6.976
High Speed Communication Circuits and Systems
Lecture 19
Basics of Wireless Communication

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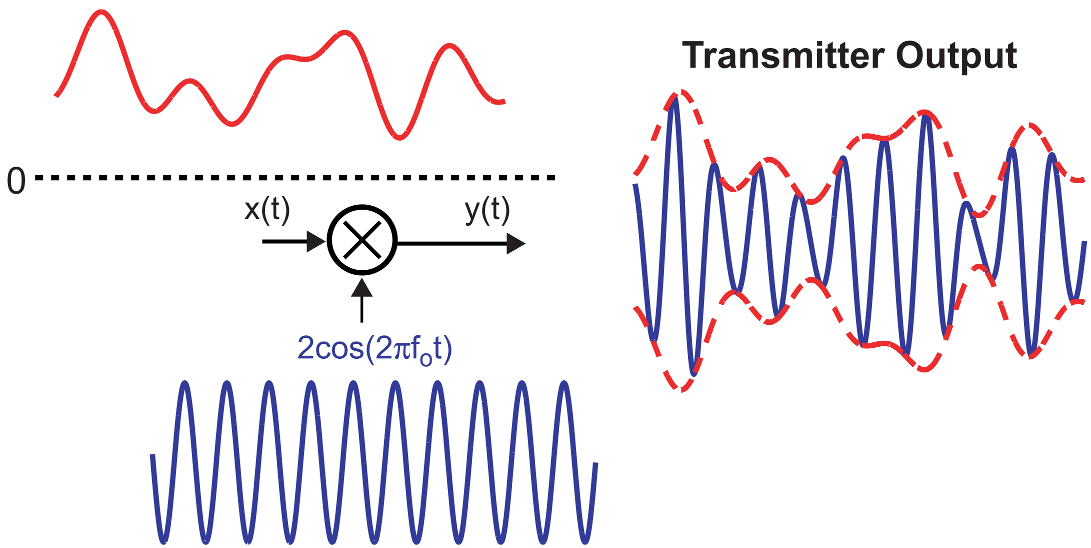
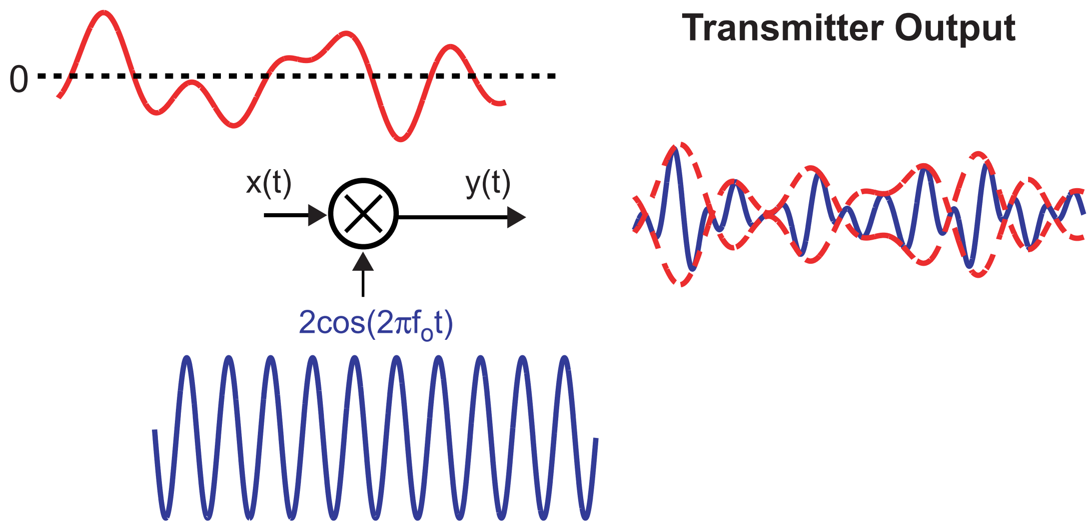
Amplitude Modulation (Transmitter)



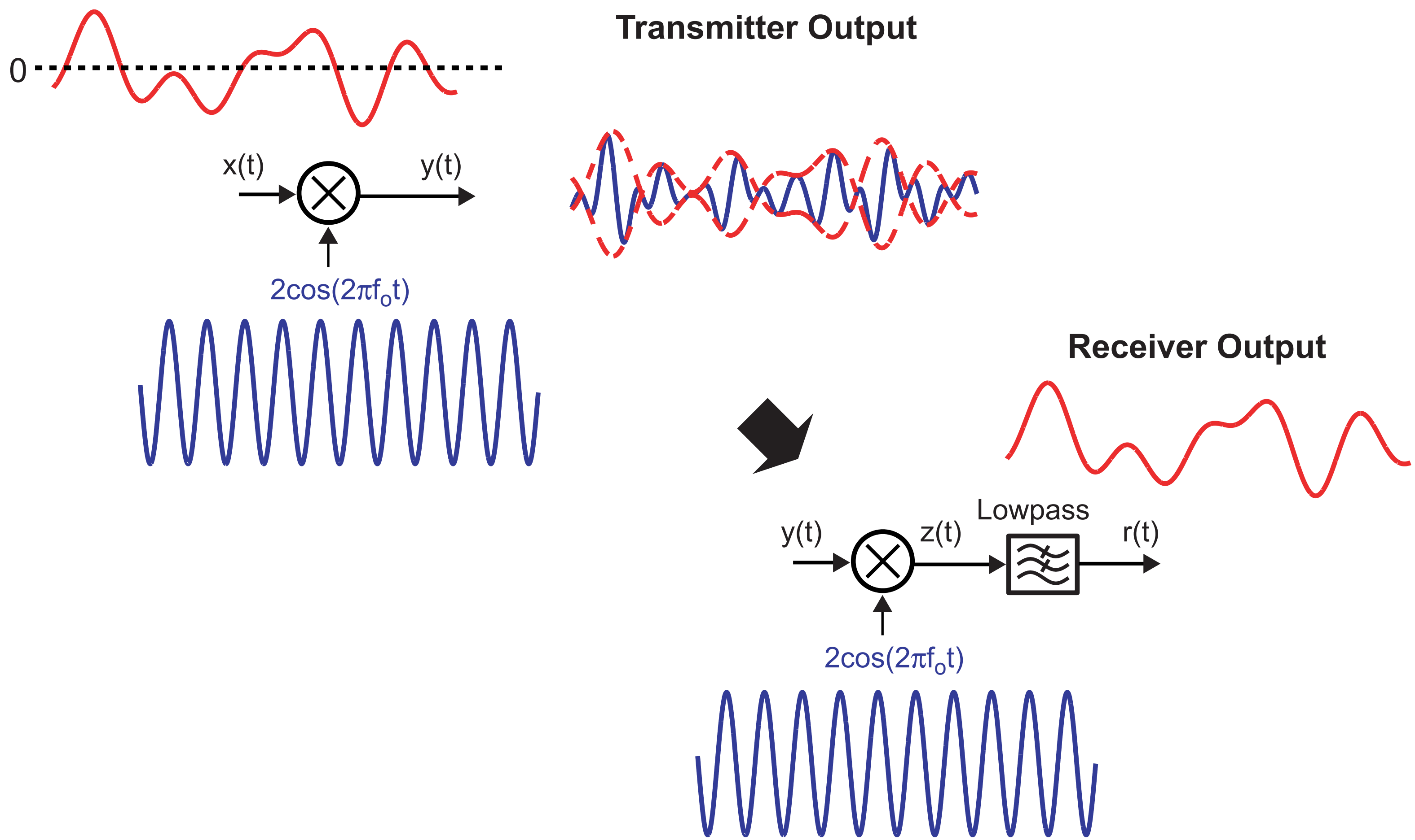
- **Vary the amplitude of a sine wave at carrier frequency f_o according to a baseband modulation signal**
- **DC component of baseband modulation signal influences transmit signal and receiver possibilities**
  - **DC value greater than signal amplitude shown above**
    - Allows simple envelope detector for receiver
    - Creates spurious tone at carrier frequency (wasted power)

Impact of Zero DC Value



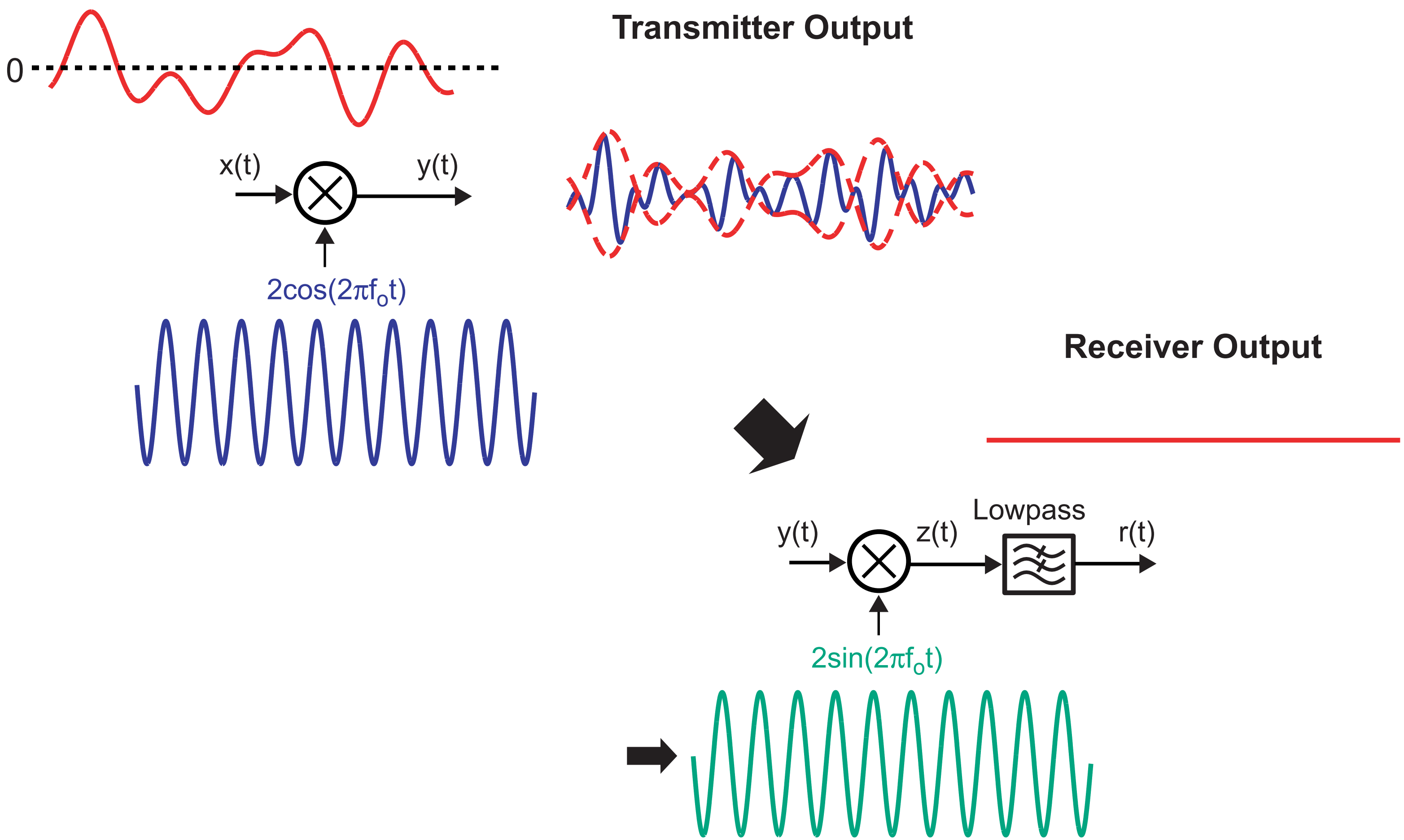
- **Envelope of modulated sine wave no longer corresponds directly to the baseband signal**
  - **Envelope instead follows the absolute value of the baseband waveform**
  - **Envelope detector can no longer be used for receiver**
- **The good news: less transmit power required for same transmitter SNR (compared to nonzero DC value)**

Accompanying Receiver (Coherent Detection)



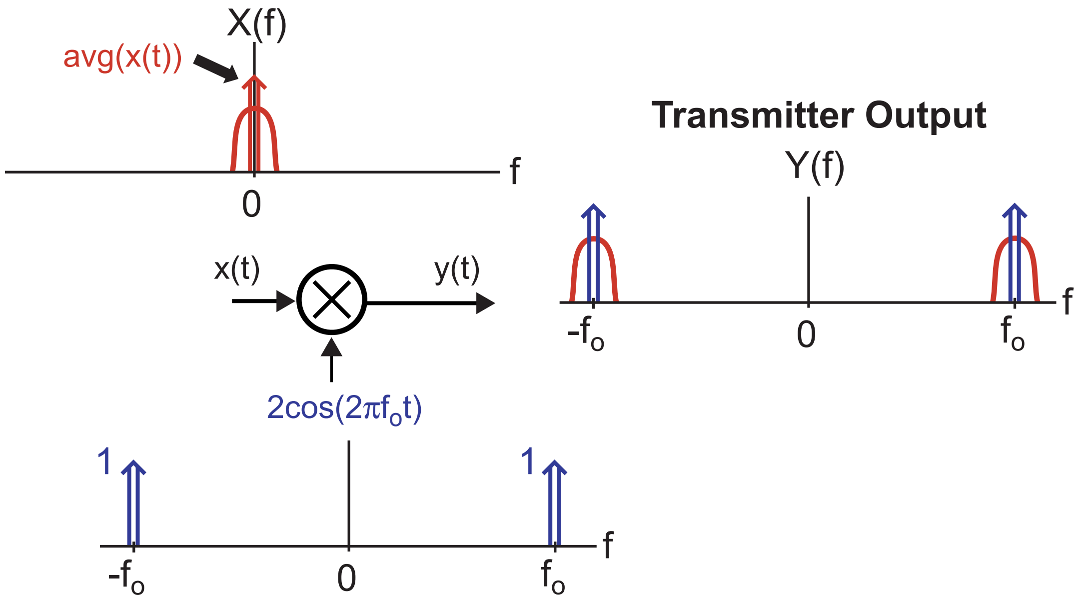
- Works regardless of DC value of baseband signal
- Requires receiver local oscillator to be accurately aligned in phase and frequency to carrier sine wave

Impact of Phase Misalignment in Receiver Local Oscillator



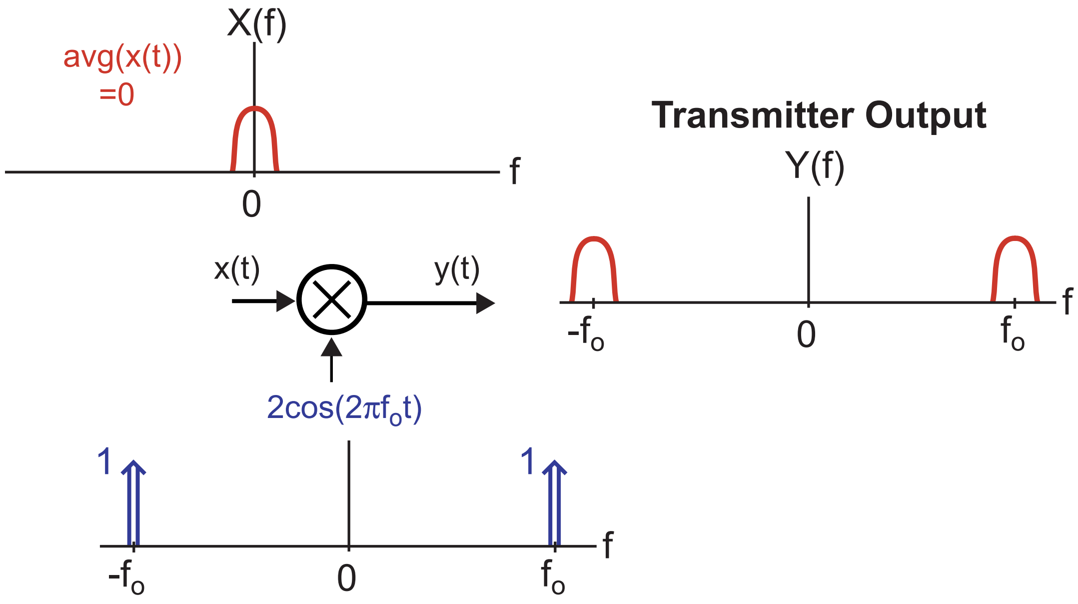
- **Worst case is when receiver LO and carrier frequency are phase shifted 90 degrees with respect to each other**
  - **Desired baseband signal is not recovered**

