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6.776
High Speed Communication Circuits
Lecture 1
Communication Systems Overview

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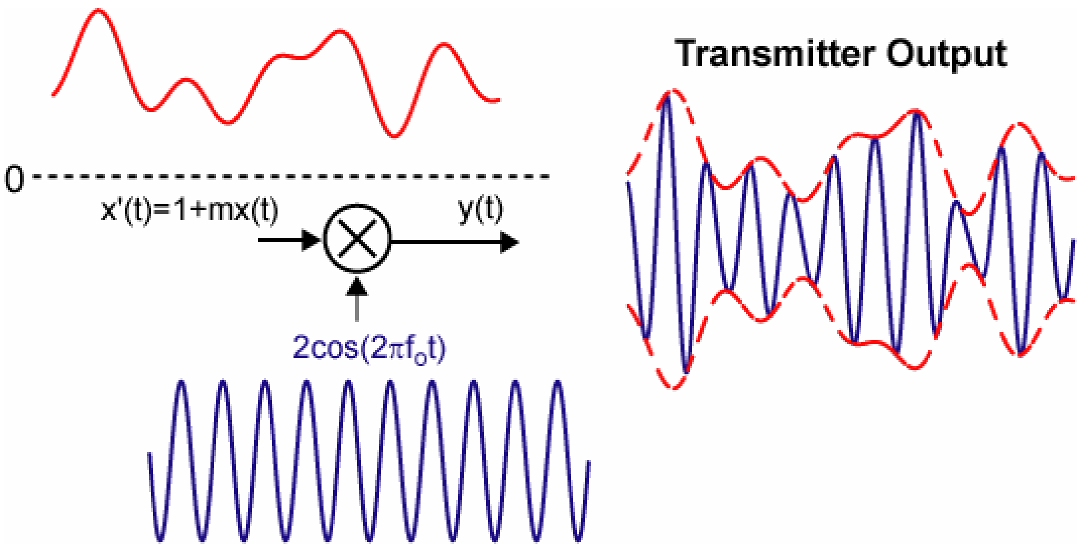
Modulation Techniques

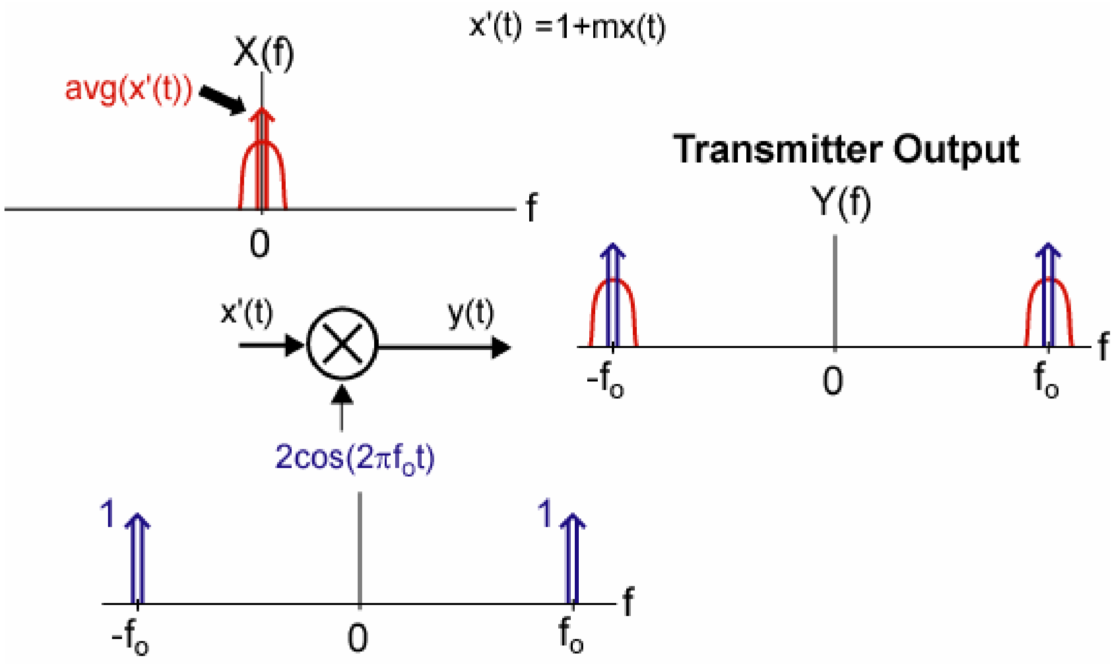
- **Amplitude Modulation (AM)**
  -Standard AM
  -Double-sideband (DSB)
  -Single-sideband (SSB)
  -Quadrature Amplitude Modulation (QAM)
- **Constant Envelope Modulation**
  -Phase Modulation (PM)
  -Frequency Modulation (FM)
- **Multiple Access**
  -FDMA
  -TDMA
  -CDMA
- **Ultra Wide Band (UWB)**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

Amplitude Modulation (Transmitter)



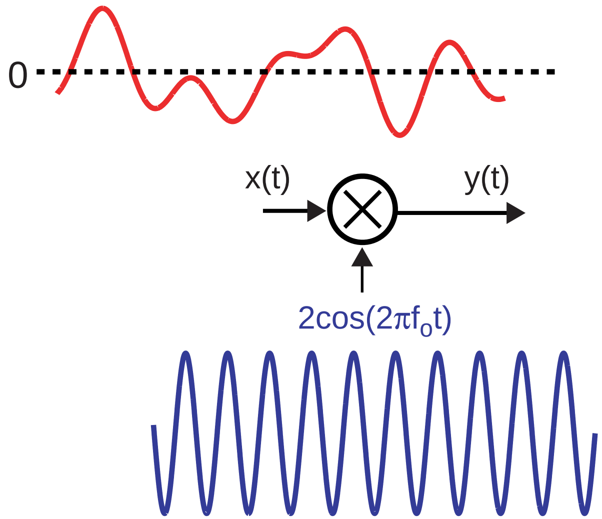
- **Vary the amplitude of a sine wave at carrier frequency f_o according to a baseband modulation signal** $x'(t) = 1 + mx(t)$
- **DC component of baseband modulation signal influences transmit signal and receiver possibilities**
  - **DC value greater than signal amplitude shown above**
    - Allows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

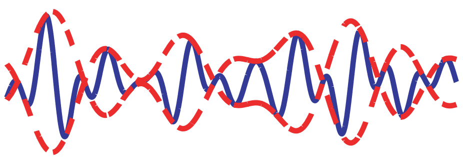
Frequency Domain View of Standard AM Transmitter



- **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)**

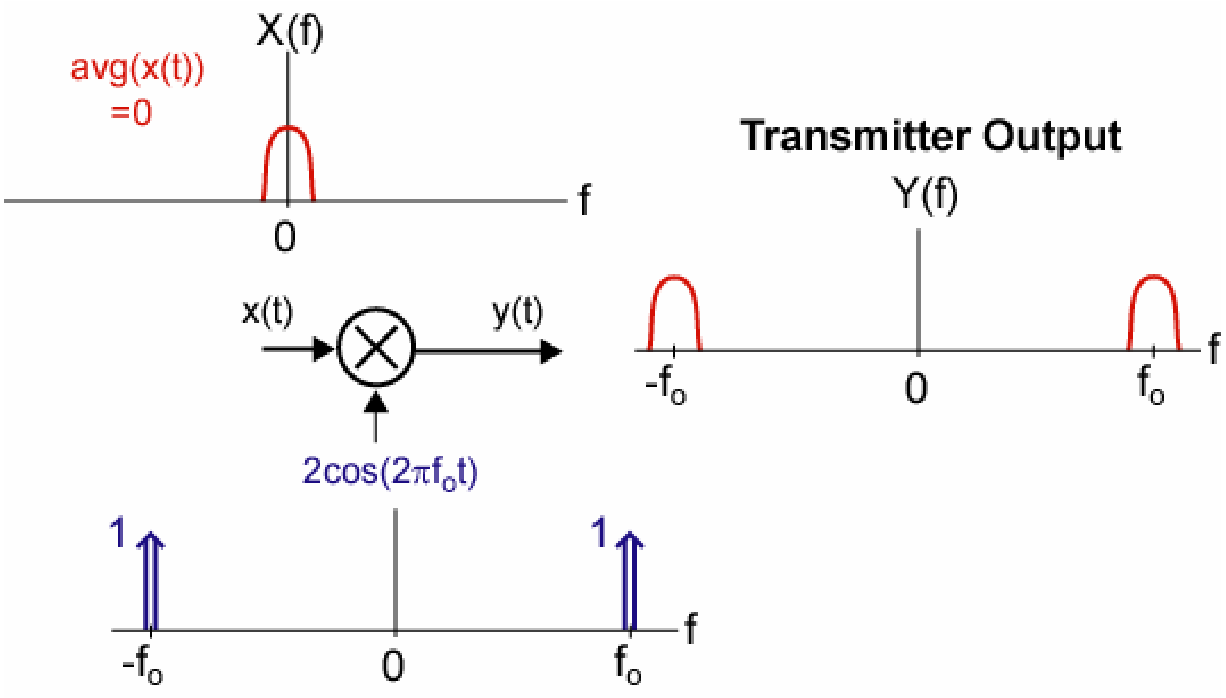
Zero DC Value (DSB or 'Suppressed Carrier')





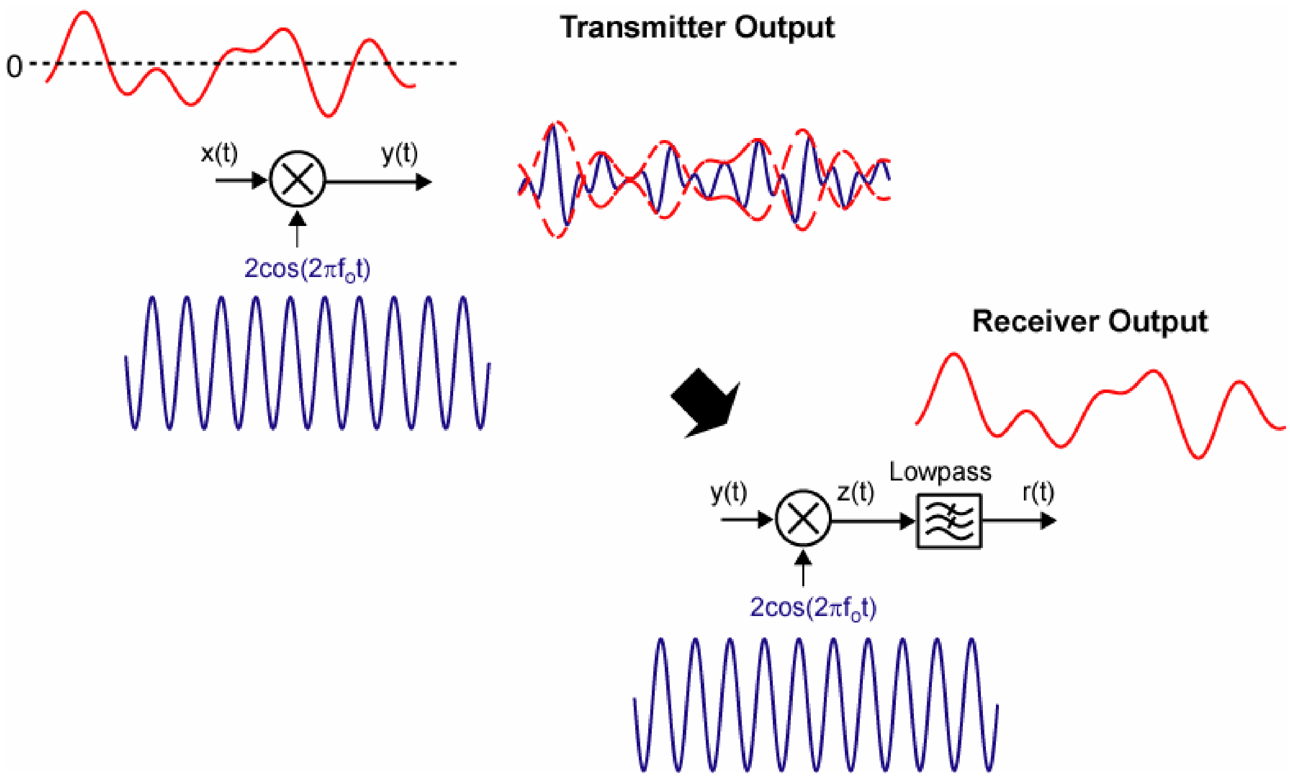
- **Envelope of modulated sine wave no longer corresponds directly to the baseband signal**
  - **Envelope instead follows the absolute value of the baseband waveform, negative value of the baseband input produces 180º phase shift in carrier**
  - **Envelope detector can no longer be used for receiver**
- **The carrier frequency tone that carries no information is removed: less transmit power required for same transmitter SNR (compared to standard AM)**

