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

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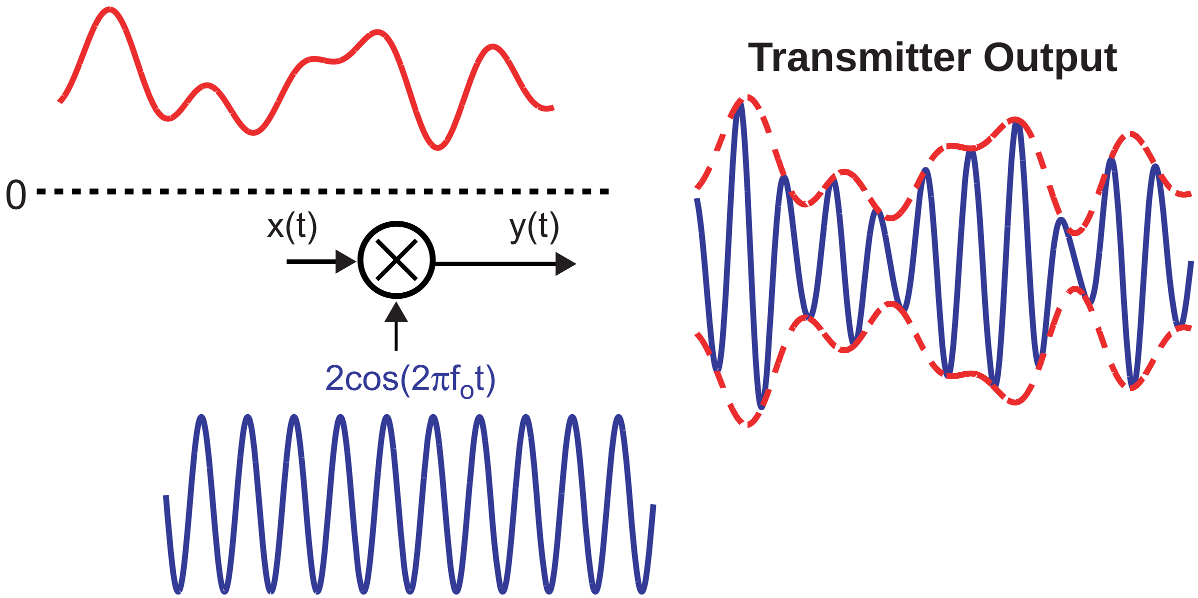
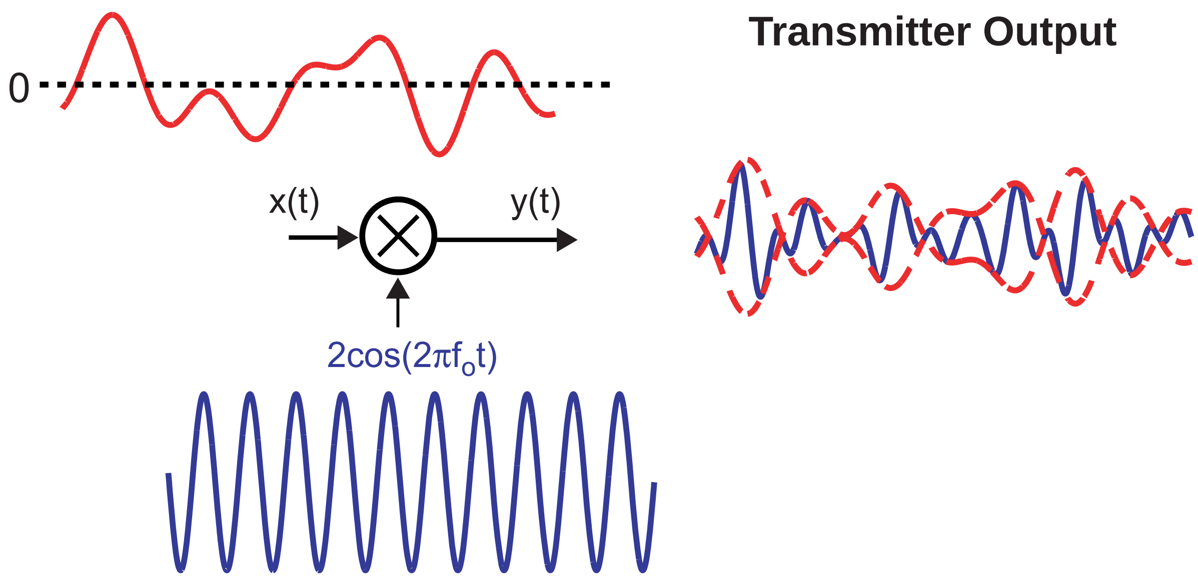
Amplitude Modulation (Transmitter)



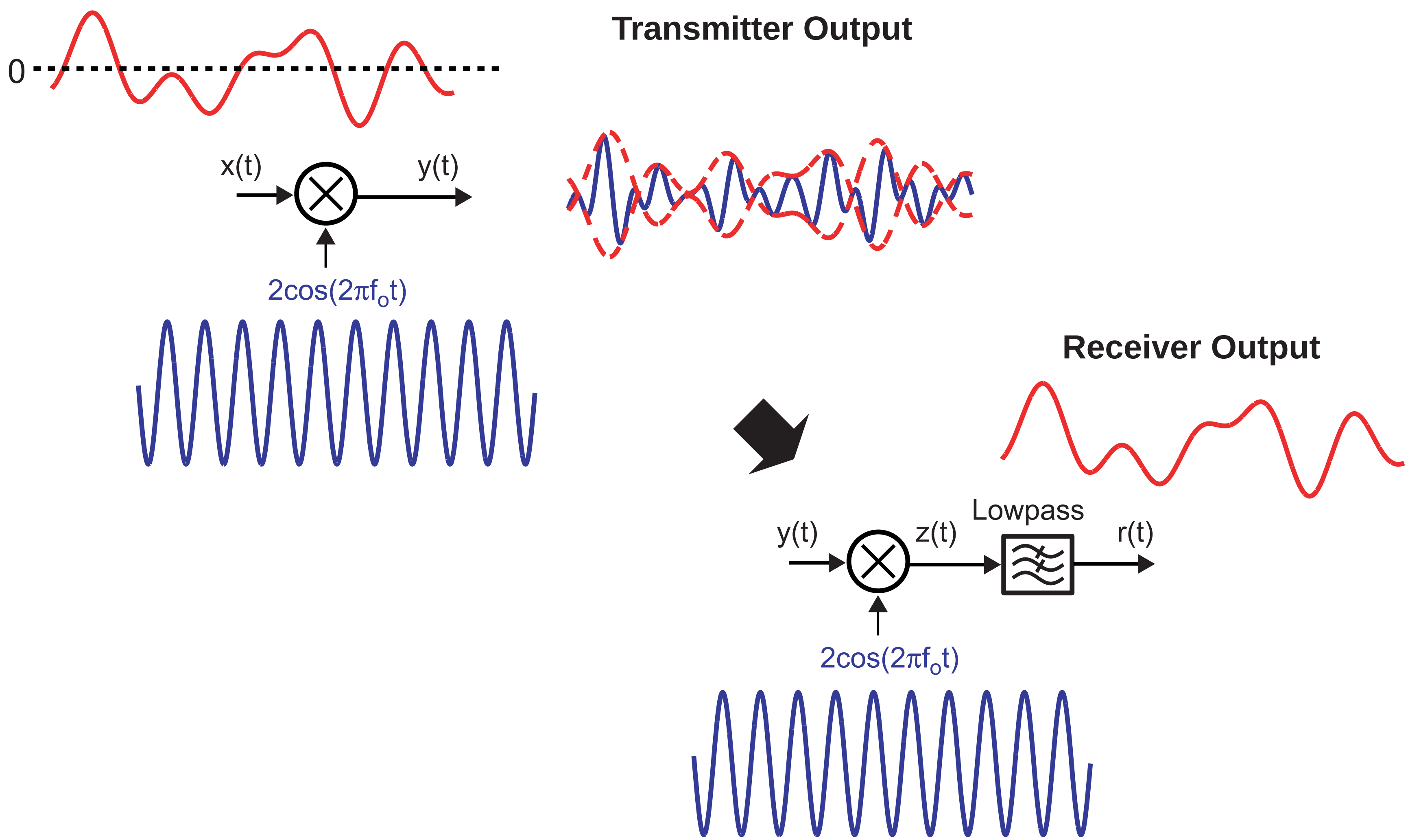
- **Vary the amplitude of a sine wave at carrier frequency f_o according to a baseband modulation signal**
- **DC component of baseband modulation signal influences transmit signal and receiver possibilities**
  - **DC value greater than signal amplitude shown above**
    - Allows simple envelope detector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

Impact of Zero DC Value



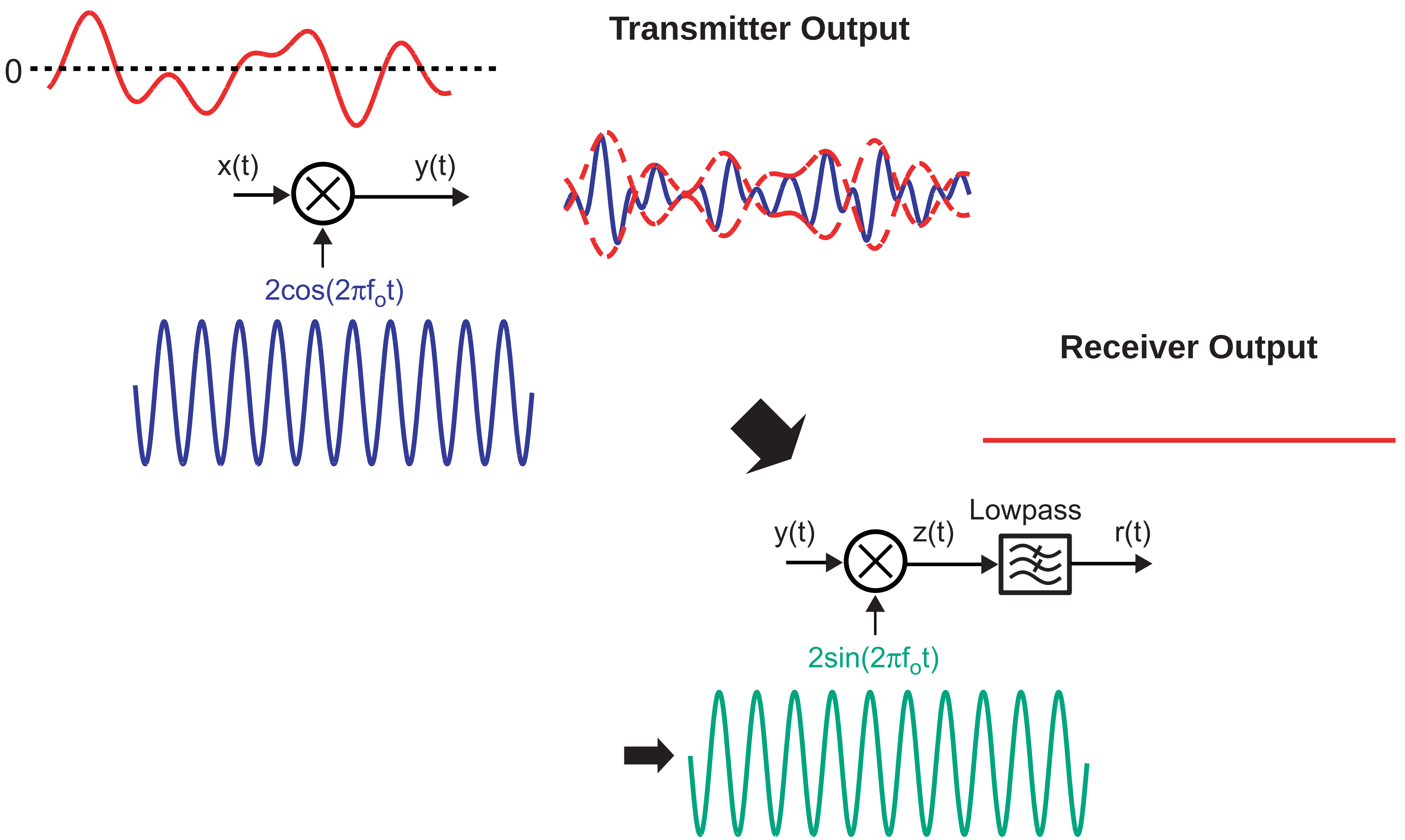
- Envelope of modulated sine wave no longer corresponds directly to the baseband signal
  - Envelope instead follows the absolute value of the baseband waveform
  - Envelope detector can no longer be used for receiver
- The good news: less transmit power required for same transmitter SNR (compared to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