Frequency Domain View of AM Transmitter



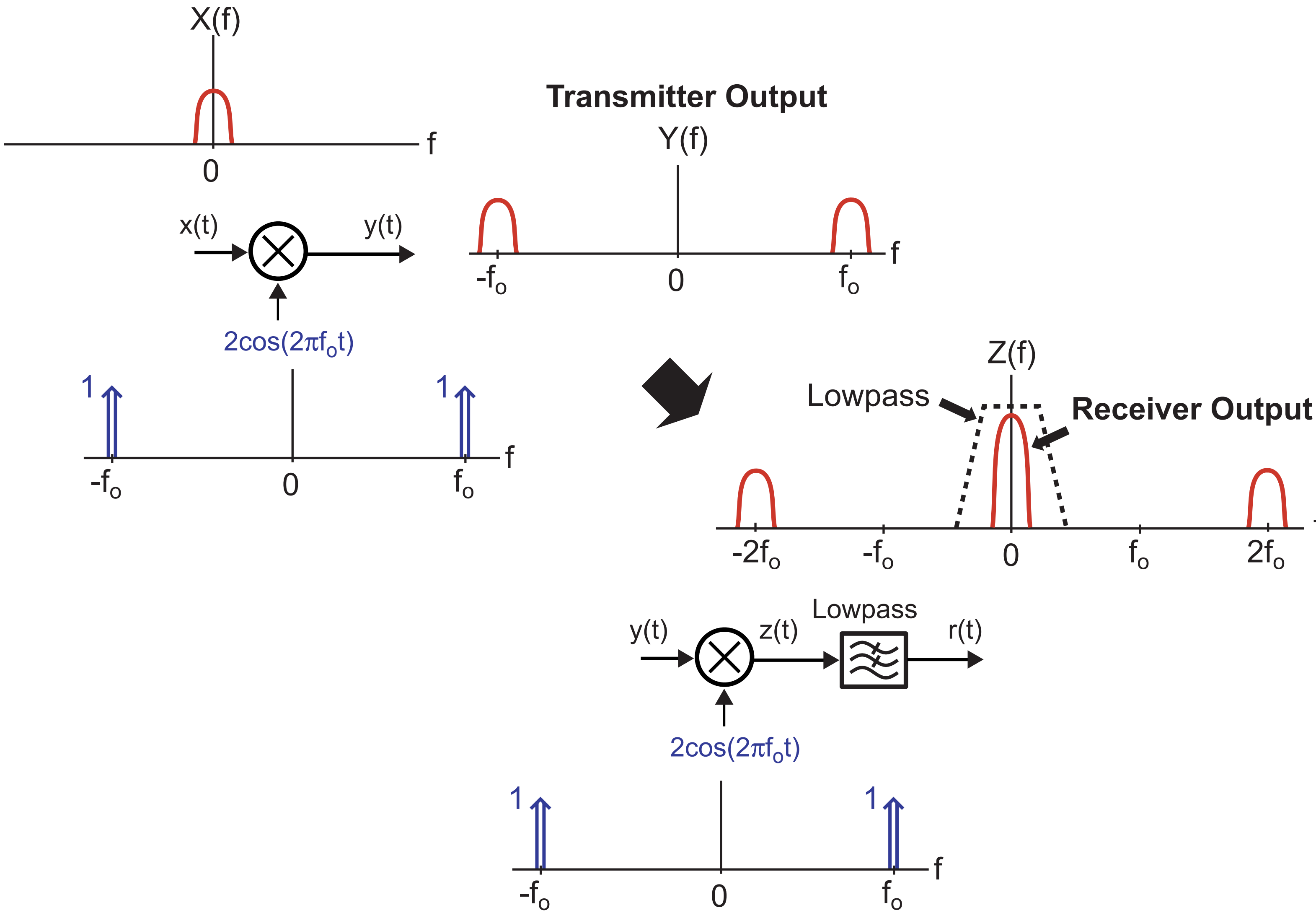
- **Baseband signal is assumed to have a nonzero DC component in above diagram**
  - **Causes impulse to appear at DC in baseband signal**
  - **Transmitter output has an impulse at the carrier frequency**
    - For coherent detection, does not provide key information about information in baseband signal, and therefore is a waste of power

Impact of Having Zero DC Value for Baseband Signal

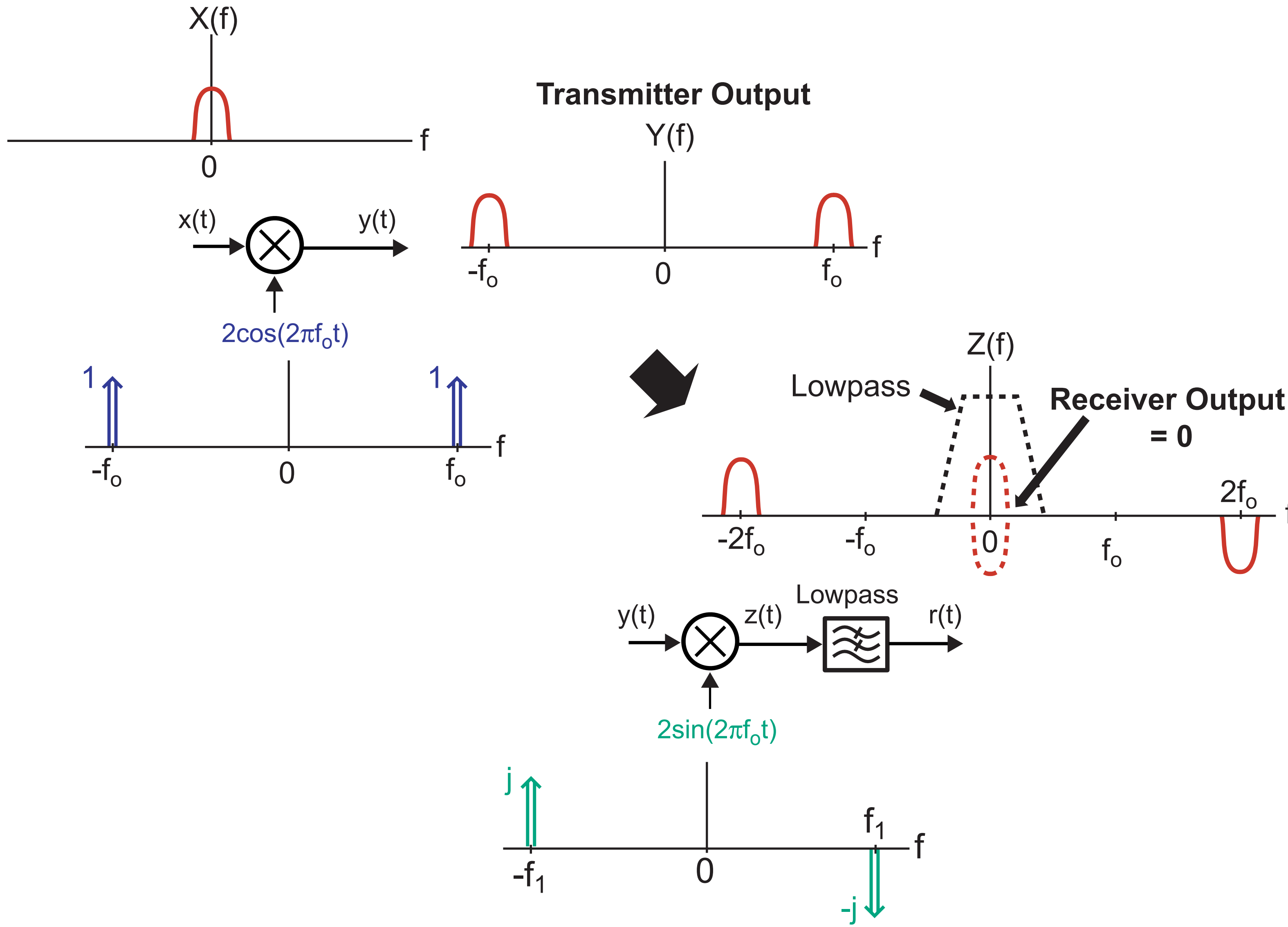


- Impulse in DC portion of baseband signal is now gone
  - Transmitter output now is now free from having an impulse at the carrier frequency (for ideal implementation)

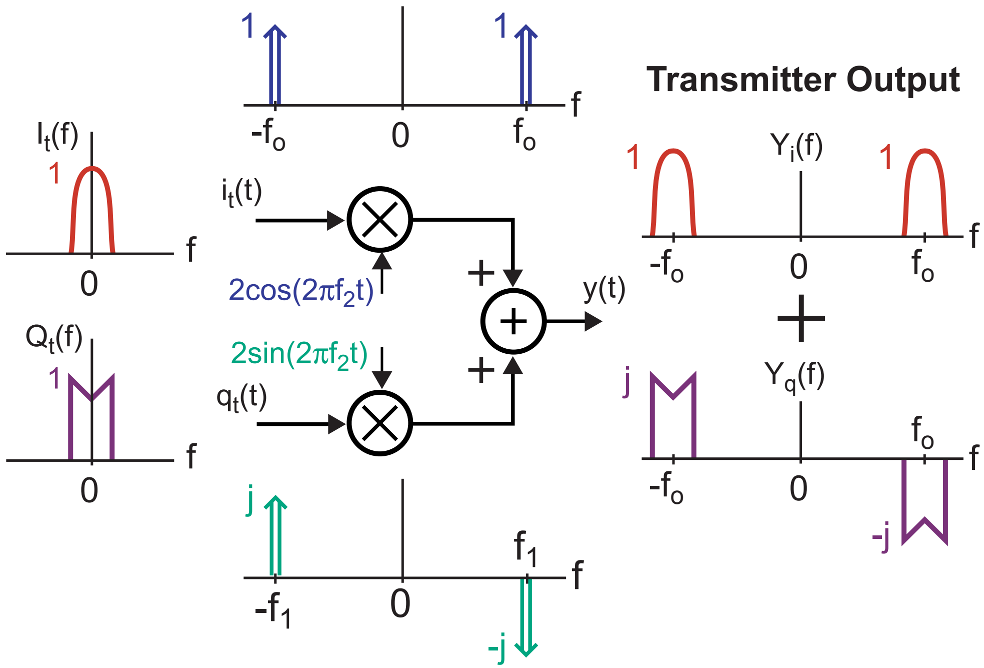
Frequency Domain View of AM Receiver (Coherent)



Impact of 90 Degree Phase Misalignment

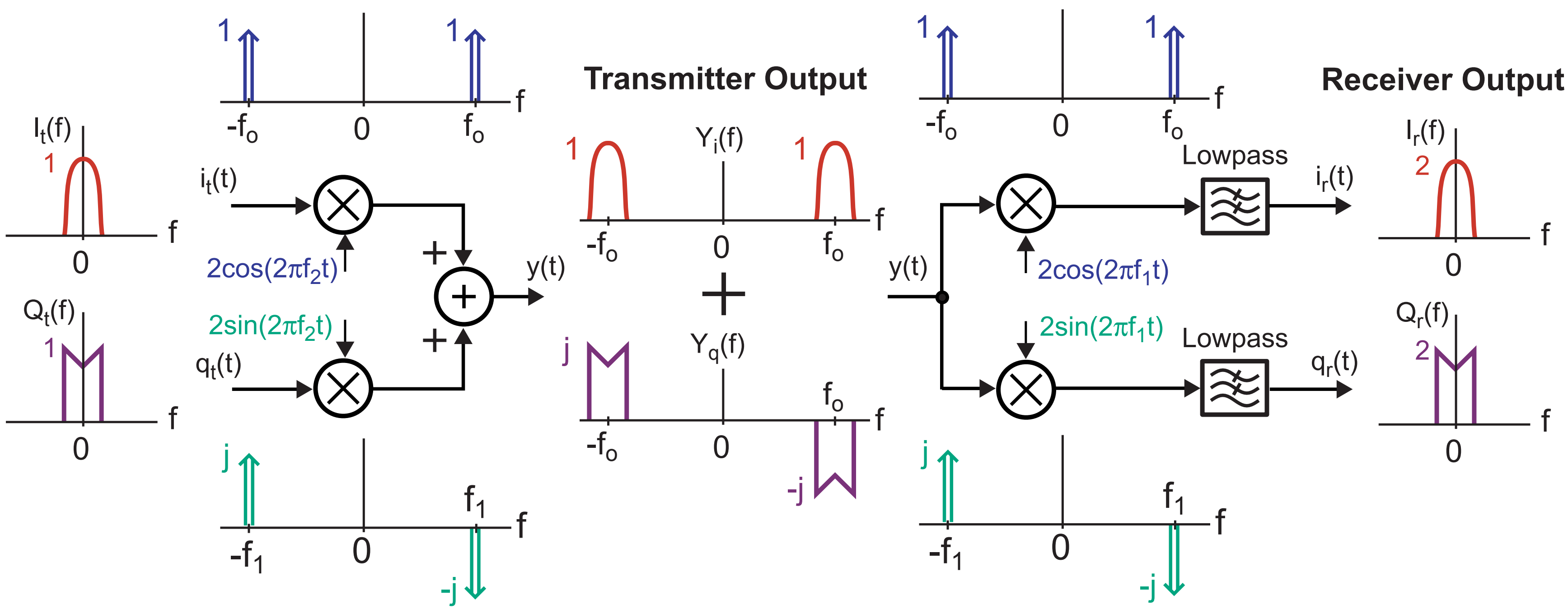


Quadrature Modulation



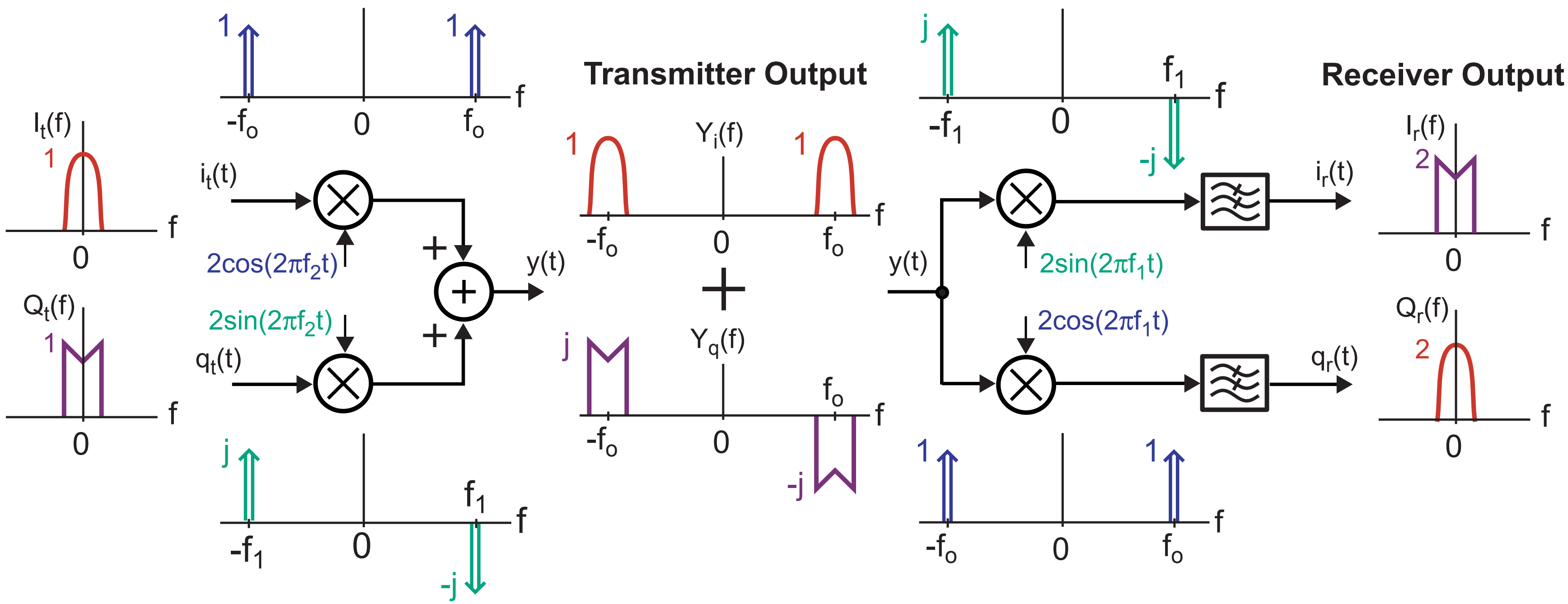
- Takes advantage of coherent receiver's sensitivity to phase alignment with transmitter local oscillator
  - We essentially have two orthogonal transmission channels (I and Q) available to us
  - Transmit two independent baseband signals (I and Q) onto two sine waves in quadrature at transmitter