DSB Spectra



- **Impulse in DC portion of baseband signal is now gone**
  - **Transmitter output now is now free from having an impulse at the carrier frequency: more *power* efficient**

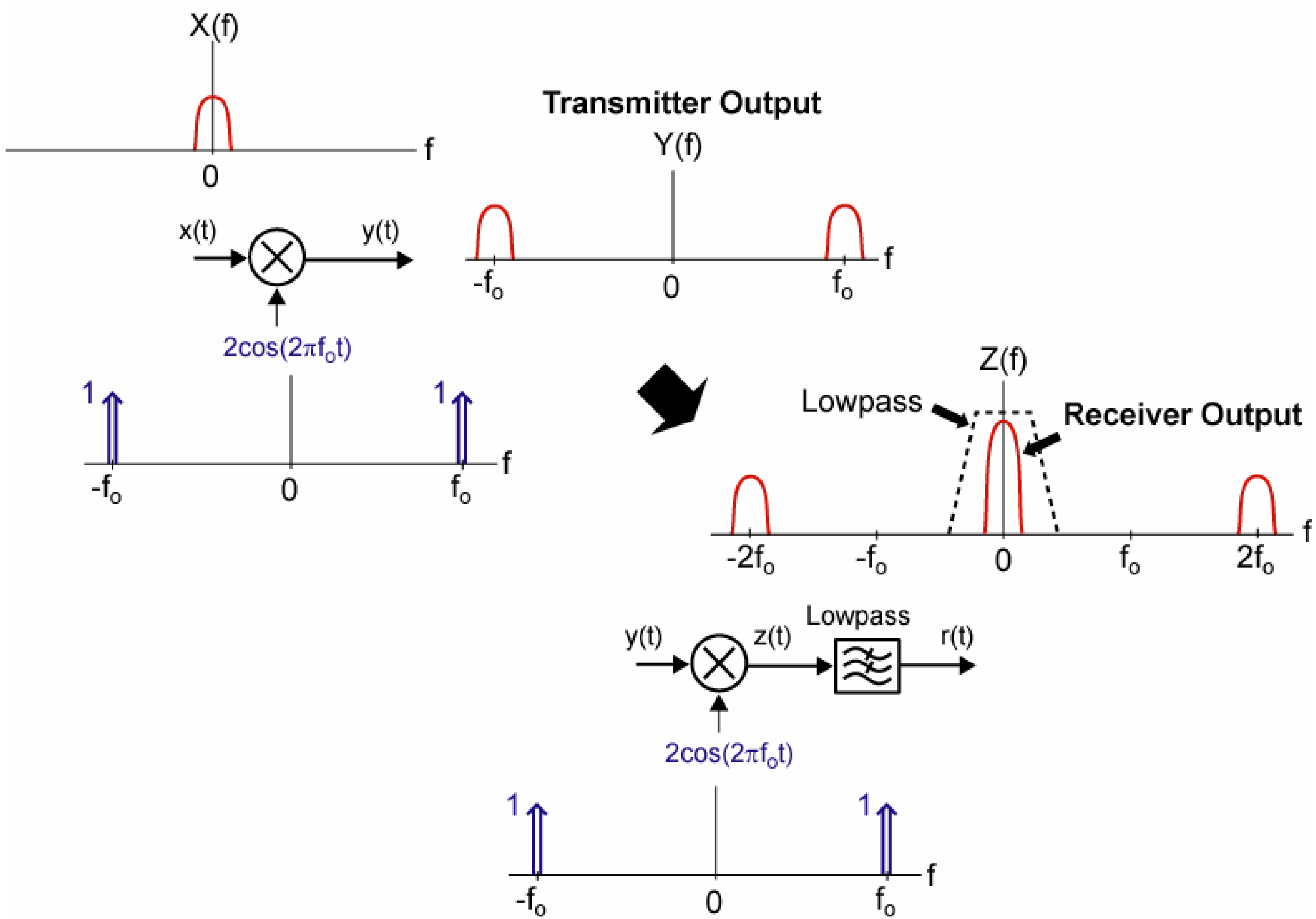
Accompanying Receiver (Coherent Detection)



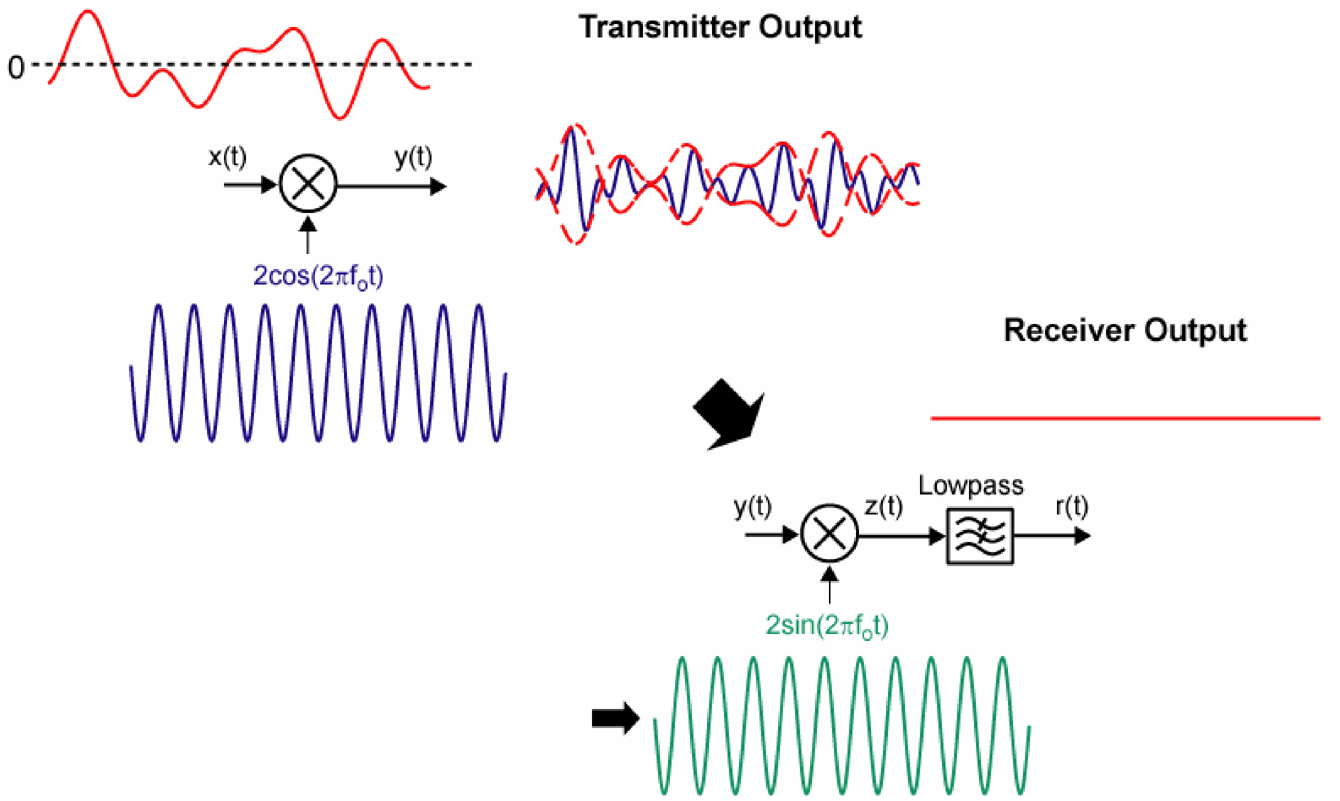
$$z(t) = 4x(t)cos(2\pi f_o t)cos(2\pi f_o t) = 2x(t)(1 + cos2\pi(2f_o))$$

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

Frequency Domain View of DSB Receiver (Coherent)



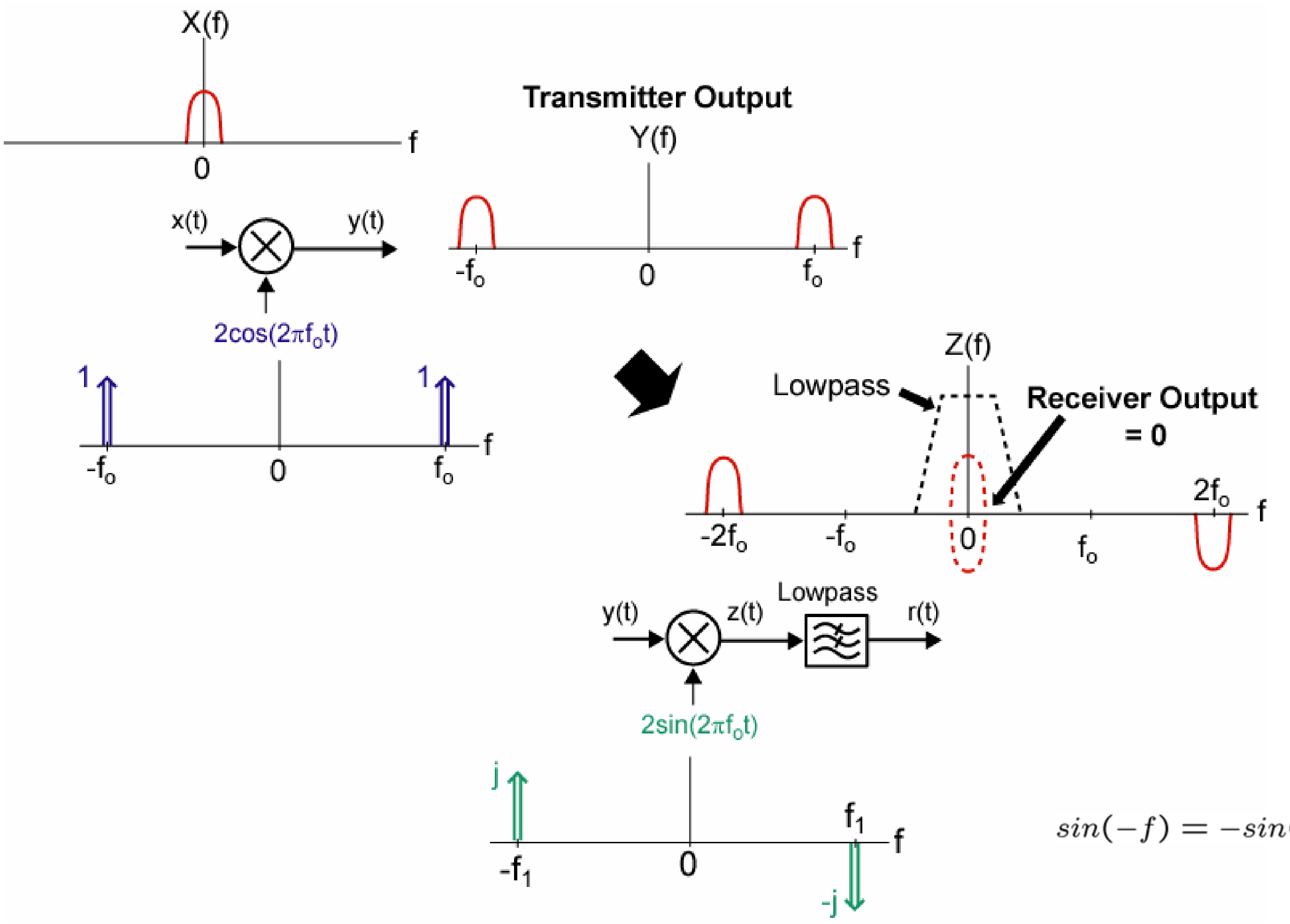
Impact of Phase Misalignment in Receiver Local Oscillator



$$z(t) = 4x(t)cos(2\pi f_o t)sin(2\pi f_o t) = 2x(t)sin2\pi(2f_o)$$

- **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)

