Modulation Techniques

- Amplitude Modulation (AM)
  - Standard AM
  - Double-sideband (DSB)
  - Single-sideband (SSB)
  - Quadrature Amplitude Modulation (QAM)
- Constant Envelope Modulation
  - Phase Modulation (PM)
  - Frequency Modulation (FM)
- Multiple Access
  - FDMA
  - TDMA
  - CDMA
- Ultra Wide Band (UWB)
  - Pulse
  - OFDM
Amplitude Modulation (Transmitter)

- Vary the amplitude of a sine wave at carrier frequency $f_0$ according to a baseband modulation signal $x'(t) = 1 + mx(t)$
- DC component of baseband modulation signal influences transmit signal and receiver possibilities
  - DC value greater than signal amplitude shown above
    - Allows simple envelope detector for receiver
    - Strong carrier frequency tone is transmitted (wasted power)
Baseband signal $x'(t)$ has a nonzero DC component

- Causes impulse to appear at DC in baseband signal
  - Transmitter output has an impulse at the carrier frequency
  - This component is fixed in frequency and phase, so carries no information (waste of transmit power)
Zero DC Value (DSB or ‘Suppressed Carrier’)

- Envelope of modulated sine wave no longer corresponds directly to the baseband signal
  - Envelope instead follows the absolute value of the baseband waveform, negative value of the baseband input produces 180° phase shift in carrier
  - Envelope detector can no longer be used for receiver

- The carrier frequency tone that carries no information is removed: less transmit power required for same transmitter SNR (compared to standard AM)

\[ y(t) = 2\cos(2\pi f_c t) \]
DSB Spectra

- Impulse in DC portion of baseband signal is now gone
  - Transmitter output now is free from having an impulse at the carrier frequency: more power efficient
Accompanying Receiver (Coherent Detection)

- Works regardless of DC value of baseband signal
- Requires receiver local oscillator to be accurately aligned in phase and frequency to carrier

\[ z(t) = 4x(t)\cos(2\pi f_0 t)\cos(2\pi f_0 t) = 2x(t)(1 + \cos 2\pi(2f_0)) \]
Frequency Domain View of DSB Receiver (Coherent)
Impact of Phase Misalignment in Receiver Local Oscillator

\[ z(t) = 4x(t)\cos(2\pi f_0 t)\sin(2\pi f_0 t) = 2x(t)\sin(2\pi f_0) \]

- **Worst case is when receiver LO and carrier frequency are phase shifted 90 degrees with respect to each other**
  - Desired baseband signal is not recovered
Impact of 90 Degree Phase Misalignment (Freq. Domain View)

\[ \sin(-f) = -\sin(f) \]
SSB (Single-Sideband)

- The upper sideband (USB) and the lower sideband (LSB) are symmetric, so they contain the same information.
- Standard AM is neither power efficient nor bandwidth efficient.
- The DSB improves power efficiency, but still takes up twice the necessary bandwidth.
- Most baseband signals have no DC or very low frequency components.
- One of the sidebands can be removed at the IF or RF stage (much easier to filter in the IF stage).
SSB Spectra

- One of the sidebands is removed by sideband filter or phase shift techniques
  - Signal bandwidth is reduced 2x: more *bandwidth efficient*
Quadrature Modulation (QAM)

- Takes advantage of coherent receiver’s sensitivity to phase alignment with transmitter local oscillator
  - We essentially have two orthogonal transmission channels (I and Q) available
  - Transmit two independent baseband signals (I and Q) onto two sine waves in quadrature at transmitter
Accompanying Receiver

- Demodulate using two sine waves in quadrature at receiver
  - Must align receiver LO signals in frequency and phase to transmitter LO signals
    - Proper alignment allows I and Q signals to be recovered as shown
Impact of 90 Degree Phase Misalignment

- I and Q channels are swapped at receiver if its LO signal is 90 degrees out of phase with transmitter
  - However, no information is lost!
  - Can use baseband signal processing to extract I/Q signals despite phase offset between transmitter and receiver
For discussion to follow, assume that
- Transmitter and receiver phases are aligned
- Lowpass filters in receiver are ideal
- Transmit and receive I/Q signals are the same except for scale factor

In reality
- RF channel adds distortion, causes fading
- Signal processing in baseband DSP used to correct problems
**Analog Modulation**

- I/Q signals take on a continuous range of values (as viewed in the time domain)
- Used for AM/FM radios, television (non-HDTV), and the first cell phones
- Newer systems typically employ digital modulation instead
Digital Modulation

- I/Q signals take on discrete values at discrete time instants corresponding to digital data
  - Receiver samples I/Q channels
    - Uses decision boundaries to evaluate value of data at each time instant
- I/Q signals may be binary or multi-bit
  - Multi-bit shown above
Advantages of Digital Modulation

- Allows information to be “packetized”
  - Can compress information in time and efficiently send as packets through network
  - In contrast, analog modulation requires 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
We can view I/Q values at sample instants on a two-dimensional coordinate system.