Accompanying Receiver



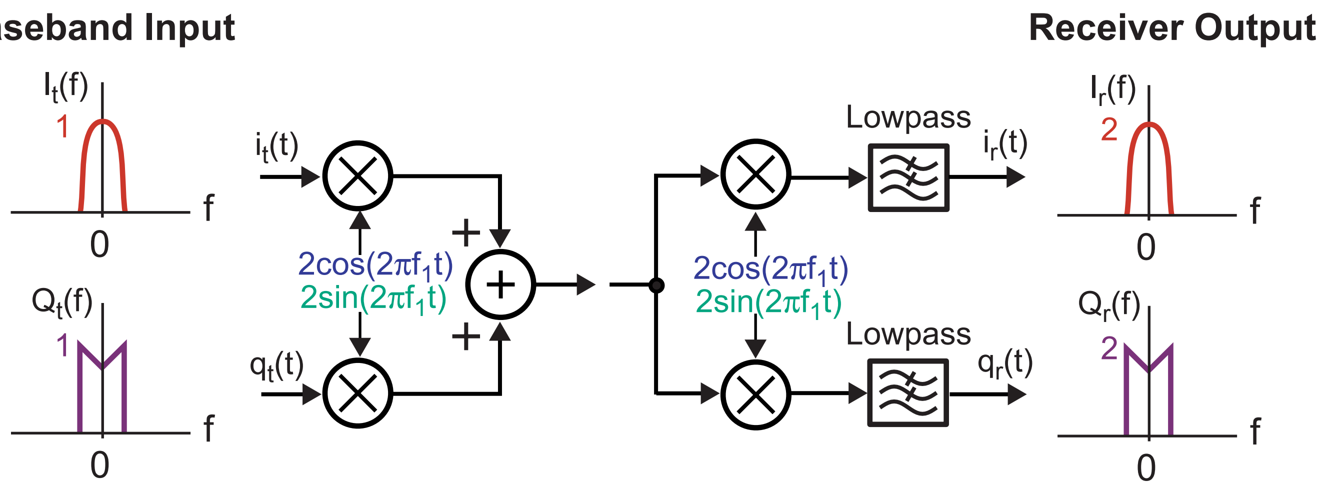
- Demodulate using two sine waves in quadrature at receiver
  - Must align receiver LO signals in frequency and phase to transmitter LO signals
    - Proper alignment allows I and Q signals to be recovered as shown

Impact of 90 Degree Phase Misalignment



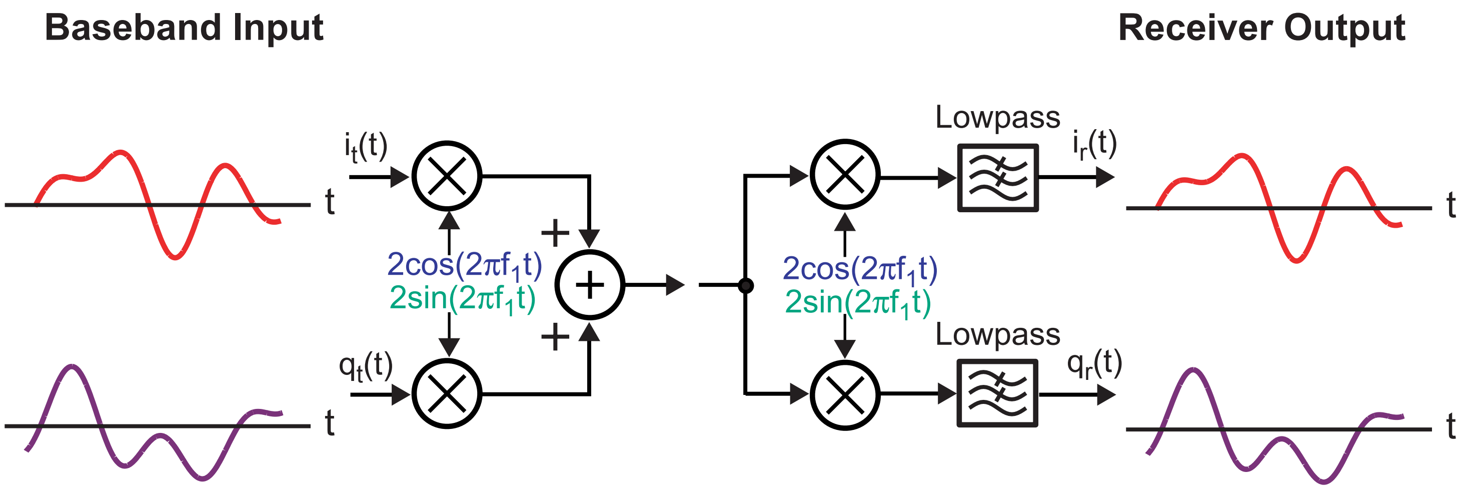
- I and Q channels are swapped at receiver if its LO signal is 90 degrees out of phase with transmitter
  - However, no information is lost!
  - Can use baseband signal processing to extract I/Q signals despite phase offset between transmitter and receiver

Simplified View



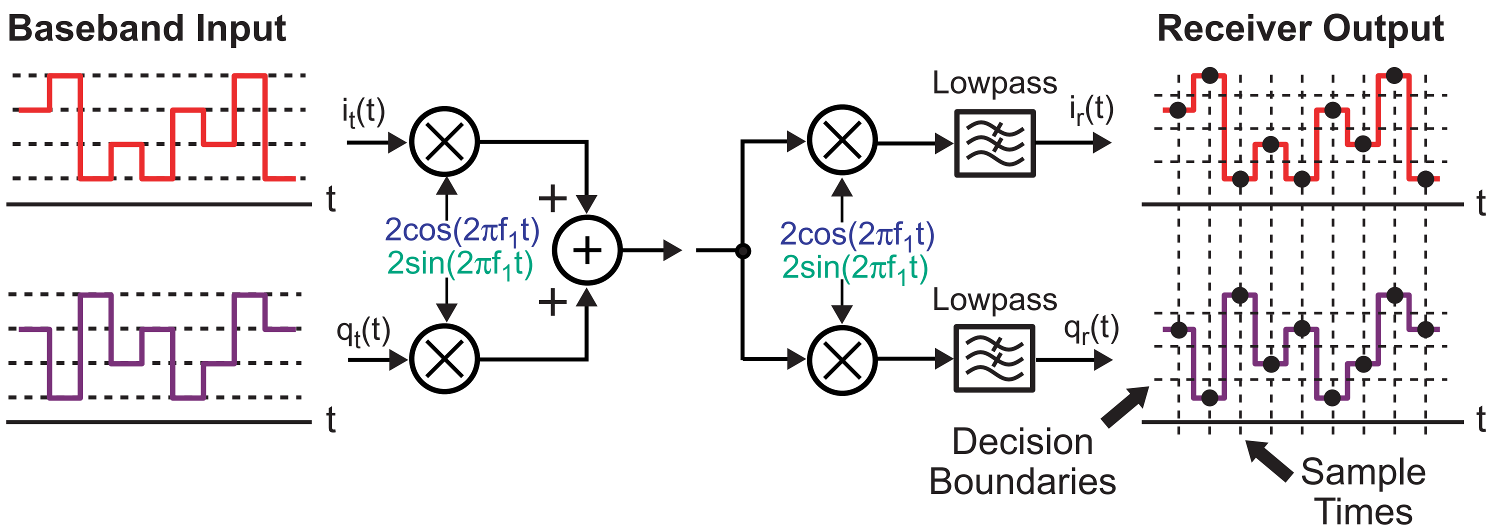
- **For discussion to follow, assume that**
  - **Transmitter and receiver phases are aligned**
  - **Lowpass filters in receiver are ideal**
  - **Transmit and receive I/Q signals are the same except for scale factor**
- **In reality**
  - **RF channel adds distortion, causes fading**
  - **Signal processing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

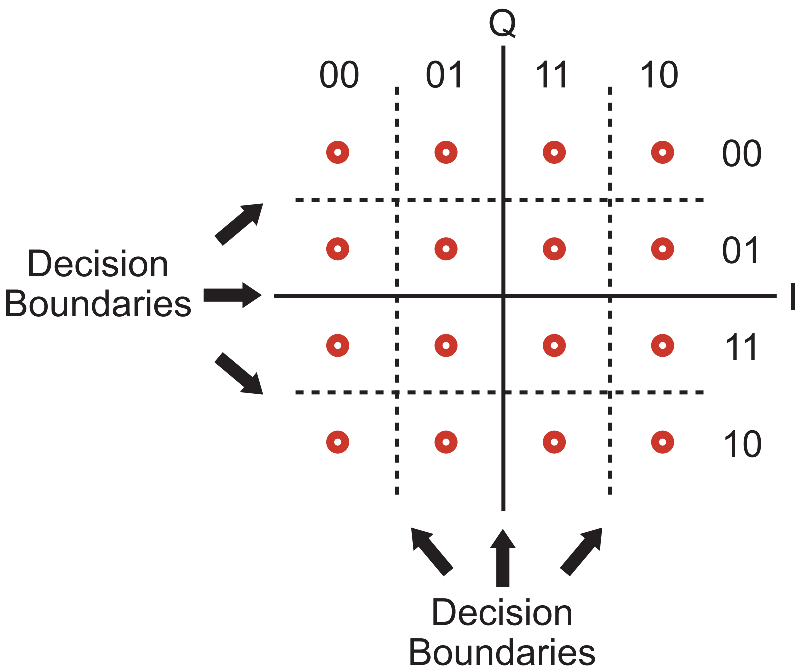


- **I/Q signals take on discrete values at discrete time instants corresponding to digital data**
  - **Receiver samples I/Q channels**
    - Uses decision boundaries to evaluate value of data at each time instant
- **I/Q signals may be binary or multi-bit**
  - **Multi-bit shown above**

Advantages of Digital Modulation

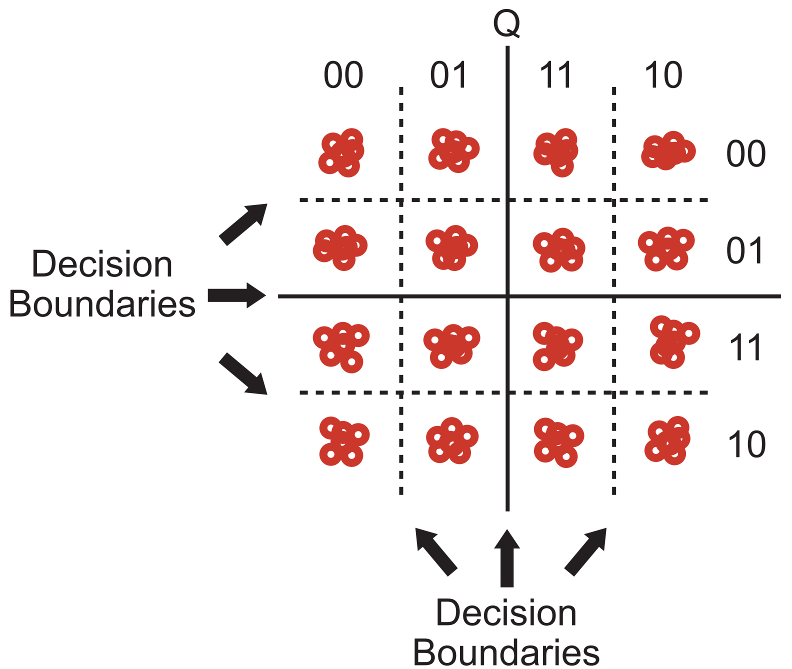
- **Allows information to be “packetized”**
  - **Can compress information in time and efficiently send as packets through network**
  - **In contrast, analog modulation requires “circuit-switched” connections that are continuously available**
    - Inefficient use of radio channel if there is “dead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



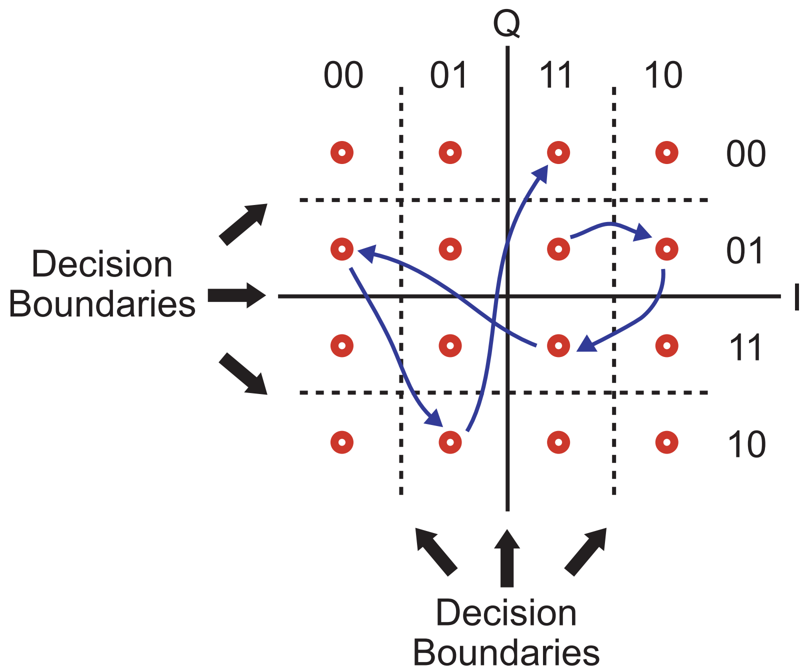
- We can view I/Q values at sample instants on a two-dimensional coordinate system
- Decision boundaries mark up regions corresponding to different data values
- Gray coding used to minimize number of bit errors that occur if wrong decision is made due to noise