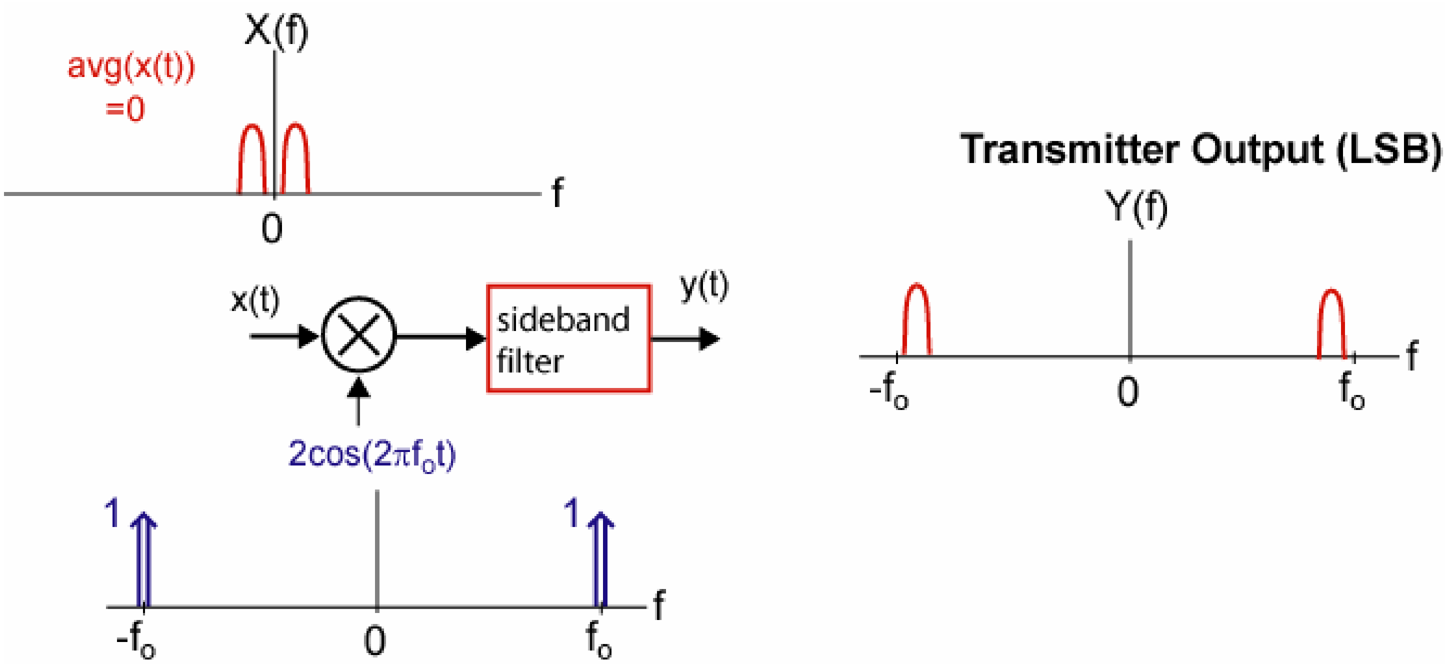


$$sin(-f) = -sin(f)$$

SSB (Single-Sideband)

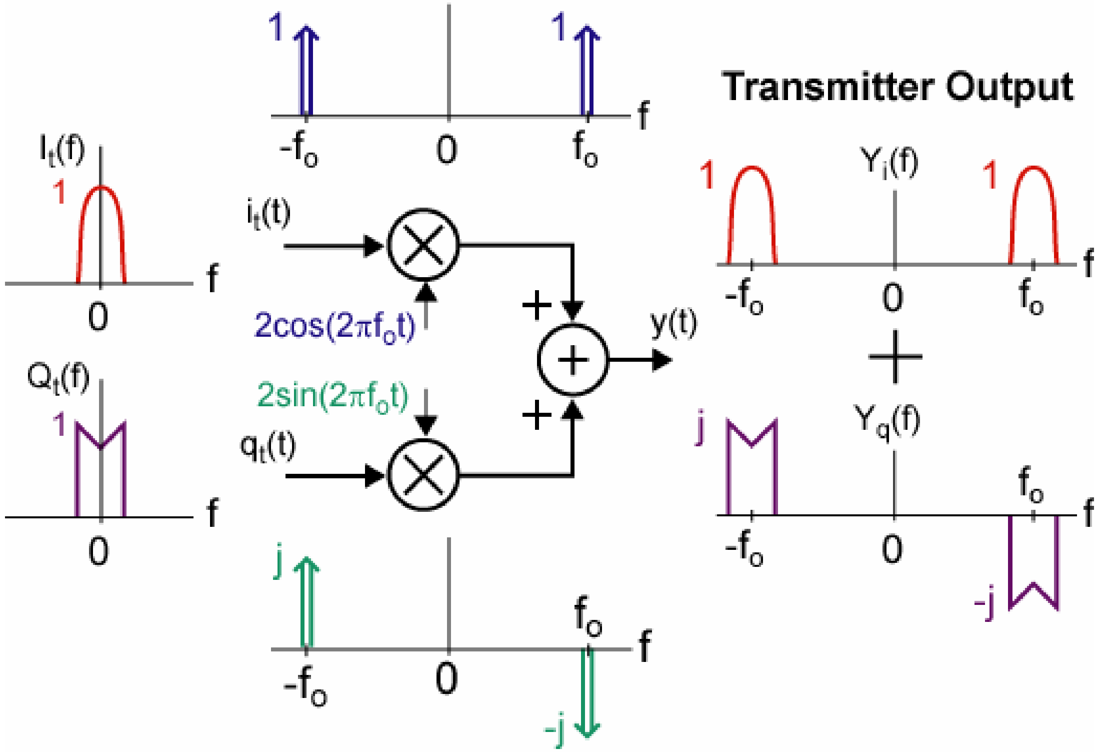
- **The upper sideband (USB) and the lower sideband (LSB) are symmetric, so they contain the same information**
- **Standard AM is neither power efficient nor bandwidth efficient**
- **The DSB improves power efficiency, but still takes up twice the necessary bandwidth**
- **Most baseband signals have 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



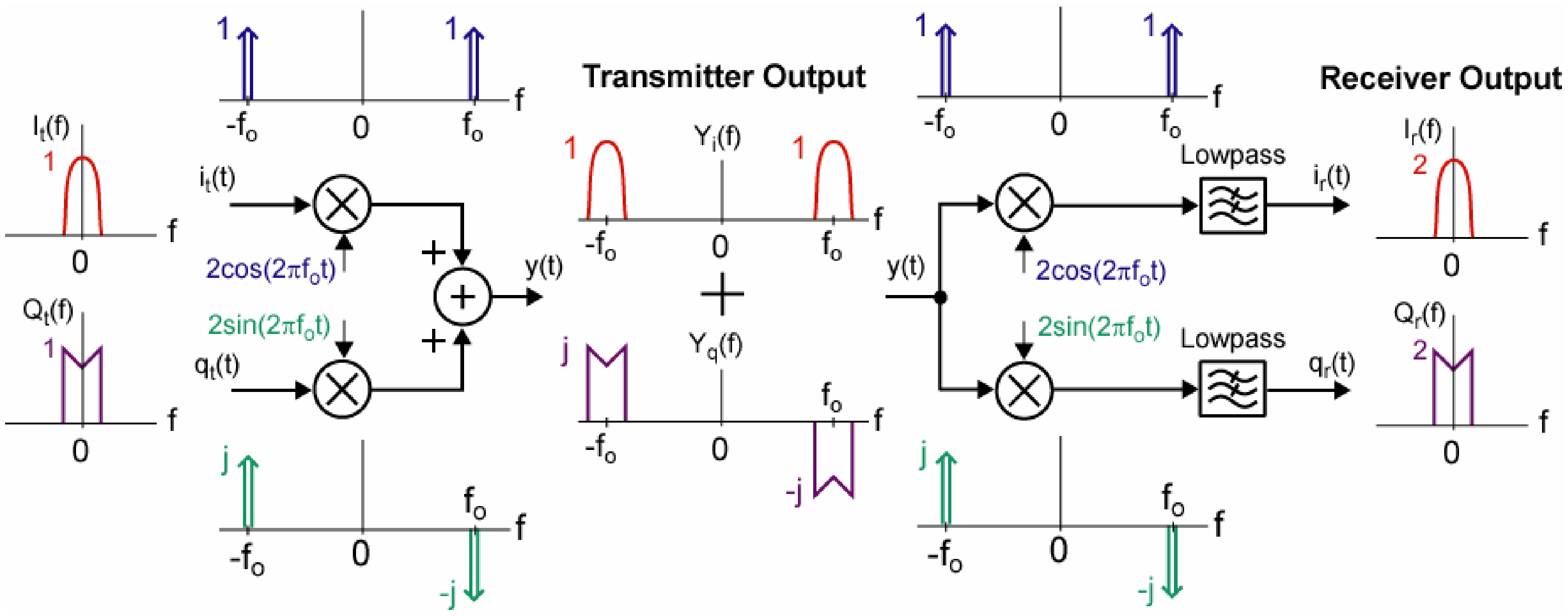
- **One of the sidebands is removed by sideband filter or phase shift techniues**
  - **Signal bandwidth is reduced 2x: more *bandwidth* efficient**

Quadrature Modulation (QAM)



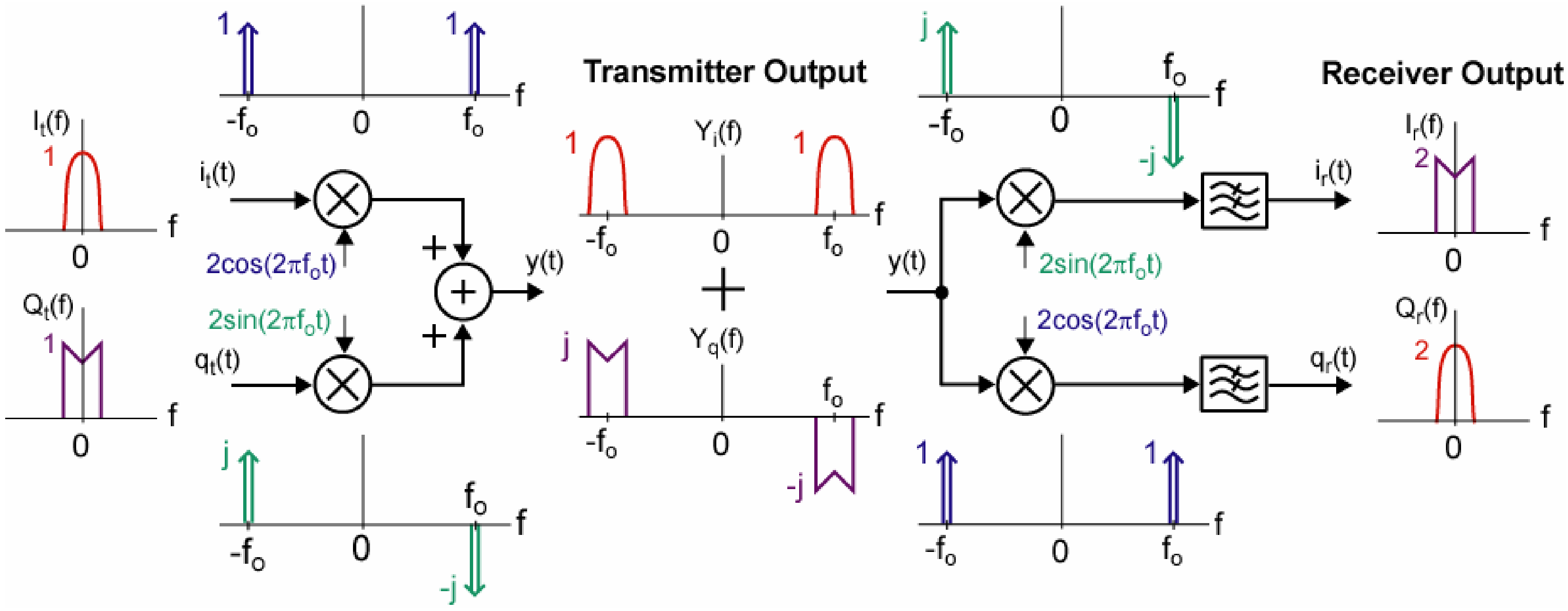
- Takes advantage of coherent receiver's sensitivity to phase alignment with transmitter local oscillator
  - We essentially have two orthogonal transmission channels (I and Q) available
  - Transmit two independent baseband signals (I and Q) onto two sine waves in quadrature at transmitter

