I-Q Transmission
Lecture 17

• I-Q transmission
• Sending Digital Data
  - Binary Phase Shift Keying (BPSK): sending binary data over a single frequency band
  - Quadrature Phase Shift Keying (QPSK): sending twice the amount of binary data
  - Constellation Diagrams and Eye Diagrams
• Summary
Modulation and Demodulation

- 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 \textit{destructively} adds at baseband

• I-Q modulation exploits this. We transmit twice as much data in the same frequency band by using two carriers 90 degrees offset in phase.
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
Here we take advantage of the property that 90 degree shift between the two local oscillators will destructively cancel out the baseband signal.

I/Q modulation allows twice the amount of information to be sent over the same frequency band.

What can go wrong here?
Modulated Signal requires 2x the Bandwidth

Original Signal

\[ X(f) \]

(We consider only positive frequencies.)

\[ \text{width} = W \]

Modulated Signal

\[ Y(f) \]

\[ \text{width} = 2W \]

I-Q modulation sends two signals in the same part of the frequency spectrum.
**Impact of 90 Degree Phase Shift**

- I and Q channels get swapped at receiver
  - Key observation: no *information* is lost!
- For intermediate phase shifts, the signals are I and Q signals are mixed.
Summary of Analog I/Q Modulation

- **Frequency domain view**

Baseband Input

\[ I_i(f) \]

\[ Q_i(f) \]

\[ f \]

\[ 0 \]

\[ 1 \]

\[ 0 \]

\[ 1 \]

\[ f \]

\[ i_i(t) \]

\[ q_i(t) \]

\[ 2 \cos(2\pi f_0 t) \]

\[ 2 \sin(2\pi f_0 t) \]

\[ + \]

\[ 2 \cos(2\pi f_0 t) \]

\[ 2 \sin(2\pi f_0 t) \]

\[ + \]

\[ H(f) \text{ Lowpass} \]

\[ i_r(f) \]

\[ Q_r(f) \]

\[ f \]

\[ 0 \]

\[ 1 \]

\[ 0 \]

\[ f \]

\[ i_r(t) \]

\[ q_r(t) \]

\[ H(f) \text{ Lowpass} \]

- **Time domain view**

Baseband Input

\[ t \]

\[ i_i(t) \]

\[ q_i(t) \]

\[ 2 \cos(2\pi f_0 t) \]

\[ 2 \sin(2\pi f_0 t) \]

\[ + \]

\[ 2 \cos(2\pi f_0 t) \]

\[ 2 \sin(2\pi f_0 t) \]

\[ + \]

\[ H(f) \text{ Lowpass} \]

\[ i_r(t) \]

\[ q_r(t) \]

\[ H(f) \text{ Lowpass} \]

\[ t \]
Digital I&Q Modulation

- Allows communication systems to be constructed from "computers", like micro processors
  - Sophisticated processing becomes possible
  - Inexpensive to build
- Allows information to be "packetized"
  - Efficiently send information as packets through network
  - Analog signal requires "circuit-switched" connections
- Allows error correction to be achieved
  - Less sensitivity to radio channel imperfections
- Enables compression of information
  - More efficient use of channel
- Supports a wide variety of information content
  - Voice, text and email messages, video can all be represented as digital bit streams
Sending Binary Data with a Carrier

Motivation: leverage analog communication channel to send digital bits

- We represent each binary zero or one as a sampled data waveform $x(t)$ held at $-A$ or $+A$ for 1 bit time.
- This sampled data waveform modulates a carrier with normalized frequency $f_0$ Hz. Typically, the period $T = 1/f_0$ is much smaller than 1 bit time.

$$y(t) = 2\cos(2\pi f_0 t)$$
Binary Phase Shift Keying (BPSK)

- The modulation is equivalent to send one of two waveforms, depending upon the bit to be transmitted.
  - If the bit is 1, we send $2\cos(2\pi f_0 t)$
  - If the bit is 0, we send $-2\cos(2\pi f_0 t) = 2\cos(2\pi f_0 t + \pi)$

- This method is called Binary Phase Shift Keying (BPSK), since a sign change is equivalent to a shift in carrier phase by $\pi$
At the receiver side

• In order to receive the digital data transmitted in this way, we **demodulate** the received signals and **sample** the data waveform at the appropriate point at the output.
Using the same principle of I/Q transmission to transmit two baseband signals.

At receiver, demodulate and sample the I/Q waveforms every bit time (e.g. at blue dots)
- Determine whether the transmitted bit on each channel was a 0 or 1 by comparing the sampled value with a threshold (e.g. 0).
Constellation Diagrams and Quadrature Phase Shift Keying (QPSK)

- **Plot I/Q sampled values on I-Q (x-y) axis**
  - Example: sampled I/Q value of \{1,-1\} forms a dot at \(I=1, Q=-1\)
  - As more samples are plotted, constellation diagram eventually displays all possible symbol values

- **Constellation diagram provides a sense of how easy it is to distinguish between different symbols**
- For the simple case of BPSK, the constellation diagram is
The Impact of Noise

- Noise perturbs sampled I/Q values
  - Constellation points no longer consist of single dots for each symbol
- If noise is big enough, this can cause bit errors!
To save transmission bandwidth

- Want transmitted spectrum with minimal bandwidth, since wireless communication channels are a shared resource
  - However, sharply changing I/Q waveforms lead to a wide bandwidth spectrum
- Thus, we add a low pass filter before modulation.
Impact of Transmit Filter

- Transmit filter enables reduced bandwidth for transmitted spectrum
- Issue: can lead to intersymbol interference (ISI)
  - By removing the high frequency components, the rise time and the fall time of the signal increase
  - Constellation diagram displays vulnerability to making bit errors
Impact of High Bandwidth Filter

- Open eye diagrams lead to tight symbol groupings in constellation
Impact of Low Bandwidth Filter

- Eye diagrams intuitively show increased ISI and sensitivity to sample time placement.
Summary

• I/Q modulation allows twice the amount of information to be sent in the same frequency band

• To leverage the analog communication channel for sending digital bits, we multiply the digital bits with a carrier

• Using the same principle of I/Q transmission, we can transmit two separate digital data over the same frequency band

• There is a tradeoff between saving transmission bandwidth and minimizing intersymbol interference (ISI)