Accompanying Receiver (Coherent Detection)



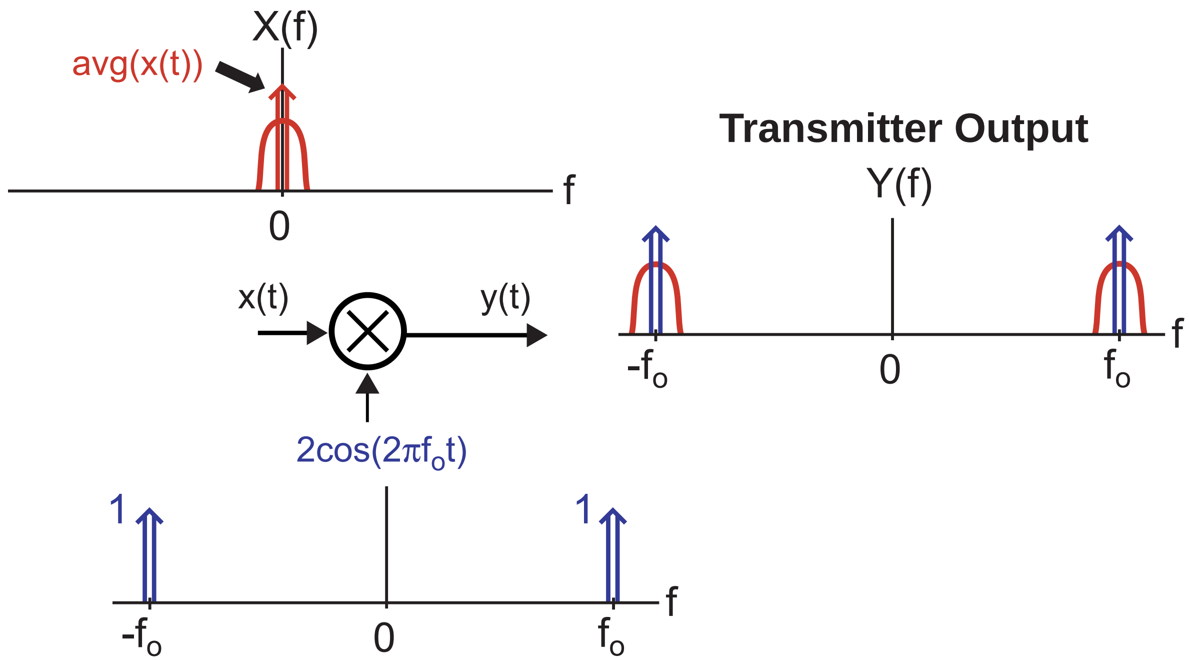
- **Works regardless of DC value of baseband signal**
- **Requires receiver local oscillator to be accurately aligned in phase and frequency to carrier sine wave**

Impact of Phase Misalignment in Receiver Local Oscillator



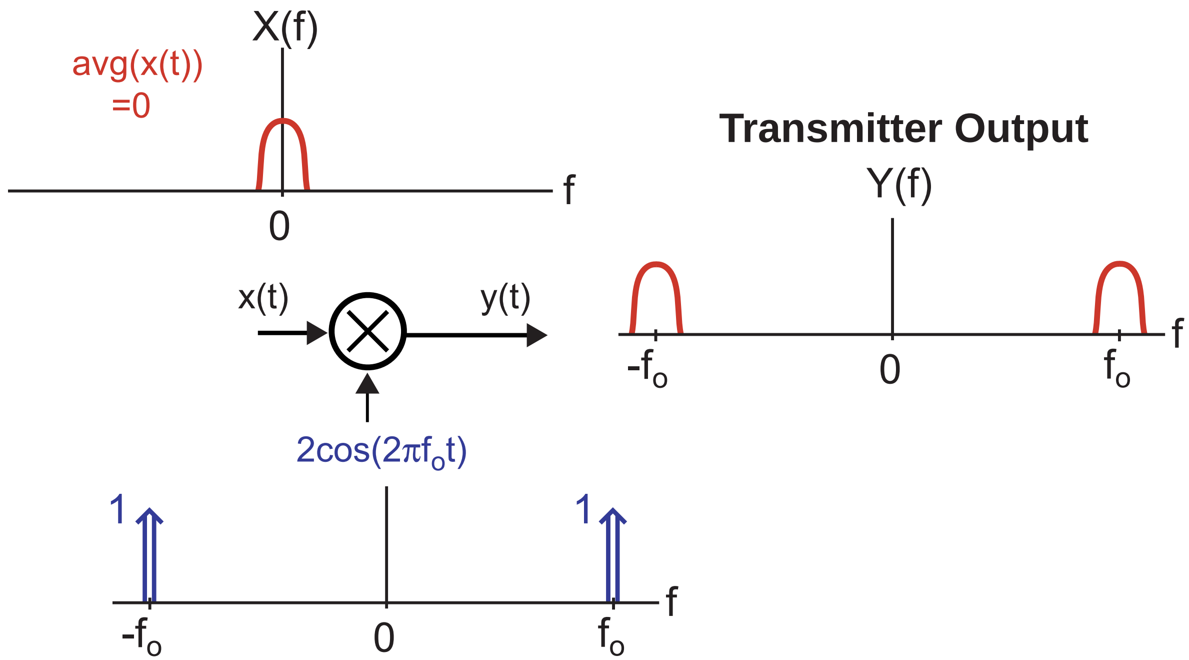
- **Worst case is when receiver LO and carrier frequency are phase shifted 90 degrees with respect to each other**
  - **Desired baseband signal is not recovered**

Frequency Domain View of AM Transmitter



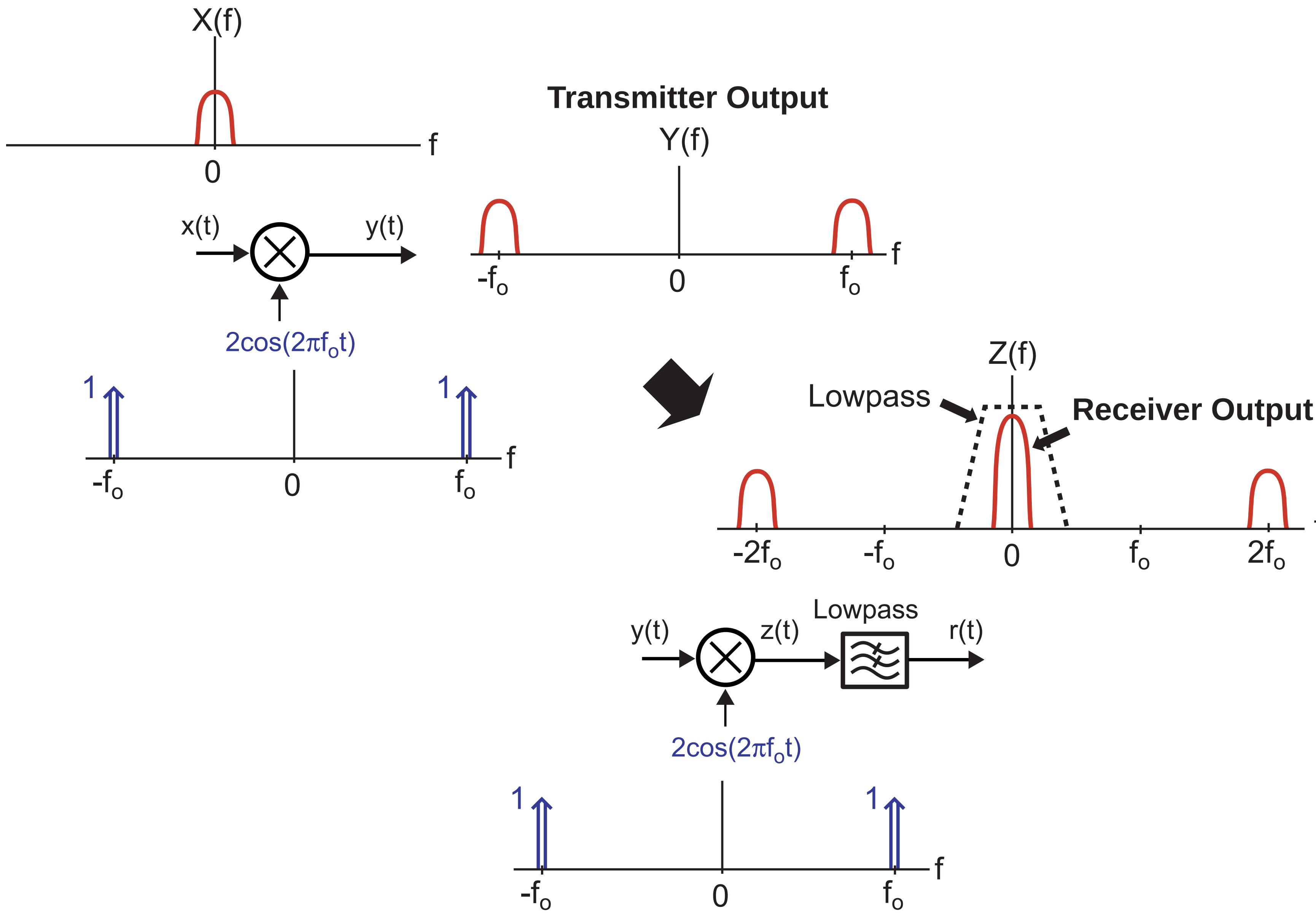
- **Baseband signal is assumed to have a nonzero DC component in above diagram**
  - **Causes impulse to appear at DC in baseband signal**
  - **Transmitter output has an impulse at the carrier frequency**
    - For coherent detection, does not provide key information about information in baseband signal,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