Impact of Noise on Constellation Diagram



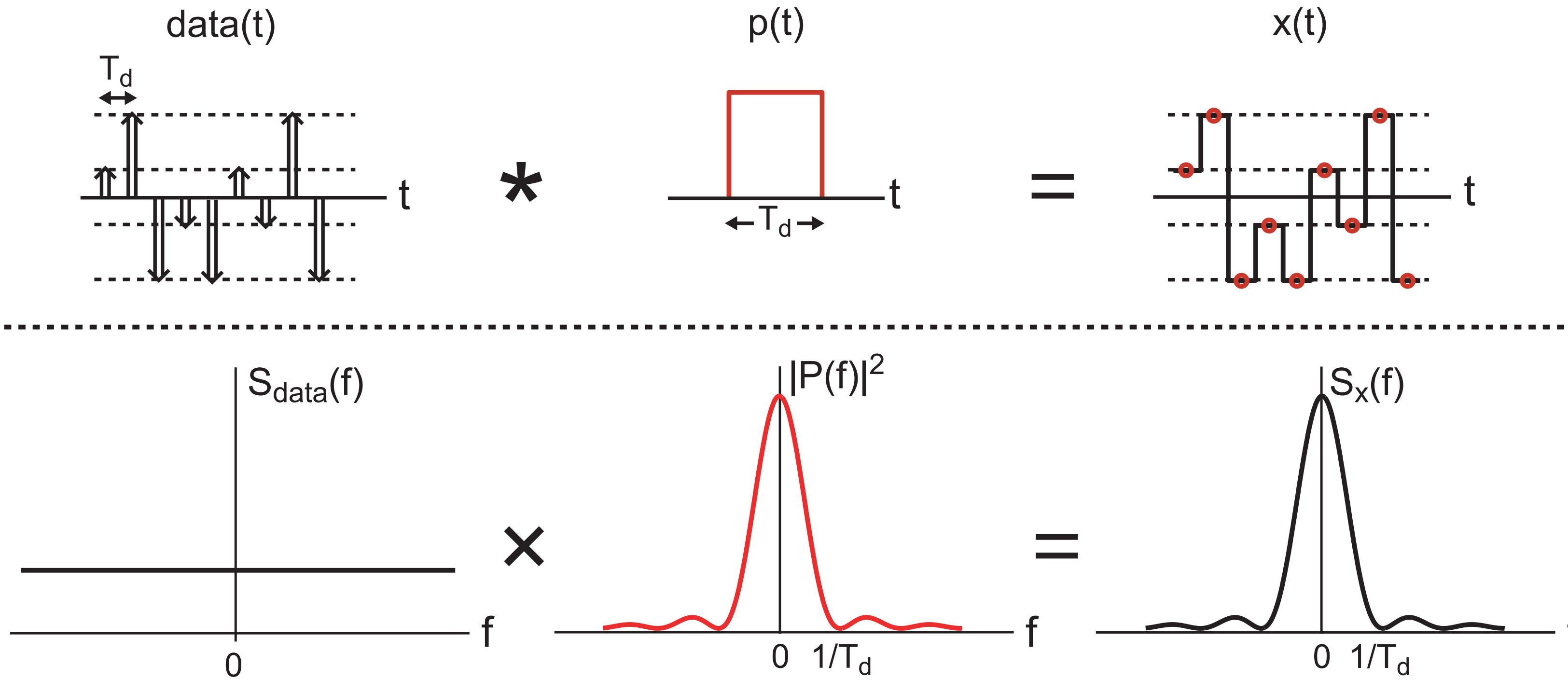
- Sampled data values no longer land in exact same location across all sample instants
- Decision boundaries remain fixed
- Significant noise causes bit errors to be made

Transition Behavior Between Constellation Points



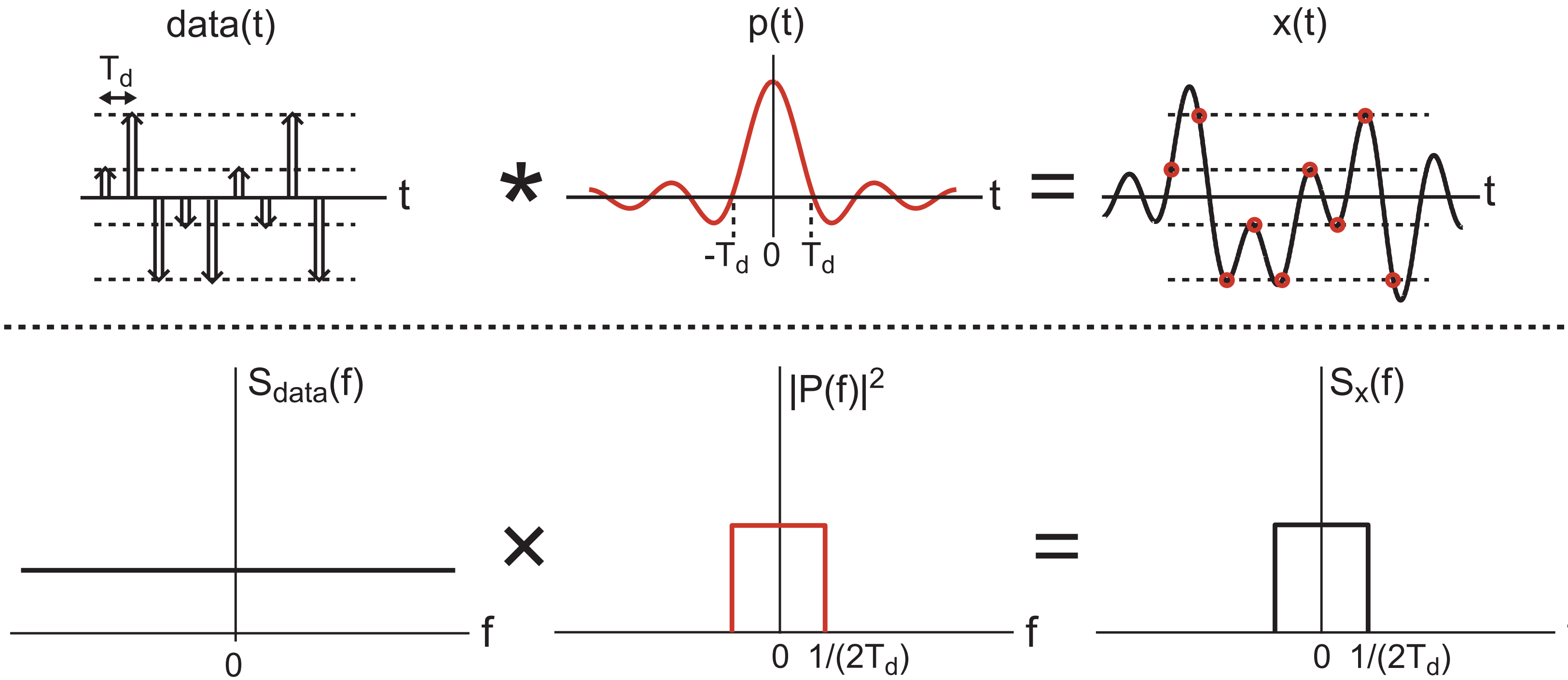
- Constellation diagrams provide us with a snapshot of I/Q signals at sample instants
- Transition behavior between sample points depends on modulation scheme and transmit filter

Choosing an Appropriate Transmit Filter



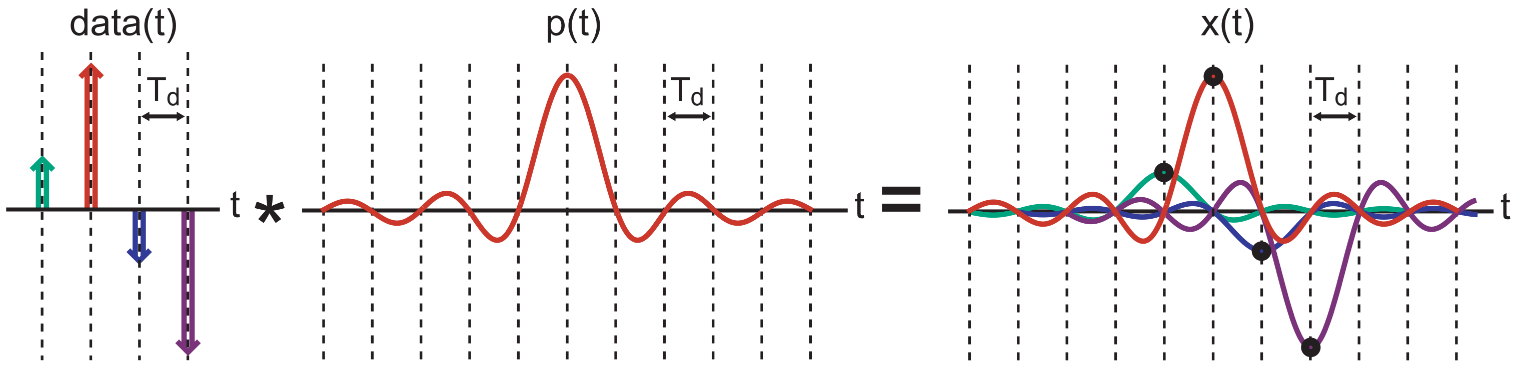
- **Transmit filter, p(t), convolved with data symbols that are viewed as impulses**
  - **Example so far: p(t) is a square pulse**
- **Output spectrum of transmitter corresponds to square of transmit filter (assuming data has white spectrum)**
  - **Want good spectral efficiency (i.e. narrow spectrum)**

Highest Spectral Efficiency with Brick-wall Lowpass



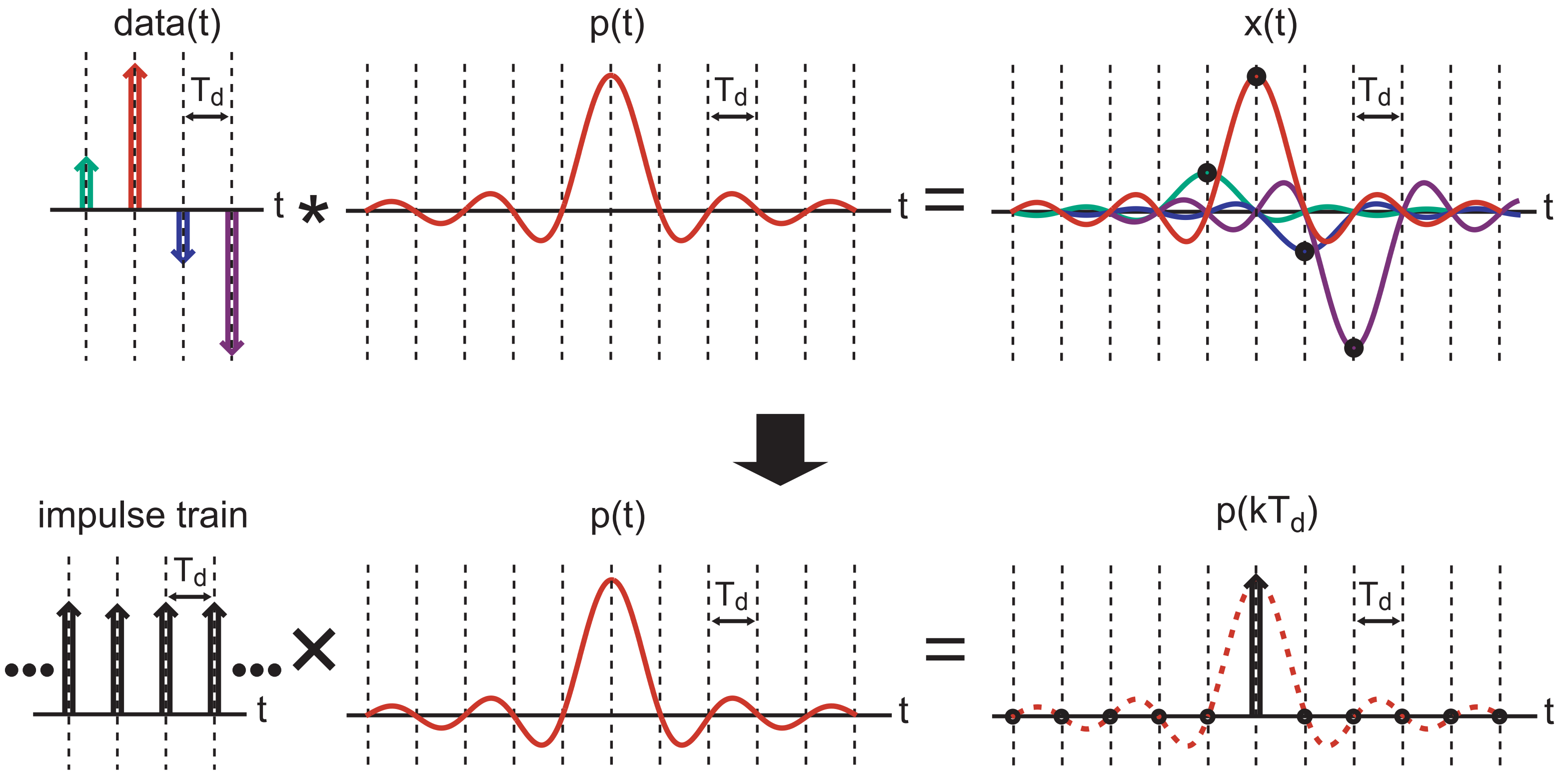
- **Use a sinc function for transmit filter**
  - **Corresponds to ideal lowpass in frequency domain**
- **Issues**
  - **Nonrealizable in practice**
  - **Sampling offset causes significant intersymbol interference**

