Communication Systems Laboratory
Lab 5: Cross-Device OFDM Transmission

Demo: in class, Nov. 18, 2025
Report Due: 11:59 pm, Nov. 18, 2025

The goal of this lab is (a) cross-USRP transmission and reception, and (b) performance enhancement using multiple antennas. One homework submission per team. As before, please use the MATLAB live script (.mlx). **Please submit two .mlx files**: one for Part 1, and the other for Part 2, as they have different antenna setups.

[Part 1] Cross-USRP Wi-Fi-Based OFDM transmission (59.5 points)

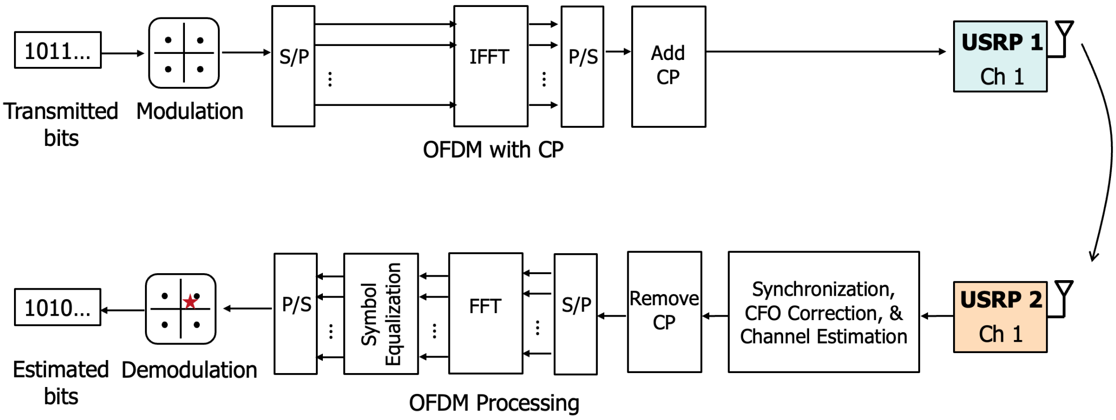

Figure 1. Signal generation and processing using two USRPs.

While transmission and reception happen on the same USRP in Lab 4, different USRPs are used for transmission and reception in Lab 5. In addition to the USRP-2920 used in Lab 4, each team will also get a USRP-2901. The configuration of the two USRP devices differs slightly; please refer to the TA's instructions for configuring the USRP-2901. Please make sure the two USRPs have the same antenna configuration (i.e., operating at the same frequency). Both USRPs are connected to the same computer for control.

Parameters used in this lab are the same as in Lab 4 if not stated otherwise. One parameter change in Lab 5 is to set the default sampling rate = 1 MHz, not 10 MHz in Lab 4. This modification is expected to make CFO estimation and correction less challenging.

In [Part 1], both USRPs are configured to use a single antenna. Later in [Part 2], USRP-2901 will be configured to use two antennas.

Resolve Cross-Device Synchronization Issues

Transmit a frame with 100 OFDM data symbols with 4-QAM modulation using USRP 1. Receive the frame with USRP 2. Develop a strategy that allows complete capture of a whole frame at USRP 2. For example, you can try:

- Append/prepend zeros to the transmit frame to make the beginning and the end of the frame visually apparent.
- Capture a longer range in the time domain than the transmitted frame.
- Retransmission scheme with ACK/NAK from USRP 2.
- …

(1) Describe your network configuration that allows the computer to control two USRPs. More specifically, please describe the network configuration at your computer (IP & subnet mask) and the IP addresses of the two USRPs. Explain how this network configuration allows you to control two USRPs from your computer.

(2) Explain the strategy you employ to ensure complete capture of a whole frame at USRP 2.

(3) Using the above proposed strategy, plot the received signal in the time domain at USRP 2. Mark the beginning and the end of the frame to show a successful capture of a whole frame.

(4) Without CFO correction, plot the received constellation (only the data tones). Do you observe the constellation rotating?

(5) Estimate the CFO of the received frame. What is the estimated CFO? Also, please explain your CFO estimation process. For instance, whether the CFO is estimated from STS, LTS, or both.

(6) Apply CFO correction to the received frame and then estimate the channel. Plot (i) the magnitude and (ii) the phase of the estimated channel vs subcarrier, with zero subcarrier in the middle. Describe and discuss the figure.

(7) Perform equalization on the received frame. Plot the CFO-corrected and equalized received constellation (only the data tones). Do you still observe the constellation rotating?

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

(9) Demodulate the received signal at USRP 2 and calculate the bit error rate for this single frame. What is the BER? The goal is to obtain no (or very few) bit errors.

(10) Change the modulation to 16-QAM and repeat the experiment. Plot the CFO corrected, equalized, and pilot-assisted constellations as in (8).

(11) Following (10), what is the BER using 16-QAM modulation? How does it compare to the BER using 4-QAM in (9)?

Establish a Framework to Transmit Multiple Frames

Expanding your framework to transmit multiple frames, each with different random bits.

(12) Transmit and receive 20 frames, each with 100 OFDM symbols using 16-QAM modulation. Calculate the BER for each of the 20 frames. Plot BER per frame vs frame number, and provide the total BER for the 20 frames. The goal is to show that your transmission framework is robust enough that you can consistently collect usable experimental data. Thus, the BER should be rather consistent across different frames.