Impact of Having Zero DC Value for Baseband Signal

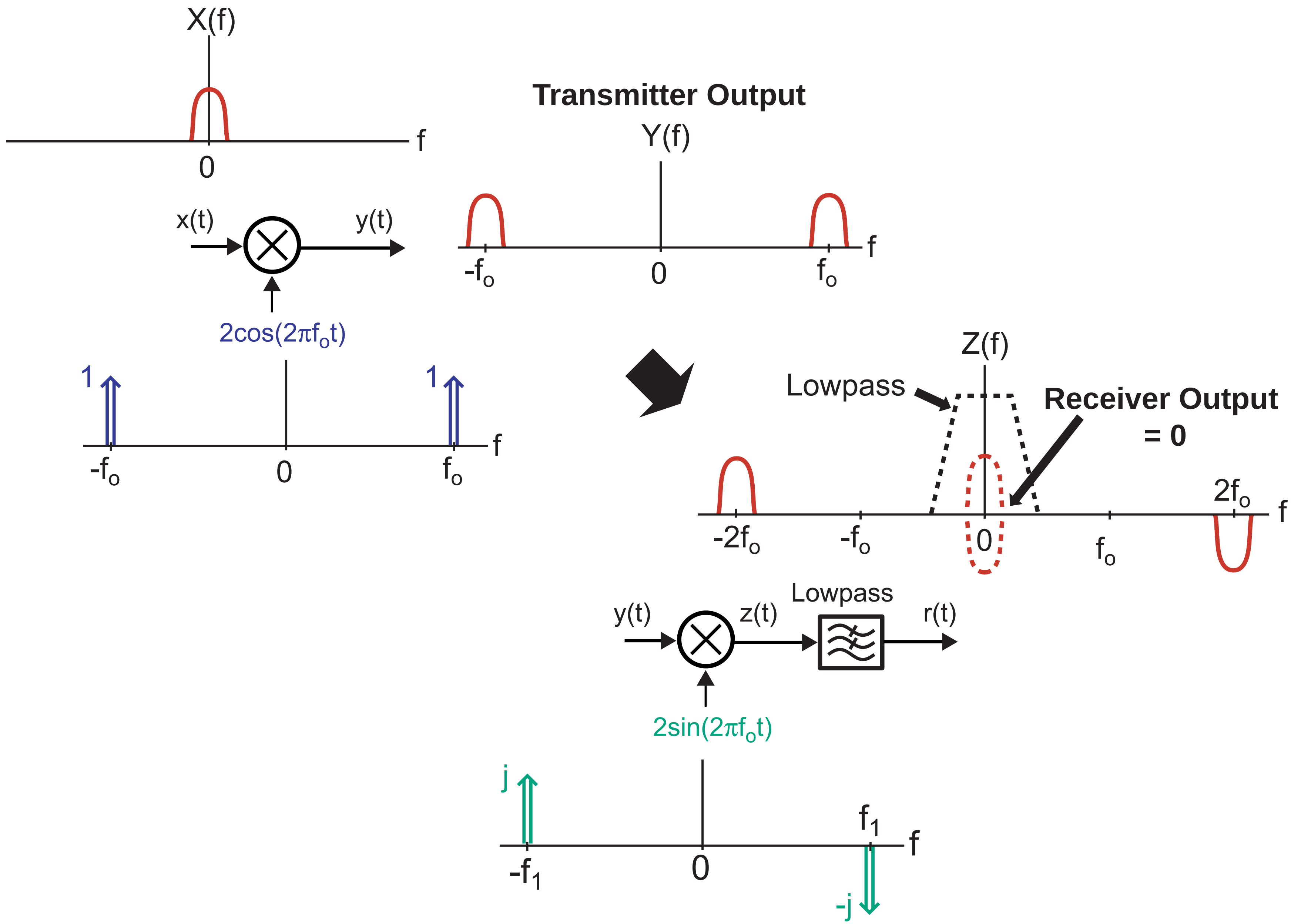


- **Impulse in DC portion of baseband signal is now gone**
  - **Transmitter output now is now free from having an impulse at the carrier frequency (for ideal implementation)**

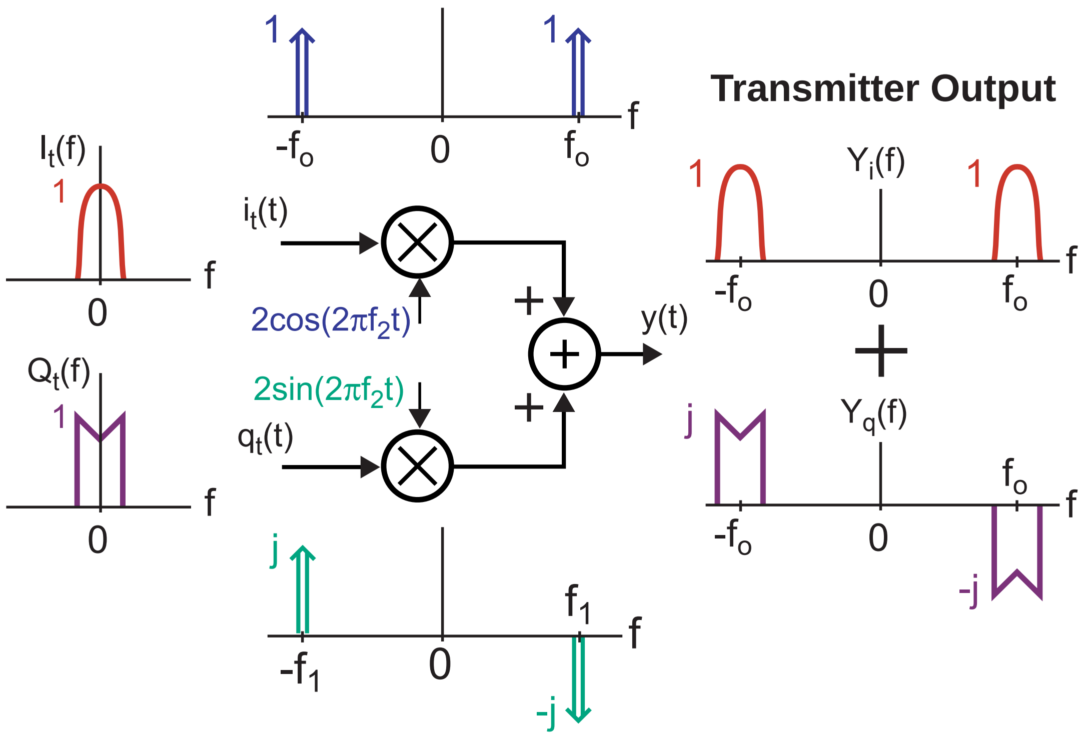
Frequency Domain View of AM Receiver (Coherent)



Impact of 90 Degree Phase Misalignment

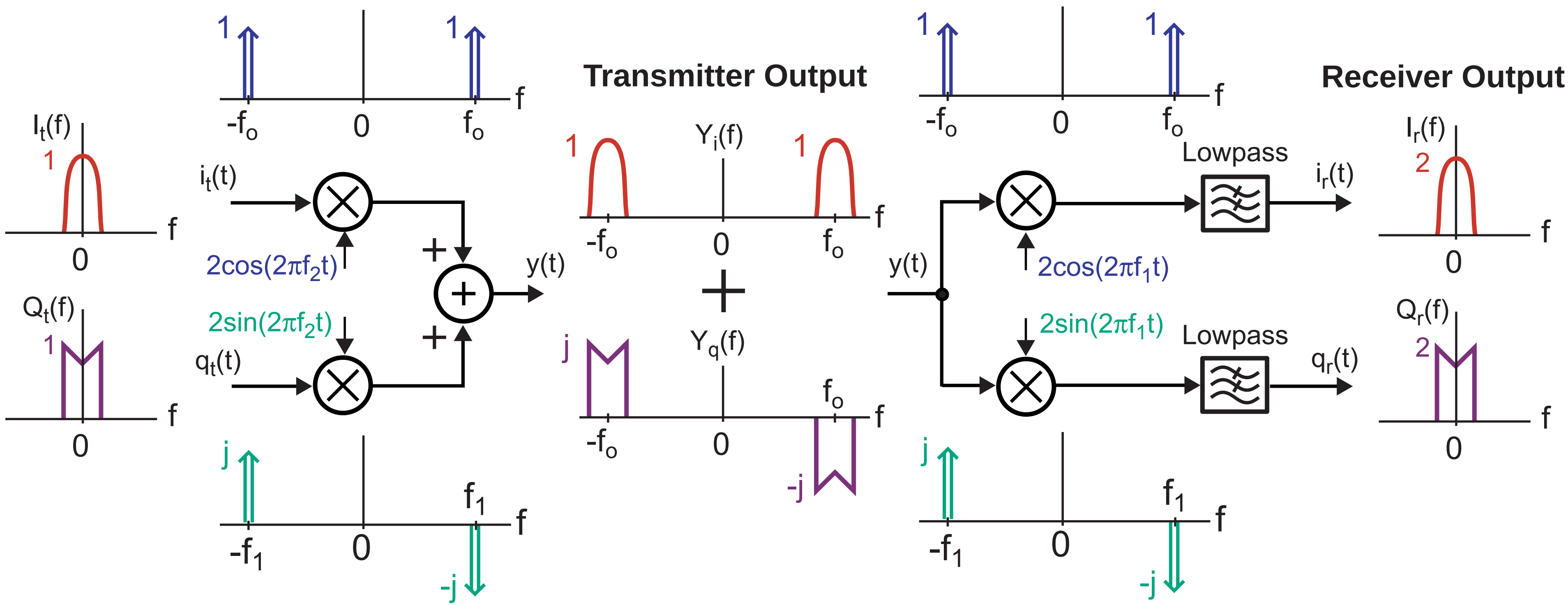


Quadrature Modulation



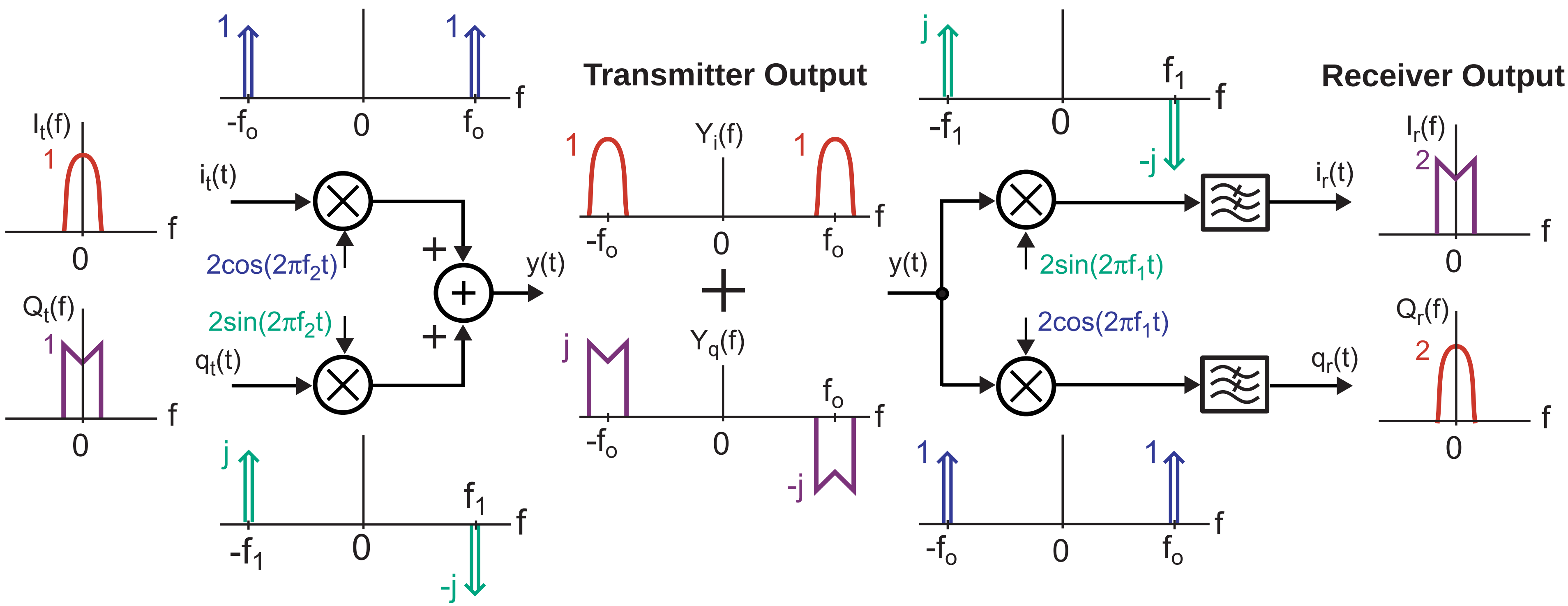
- **Takes advantage of coherent receiver's sensitivity to phase alignment with transmitter local oscillator**
  - **We essentially have two orthogonal transmission channels (I and Q) available to us**
  - **Transmit two independent baseband signals (I and Q) onto two sine waves in quadrature at transmitter**