Requirement for Transmit Filter to Avoid ISI



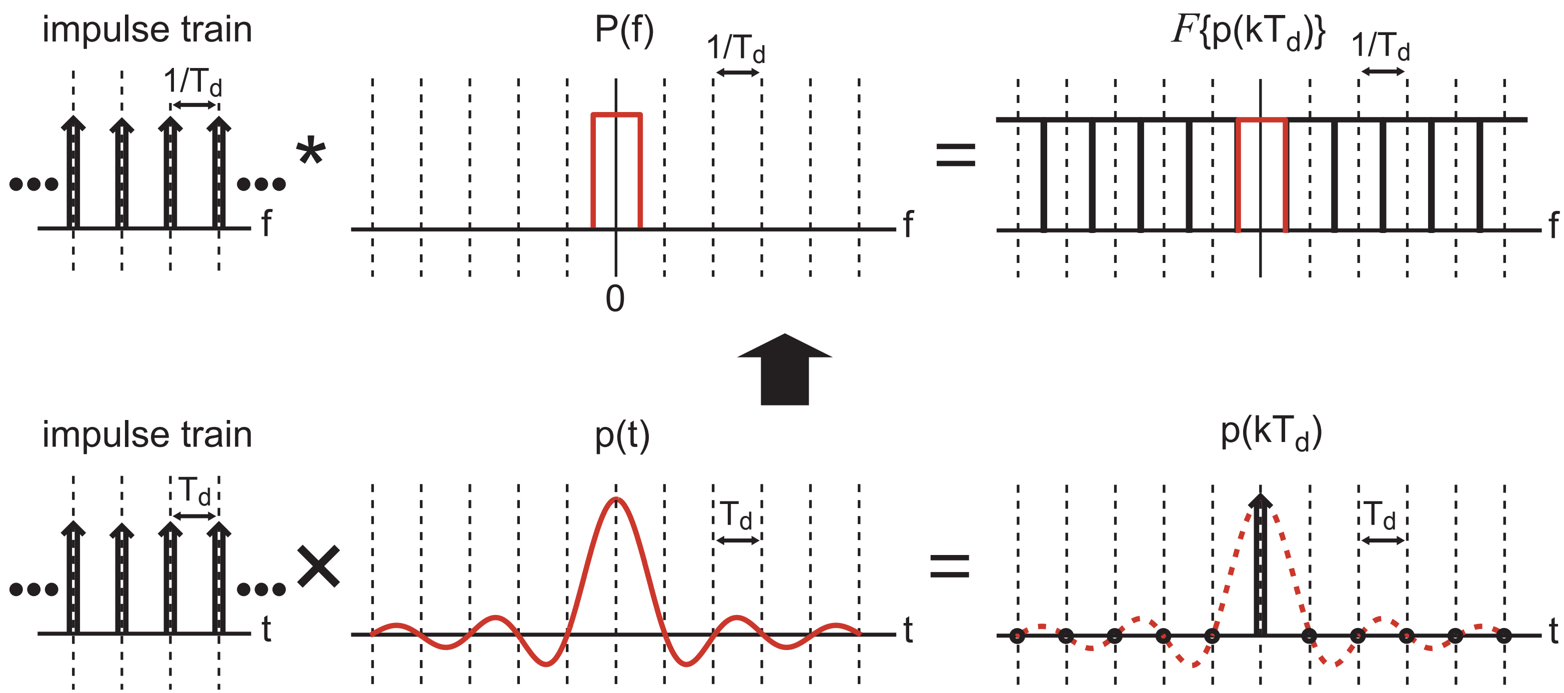
- Time samples of transmit filter (spaced T_d apart) must be nonzero at only one sample time instant
  - Sinc function satisfies this criterion if we have no offset in the sample times
- Intersymbol interference (ISI) occurs otherwise
- Example: look at result of convolving p(t) with 4 impulses
  - With zero sampling offset, $x(kT_d)$ correspond to associated impulse areas

Derive Nyquist Condition for Avoiding ISI (Step 1)



- Consider multiplying p(t) by impulse train with period T_d
  - Resulting signal must be a single impulse in order to avoid ISI (same argument as in previous slide)

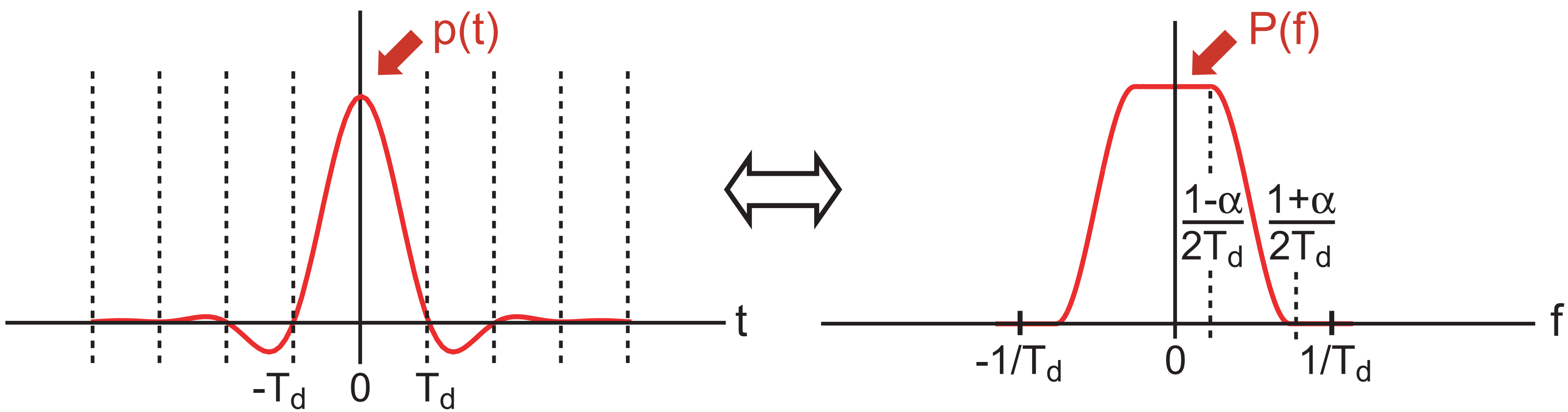
Derive Nyquist Condition for Avoiding ISI (Step 2)



- **In frequency domain, the Fourier transform of sampled p(t) must be flat to avoid ISI**
  - **We see this in two ways for above example**
    - Fourier transform of an impulse is flat
    - Convolution of P(f) with impulse train in frequency is flat

A More Practical Transmit Filter

- **Raised-cosine filter is quite popular in many applications**



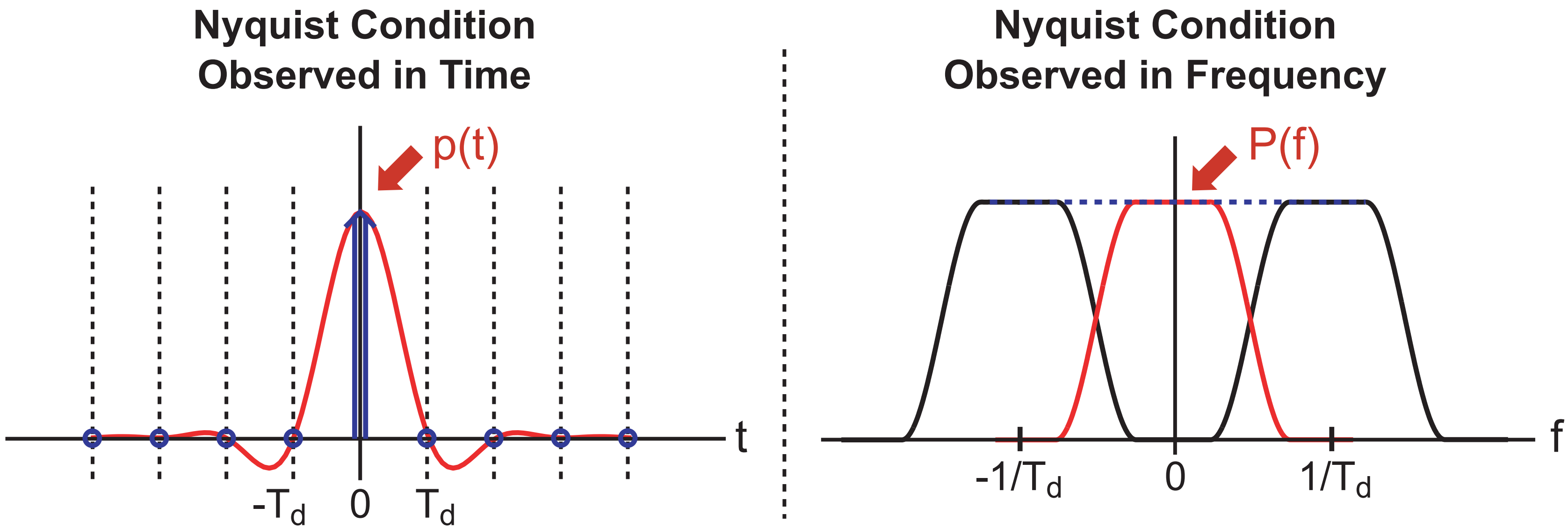
$$p(t) = \frac{\sin(\pi t/T_d)}{\pi t/T_d}\,\frac{\cos(\pi\alpha t/T_d)}{1-4\alpha^2 t^2/T_d^2}$$

- **Transition band in frequency set by "rolloff" factor, α**

possible range: $0 \le \alpha \le 1$ (typical setting: $0.3 \le \alpha \le 0.5$)

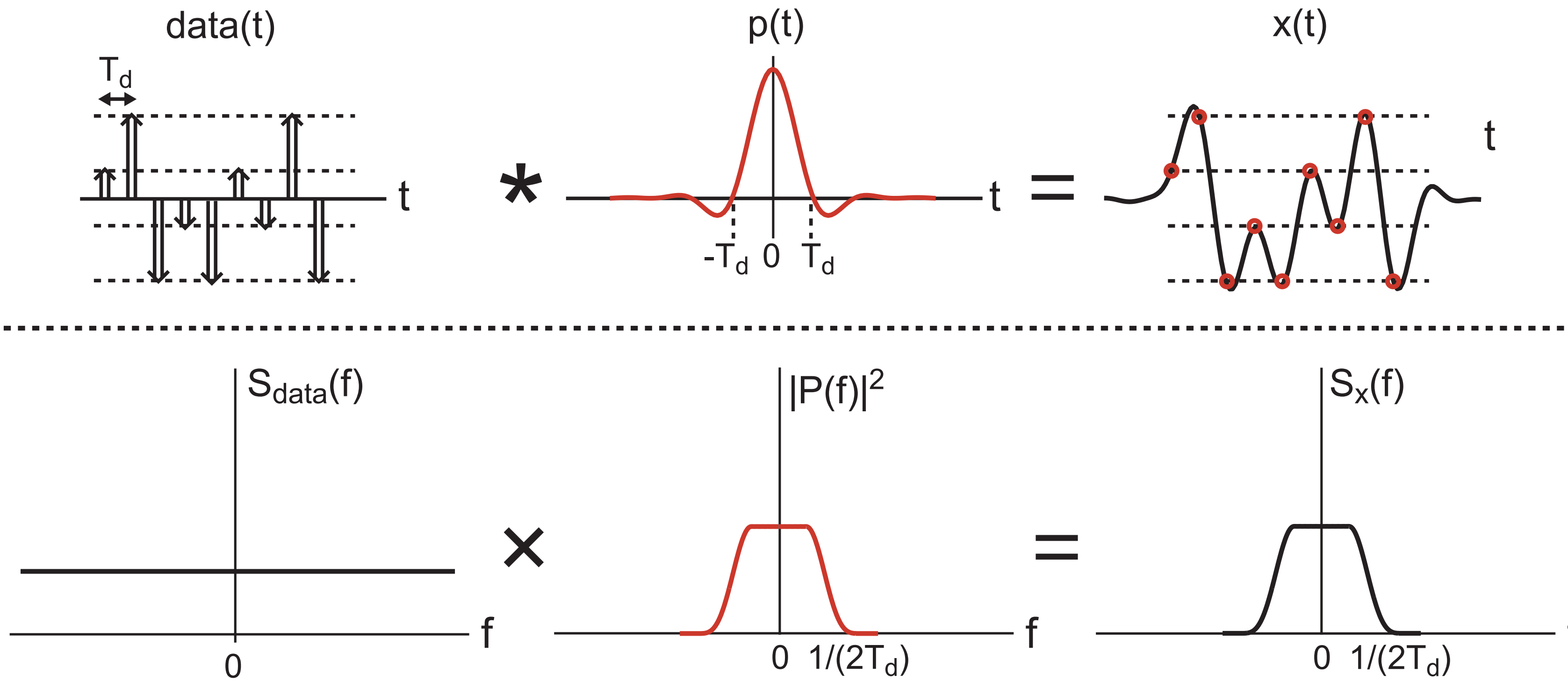
  - Rolloff factor = 0: P(f) becomes a brick-wall filter
  - Rolloff factor = 1: P(f) looks nearly like a triangle
  - Rolloff factor = 0.5: shown above

Raised-Cosine Filter Satisfies Nyquist Condition



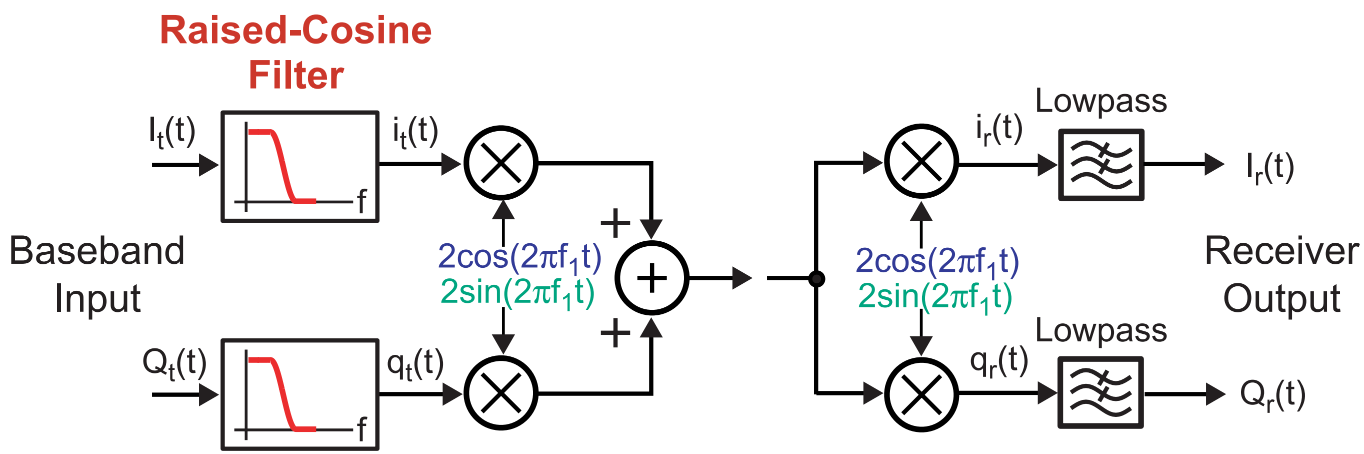
- **In time**
  - **$p(kT_d) = 0$ for all k not equal to 0**
- **In frequency**
  - **Fourier transform of $p(kT_d)$ is flat**
  - **Alternatively: Addition of shifted P(f) centered about k/T_d leads to flat Fourier transform (as shown above)**

Spectral Efficiency With Raised-Cosine Filter



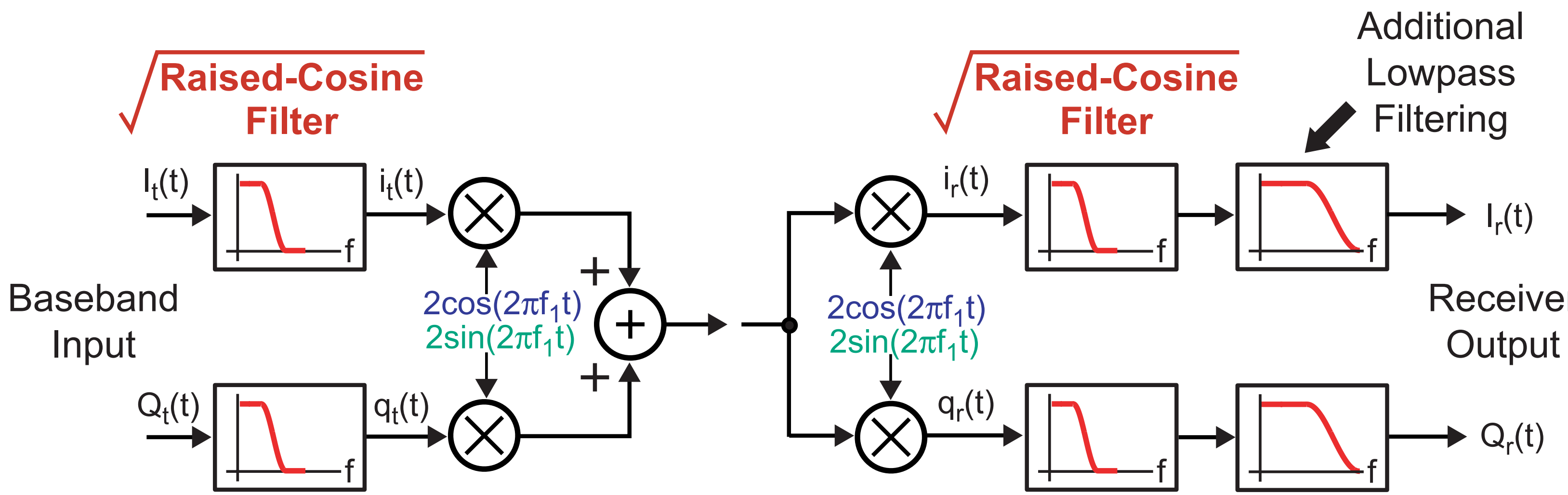
- **More efficient than when p(t) is a square pulse**
- **Less efficient than brick-wall lowpass**
  - **But implementation is much more practical**
- **Note: Raised-cosine P(f) often "split" between transmitter and receiver**

