Digital Modulation (Part I)

- Communication using symbols and bits
- Constellation diagrams and decision boundaries
- Transmit bandwidth vs. intersymbol interference
- Eye Diagrams and sample time sensitivity

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Review of Analog 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 can recover both of these signals

\[ y(t) = i(t) + j q(t) \]

\[ y(t) = 2 \cos(2\pi f_o t) + j 2 \sin(2\pi f_o t) \]

\[ Y_i(j2\pi f) = I \]

\[ Y_q(j2\pi f) = Q \]

\[ I \text{ stands for in-phase component} \]

\[ Q \text{ stands for quadrature component} \]
Review of Analog 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*
Summary of Analog I/Q Demodulation

- **Frequency domain view**

  Baseband Input
  \[ I_r(j2\pi f) \]
  \[ Q_r(j2\pi f) \]
  \[ i(t) \]
  \[ q(t) \]

  Receiver Output
  \[ I_r(j2\pi f) \]
  \[ Q_r(j2\pi f) \]
  \[ H(j2\pi f) \]
  \[ 2 \]
  \[ 2 \]

- **Time domain view**

  Baseband Input
  \[ i(t) \]
  \[ 2\cos(2\pi f_0 t) \]
  \[ 2\sin(2\pi f_0 t) \]

  Receiver Output
  \[ i_r(t) \]
  \[ 2 \]
  \[ q_r(t) \]
Digital I/Q Modulation

- Leverage analog communication channel to send discrete-valued symbols
  - Example: send symbol from set \{-3,-1,1,3\} on both I and Q channels each symbol period
- At receiver, sample I/Q waveforms every symbol period
  - Associate each sampled I/Q value with symbols from set \{-3,-1,1,3\} on both I and Q channels
Advantages of going Digital

- Allows information to be “packetized”
  - Can compress information in time and efficiently send as packets through network
  - In contrast, analog modulation requires “circuit-switched” connections that are continuously available
    - Inefficient use of radio channel if there is “dead time” in information flow
- 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
**Constellation Diagrams**

- **Plot I/Q samples on x-y axis**
  - Example: sampled I/Q value of \{1, -3\} forms a dot at \(x=1, y=-3\)
  - 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**

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\[ i(t) = 2\cos(2\pi f_o t) \]
\[ q(t) = 2\sin(2\pi f_o t) \]

\[ \text{Receiver Output} \quad H(j2\pi f) \quad \text{Lowpass} \]

\[ i_r(t) \]
\[ q_r(t) \]

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Assign each I/Q symbol to a set of digital bits

- Example: I/Q = \{1,3\} translates to bits of 1110
- Gray coding minimizes bit errors when symbol errors are made
  - Example: I/Q = \{1,1\} translates to bits of 1010
  - Only one bit change from I/Q = \{1,3\}
The Impact of Noise

- **Noise perturbs sampled I/Q values**
  - Constellation points no longer consist of single dots for each symbol
- **Issue:** what is the best way to match received I/Q samples with their corresponding symbols?
Symbol Selection Based on Slicing

- **Match I/Q samples to their corresponding symbols based on decision regions**
  - Choose decision regions to minimize symbol errors
  - Decision boundaries are also called slicing levels
Transitioning Between Symbols

- Transition behavior between symbols is influenced by both transmit I/Q input waveforms and receive filter
  - We will focus on impact of transition behavior at transmitter today
  - Ignore the impact of noise for this analysis
Influence of Transitions at Transmitter

- **Ideal analog communication channel** simply transports the transmitter I/Q signals to the receiver.
- **Constellation diagram** can be constructed at *transmitter* to evaluate its performance.
  - Bad constellation at transmitter implies bad one at receiver.
Transitions and the Transmitted Spectrum

- Want transmitted spectrum with minimal bandwidth
  - Wireless communication channels are a shared resource
- Issue: sharply changing I/Q waveforms lead to a wide bandwidth spectrum
Impact of Transmit Filter

- Transmit filter enables reduced bandwidth for transmitted spectrum
- Issue: can lead to *intersymbol interference (ISI)*
  - Constellation diagram displays vulnerability to making bit errors
Impact of Low Bandwidth Transmit Filter

- Lowering the transmit filter bandwidth leads to
  - Lower bandwidth transmitted spectrum
  - Increased ISI
- Eye diagrams allow ISI to be intuitively examined
Eye Diagrams

- Key idea: wrap signal back onto itself in periodic time intervals and retain all traces
  - Similar to action of oscilloscope
Looking at Many Symbols

- Increasing the number of symbols eventually reveals all possible symbol transition trajectories
  - Intuitively displays the impact of filtering on ISI
Assessing the Quality of an Eye Diagram

- Eye diagram allows visual inspection of the impact of sample time and decision boundary choices
  - Large *eye opening* implies less vulnerability to symbol errors
Relating Eye Diagrams to Constellation

- **Open eye diagrams lead to tight symbol groupings in constellation**
  - Assumes proper sample time placement
Impact of Low Transmit Bandwidth

- Eye diagrams intuitively show increased ISI
  - Also show sensitivity of bit errors to sample time placement
Summary

• Digital modulation operates by sending discrete-valued symbols through an analog communication channel
  - Receiver must sample I/Q signals at the appropriate time
  - Receiver matches I/Q sample values to corresponding symbols based on decision regions
  - Constellation diagrams are a convenient tool to see likelihood of bit errors being made

• Choice of transmit filter is a tradeoff between achieving a minimal bandwidth transmitted spectrum and minimal intersymbol interference (ISI)
  - Eye diagrams are a convenient tool to see effects of ISI and sensitivity of bit errors to sample time choice

• Next lecture: a closer look at the receiver...