Accompanying Receiver



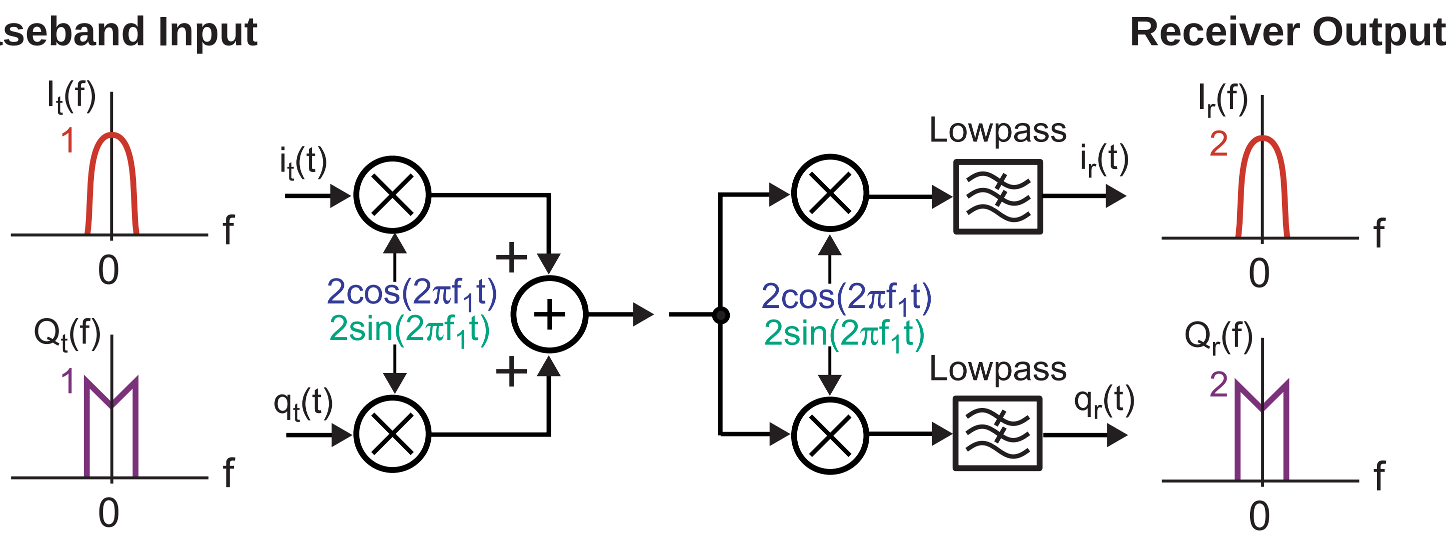
- **Demodulate using two sine waves in quadrature at receiver**
  - **Must align receiver LO signals in frequency and phase to transmitter LO signals**
    - Proper alignment allows I and Q signals to be recovered as shown

Impact of 90 Degree Phase Misalignment



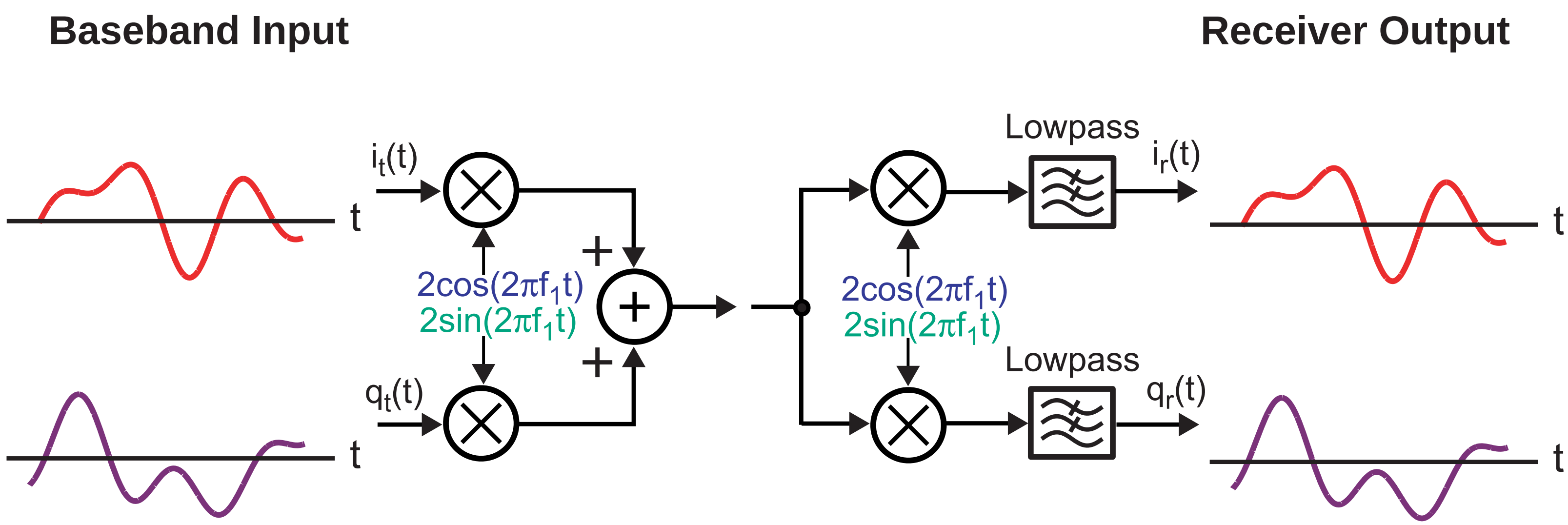
- I and Q channels are swapped at receiver if its LO signal is 90 degrees out of phase with transmitter
  - However, no information is lost!
  - Can use baseband signal processing to extract I/Q signals despite phase offset between transmitter and receiver

Simplified View



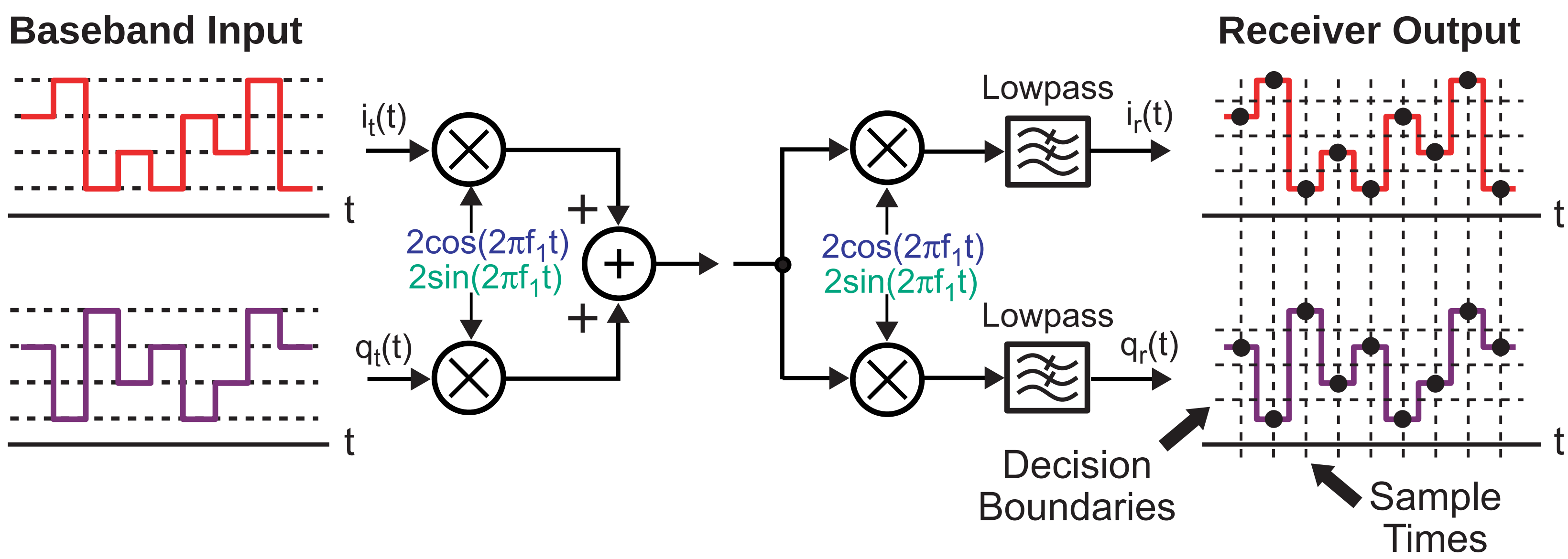
- For discussion to follow, assume that
  - Transmitter and receiver phases are aligned
  - Lowpass filters in receiver are ideal
  - Transmit and receive I/Q signals are the same except for scale factor
- In reality
  - RF channel adds distortion, causes fading
  - Signal processing in baseband DSP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

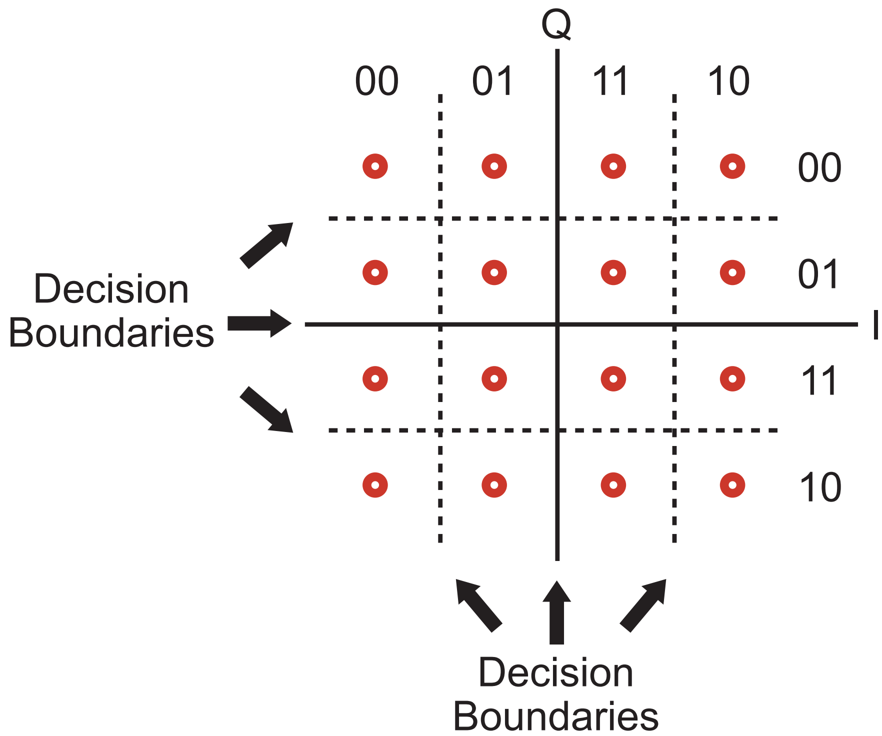


- **I/Q signals take on discrete values at discrete time instants corresponding to digital data**
  - **Receiver samples I/Q channels**
    - Uses decision boundaries to evaluate value of data at each time instant
- **I/Q signals may be binary or multi-bit**
  - **Multi-bit shown above**