Receiver Filter: ISI Versus Noise Performance



- **Conflicting requirements for receiver lowpass**
  - **Low bandwidth desirable to remove receiver noise and to reject high frequency components of mixer output**
  - **High bandwidth desirable to minimize ISI at receiver output**

Split Raised-Cosine Filter Between Transmitter/Receiver



- **We know that passing data through raised-cosine filter does not cause additional ISI to be produced**
  - **Implement P(f) as cascade of two filters corresponding to square root of P(f)**

$$P(f) = \sqrt{P(f)}\sqrt{P(f)}$$

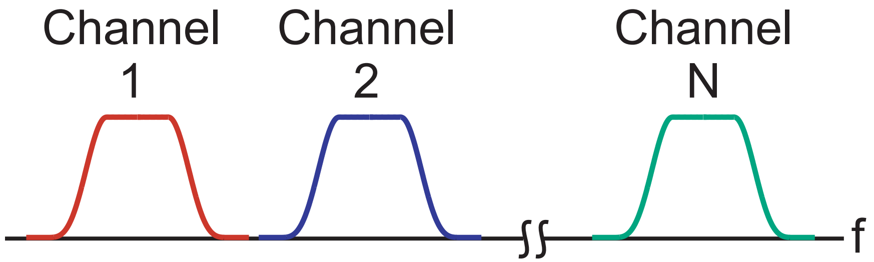
    - Place one in transmitter, the other in receiver
- **Use additional lowpass filtering in receiver to further reduce high frequency noise and mixer products**

Multiple Access Techniques

The Issue of Multiple Access

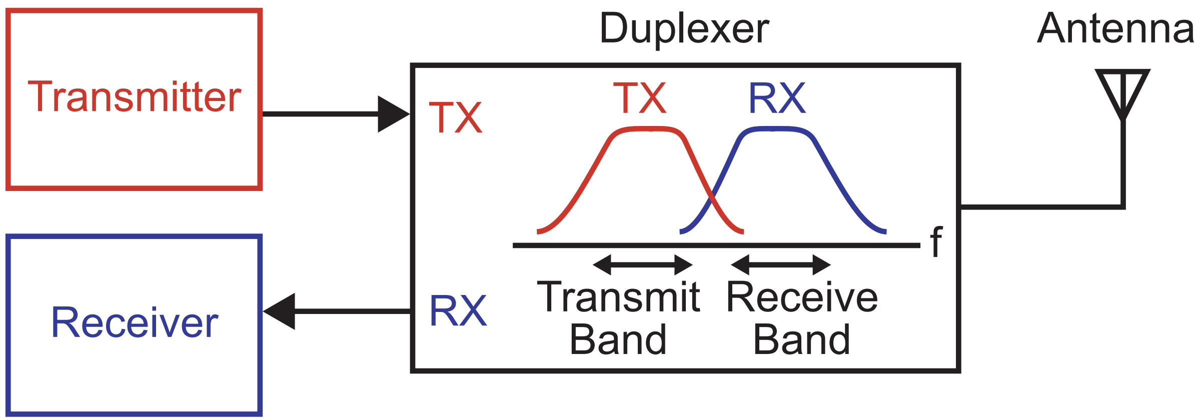
- Want to allow communication between many different users
- Freespace spectrum is a shared resource
  - Must be partitioned between users
- Can partition in either time, frequency, or through “orthogonal coding” (or nearly orthogonal coding) of data signals

Frequency-Division Multiple Access (FDMA)



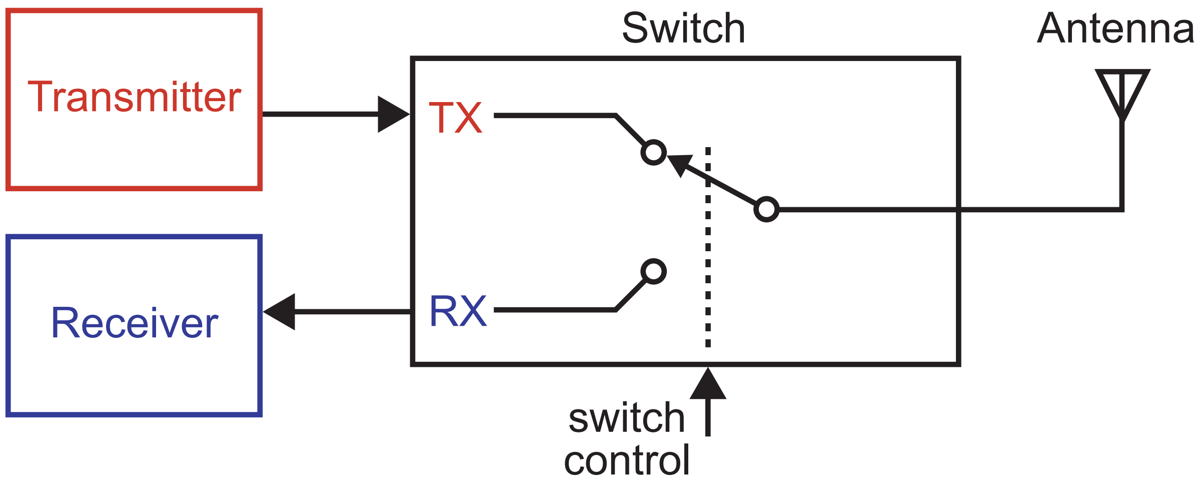
- **Place users into different frequency channels**
- **Two different methods of dealing with transmit/receive of a given user**
  - **Frequency-division duplexing**
  - **Time-division duplexing**

Frequency-Division Duplexing



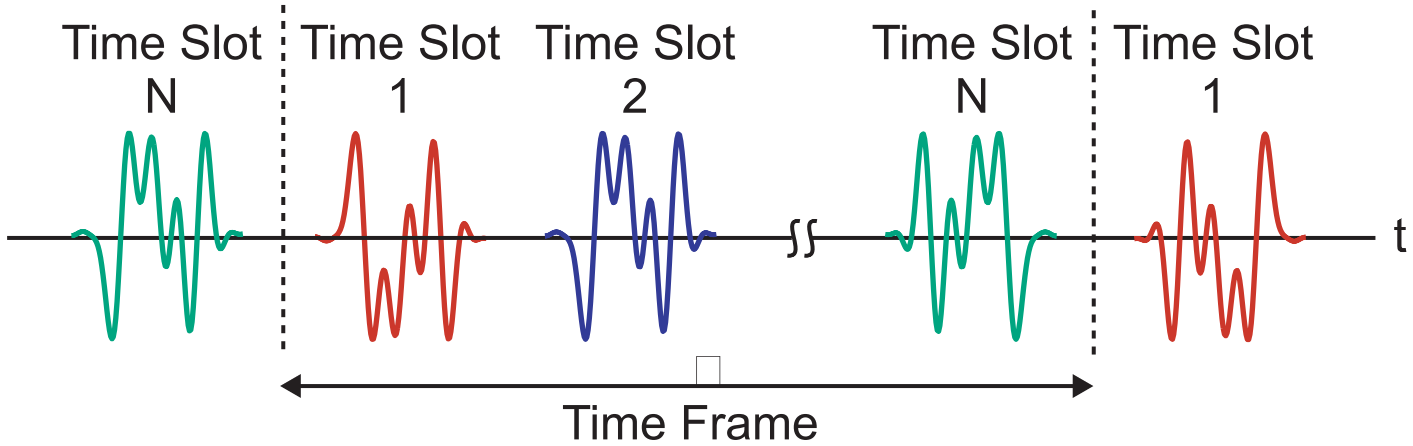
- Separate frequency channels into transmit and receive bands
- Allows simultaneous transmission and reception
  - Isolation of receiver from transmitter achieved with duplexer
  - Cannot communicate directly between users, only between handsets and base station
- Advantage: isolates users
- Disadvantage: deplexer has high insertion loss (i.e. attenuates signals passing through it)

Time-Division Duplexing



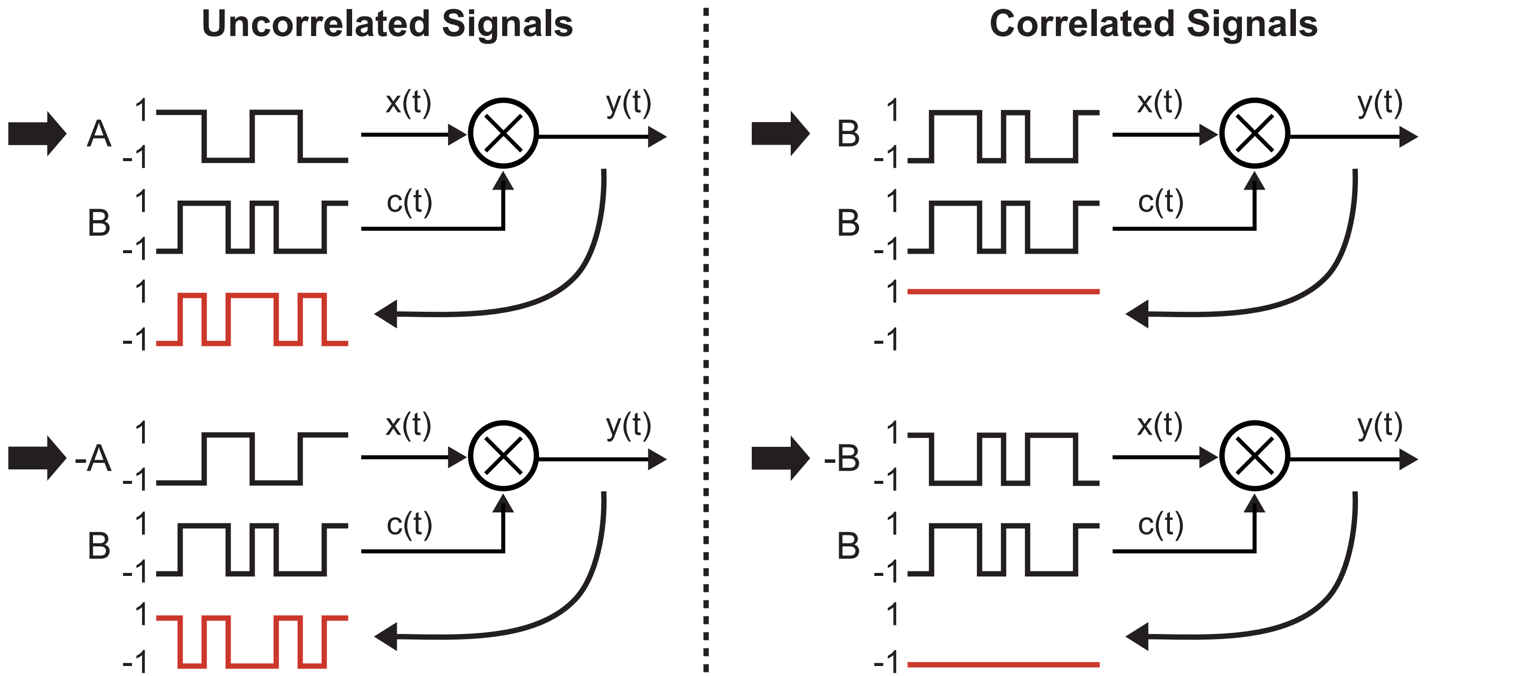
- Use any desired frequency channel for transmitter and receiver
- Send transmit and receive signals at different times
- Allows communication directly between users (not necessarily desirable)
- Advantage: switch has low insertion loss relative to duplexer
- Disadvantage: receiver more sensitive to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

Time-Division Multiple Access (TDMA)



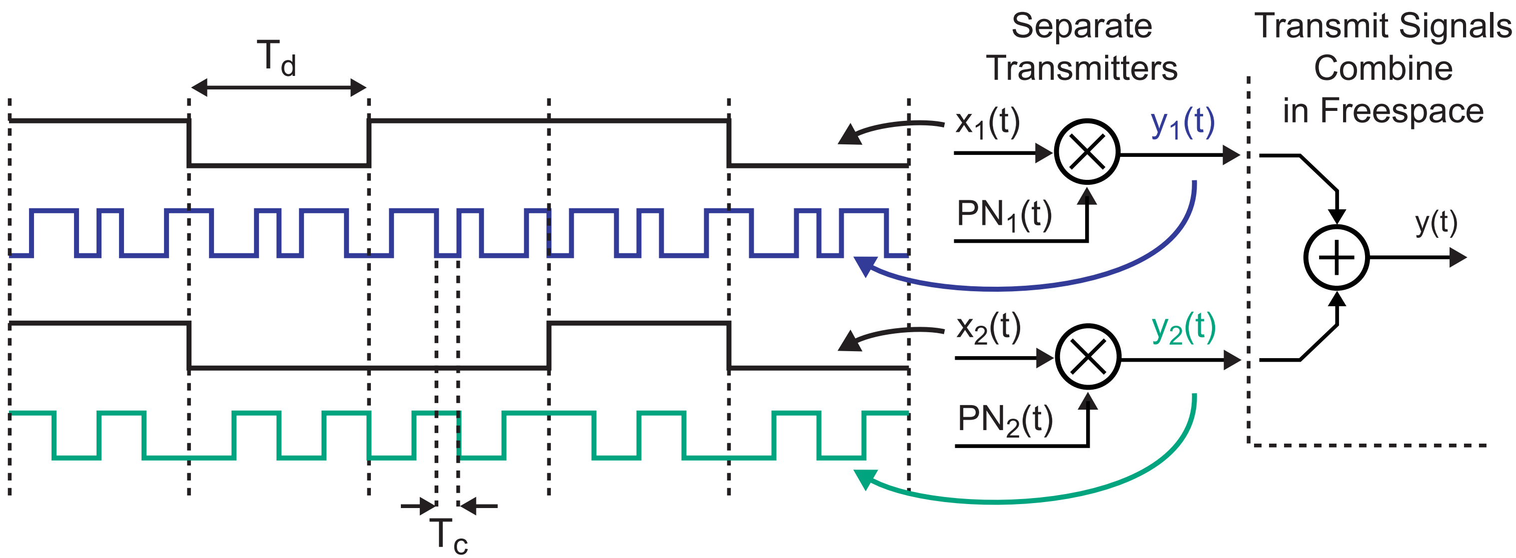
- **Place users into different time slots**
  - **A given time slot repeats according to time frame period**
- **Often combined with FDMA**
  - **Allows many users to occupy the same frequency channel**

Channel Partitioning Using (Nearly) "Orthogonal Coding"