Accompanying Receiver



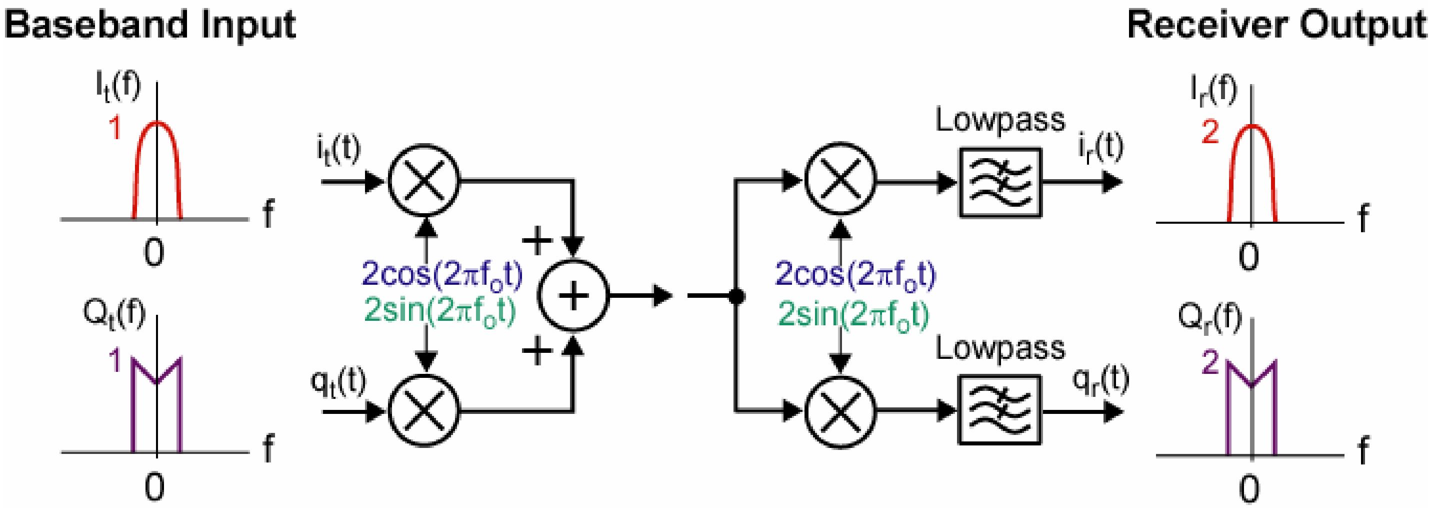
- **Demodulate using two sine waves in quadrature at receiver**
  - **Must align receiver LO signals in frequency and phase to transmitter LO signals**
    - Proper alignment allows I and Q signals to be recovered as shown

Impact of 90 Degree Phase Misalignment



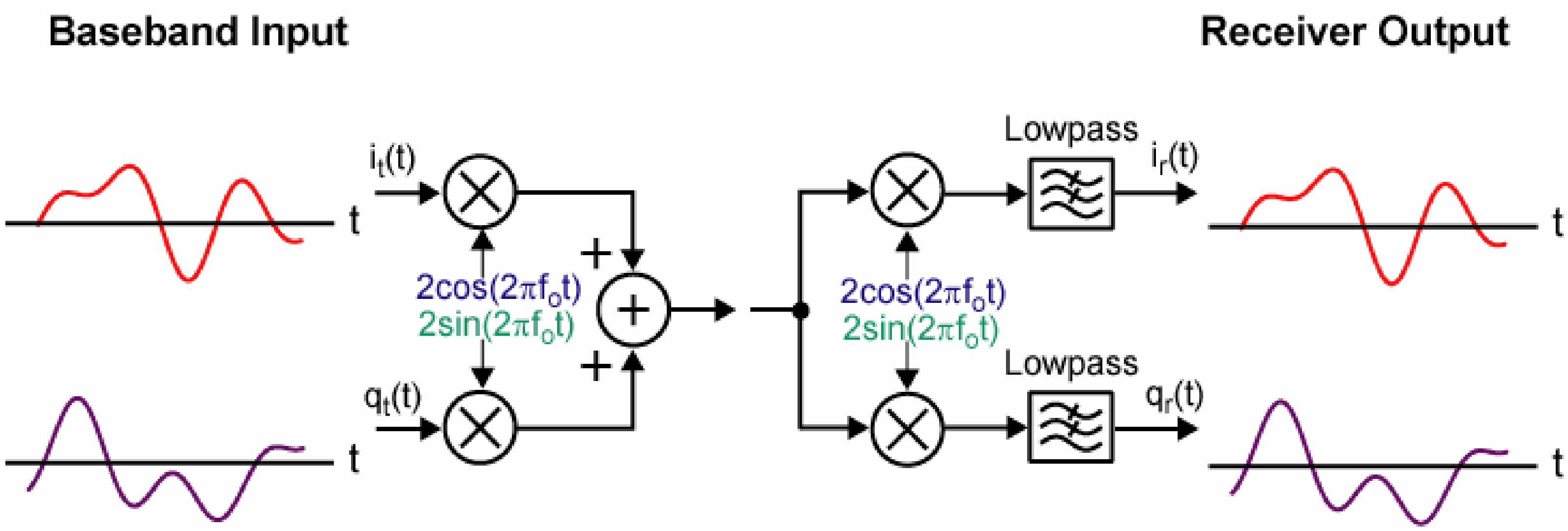
- **I and Q channels are swapped at receiver if its LO signal is 90 degrees out of phase with transmitter**
  - **However, no information is lost!**
  - **Can use baseband signal processing to extract I/Q signals despite phase offset between transmitter and receiver**

Simplified View



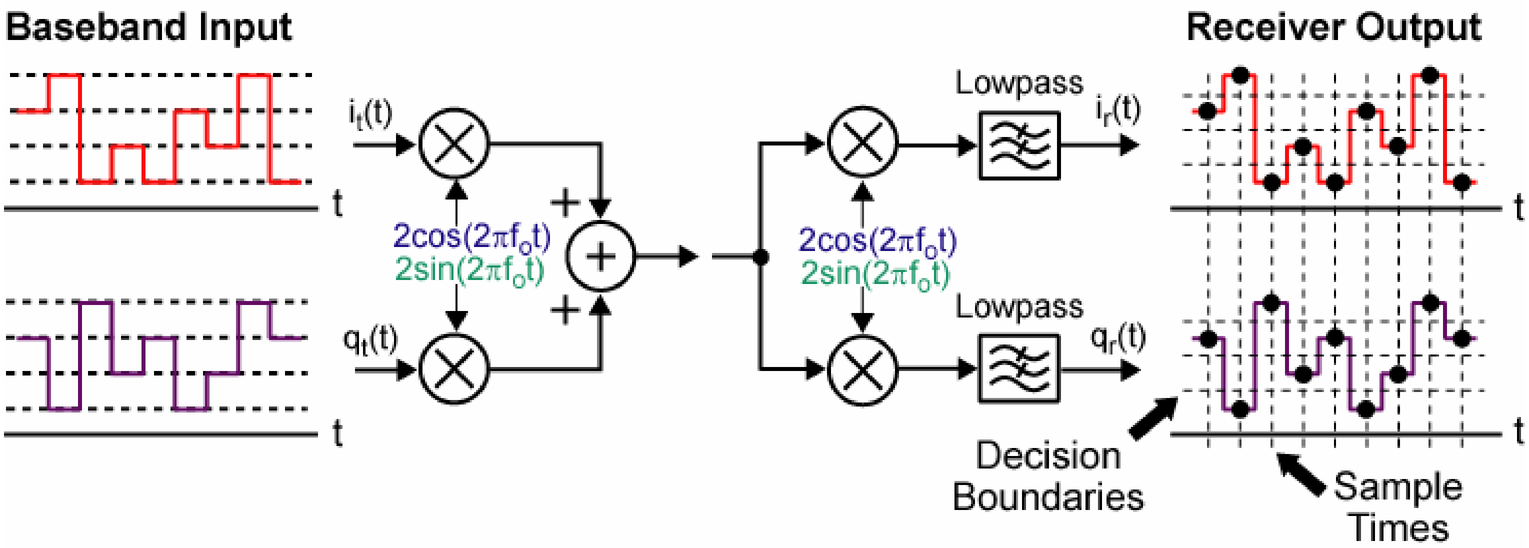
- **For discussion to follow, assume that**
  - **Transmitter and receiver phases are aligned**
  - **Lowpass filters in receiver are ideal**
  - **Transmit and receive I/Q signals are the same except for scale factor**
- **In reality**
  - **RF channel adds distortion, causes fading**
  - **Signal processing 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

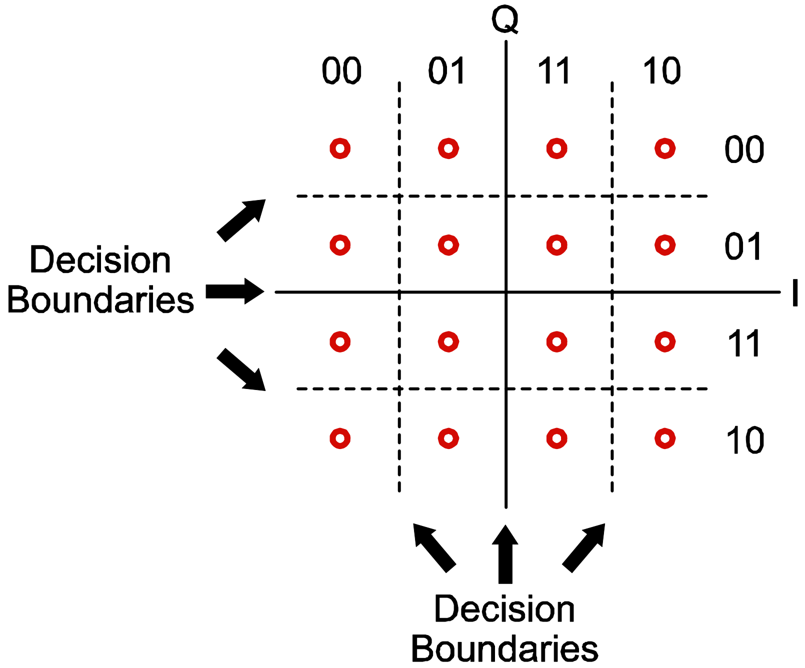


- I/Q signals take on discrete values at discrete time instants corresponding to digital data
  - Receiver samples I/Q channels
    - Uses decision boundaries to evaluate value of data at each time instant
- I/Q signals may be binary or multi-bit
  - Multi-bit shown above

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**

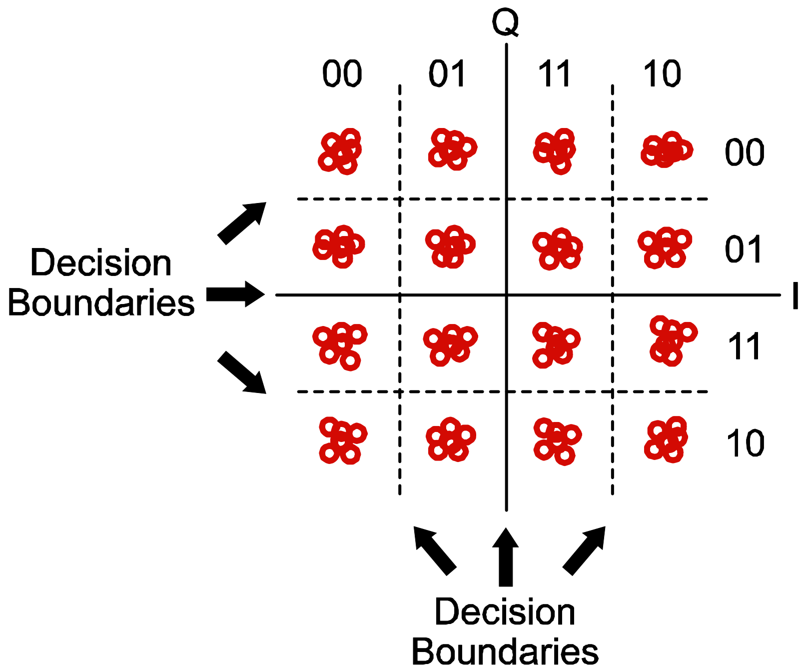
Constellation Diagram of Multi-bit Quadrature Digital Modulation (2-bit example)