Advantages of Digital Modulation

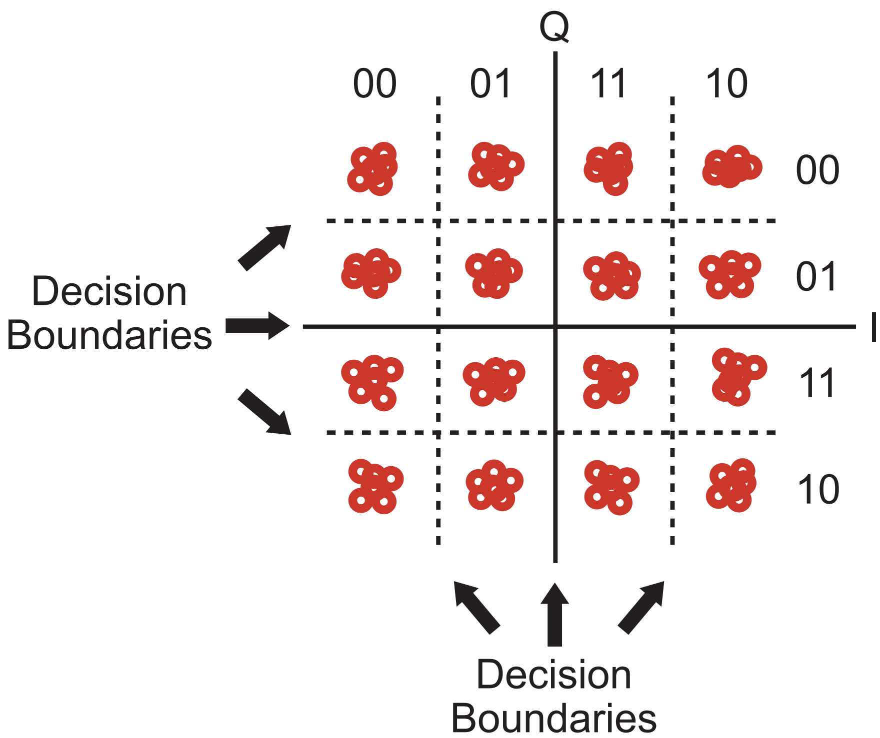
- **Allows information to be “packetized”**
  - **Can compress information in time and efficiently send as packets through network**
  - **In contrast, analog modulation requires “circuit-switched” connections that are continuously available**
    - Inefficient use of radio channel if there is “dead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



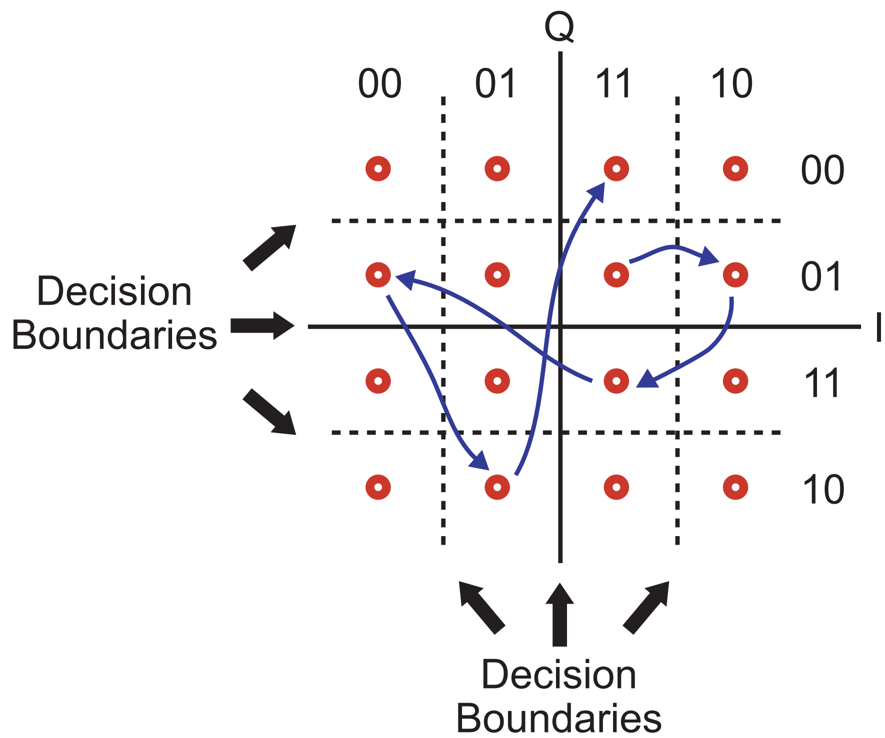
- **We can view I/Q values at sample instants on a two-dimensional coordinate system**
- **Decision boundaries mark up regions corresponding to different data values**
- **Gray coding used to minimize number of bit errors that occur if wrong decision is made due to noise**

Impact of Noise on Constellation Diagram



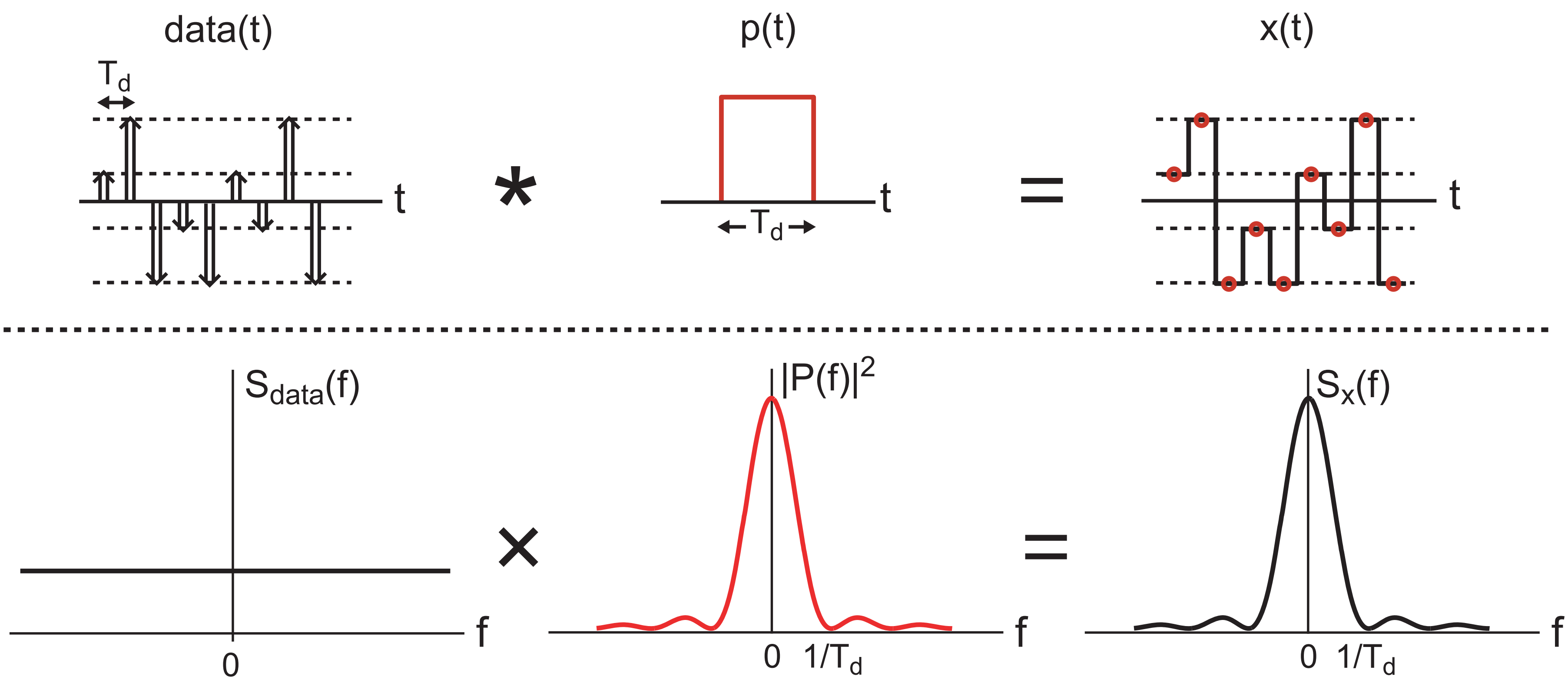
- **Sampled data values no longer land in exact same location across all sample instants**
- **Decision boundaries remain fixed**
- **Significant noise causes bit errors to be made**

Transition Behavior Between Constellation Points



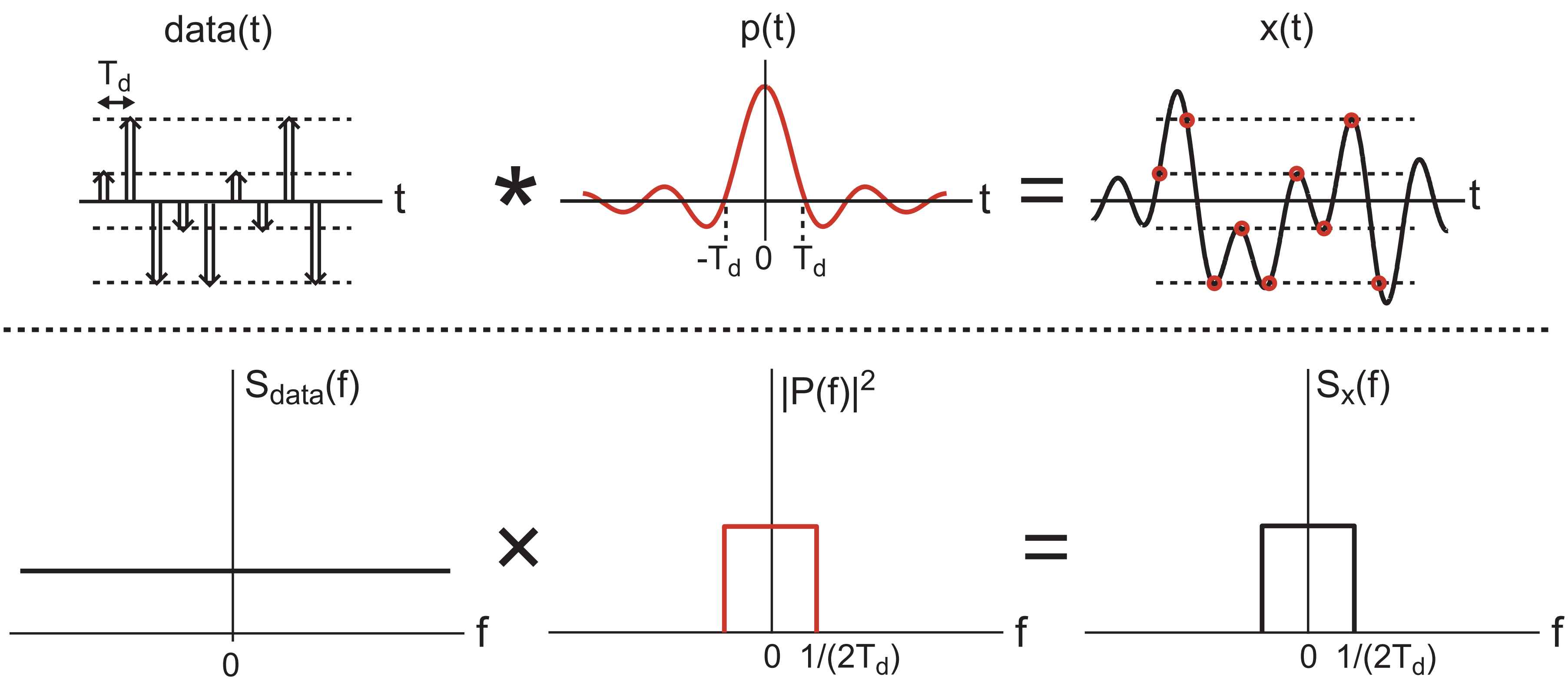
- **Constellation diagrams provide us with a snapshot of I/Q signals at sample instants**
- **Transition behavior between sample points depends on modulation scheme and transmit filter**