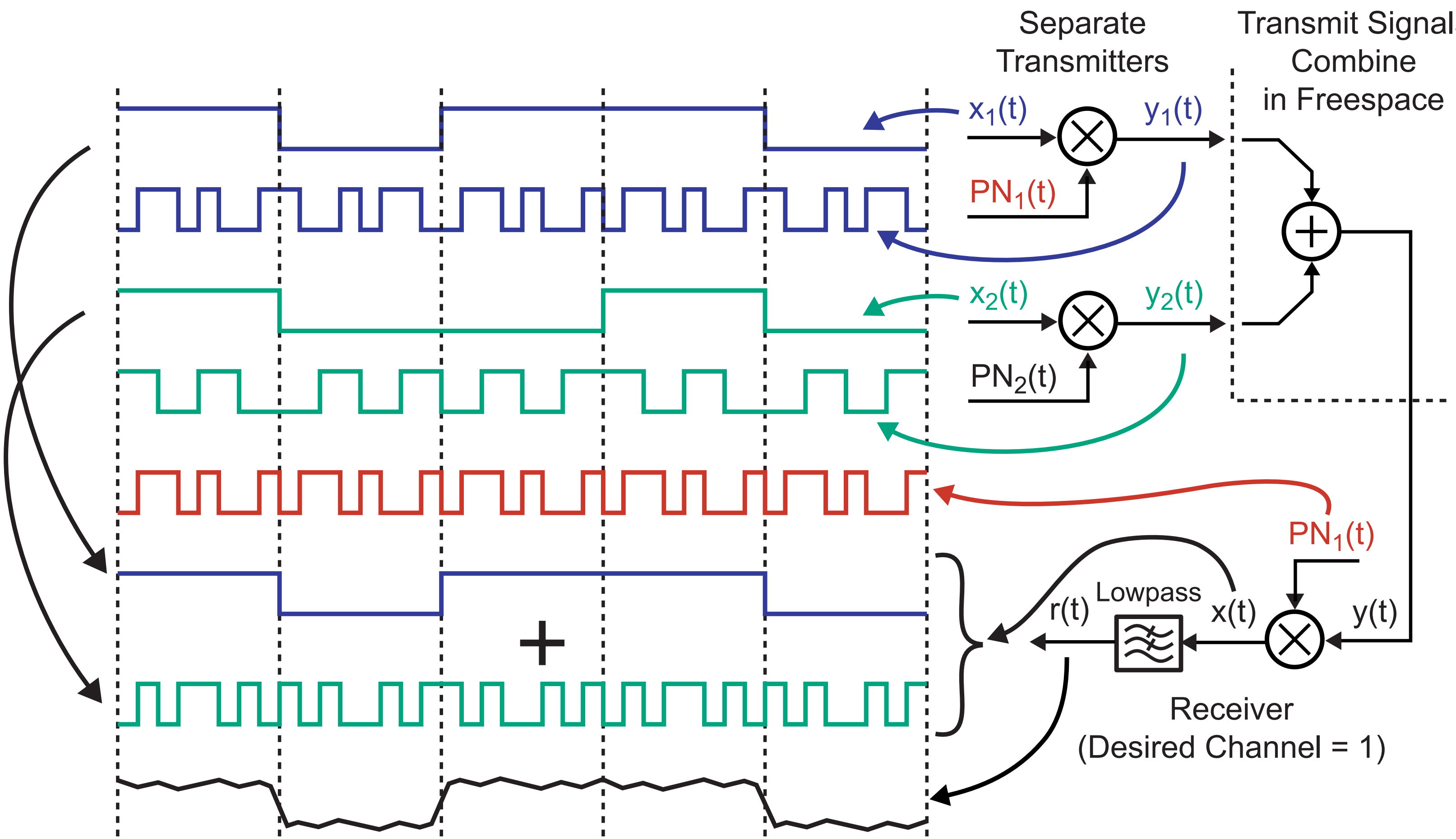
- **Consider two correlation cases**
  - **Two independent random Bernoulli sequences**
    - Result is a random Bernoulli sequence
  - **Same Bernoulli sequence**
    - Result is 1 or -1, depending on relative polarity

Code-Division Multiple Access (CDMA)



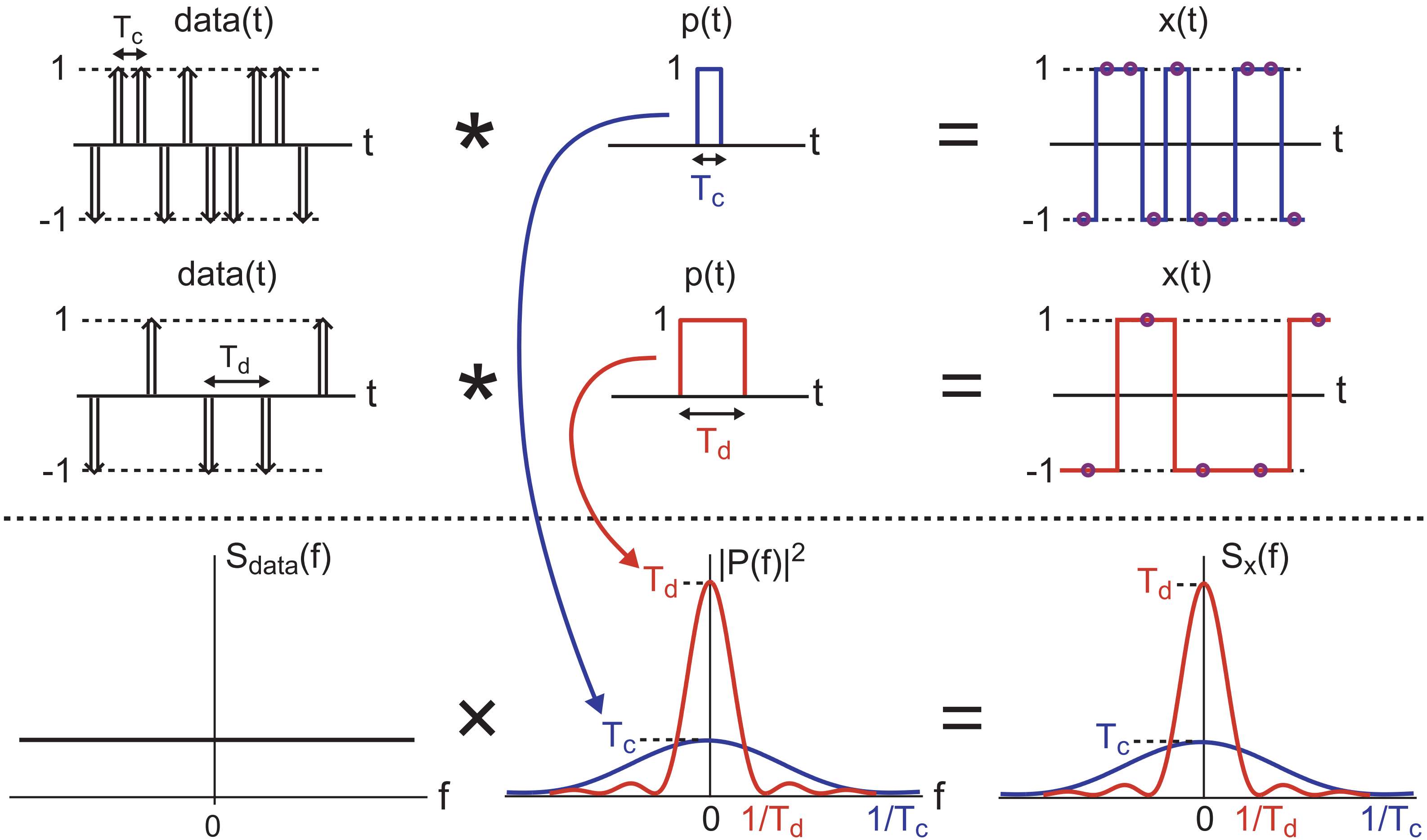
- **Assign a unique code sequence to each transmitter**
- **Data values are encoded in transmitter output stream by varying the polarity of the transmitter code sequence**
  - **Each pulse in data sequence has period T_d**
    - Individual pulses represent binary data values
  - **Each pulse in code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

Receiver Selects Desired Transmitter Through Its Code



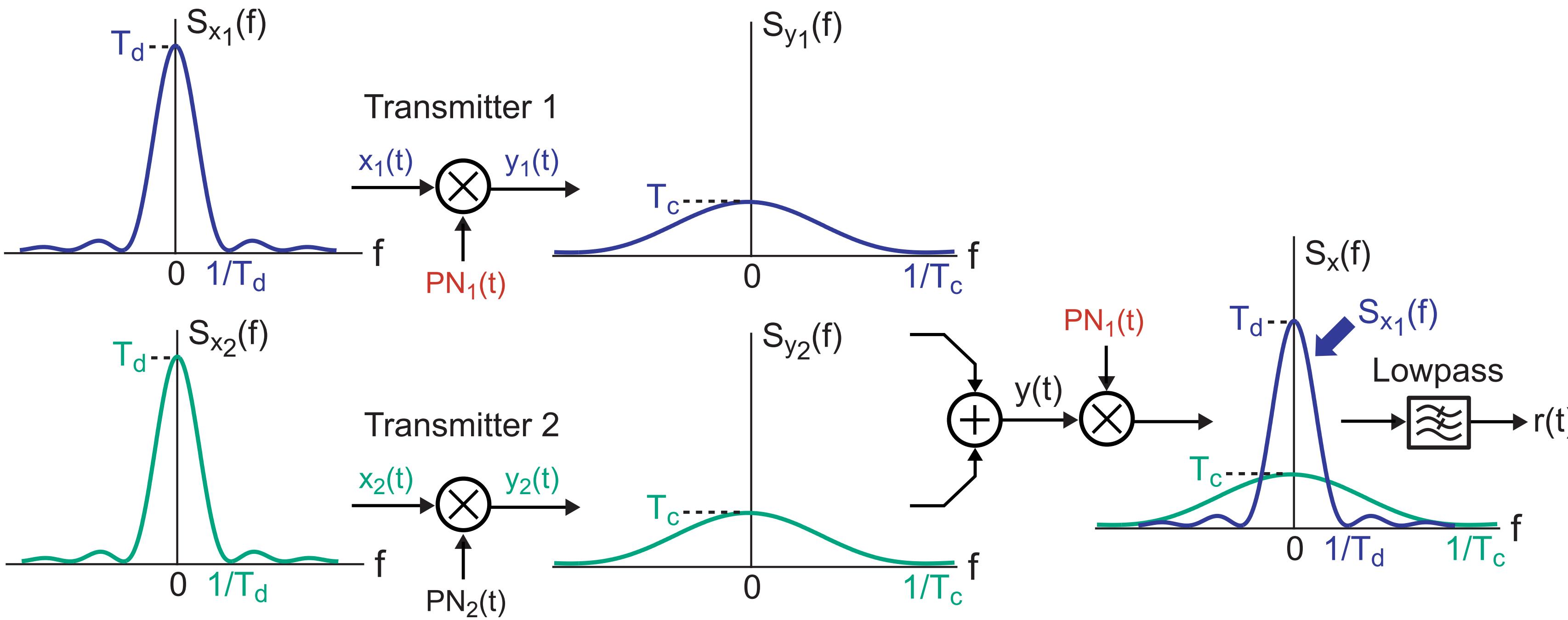
- Receiver correlates its input with desired transmitter code
  - Data from desired transmitter restored
  - Data from other transmitter(s) remains randomized

Frequency Domain View of Chip Vs Data Sequences



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

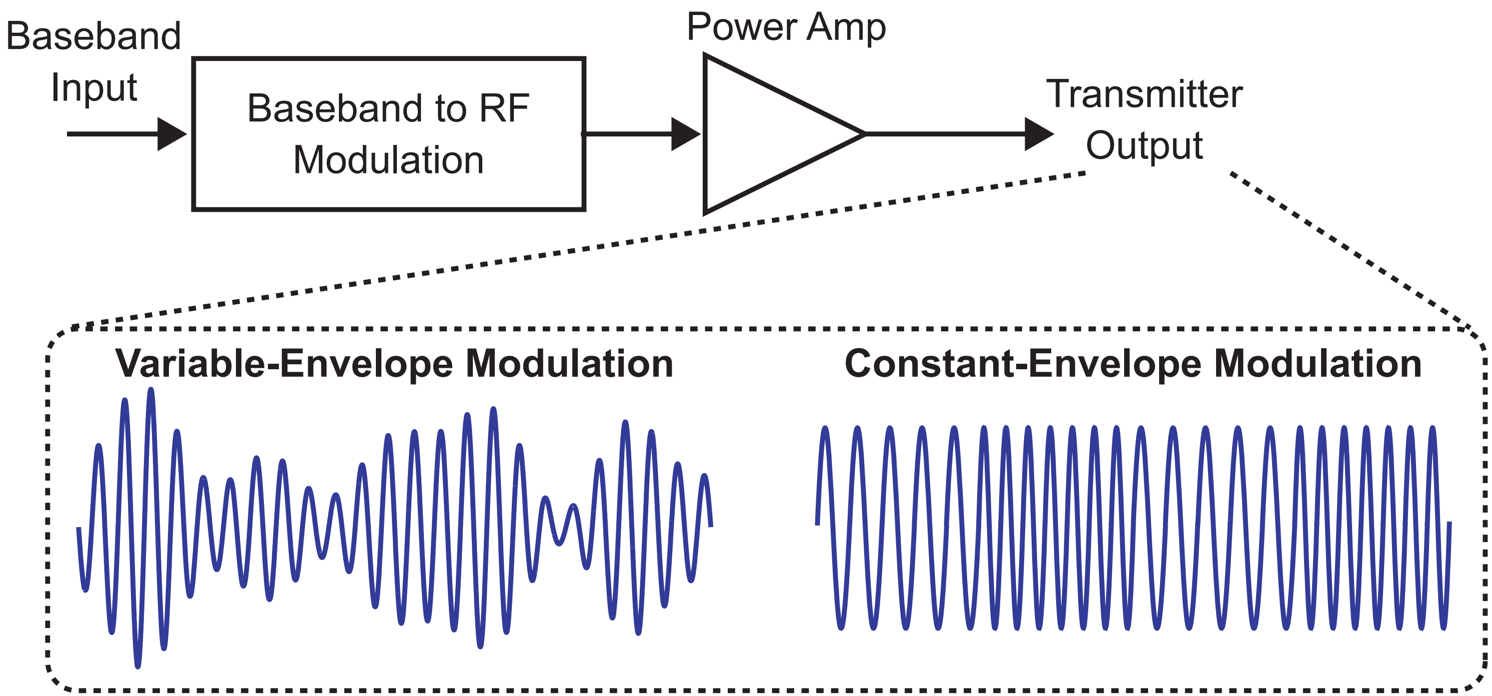
Frequency Domain View of CDMA



- **CDMA transmitters broaden data spectra by encoding it onto chip sequences**
- **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