Amplitudes I and Q are encoded In 2-bit digital values

- **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**

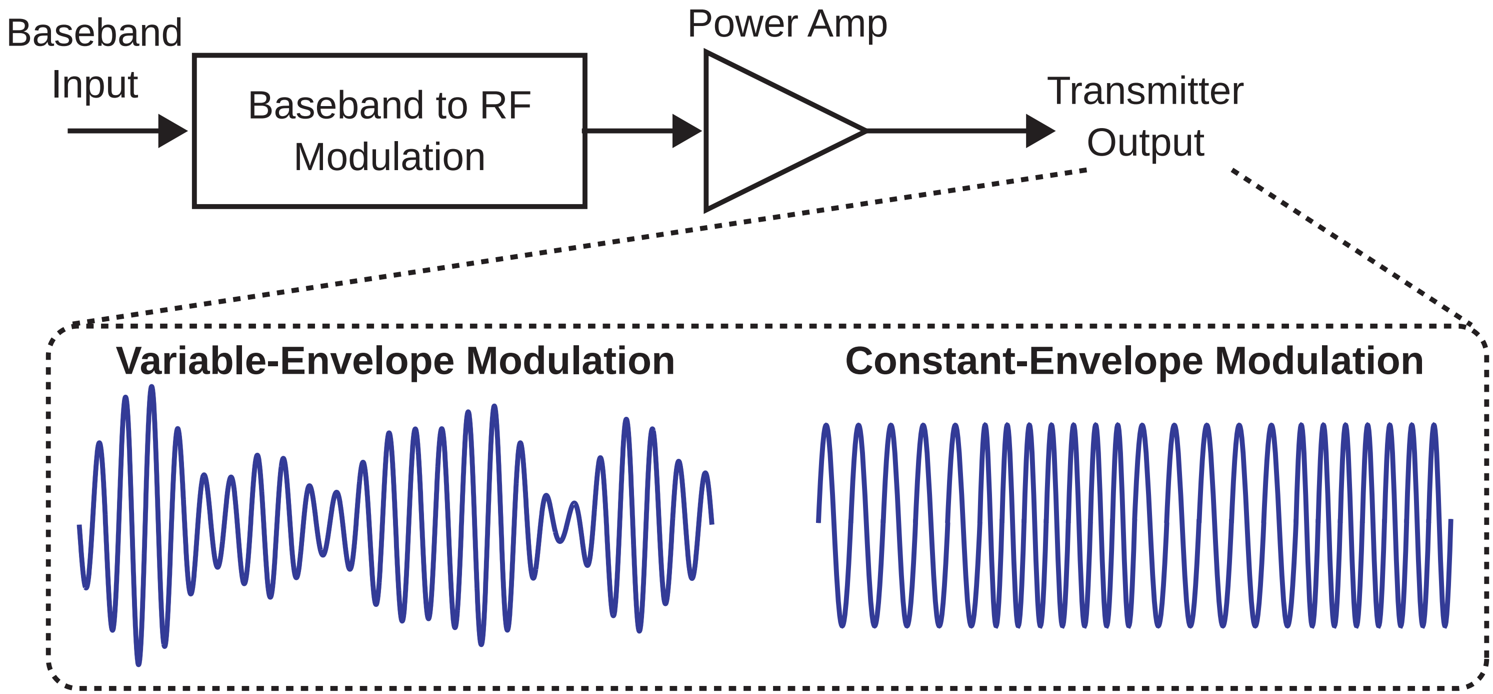
Impact of Noise on Constellation Diagram



- 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)

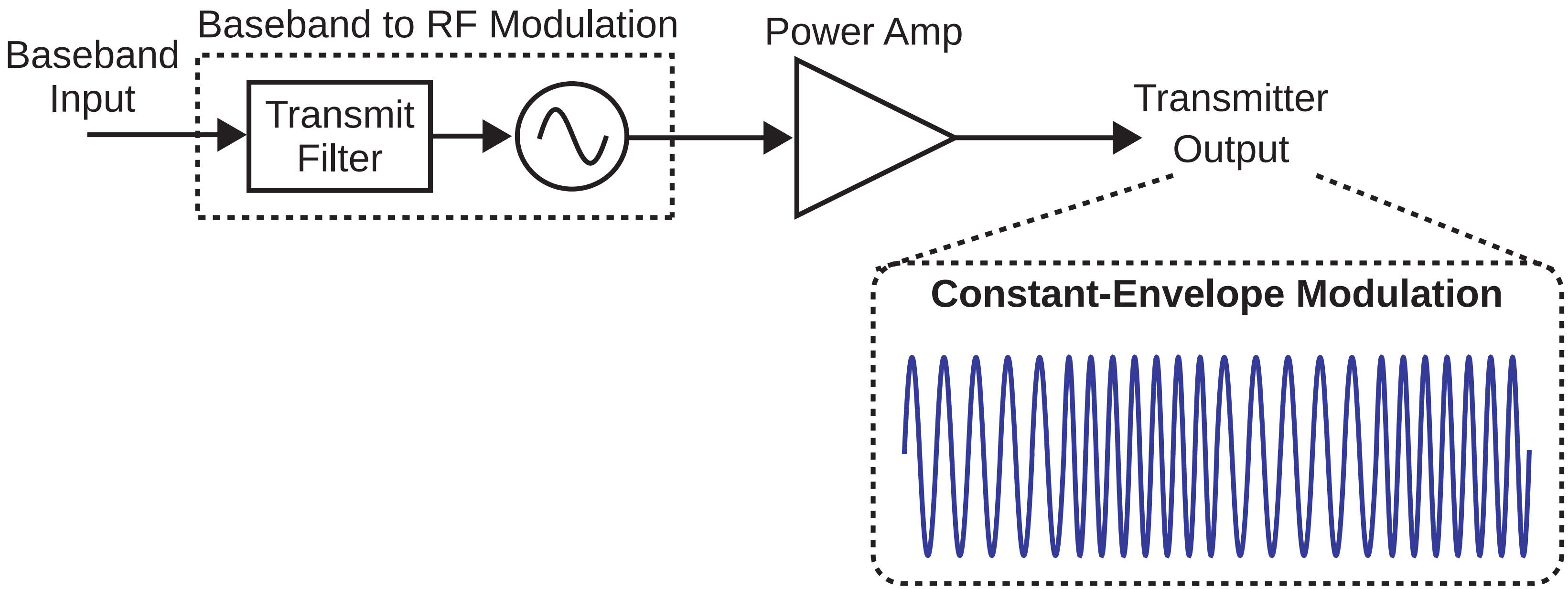
Constant Envelope Modulation

The Issue of Power Efficiency



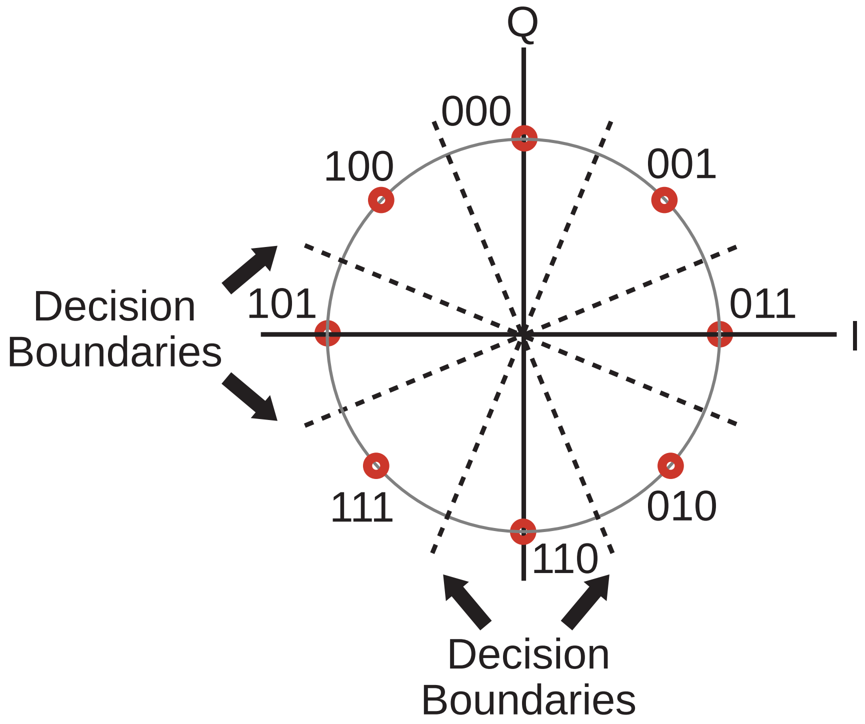
- Power amp dominates power consumption for many wireless systems
  - Linear power amps more power consuming than nonlinear ones
- Constant-envelope modulation allows nonlinear power amp
  - Lower power consumption possible

Simplified Implementation for Constant-Envelope



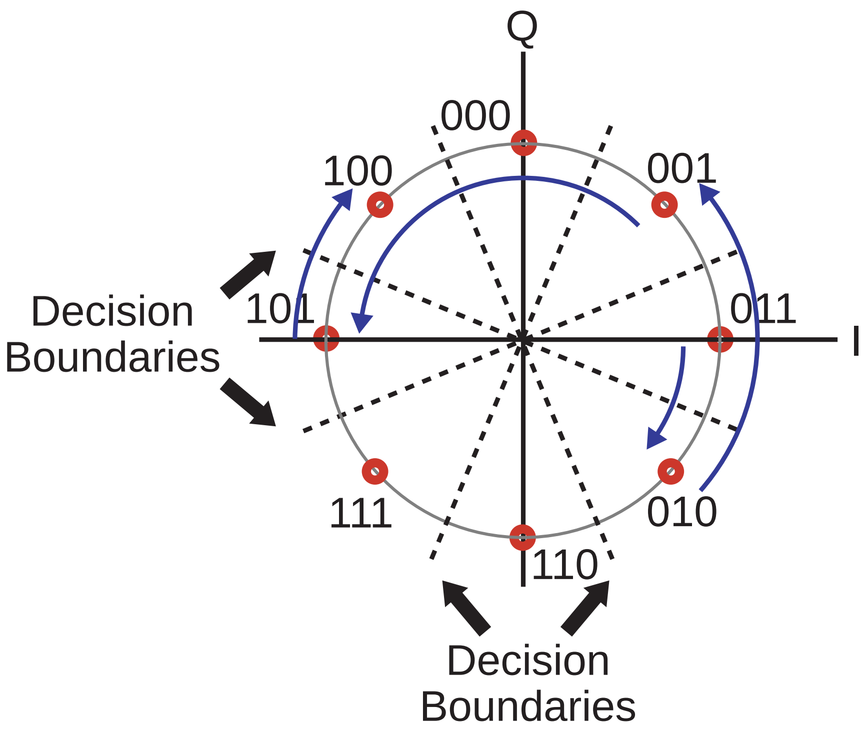
- **Constant-envelope modulation limited to phase and frequency modulation methods**
- **Can achieve both phase and frequency modulation with ideal VCO**
  - **Use as model for analysis purposes**
  - **Note: phase modulation nearly impossible with practical VCO**

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



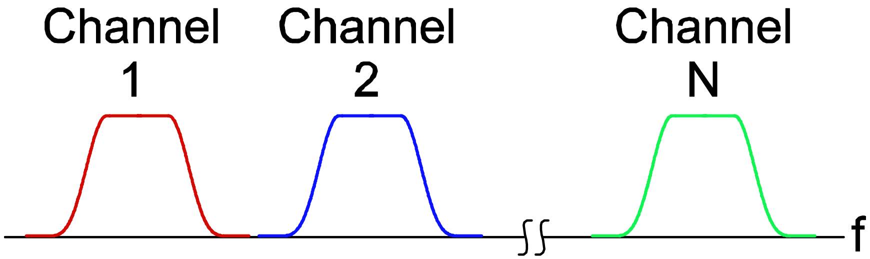
- **Constant-envelope requirement forces transitions to allows occur along circle that constellation points sit on**
  - **I/Q filtering cannot be done independently!**
  - **Significantly impacts output spectrum**