Choosing an Appropriate Transmit Filter



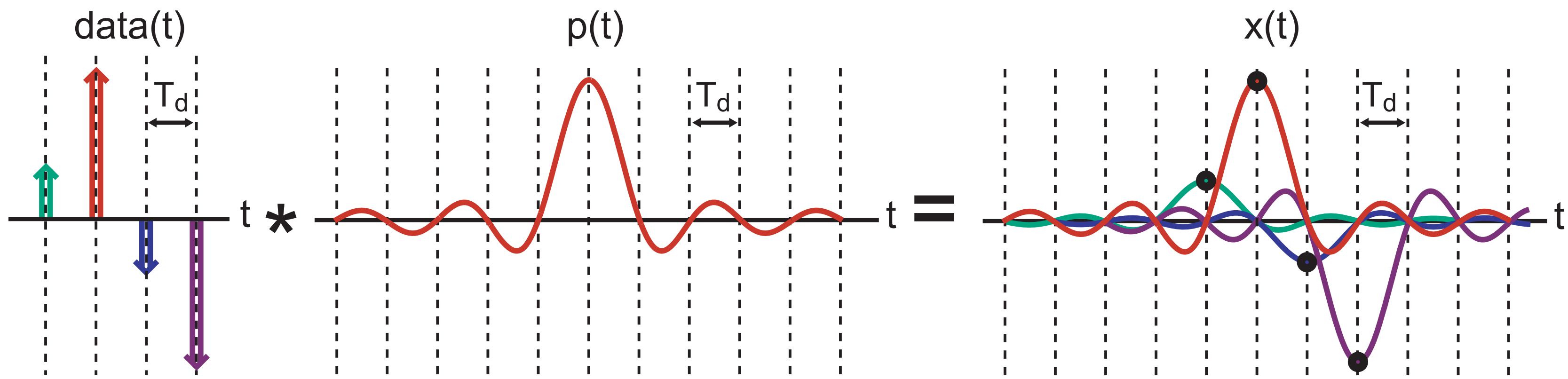
- **Transmit filter, p(t), convolved with data symbols that are viewed as impulses**
  - **Example so far: p(t) is a square pulse**
- **Output spectrum of transmitter corresponds to square of transmit filter (assuming data has white spectrum)**
  - **Want good spectral efficiency (i.e. narrow spectrum)**

Highest Spectral Efficiency with Brick-wall Lowpass



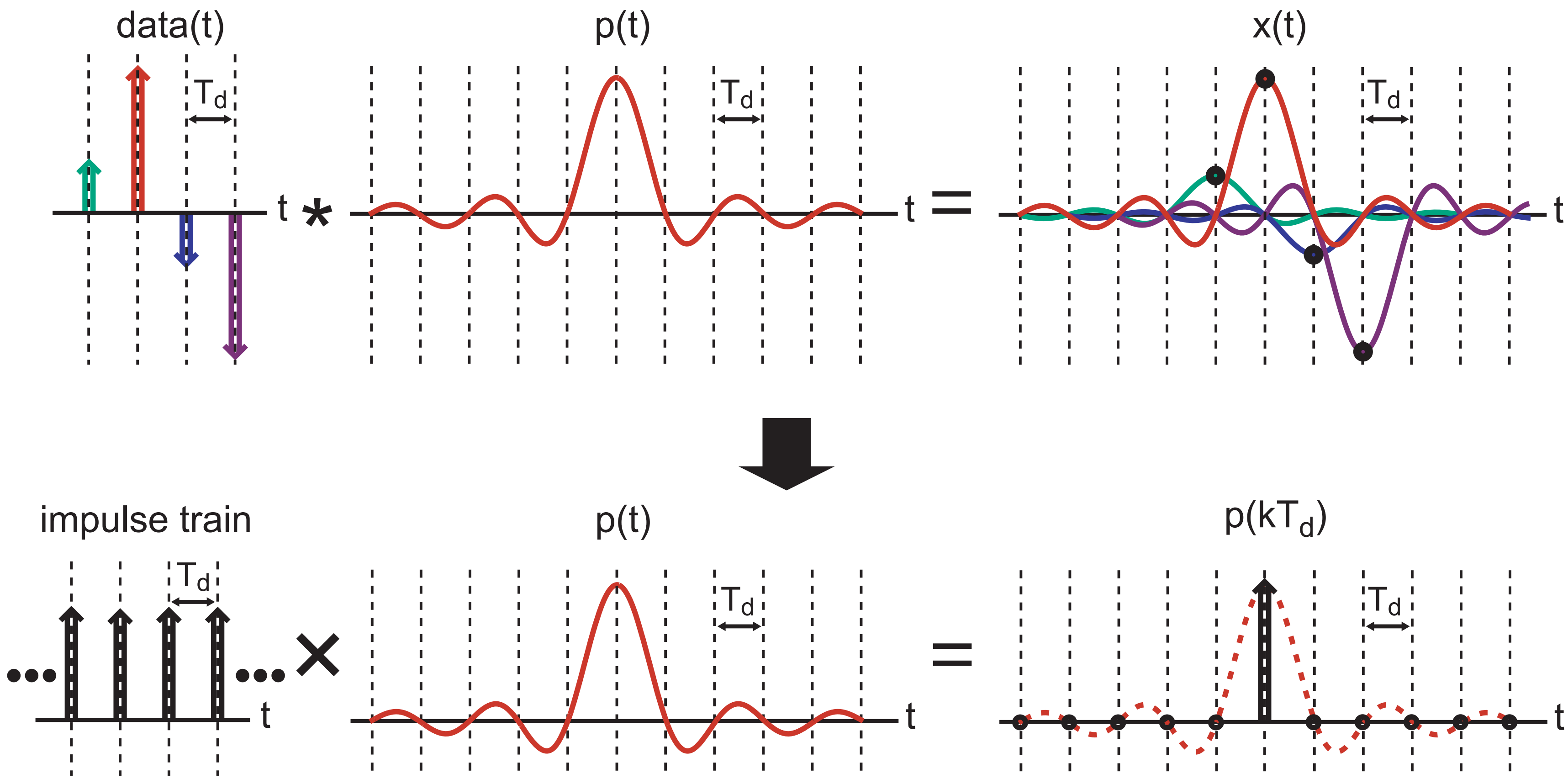
- **Use a sinc function for transmit filter**
  - **Corresponds to ideal lowpass in frequency domain**
- **Issues**
  - **Nonrealizable in practice**
  - **Sampling offset causes significant intersymbol interference**

Requirement for Transmit Filter to Avoid ISI



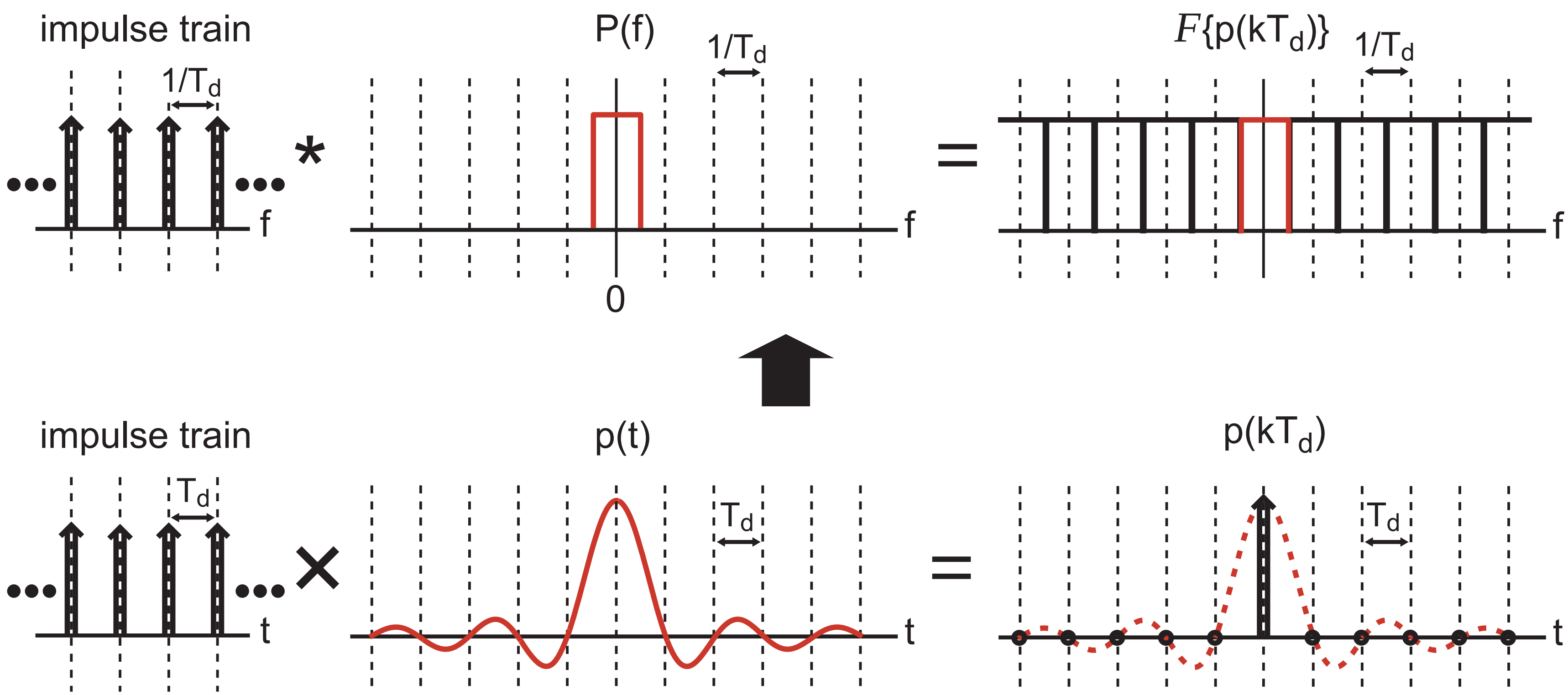
- **Time samples of transmit filter (spaced T_d apart) must be nonzero at only one sample time instant**
  - **Sinc function satisfies this criterion if we have no offset in the sample times**
- **Intersymbol interference (ISI) occurs otherwise**
- **Example: look at result of convolving p(t) with 4 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)**

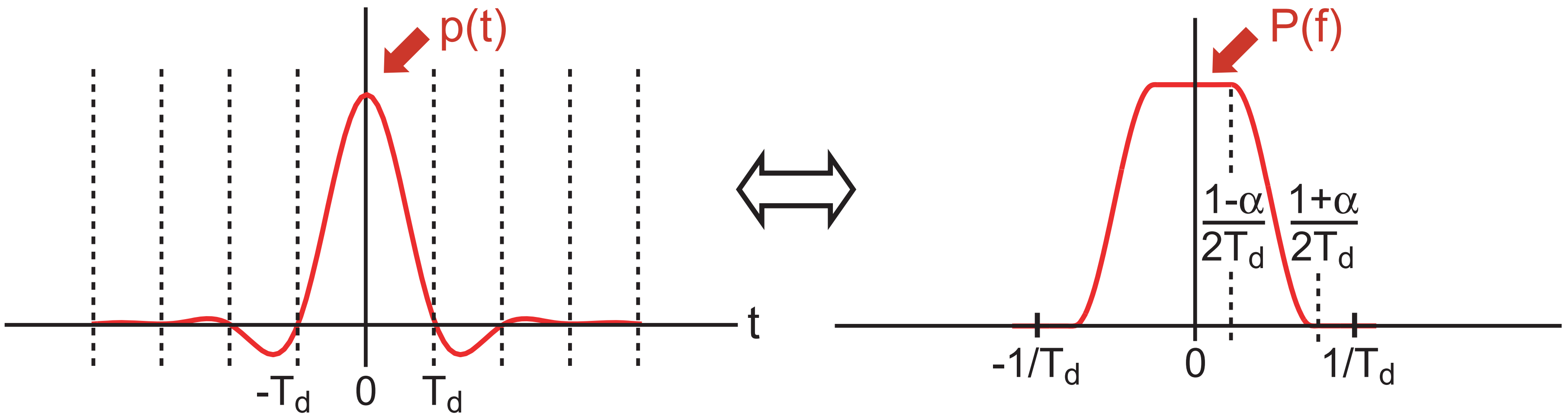
Derive Nyquist Condition for Avoiding ISI (Step 2)



