Communication Systems Laboratory
Lab 4: OFDM Transmission Using USRP

Report Due: 11:59 pm, Nov. 4, 2025

The goals of this lab are: (a) implementation of Wi-Fi-based OFDM transmission on USRP and (b) CFO estimation and correction. One homework submission per team. As before, please use the MATLAB live script (.mlx).

[Part 1] A Successful Wi-Fi-Based OFDM transmission (64 points)

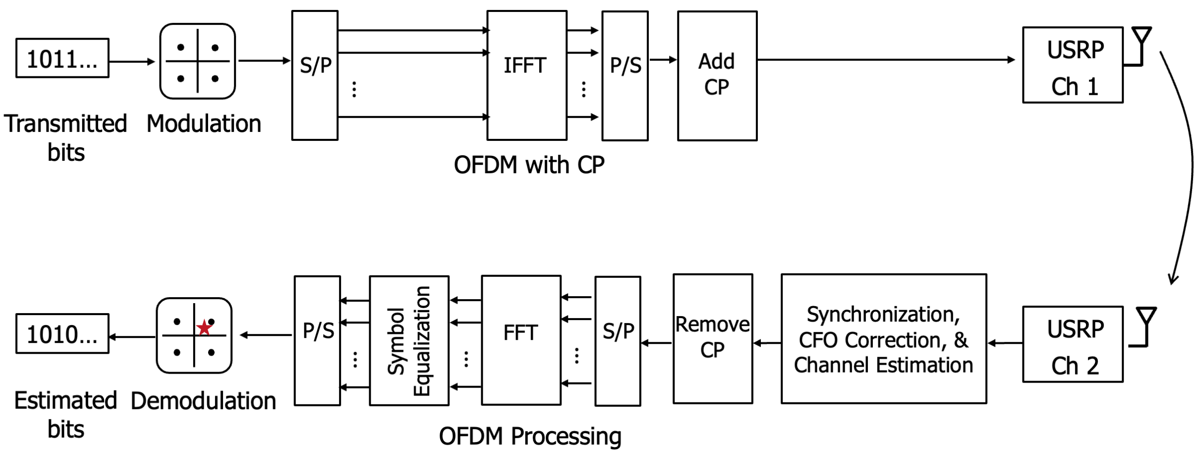

Figure 1. Experimental procedure.

In Part 1, you will generate the Wi-Fi OFDM-based waveform and transmit it using a USRP. The questions will walk you through a typical over-the-air experiment that characterizes the relationship between BER and SNR. The parameters are as follows:

- FFT size = 64. Size of cyclic prefix = 16
- Carrier frequency f_c: as assigned by the TA.
- Sampling rate = 10 MHz.
- Use data tones and pilot tones as defined in 802.11a/g.
- Use BPSK for pilot tones. Use specified modulation for data tones.

Experiment Procedure:

- Turn on USRP and configure USRP: Channel 1 – Transmit; Channel 2 – Receive.
- Configure transmit power (and receiver gain if needed).
- Generate a frame with STS, LTS, and OFDM data symbols. Beware of using known bits for the pilot (BPSK) and unknown bits for the data transmission (varying modulation).
- Send the generated frame to USRP channel 1 and receive it from channel 2. You may need to repeat the transmission many times until the transmission is successful.
- Process the received frame: detect the start of the frame, estimate and correct for carrier frequency offset, estimate the channel, equalize the received symbols, and demodulate the received symbols.
- Compare the transmitted bit and obtain the bit error rate.
- Turn off the USRP.

Transmit and receive the Wi-Fi OFDM-based frame

(1) Generate a frame with STS, LTS, and 5 OFDM symbols using 4-QAM modulation for the data tones. Pre-pad and post-pad the frame with 100 zeros (100 zeros, STS, LTS, 5 OFDM symbols, 100 zeros). Plot the generated frame in the time domain with the correct time unit in microseconds. Please mark the STS, LTS, and data symbols. Notice that the sampling rate of the USRP is 10 MHz, which is different from the sampling rate of 20 MHz in Lab 3, and thus, the frame duration is different.

(2) Transmit the frame generated in (1). Plot the received frame in the time domain with the correct time unit in microseconds. As in (1), please mark the STS, LTS, and data symbols. Please make sure the received signal is of proper signal strength – it should not show signs of clipping, and the signal can be easily distinguishable from the zeros. (Hint: to ensure capturing a whole frame, you may configure the USRP to capture a longer duration than the transmit frame.)

(3) Apply the frame synchronization algorithm you designed in Lab 3 to identify the correct beginning of the OFDM symbols. Please plot the match filter result.

(4) Based on the result, what index marks the beginning of the first long training symbols?

