Learning Objective 7.1: I can describe QAM and OFDM and identify use cases for each.

Show your work. Write a **Documentation** line at the end (**None** if you did not collaborate).

1. **Reading constellations.** A link sends 10,000 symbols per second with RRC pulses of roll-off $\alpha = 0.25$. Its constellation display shows, at different times, a grid of 4 by 4 points and a grid of 8 by 8 points, both scaled to the same average power.

   (a) Name each constellation and find its bits per symbol and its bit rate.

   4 by 4 is 16-QAM: $\log_2 16 = 4$ bits per symbol, so 40 kb/s.
   8 by 8 is 64-QAM: $\log_2 64 = 6$ bits per symbol, so 60 kb/s.

   16-QAM: 40 kb/s

   64-QAM: 60 kb/s

   (b) Find the occupied bandwidth with each constellation.

   $$B = (1+\alpha)R_s = 1.25 \times 10\,\text{kHz} = 12.5\,\text{kHz}$$

   12.5 kHz

   The same for both: the bandwidth depends on the symbol rate, not on the number of points.

   (c) In words, explain how a QAM constellation differs from Lesson 15's 8PSK, and why a QAM receiver needs an AGC that a PSK receiver can do without.

   8PSK puts every point on one circle, so only the phase carries data. QAM puts the points on a grid, so both the amplitude and the phase carry data. The decision between an inner and an outer QAM point depends on the amplitude, so the receiver has to hold the signal at the level the constellation expects; a PSK receiver decides by phase alone and can ignore the level.

2. **Watching the noise.** You run `L20-qam-noise.grc` and raise the Noise amplitude slider, which adds the same noise to the QPSK, 16-QAM, and 64-QAM rows.

   (a) At one setting, the QPSK display shows four round clouds well apart, the 16-QAM display shows sixteen clouds with gaps between them and a few stray points, and the 64-QAM display shows one square of scattered dots with no gaps. Describe what a receiver decoding each signal would deliver at this setting.

   QPSK: every symbol lands in its own point's region, so the data arrives intact. 16-QAM: most symbols land in the right region, but the clouds' edges cross into neighboring regions now and then, so occasional bits are wrong. 64-QAM: the clouds overlap completely, so the receiver picks the wrong point constantly and the data is unusable.

   (b) The noise is the same in all three rows. In words, explain why the three displays look so different.

   The noise spreads every point into a cloud of the same size. All three constellations have the same average power, so the more points a constellation has, the closer together they sit: about 1.41 apart for QPSK, 0.63 for 16-QAM, and 0.31 for 64-QAM. The same clouds overlap first where the points are closest.

   (c) A link carries 64-QAM cleanly at short range. In words, describe what you would see on its constellation display as the receiver moves away, and what Wi-Fi or LTE does at that point.

   The signal weakens relative to the noise, so the 64 clouds grow until they touch and merge. Wi-Fi and LTE then step down to a constellation with fewer points, 16-QAM and then QPSK, and add more error-correcting code, giving up bit rate to keep the link working.

3. **An OFDM spectrum and its guard.** A 20 MHz 802.11g Wi-Fi channel uses the subcarrier layout of `L20-ofdm-link.grc`: a 64-point FFT, subcarriers -26 to 26 with the one at 0 Hz left empty, and a 16-sample guard. It runs at 20 million samples per second.

   (a) Find the subcarrier spacing and the width of the occupied band, from the center of subcarrier -26 to the center of subcarrier 26.

   $$\Delta f = 20\ \text{MHz}/64 = 312.5\ \text{kHz}$$
   $$52 \times 312.5\ \text{kHz} = 16.25\ \text{MHz}$$

   312.5 kHz

   16.25 MHz

   (b) Find the length of the guard in microseconds.

   $$16/(20 \times 10^6\ \text{samples/s}) = 0.8\ \mu\text{s}$$

   0.8 μs

   (c) `L20-ofdm-link.grc` uses the same 16-sample guard at 100,000 samples per second. Find the guard's length there, and the delays of its Echo delay slider at 8 and at 20 samples. Which echo ends inside the guard?

   $$16/100{,}000 = 160\ \mu\text{s}$$

   160 μs

   8 samples (80 μs)

   8 samples is 80 μs, inside the guard; 20 samples is 200 μs, past it.

   (d) In words, describe what `L20-ofdm-link.grc` showed for an echo inside the guard and for one past it: the spectrum, the points after the equalizer, and the text.

   Inside the guard (8 samples): the spectrum rippled, but the equalizer turned the points back into a clean 16-QAM grid and every line arrived. Past the guard (20 samples): the spectrum rippled more finely, the points after the equalizer scattered with no clear grid, and no line arrived intact, although the noise had not changed.

4. **Recognizing signals on a waterfall.** For each description, name the system and whether it uses OFDM or a single carrier, and give one feature that identifies it.

   (a) A PlutoSDR at 20 MS/s tuned to 2.437 GHz shows short bursts that come and go. Most have a flat top about 17 MHz wide with steep edges and a small dip at the center of each burst, which moves with the burst when you retune.

   Wi-Fi, OFDM. The bursts are packets; the flat top and steep edges are the subcarriers all at the same power, and the dip is the empty subcarrier at 0 Hz.

   (b) The same PlutoSDR tuned to 740 MHz shows a flat band about 9 MHz wide with steep edges, which stays on.

   An LTE downlink, OFDM. A 10 MHz LTE carrier fills about 9 MHz with subcarriers, and the base station transmits continuously, unlike Wi-Fi's bursts.

   (c) A PlutoSDR at 2 MS/s tuned to an FM station shows a rounded signal whose width changes with the audio, with a flat shelf of constant width on each side from about 130 to 200 kHz from its center.

   A hybrid HD Radio station, from Lesson 14: the rounded signal is the analog FM host, and the shelves are the OFDM sidebands carrying QPSK.

   (d) A cable modem uses 256-QAM. In words, explain why you cannot find its signal with an SDR and an antenna, and why it can use a single carrier.

   It travels on coaxial cable, which keeps it off the air. The cable also has few echoes, so a single carrier with a simple equalizer works and OFDM's guard is not needed for that reason.

5. **Choosing a scheme.** For each use case, choose OFDM or a single carrier, and choose QPSK, 16-QAM, or 64-QAM. Explain each choice in a sentence or two.

   (a) A 20 MHz-wide data link inside a large metal hangar, where reflections arrive up to 1.5 μs after the direct signal and the signal is strong.

   OFDM with a guard longer than 1.5 μs. A single carrier filling 20 MHz would send symbols well under a tenth of a microsecond long, so each echo would smear across dozens of them; with OFDM every reflection stays inside the guard and the equalizer removes it. The signal is strong, so the clouds stay small and 64-QAM can carry the most bits.

   (b) A telemetry downlink from a small drone at the edge of its range, in open country with no reflectors nearby, where the signal is weak.

   A single carrier is enough, because there are few echoes. The signal is weak, so QPSK, whose points sit farthest apart, keeps the link working where 16-QAM's clouds would merge.

   (c) A point-to-point link between two towers with dish antennas aimed at each other, a clear line of sight, and a strong signal.

   A single carrier, because the narrow beams leave almost no echoes. The strong signal supports 64-QAM, as microwave links between towers use.

   (d) In words, state what decides OFDM or a single carrier, and what decides the number of constellation points.

   The echoes decide the first: echoes call for OFDM, with a guard longer than the longest echo, while a clean cable or a tower-to-tower link can use one carrier. The noise decides the second: a clean signal supports more points and more bits per symbol, and a noisy one needs fewer.