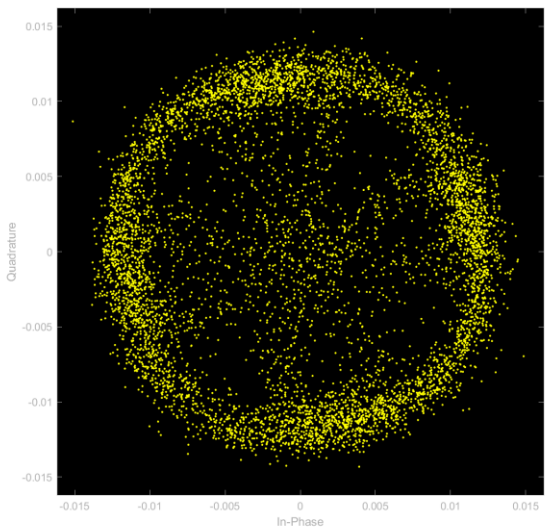

Figure 2.1. 100 symbols, without equalization

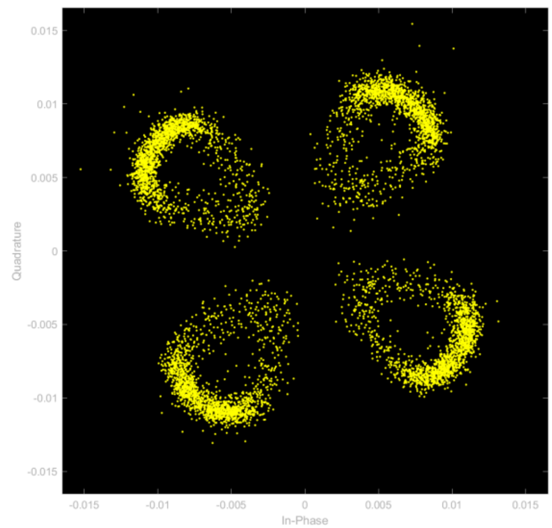

Figure 2.2. 100 symbols, without equalization

Figure 3.1 and Figure 3.2 depict the received OFDM signal after equalization of Figure 2.1 and Figure 2.2, respectively. After equalization, we can observe that there are 4 clusters, but we can observe that almost all points were "moved" to one of the clusters in Figure 3.2.