(5) Transform the first long training symbol into the frequency domain and perform channel estimation. Plot the magnitude and phase of the channel across the subcarriers, from subcarrier index -26 to 26 (zero-subcarrier in the center).

(6) Similar to (5), perform channel estimation using the second long training symbol. Plot the magnitude and phase of the channel across the subcarriers, from subcarrier index -26 to 26 (zero-subcarrier in the center). For comparison, plot the results using the first long training symbol on the same figure with a clear legend.

(7) What is the subcarrier spacing? What frequencies do subcarriers -26, 0, and 26 correspond to in this USRP transmission?

(8) Find the samples corresponding to the OFDM symbols. Before equalization, plot the received constellation for data tones. What do you observe?

(9) We skip the carrier frequency offset estimation and correction since we use the same USRP for transmission and reception in this experiment. Thus, without correcting the carrier frequency offset, equalize the OFDM symbols using the estimated channel in (5) and (6) in the frequency domain. Plot the equalized received constellation for the data tones. Also, plot the transmitted constellation in the same figure for comparison. What do you observe?

(10) Use the samples of the 5 OFDM symbols for signal strength calculation, and use the padded zeros for noise calculation. What is the SNR of this received frame in dB?

Characterize BER vs SNR in the experiment

(11) Instead of transmitting only 5 OFDM symbols in each frame, increase to 100 OFDM symbols per frame. Repeat frame transmission 100 times and calculate BER.

(12) Following (11), how long does it take for you to complete 100 frame transmissions? How many bits are transmitted to obtain this BER value?

(13) Many wireless experiments aim for a BER level in the order of 10^{-9}. If we want to reach a BER precision in the order of 10^{-9}, how many times do you need to repeat the frame transmission? How much time is expected if we were to reach a BER precision in the order of 10^{-9}?

(14) Vary the transmit power digitally and calculate BER in each power setting as in (11). Plot BER

vs SNR in dB. Please explore a range of power so that you observe BER reduction with increasing transmit power. Also, increase the transmit power until clipping happens, which may result in additional errors despite a large received signal strength. Please briefly describe your figure. As a side note, a trick to vary the transmit power is to vary only the amplitude of the OFDM symbols, not the STS and LTS. As a result, you will be able to detect the beginning of the frame regardless of the power of the OFDM symbols. However, when using this method, you need to remember the amplification factor between LTS and the OFDM symbols and scale the estimated channel accordingly.

(15) Repeat (14) for 16-QAM. Plot BER vs SNR in dB.

(16) Compare the results for 4-QAM in (14) with the results for 16-QAM in (15). What do you observe?

[Part 2] CFO Estimation and correction (36 points)

In this lab, we will add an artificial CFO to the transmitted waveform, estimate the CFO for the received signals, and further perform CFO correction.

(1) Add a 5 ppm artificial CFO to the transmitted frame (with 100 OFDM symbols). Transmit and receive the frame using the same USRP. Estimate the channel using the two long training symbols. Plot the magnitude and phase of the estimated channel for both estimates across the subcarriers, from subcarrier index -26 to 26 (zero-subcarrier in the center). What do you observe?

(2) Use the estimated channel in (1) for equalization. Plot the received constellation with equalization but without CFO correction (as in Part 1). What do you observe?

(3) Estimate the CFO from the received frame using two consecutive short training symbols. What is the estimated CFO? Next, estimate the CFO using two non-consecutive short training symbols, in particular, the 8th and the 10th short training symbols. What is the estimated CFO using non-consecutive short training symbols?

(4) Estimate the CFO from the received frame using two consecutive long training symbols. What is the estimated CFO? Compared to the known added artificial CFO value, what is the CFO estimation error?

(5) Using the estimated CFO in (4), apply the CFO correction to the waveform. After the CFO correction, estimate the channel again using the two long training symbols. Plot the magnitude and phase of the estimated channel for both estimates across the subcarriers, from subcarrier index -26 to 26 (zero-subcarrier in the center). What do you observe?

(6) Use the estimated channel in (5) for equalization. Plot the equalized received constellation of the data tones. What do you observe?

(7) Use the four pilot tones to track the residual CFO and correct the data tones accordingly. With the assistance of the pilot tones, plot the received constellation. What do you observe?

(8) Increase the artificial CFO and improve your CFO estimation algorithm to the best you can. For the artificial CFO values you tested, plot the true CFO on the x-axis and the estimated CFO on the y-axis in a scatter plot. What is the largest CFO your algorithm can correct?

(9) Explain your CFO estimation algorithm in (8).

Grading:

- 4 points for each problem. 100 points in total for 25 questions.