I/Q Modulation

• Issues with coherent modulation
• Analog I/Q modulation principles
AM Modulation and Demodulation

- Multiplication (i.e., mixing) operation shifts in frequency
  - Also creates undesired high frequency components at receiver

- Lowpass filtering passes only the desired baseband signal at receiver

What can go wrong here?
Impact of 90 Degree Phase Shift

- If receiver cosine wave turns into a sine wave, we suddenly receive no baseband signal!
  - We apparently need to synchronize the phase of the transmitter and receiver local oscillators
    - This is called coherent demodulation

- Some key questions:
  - How do we analyze this issue?
  - What would be the impact of a small frequency offset?
Frequency Domain Analysis

- When transmitter and receiver local oscillators are matched in phase:
  - Demodulated signal *constructively* adds at baseband
Impact of 90 Degree Phase Shift

- When transmitter and receiver local oscillators are 90 degree offset in phase:
  - Demodulated signal destructively adds at baseband

What would happen with a small frequency offset?
I/Q Modulation

- Consider modulating with both a cosine and sine wave and then adding the results
  - This is known as I/Q modulation
- The I/Q signals occupy the same frequency band, but one is real and one is imaginary
  - We will see that we can recover both of these signals
I/Q Demodulation

- Demodulate with *both* a cosine and sine wave
  - Both I and Q channels are recovered!
- I/Q modulation allows twice the amount of information to be sent compared to basic AM modulation with same bandwidth

What can go wrong here?
Impact of 90 Degree Phase Shift

- **I and Q channels get swapped at receiver**
  - **Key observation:** no information is lost!
- **Questions**
  - What would happen with a small frequency offset?
  - What would happen with a large frequency offset?
Summary of Analog I/Q Modulation

- **Frequency domain view**

  Baseband Input
  \[ I(t) = 1, \quad Q(t) = Q(t) \]
  \[ f \]
  \[ f \]

  Receiver Output
  \[ I(f) = 2, \quad Q(f) = 2Q(f) \]
  \[ f \]
  \[ f \]

  - **Time domain view**

  Baseband Input
  \[ i(t) = 2\cos(2\pi f_0 t) + 2\sin(2\pi f_0 t), \quad q(t) = 0 \]
  \[ t \]

  Receiver Output
  \[ i_r(t) = 2\cos(2\pi f_0 t) + 2\sin(2\pi f_0 t) \]
  \[ t \]
Summary

• Coherent modulation requires synchronized local oscillators at transmitter and receiver
  - Impact of phase offset is to change baseband amplitude
  - Impact of frequency offset is fading (small offset) or catastrophic corruption (large offset) of baseband signal

• I/Q modulation allows twice the amount of information to be sent compared to basic AM
  - Impact of phase offset is to swap I/Q
  - Impact of frequency offset is I/Q swapping (small offset) or catastrophic corruption (large offset) of received signal