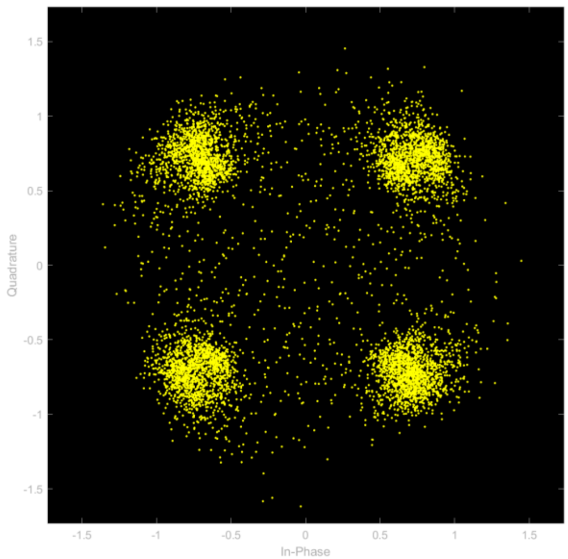

Figure 3.1. 100 symbols, after equalization

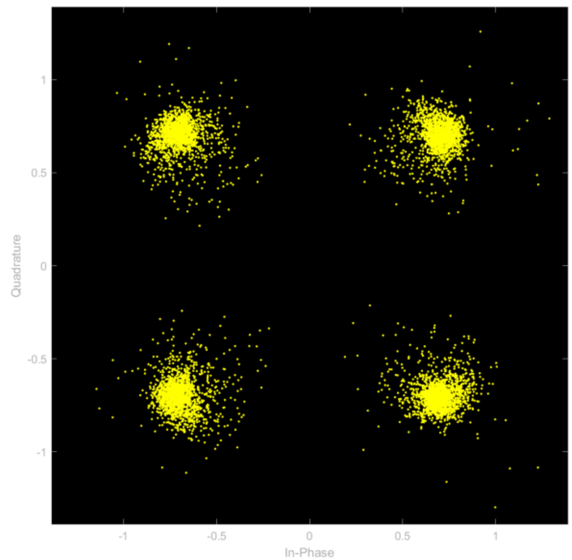

Figure 3.2. 100 symbols, after equalization

C. Repeat frame transmission 100 times and calculate BER.

In our simulation, the default gain of the hardware is set to 10. Our average BER is 0.0068595, which supports the effect of equalization shown in Figure 3.1 and 3.2.

D. Vary the transmit power digitally and calculate BER in each power setting as in C. Plot BER vs SNR. What happens when the transmit power is too large?

Since we cannot measure the power of noise, we changed the gain values and used relative SNR to examine the BER. We have tried gain values 0, 5, 10, 15, 20, 25, and 30 dB. The result is shown in Table 4.

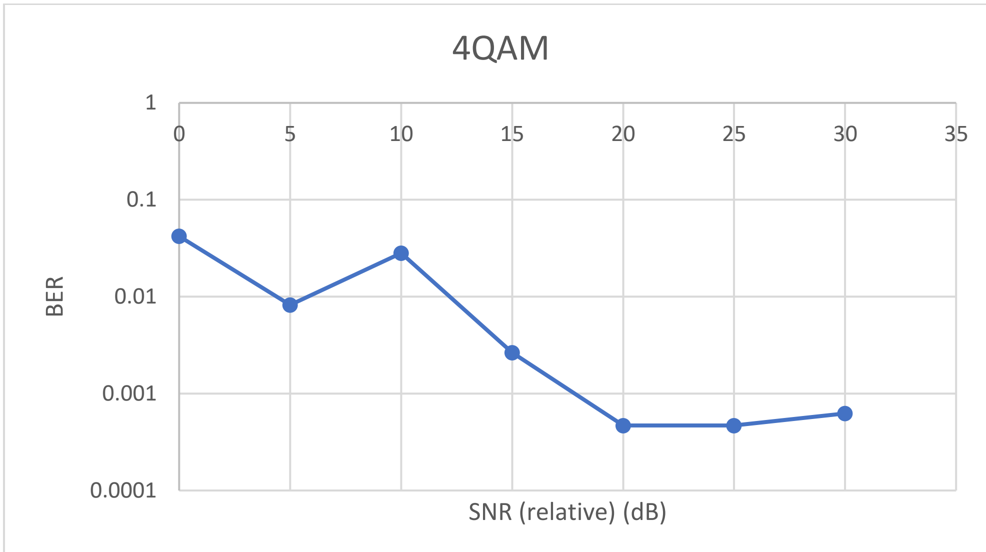

Table 4. BER vs SNR in 4-QAM

The power amplifier in USRP is linear only in a limited range. When the gain is set too large, the input signal is subject to nonlinear distortion due to amplifier saturation. Since the input signal is distorted by the hardware, there may be additional frequency components in the signal. After modulation and demodulation, such distortion may contribute to the increase in BER. However, the BER is also related to modulation order and channel quality, nonlinear distortion may not be obvious.

E. Repeat D for 16-QAM. Plot BER vs SNR.

The result is shown in Table 5.