- **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**



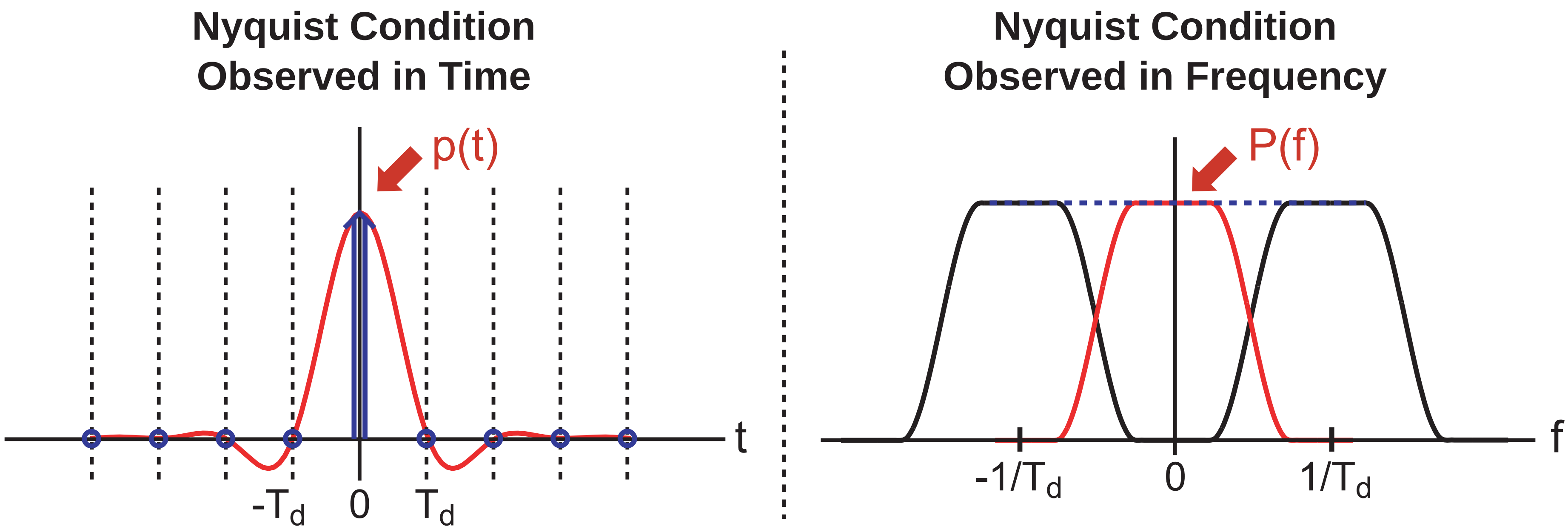
$$p(t) = \frac{\sin(\pi t/T_d)}{\pi t/T_d} \frac{\cos(\pi \alpha t/T_d)}{1 - 4\alpha^2 t^2/T_d^2}$$

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

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

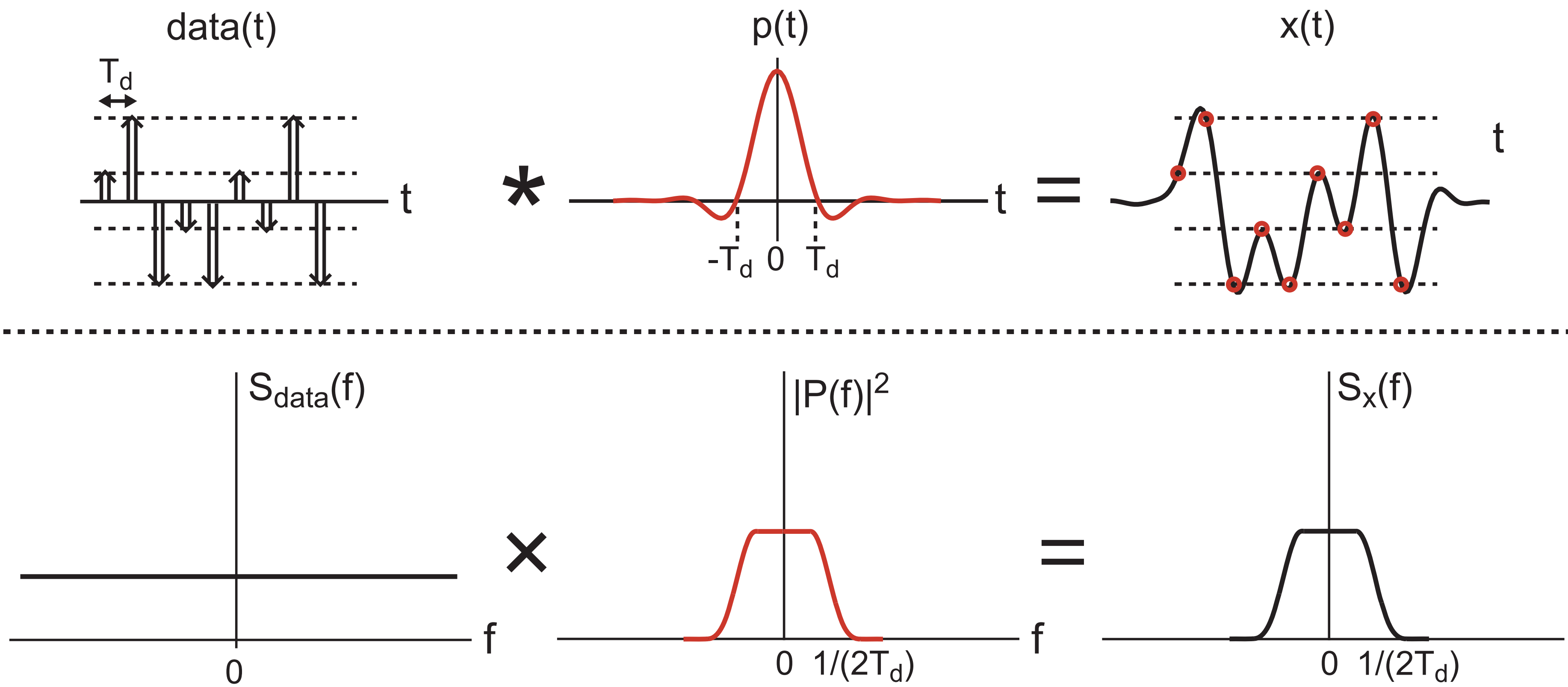
  - Rolloff factor = 0: P(f) becomes a brick-wall filter
  - Rolloff factor = 1: P(f) looks nearly like a triangle
  - Rolloff factor = 0.5: shown above

Raised-Cosine Filter Satisfies Nyquist Condition



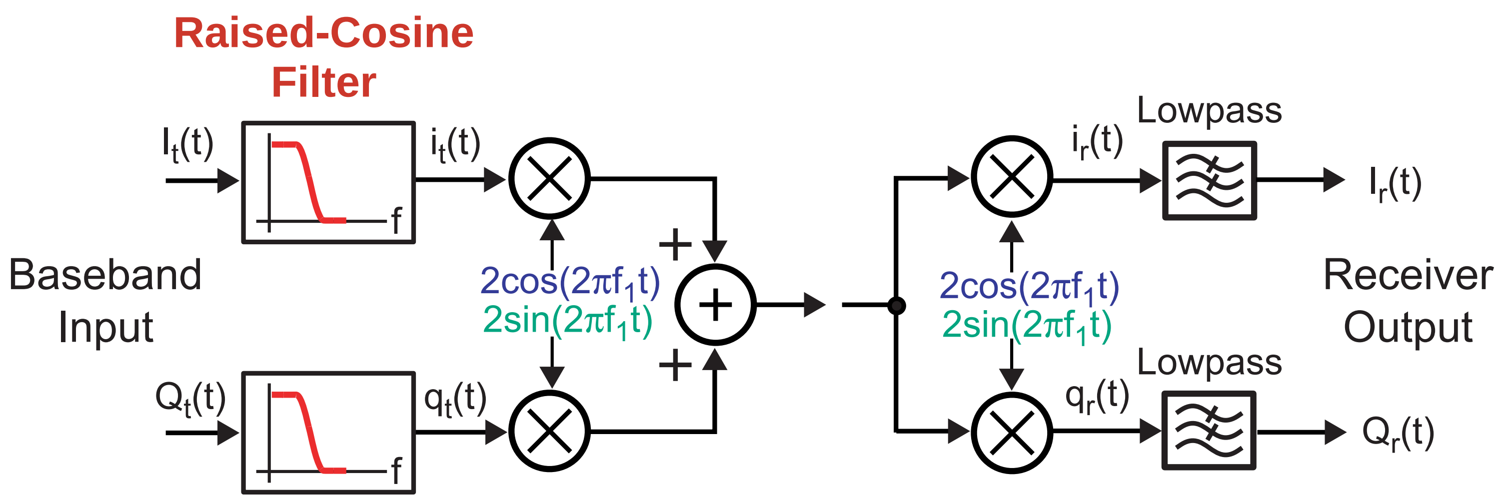
- **In time**
  - **$p(kT_d) = 0$ for all k not equal to 0**
- **In frequency**
  - **Fourier transform of $p(kT_d)$ is flat**
  - **Alternatively: Addition of shifted P(f) centered about k/T_d leads to flat Fourier transform (as shown above)**

Spectral Efficiency With Raised-Cosine Filter



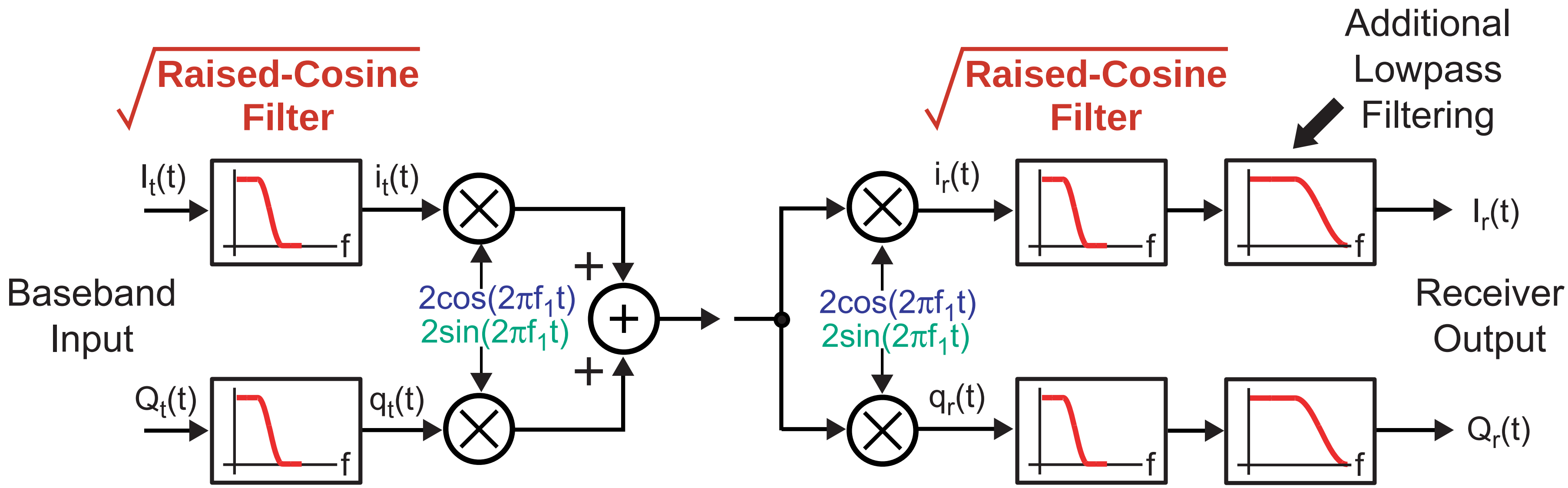
- More efficient than when p(t) is a square pulse
- Less efficient than brick-wall lowpass
  - But implementation is much more practical
- Note: Raised-cosine P(f) often "split" between transmitter and receiver

