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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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
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

$I$ stands for in-phase component
$Q$ stands for quadrature component

$I_t(t)$ and $Q_t(t)$ represent the in-phase and quadrature components, respectively. The transmitted signal is the sum of $I_t(t)$ and $Q_t(t)$.

$Y(t)$ is the transmitted signal, and $Y_i(f)$ and $Y_q(f)$ represent the in-phase and quadrature components of the transmitted signal, respectively.
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
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 the set \{-3, -1, 1, 3\} on both I and Q channels (16 possibilities ----> 4 bits)
Constellation Diagrams

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

- 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 1111
      - 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
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...