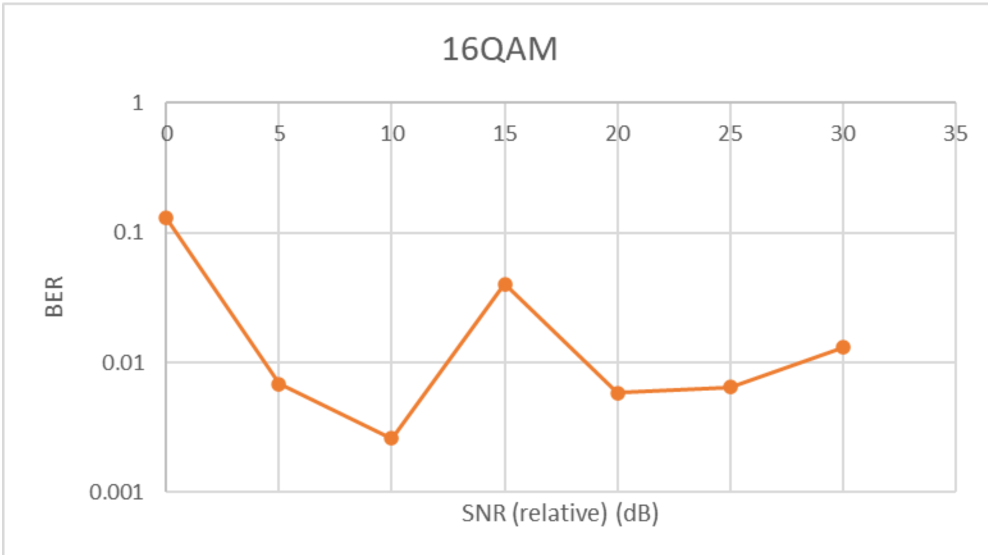

Table 5. BER vs SNR in 16-QAM

When we change the modulation scheme to 16-QAM, the result is different from 4-QAM. As the modulation order increases, the bit error rate increases because there are more possibilities. Moreover, we observe an increase in BER for larger gain. This may be attributed to the nonlinear distortion of the signal.

Part 2. CFO Estimation (Finished at 2024-11-26, 22:37)

A. Add artificial CFO (5 ppm) to the transmitted frame (with 100 OFDM symbols). Plot the received constellation without CFO correction.

   Figure 6 represents the result.

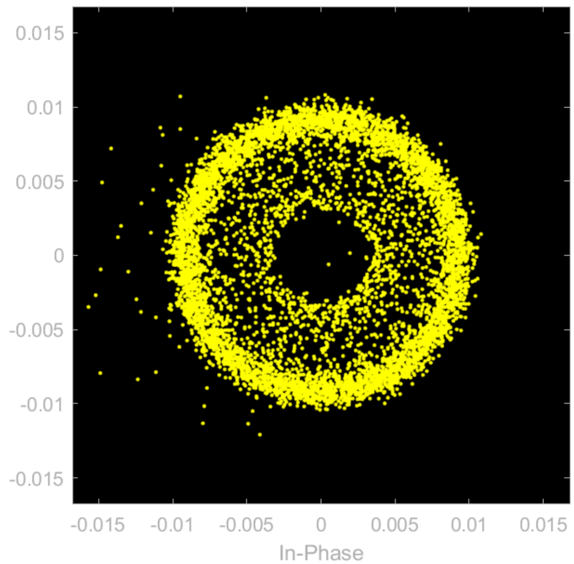

Figure 6. Received constellation without CFO correction.

   From the figure, we can observe that the symbols form a circle due to the phase shift.

B. Estimate CFO from the received frame. Compare the value with the added artificial CFO.

   We add an artificial CFO of 5 ppm in the simulation. From the calculation presented in the lecture slide, we obtained a CFO of 5.165376 ppm. Such slight difference contributed to the rotation of symbols in the constellation map.

C. Apply the estimated CFO for the received frame. Plot the received constellation.

The result is presented in Figure 7.

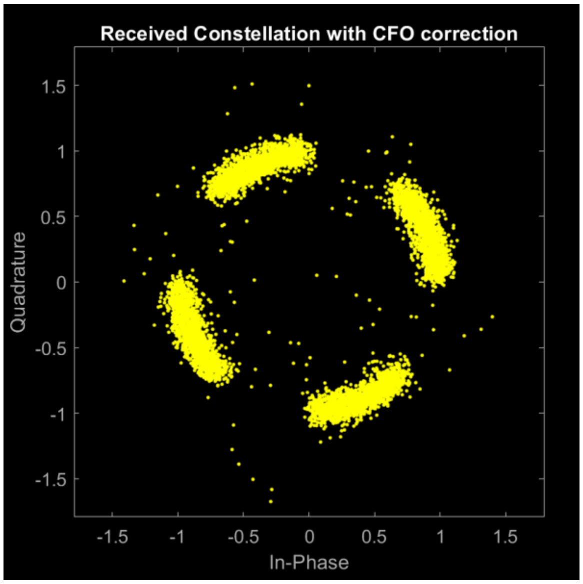

Figure 7. Received constellation with CFO correction.