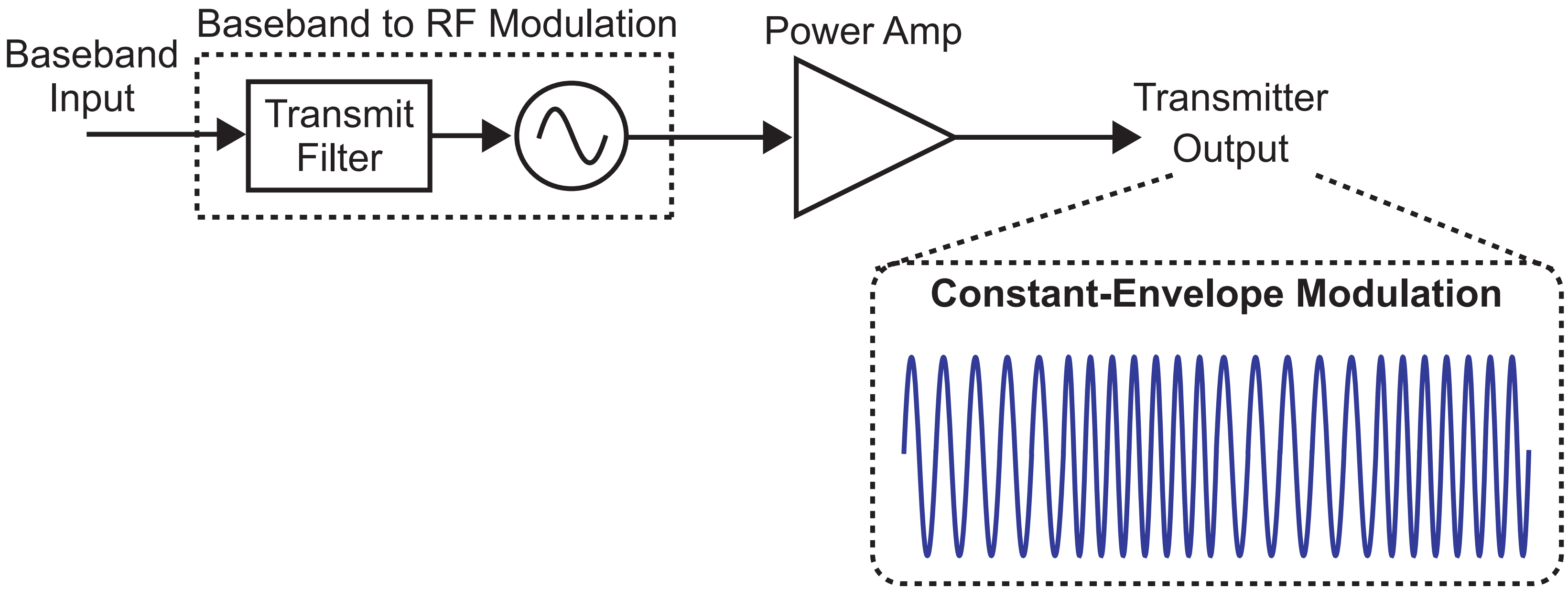
Constant Envelope Modulation

The Issue of Power Efficiency



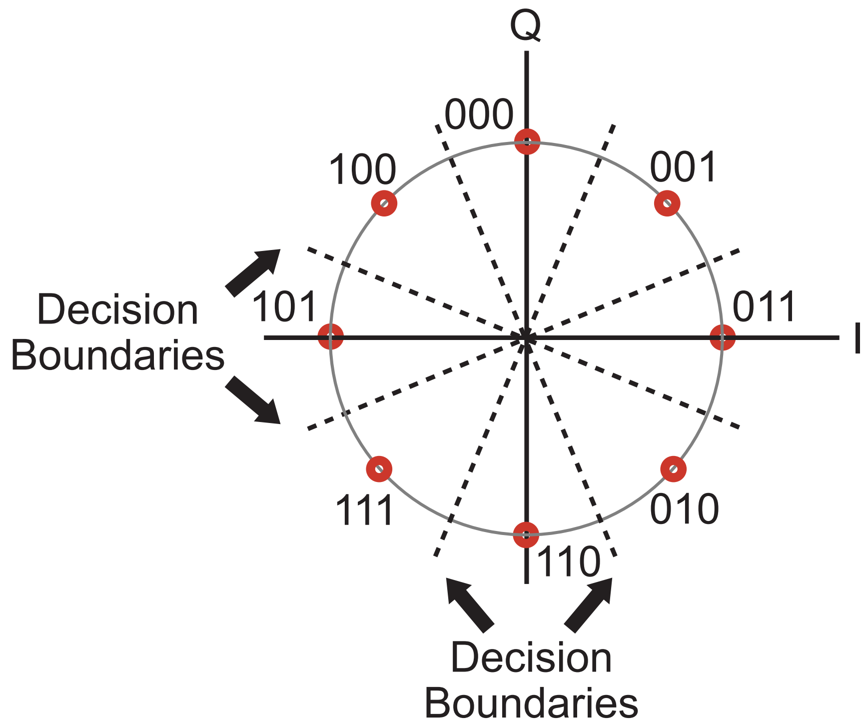
- **Power amp dominates power consumption for many wireless systems**
  - **Linear power amps more power consuming than nonlinear ones**
- **Constant-envelope modulation allows nonlinear power amp**
  - **Lower power consumption possible**

Simplified Implementation for Constant-Envelope



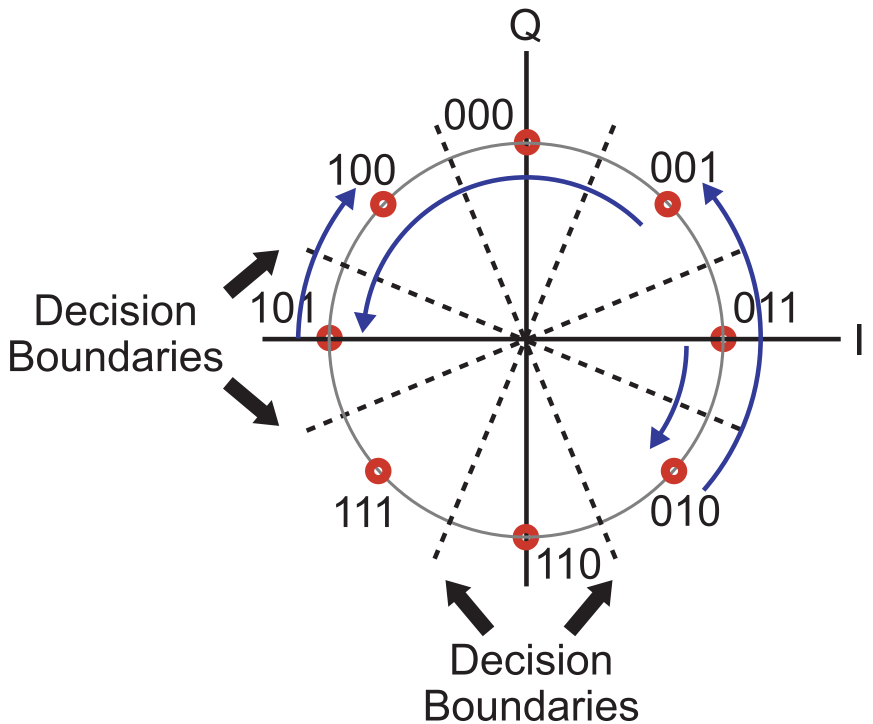
- Constant-envelope modulation limited to phase and frequency modulation methods
- Can achieve both phase and frequency modulation with ideal VCO
  - Use as model for analysis purposes
  - Note: phase modulation nearly impossible with practical VCO

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

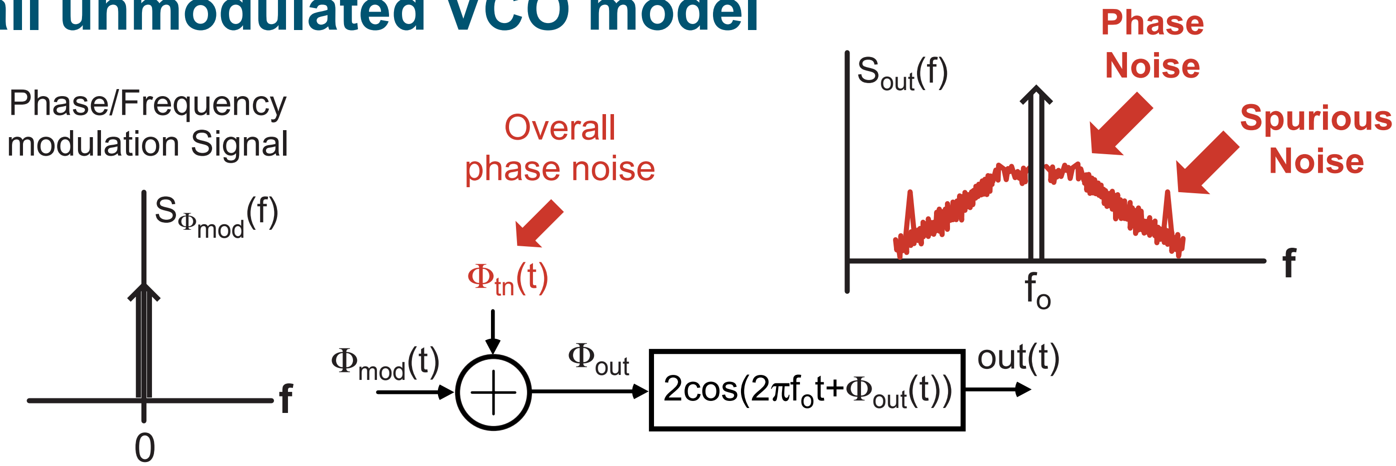
Transitioning Between Constellation Points



- **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**

Modeling The Impact of VCO Phase Modulation

- **Recall unmodulated VCO model**



- **Relationship between sine wave output and instantaneous phase**

$$out(t) = 2\cos(2\pi f_o t + \Phi_{out}(t))$$

- **Impact of modulation**
  - **Same as examined with VCO/PLL modeling, but now we consider $\Phi_{out}(t)$ as sum of *modulation* and noise components**

$$\boxed{\Phi_{out}(t) = \Phi_{mod}(t) + \Phi_{tn}(t)}$$

Relationship Between Sine Wave Output and its Phase

- **Key relationship (note we have dropped the factor of 2)**

$$out(t) = \cos(2\pi f_o t + \Phi_{mod}(t) + \Phi_{tn}(t))$$

- **Using a familiar trigonometric identity**

$$\begin{aligned} out(t) = {} & \cos(2\pi f_o t + \Phi_{mod}(t)) \cos(\Phi_{tn}(t)) \\ & - \sin(2\pi f_o t + \Phi_{mod}(t)) \sin(\Phi_{tn}(t)) \end{aligned}$$

- **Approximation given $|\Phi_{tn}(t)| << 1$**

$$\begin{aligned} out(t) \approx {} & \cos(2\pi f_o t + \Phi_{mod}(t)) \\ & - \sin(2\pi f_o t + \Phi_{mod}(t))\Phi_{tn}(t) \end{aligned}$$

Relationship Between Output and Phase Spectra

- **Approximation from previous slide**

$$out(t) \approx \cos(2\pi f_o t + \Phi_{mod}(t))$$
$$- \sin(2\pi f_o t + \Phi_{mod}(t))\Phi_{tn}(t)$$

- **Autocorrelation (assume modulation signal independent of noise)**

$$R\{out(t)\} = R\{\cos(2\pi f_o t + \Phi_{mod}(t))\}$$
$$+R\{\sin(2\pi f_o t + \Phi_{mod}(t))\}R\{\Phi_{tn}(t)\}$$

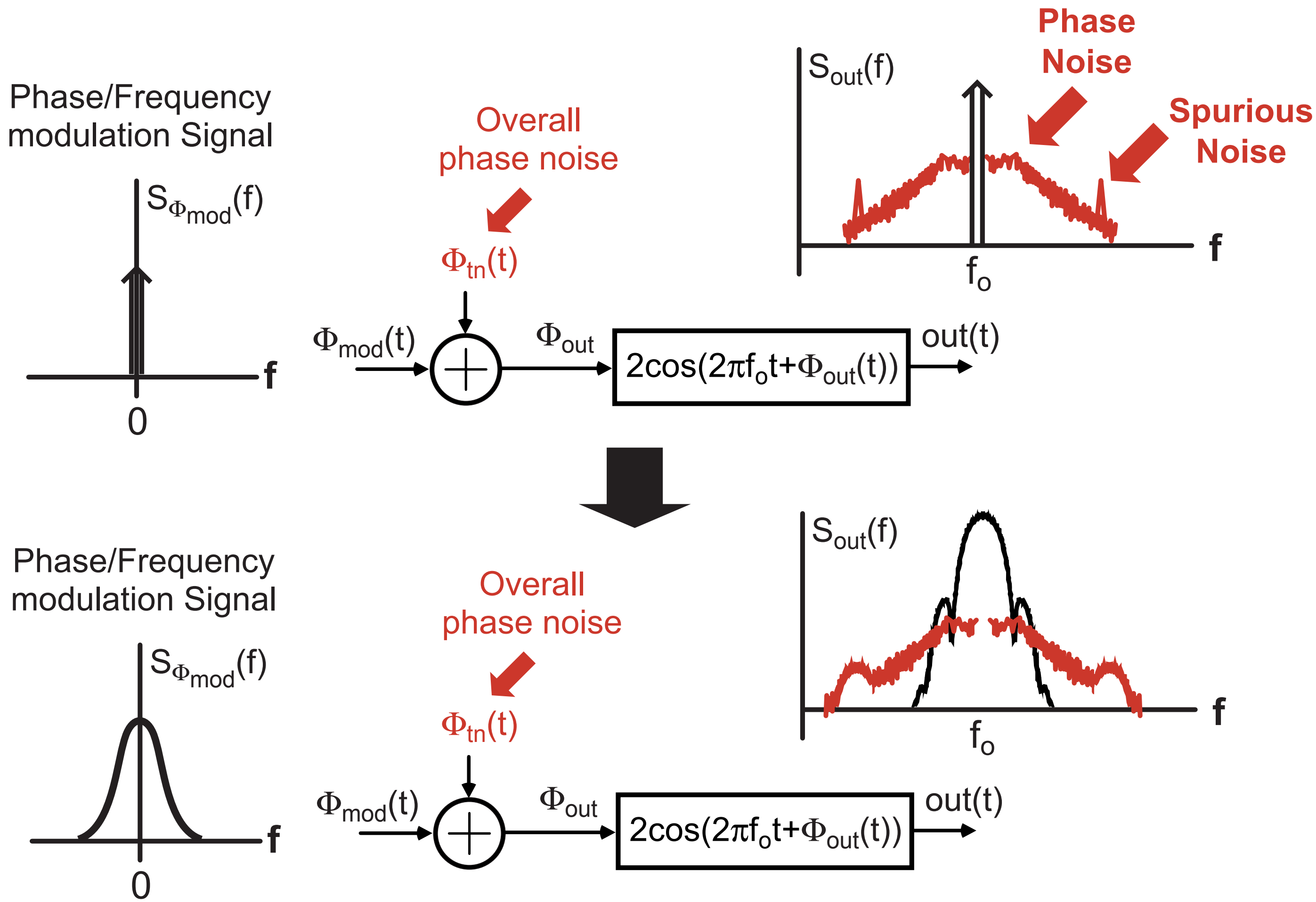
- **Output spectral density (Fourier transform of autocorrelation)**

$$\boxed{S_{out}(f) = S_{out_m}(f) + S_{out_m}(f) * S_{\Phi_{tn}}(f)}$$

  - **Where * represents convolution and**

$$S_{out_m}(f) = S\{\cos(2\pi f_o t + \Phi_{mod}(t))\}, \quad S_{\Phi_{tn}}(f) = S\{\Phi_{tn}(t)\}$$

Impact of Phase Modulation on the Output Spectrum



- **Spectrum of output is distorted compared to $S_{\Phi mod}(f)$**
- **Spurs converted to phase noise**

I/Q Model for Phase Modulation

$$S_{out_m}(f) = S\{\cos(2\pi f_o t + \Phi_{mod}(t))$$

- **Applying trigonometric identity**

$$\boxed{S_{out}(t) = S\{\cos(2\pi f_o t)\cos(\Phi_{mod}(t)) - \sin(2\pi f_o t)\sin(\Phi_{mod}(t))\}}$$

- **Can view as I/Q modulation**
  - **I/Q components are coupled and related nonlinearly to $\Phi_{mod}(t)$**