Multiple Access Techniques

The Issue of Multiple Access

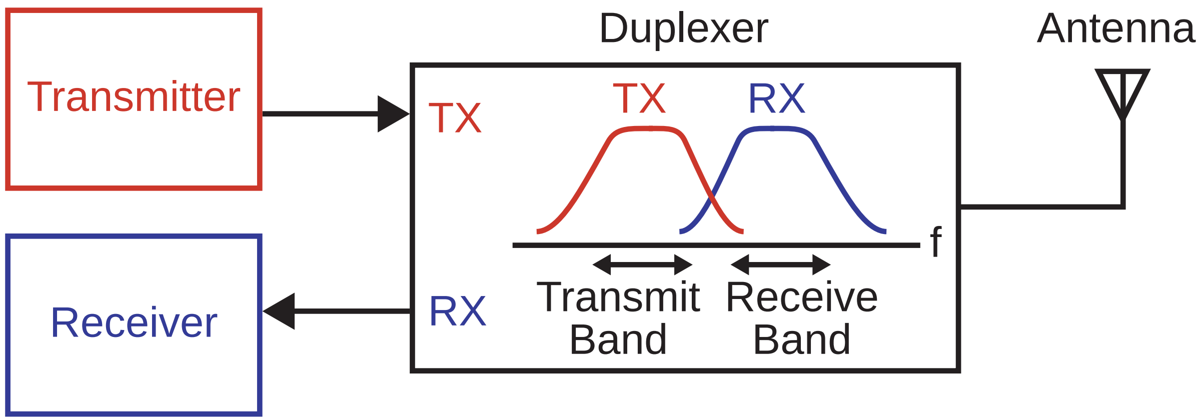
- **Want to allow communication between many different users**
- **Freespace spectrum is a shared resource**
  - **Must be partitioned between users**
- **Can partition in either time, frequency, or through "orthogonal coding" (or nearly orthogonal coding) of data signals**

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)

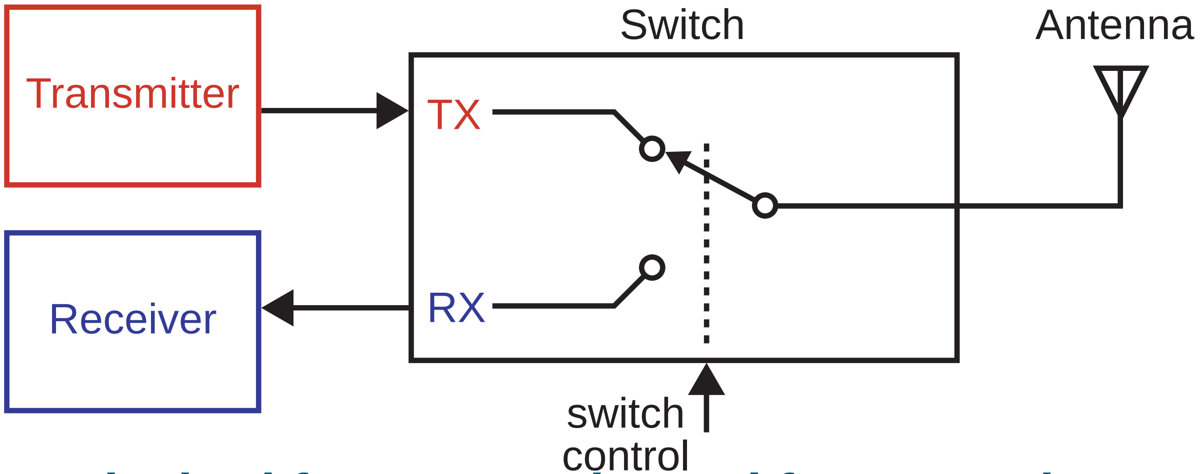


- **Separate frequency channels into transmit and receive bands**
- **Allows simultaneous transmission and reception**
  - **Isolation of receiver from transmitter achieved with duplexer**
  - **Cannot communicate directly between users, only between handsets and base station**
- **Advantage: isolates users**
- **Disadvantages:**

  -duplexer has high insertion loss (i.e. attenuates signals passing through it)

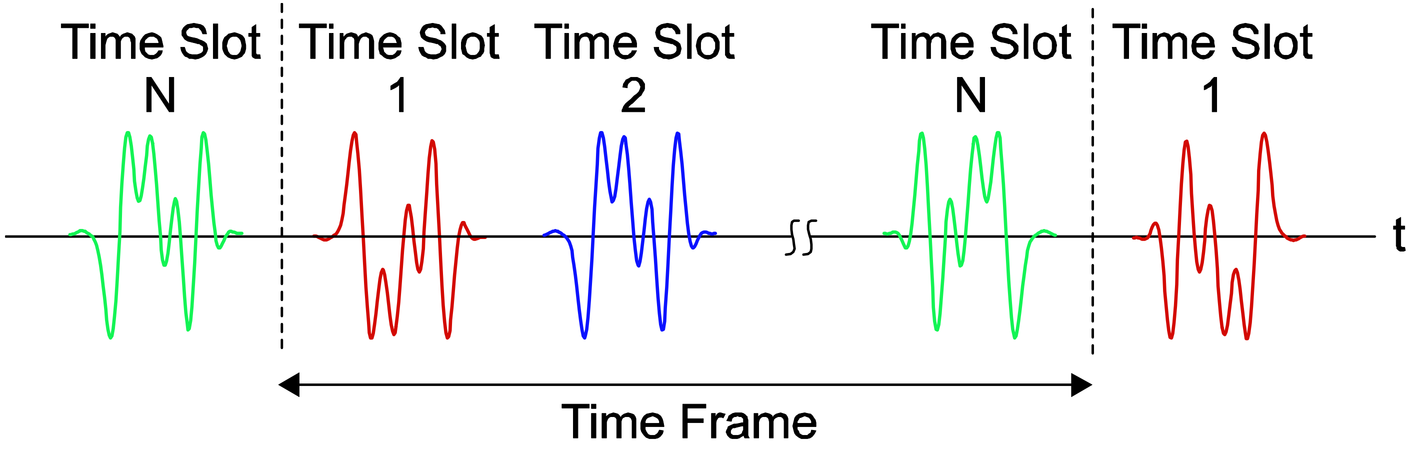
  -takes up twice the bandwidth

Time-Division Duplexing (Half-duplex)



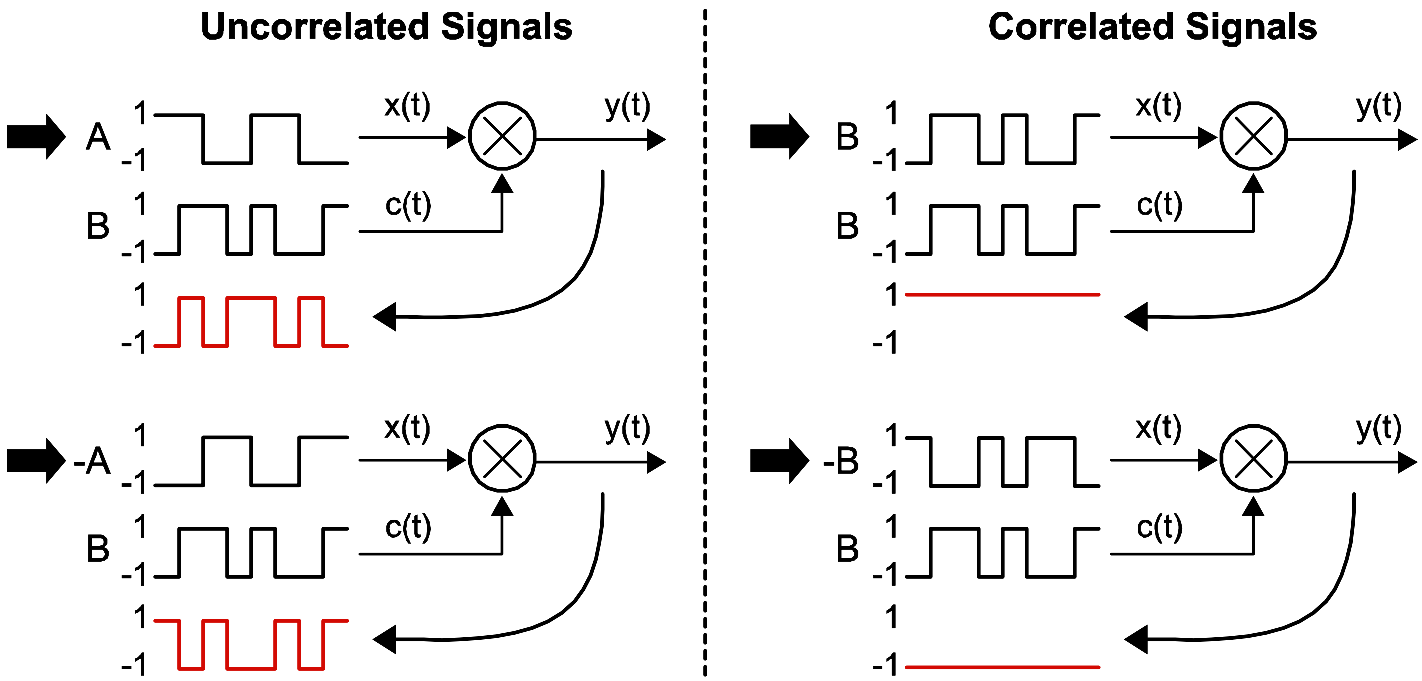
- Use any desired frequency channel for transmitter and receiver
- Send transmit and receive signals at different times
- Allows communication directly between users (not necessarily desirable)
- Advantage: switch has low insertion loss relative to duplexer
- Disadvantage: receiver more sensitive to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

Time-Division Multiple Access (TDMA)



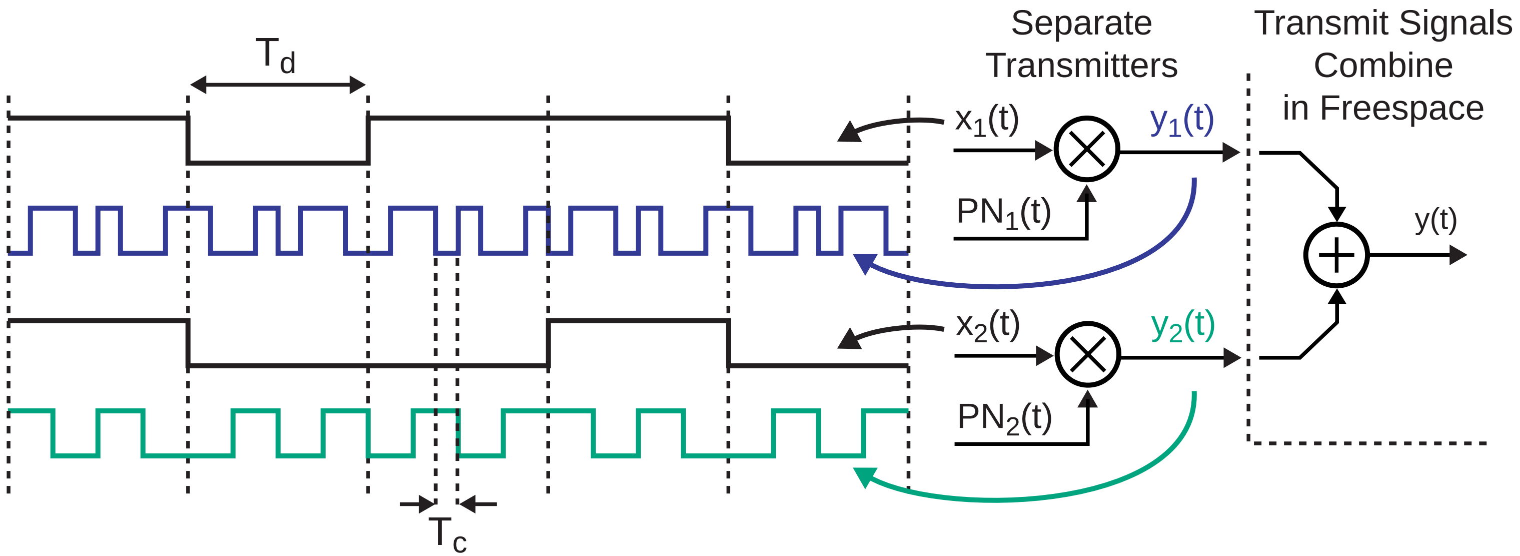
- **Place users into different time slots**
  - **A given time slot repeats according to time frame period**
- **Often combined with FDMA**
  - **Allows many users to occupy the same frequency channel**