(13) Calculate the BER per subcarrier based on the received 20 frames. Plot BER vs subcarrier. Describe and analyze the BER figure you obtain. Is there frequency-dependent BER behavior? If some subcarriers experience higher bit errors, what do you think is the reason?

(14) Please select three (or more) transmission distances (please measure the distance). At each distance, transmit and receive 20 frames, each with 100 OFDM symbols using 16-QAM modulation as in (13). Plot the total BER vs transmission distance, showing that the BER increases with distance.

Transmissions with a Higher Sampling Rate

In this part, increase the sampling rate from 1 MHz to 10 MHz.

(15) To transmit and receive at a sampling rate of 10 MHz, what is the master clock rate of both USRPs and the decimation and interpolation factors you use? What is the maximum master clock rate you can set?

(16) Configure your USRP-2901 with a 20 MHz master clock rate. Transmit 20 frames using 16-QAM modulation. Start the timer when the first frame is received and stop it after receiving 20 frames. Repeat the experiment for sampling rates of 1 MHz and 10 MHz, present your results, what do you observe, and why?

(17) Following (16), decode the 20 received frames when using a sampling rate of 10 MHz, and plot the BER versus frame number for both 1 MHz and 10 MHz sampling rates. You can reuse your results in (12). Can your receiving method stably synchronize and decode the data? Does changing the sampling rate affect your method? (There is no correct answer — it is acceptable if your system occasionally fails to decode.)

[Part 2] Multi-Antenna Operation (21 points)

In [Part 2], USRP-2901 will be configured to use two antennas.

Maximum Ratio Combining

In this part, we transmit with one antenna and receive with two antennas. Configure USRP-2920 as the TX, and USRP-2901 as the RX. As in Part 1, transmit a frame with 100 OFDM data symbols with 16-QAM modulation. Set the sampling rate to 1 MHz.

(1) Plot the time domain signals of the signals received at the two antennas with the correct time unit in microseconds, showing that both antennas successfully capture the whole frame.

(2) Process the two received signals separately. Find the beginning of the frames, i.e., the first sample of STS. What are the two indices that mark the beginning of the frames? Are the two indices the same?

(3) Following (2), process the two received signals separately as in [Part 1], including CFO correction and channel estimation. Using the estimated channel per subcarrier, calculate the SNR per subcarrier. On the same figure, plot the SNR per subcarrier across subcarriers for RX antenna 1 and RX antenna 2, respectively, for comparison. What do you observe? (Hint: the noise power at RX can be obtained when TX is not transmitting.)

(4) Following (3), continue to equalize the OFDM symbols. Plot the received constellations at RX antenna 1 and antenna 2 on separate figures for comparison. What do you observe?

(5) Using the estimated channel of the two receive antennas obtained in (3), perform maximum ratio combining (MRC) on LTS in the frequency domain and calculate the new SNR per subcarrier. On the same figure, plot the SNR per subcarrier across subcarriers for three strategies: (i) only RX antenna 1, (ii) only RX antenna 2, and (iii) MRC of both RX antennas. What do you observe?

(6) Following (5), continue to apply the maximum ratio combining on the OFDM symbols. Plot the received constellations using maximum ratio combining. Compared to the constellations in (4), what do you observe?

[Part 3] Demo (19.5 points, no report needed)

There are two options for the demo:
1. Demo on Nov. 18 in class.
2. Demo on Nov. 20 at 6:30 pm with a 20% penalty (i.e., 0.8*original score).

If some part of your demo is not successful on Nov. 18, you may demo again on Nov. 20. The part you successfully demonstrated on Nov. 18 will get full points without penalty.

(1) **(6 points) Successful cross-device single-antenna transmission**. Please transmit a frame with 100 OFDM symbols using 4-QAM modulation. Please show:
   a) **Received time domain signal**. Please mark the beginning and the end of the frame detected by your synchronization method, showing a correct detection of the transmitted frame.
   b) **CFO**. Please show the constellation before CFO correction, and the estimated CFO value.
   c) **Channel**. Please plot the estimated channel vs subcarrier (amplitude and phase).
   d) **Equalization**. Please plot the received constellation after CFO correction and equalization.
   e) **BER**. Please show that the BER is close to zero.

(2) **(3 points) Stability of Transmit Multiple Frames**. Please repeat (1) once more to show that your system is robust enough. That is, (a) to (e) should be successful every time you test it.

(3) **(3 points) Transmissions with a Higher Sampling Rate**. Increase the sampling rate to 10 MHz and show at least one successful transmission. At most 5 attempts are accepted.

(4) **(7.5 points) Successful maximum ratio combining**.
   a) Please plot the per-subcarrier SNR across subcarriers, comparing using (i) only antenna 1, (ii) only antenna 2, and (iii) both antennas.
   b) Plot the received constellations, comparing using (i) only antenna 1, (ii) only antenna 2, and (iii) both antennas.

Grading:

- 3.5 points for each problem in Part 1 & Part 2. 80.5 points in total for 23 questions.
- 19.5 points for the class demo.