Decision boundaries mark up regions corresponding to different data values.

Gray coding used to minimize number of bit errors that occur if wrong decision is made due to noise.

Amplitudes I and Q are encoded in 2-bit digital values.
Impact of Noise on Constellation Diagram

- Sampled data values no longer land in exact same location across all sample instants
- Decision boundaries remain fixed
- Significant noise causes bit errors to be made (channel SNR determines maximum number of bits)

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Constant Envelope Modulation
The Issue of Power Efficiency

- Power amp dominates power consumption for many wireless systems
  - Linear power amps more power consuming than nonlinear ones
- Constant-envelope modulation allows nonlinear power amp
  - Lower power consumption possible
Constant-envelope modulation limited to phase and frequency modulation methods

Can achieve both phase and frequency modulation with ideal VCO

- Use as model for analysis purposes
- Note: phase modulation nearly impossible with practical VCO
Example Constellation Diagram for Phase Modulation

- I/Q signals must always combine such that amplitude remains constant
  - Limits constellation points to a circle in I/Q plane
  - Draw decision boundaries about different phase regions
Transitioning Between Constellation Points

- Constant-envelope requirement forces transitions to allow occur along circle that constellation points sit on
  - I/Q filtering cannot be done independently!
  - Significantly impacts output spectrum
Multiple Access Techniques
The Issue of Multiple Access

- Want to allow communication between many different users
- Freespace spectrum is a shared resource
  - Must be partitioned between users
- Can partition in either time, frequency, or through “orthogonal coding” (or nearly orthogonal coding) of data signals
Frequency-Division Multiple Access (FDMA)

- Place users into different frequency channels
- Two different methods of dealing with transmit/receive of a given user
  - Frequency-division duplexing
  - Time-division duplexing
**Frequency-Division Duplexing (Full-duplex)**

- Separate frequency channels into transmit and receive bands
- Allows simultaneous transmission and reception
  - Isolation of receiver from transmitter achieved with duplexer
  - Cannot communicate directly between users, only between handsets and base station
- Advantage: isolates users
- Disadvantages:
  - Duplexer has high insertion loss (i.e. attenuates signals passing through it)
  - Takes up twice the bandwidth
Time-Division Duplexing (Half-duplex)

- Use any desired frequency channel for transmitter and receiver
- Send transmit and receive signals at different times
- Allows communication directly between users (not necessarily desirable)
- Advantage: switch has low insertion loss relative to duplexer
- Disadvantage: receiver more sensitive to transmitted signals from other users
**Time-Division Multiple Access (TDMA)**

- Place users into different time slots
  - A given time slot repeats according to time frame period
- Often combined with FDMA
  - Allows many users to occupy the same frequency channel
Consider two correlation cases
- Two independent random Bernoulli sequences
  - Result is a random Bernoulli sequence
- Same Bernoulli sequence
  - Result is 1 or -1, depending on relative polarity
- Assign a unique code sequence to each transmitter
- Data values are encoded in transmitter output stream by varying the polarity of the transmitter code sequence
  - Each pulse in data sequence has period $T_d$
    - Individual pulses represent binary data values
  - Each pulse in code sequence has period $T_c$
    - Individual pulses are called “chips”
Receiver Selects Desired Transmitter Through Its Code

- Receiver correlates its input with desired transmitter code
  - Data from desired transmitter restored
  - Data from other transmitter(s) remains randomized
Data and chip sequences operate on different time scales
- Associated spectra have different width and height
Frequency Domain View of CDMA

- CDMA transmitters broaden data spectra by encoding it onto chip sequences (‘spread-spectrum’)
- CDMA receiver correlates with desired transmitter code
  - Spectra of desired channel reverts to its original width
  - Spectra of undesired channel remains broad
    - Can be “mostly” filtered out by lowpass