Channel Partitioning Using (Nearly) "Orthogonal Coding"



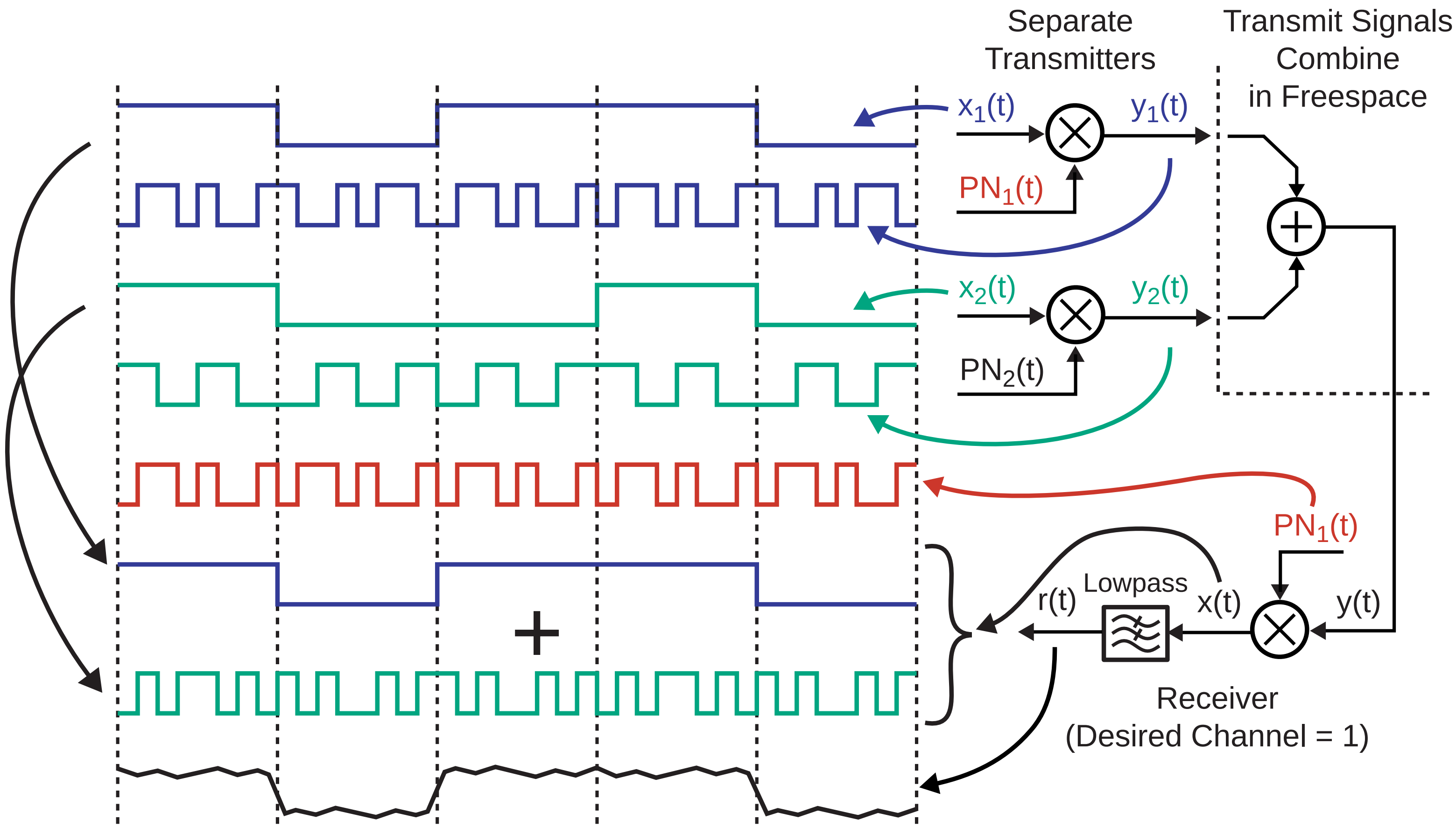
- Consider two correlation cases
  - Two independent random Bernoulli sequences
    - Result is a random Bernoulli sequence
  - Same Bernoulli sequence
    - Result is 1 or -1, depending on relative polarity

Code-Division Multiple Access (CDMA)



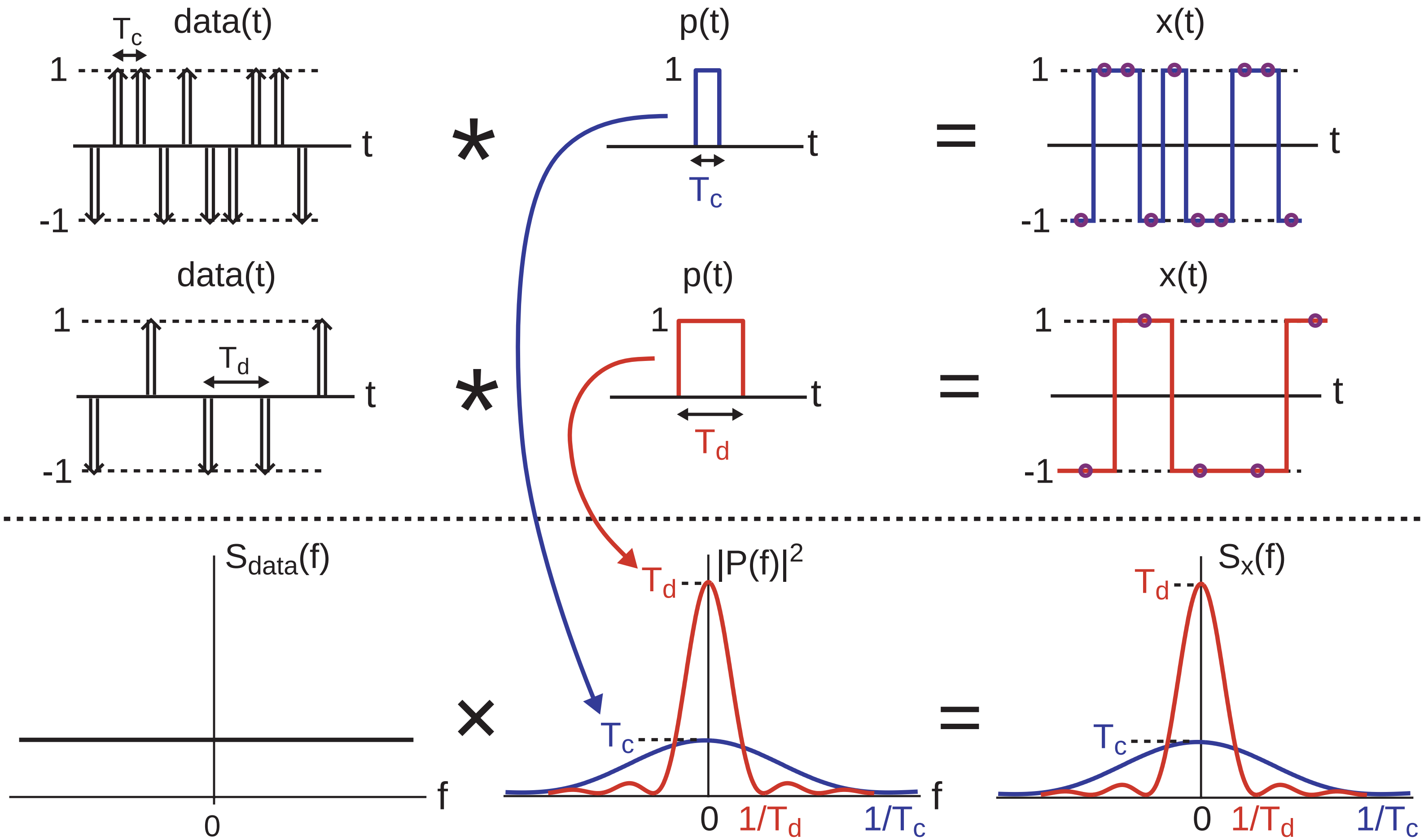
- **Assign a unique code sequence to each transmitter**
- **Data values are encoded in transmitter output stream by varying the polarity of the transmitter code sequence**
  - **Each pulse in data sequence has period T_d**
    - Individual pulses represent binary data values
  - **Each pulse in code sequence has period T_c**
    - Individual pulses are called "chips"

Receiver Selects Desired Transmitter Through Its Code



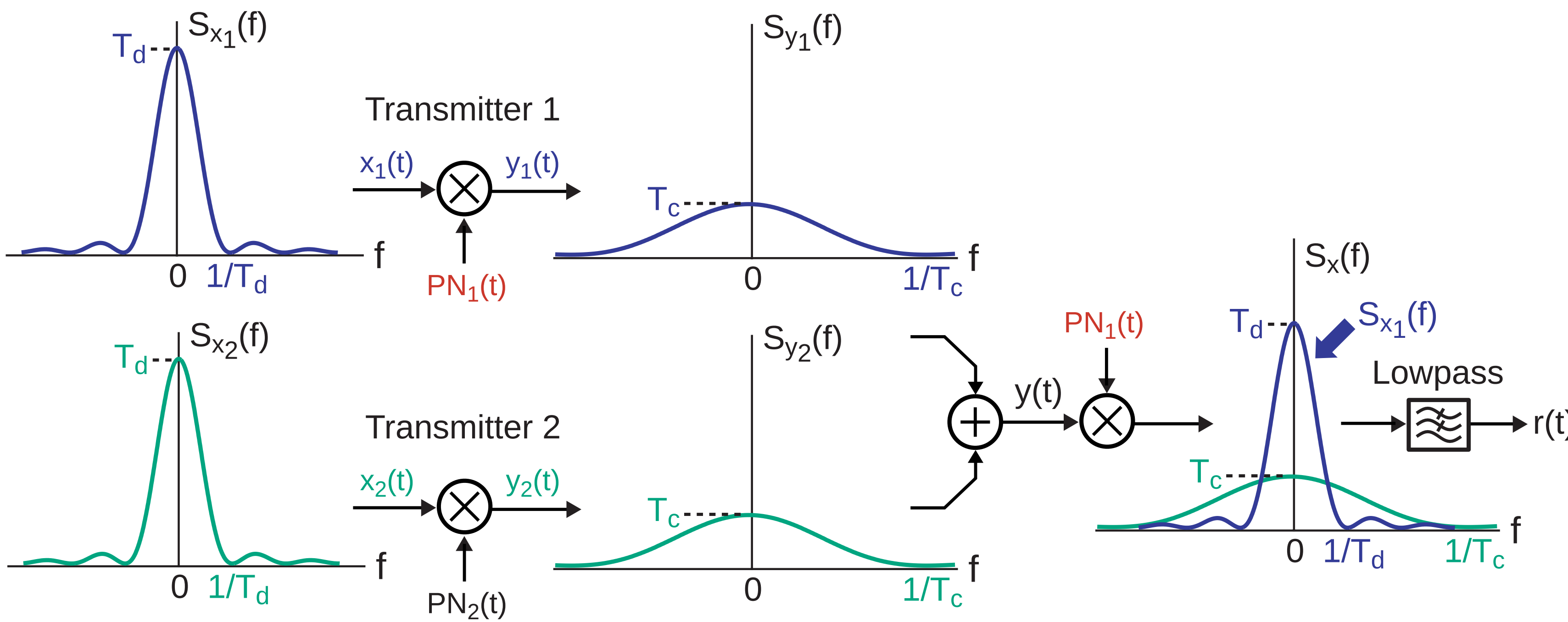
- **Receiver correlates its input with desired transmitter code**
  - **Data from desired transmitter restored**
  - **Data from other transmitter(s) remains randomized**