We can see that the symbols exhibit some phase shift. This comes from the mismatch between our artificial CFO and the real CFO.

D. Keep increasing the artificial CFO. Improve your CFO estimation algorithm to the best you can. Report the largest CFO that can be corrected using your algorithm.

In theory, we use the formula form maximum frequency offset, which yields

$$\Delta f_{\text{max,LTS}} = \frac{10\ \text{MHz}}{2 * 16} = 312.5\ \text{KHz} \rightarrow 347\ \text{ppm}\ (f_c = 900\ \text{MHz}) \tag{1}$$

$$\Delta f_{\text{max,STS}} = \frac{10\ \text{MHz}}{2 * 64} = 78.125\ \text{KHz} \rightarrow 86.8\ \text{ppm}\ (f_c = 900\ \text{MHz}) \tag{2}$$

We simulated the BER of received signal under different CFO values, which is given in Table 8.

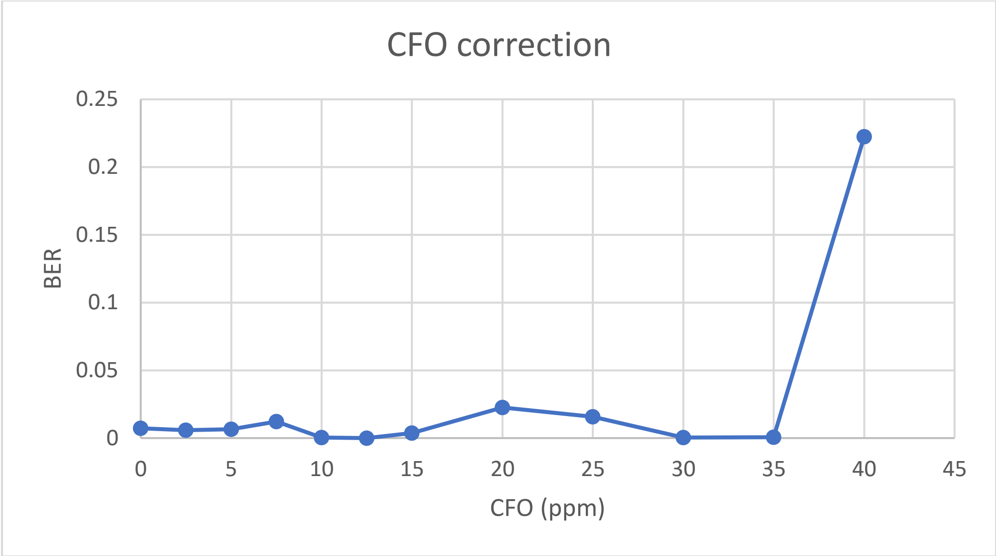

Table 8. BER of received signal under different CFO.

As depicted in Table 8, we can see that the Maximum Likelihood Estimation shown in the lecture slides is robust up to 35 ppm.

E. Explain your CFO estimation algorithm.

We first used the method presented in the lecture slides (i.e., Maximum Likelihood Estimation). Judging from the simulation result, this estimation is good enough.

However, we may also use a method called Best Linear Unbiased Estimator (BLUE)[1]. This made use of U identical preambles (e.g., STS or longer LTS). BLUE calculates auto-correlation functions for different delays. It then computes the phase differences between these functions, which help estimate the CFO. A weighted average of these phase differences gives the final CFO estimate. The method works best when U is large, and the CFO estimate range is between $-Uf_s/2$ and $Uf_s/2$. This technique is also adaptable to preambles with sign changes.

[1] M. Morelli and U. Mengali, "Carrier-frequency estimation for transmissions over selective channels," in IEEE Transactions on Communications, vol. 48, no. 9, pp. 1580-1589, Sept. 2000