Frequency Domain View of Chip Vs Data Sequences



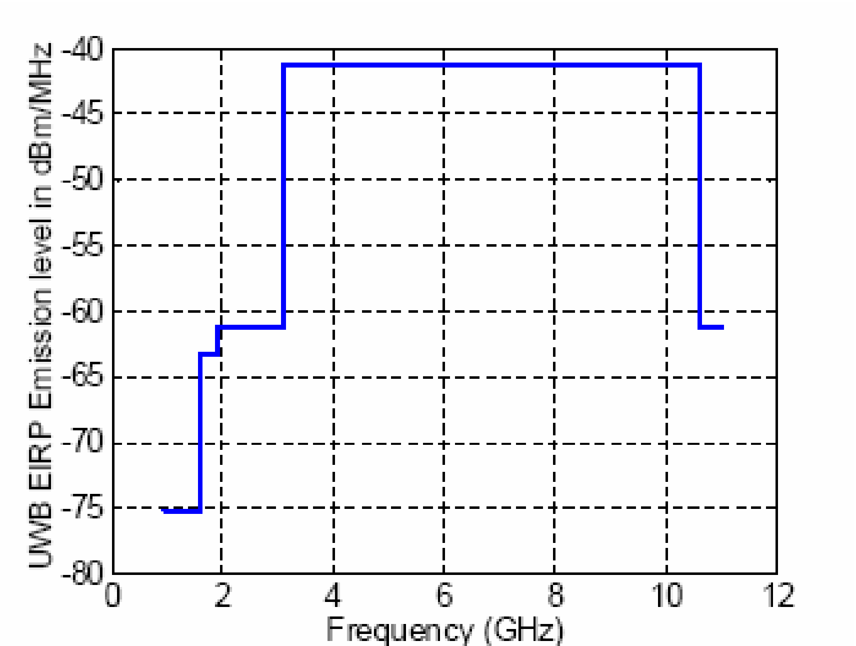
- **Data and chip sequences operate on different time scales**
  - **Associated spectra have different width and height**

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

UWB (Ultra-Wideband)



- **Extreme case of spread-spectrum communication**
- **Takes advantage of Shannon's theorem :**

  -data rate goes up proportionally to bandwidth but degrades only logarithmically with SNR.

- **Very low energy emission per Hz**

Pictures Courtesy of R. Blazquez, et. al.

UWB Standards

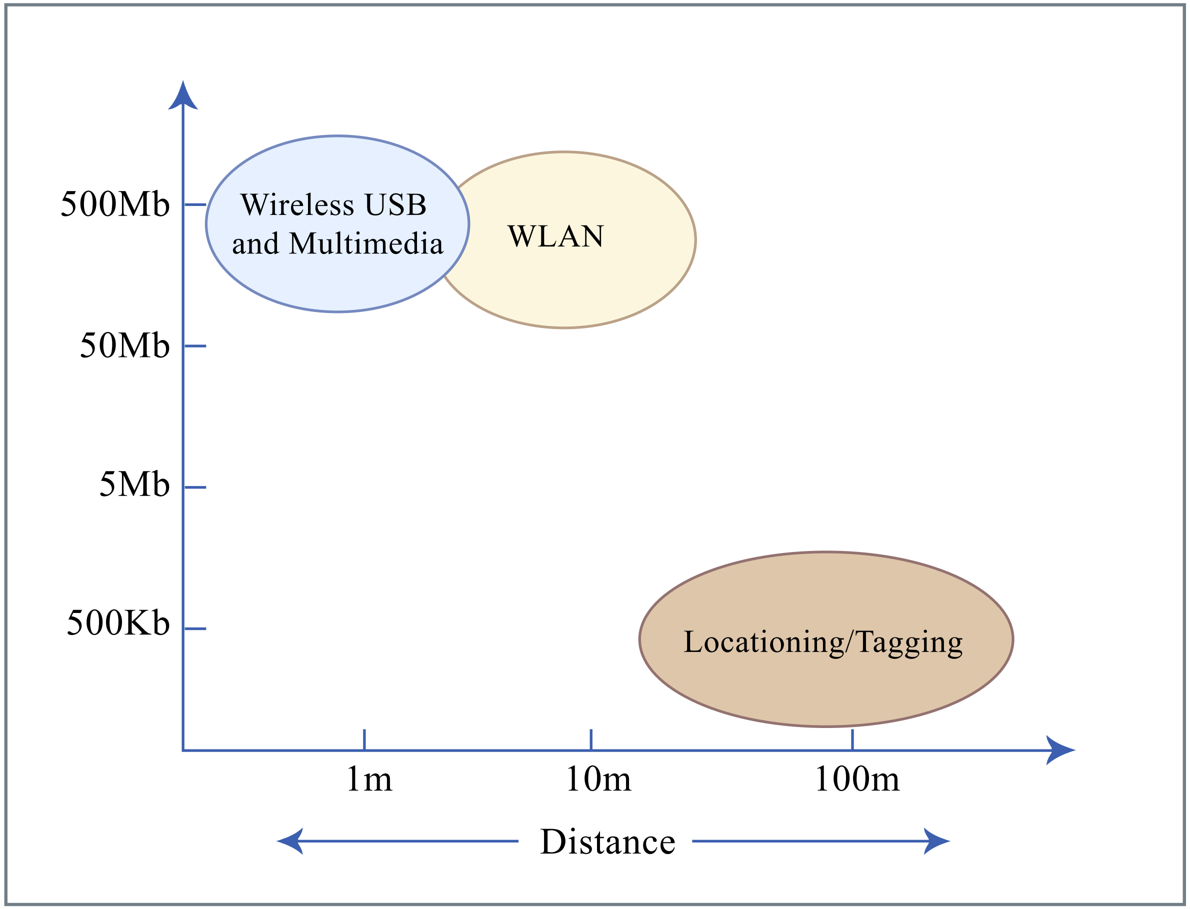
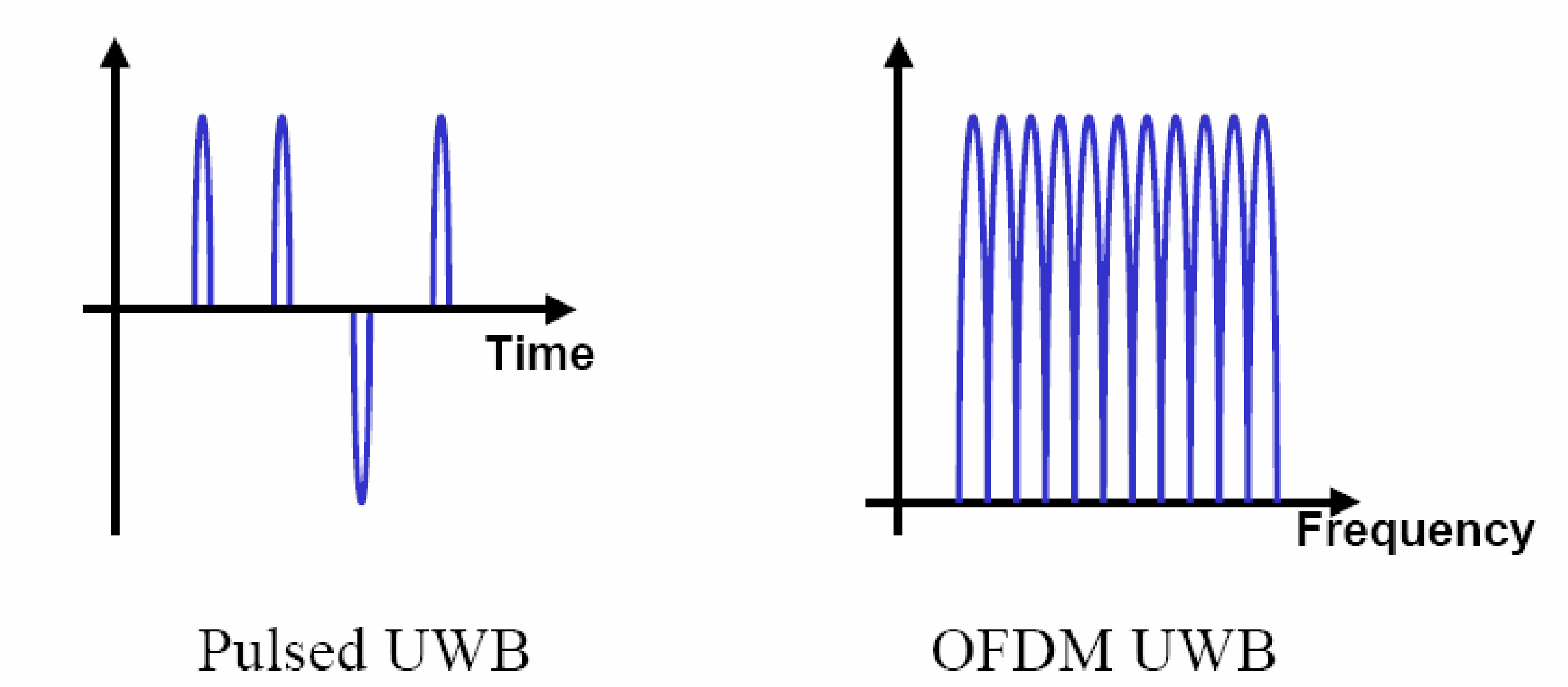


Figure by MIT OCW.

- **FCC recently allowed 3.1-10.6 GHz for UWB**
- **Two separate IEEE standards are under development**

Pictures Courtesy of R. Blazquez, et. al.

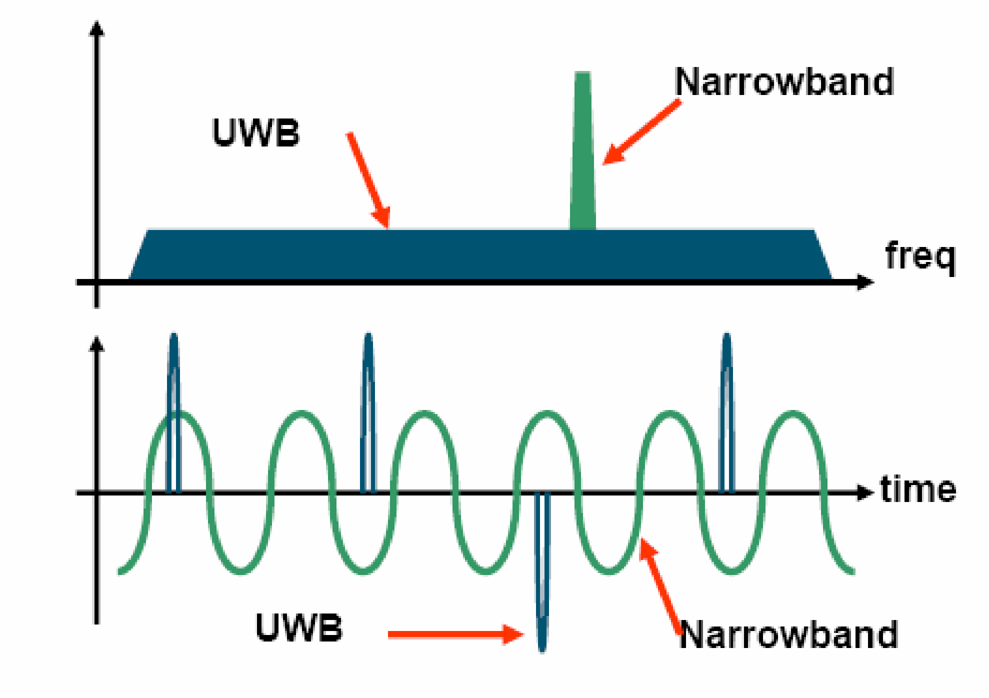
UWB Approaches



- **Pulsed UWB: Marconi invented it! It's a form of TDMA**
- **OFDM UWB: Utilizes knowledge base of narrowband systems. Strong jammers can be avoided.**

Pictures Courtesy of F. R. Lee, et. al.

Pulsed UWB



- Data encoded in impulse train
- Multipath can be exploited
- No narrowband filters (RF or baseband) needed in tranceivers
- Extremely tight time-synchronization is essential

Pictures Courtesy of R. Blazquez, et. al.

OFDM UWB

- **Can take advantage of wealth of knowledge in narrowband communication**
- **Involves the usual blocks of narrowband systems – filters, LNA's etc.**
- **Bandwidth of each channel is much wider: filtering is easier than narrowband systems**
- **SNR requirement in each channel is much lower than narrowband systems**
- **More digital processing than pulsed OFDM**
- **Strong jammers can be avoided**