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)**

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

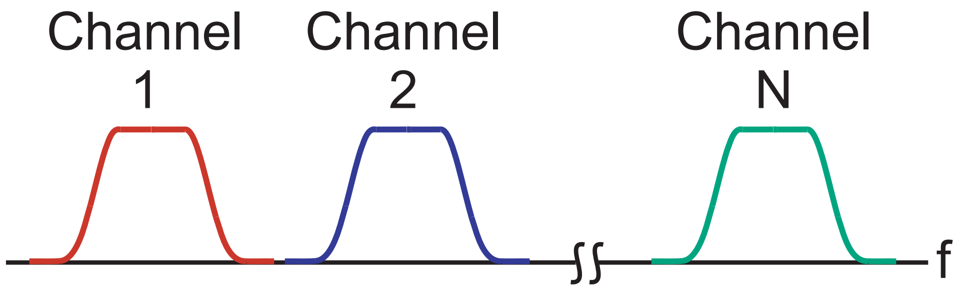
    - Place one in transmitter, the other in receiver
- **Use additional lowpass filtering in receiver to further reduce high frequency noise and mixer products**

Multiple Access Techniques

The Issue of Multiple Access

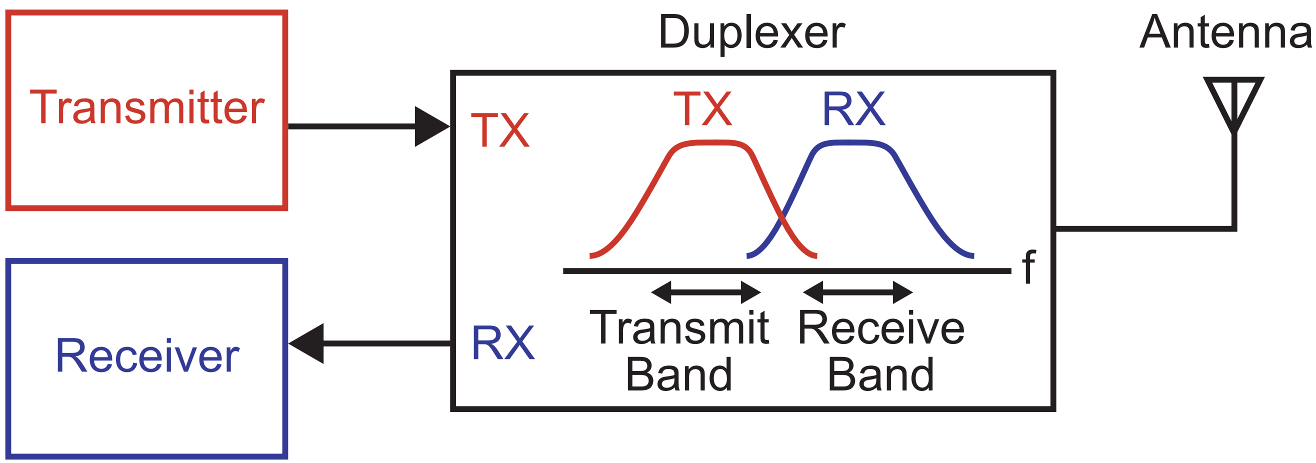
- **Want to allow communication between many different users**
- **Freespace spectrum is a shared resource**
  - **Must be partitioned between users**
- **Can partition in either time, frequency, or through "orthogonal coding" (or nearly orthogonal coding) of data signals**

Frequency-Division Multiple Access (FDMA)



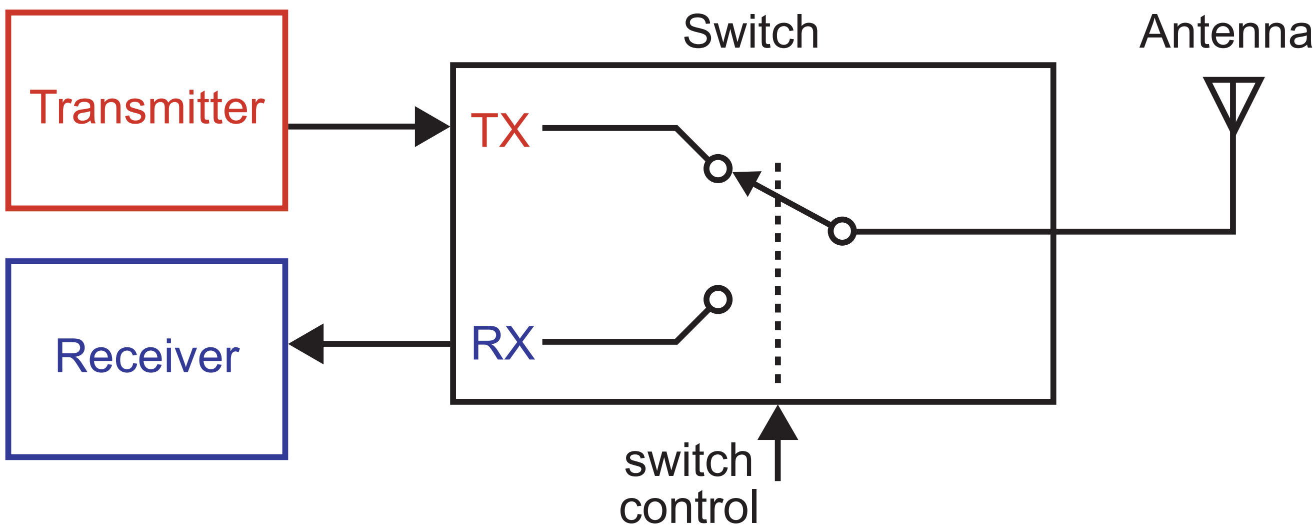
- Place users into different frequency channels
- Two different methods of dealing with transmit/receive of a given user
  - Frequency-division duplexing
  - Time-division duplexing

Frequency-Division Duplexing



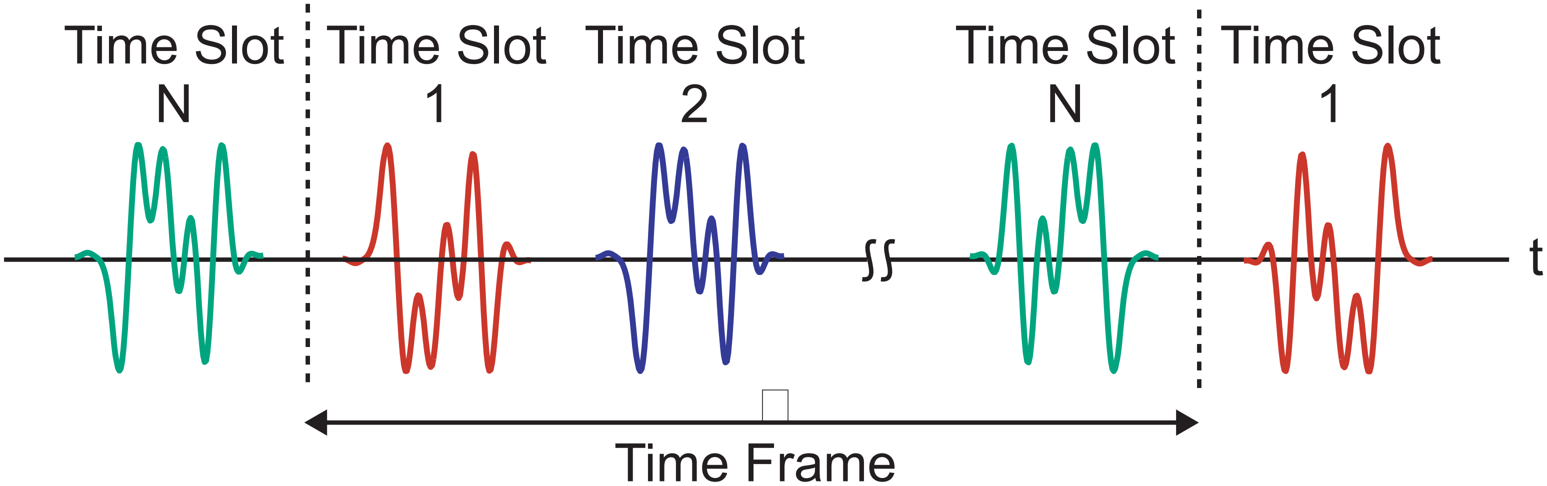
- Separate frequency channels into transmit and receive bands
- Allows simultaneous transmission and reception
  - Isolation of receiver from transmitter achieved with duplexer
  - Cannot communicate directly between users, only between handsets and base station
- Advantage: isolates users
- Disadvantage: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

Time-Division Duplexing



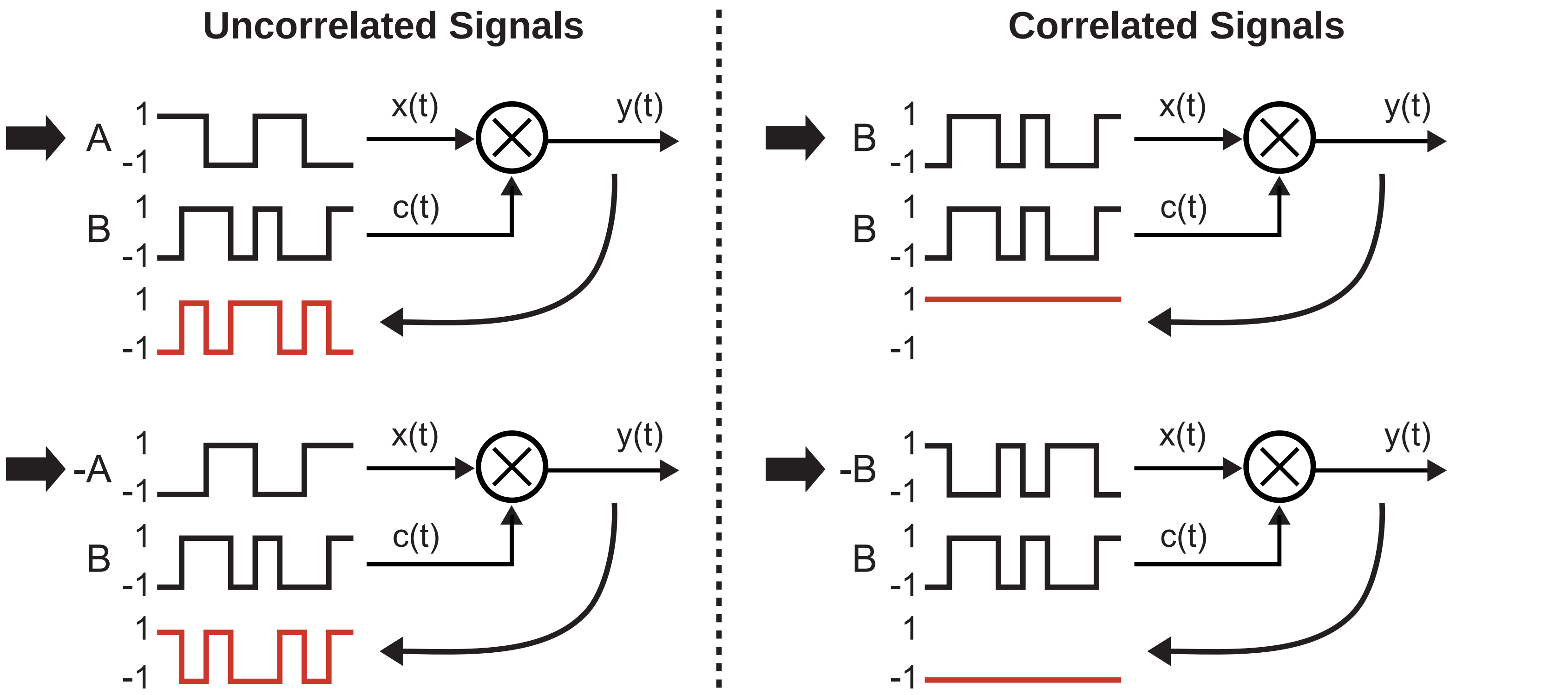
- Use any desired frequency channel for transmitter and receiver
- Send transmit and receive signals at different times
- Allows communication directly between users (not necessarily desirable)
- Advantage: switch has low insertion loss relative to duplexer
- Disadvantage: receiver more sensitive to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

Time-Division Multiple Access (TDMA)



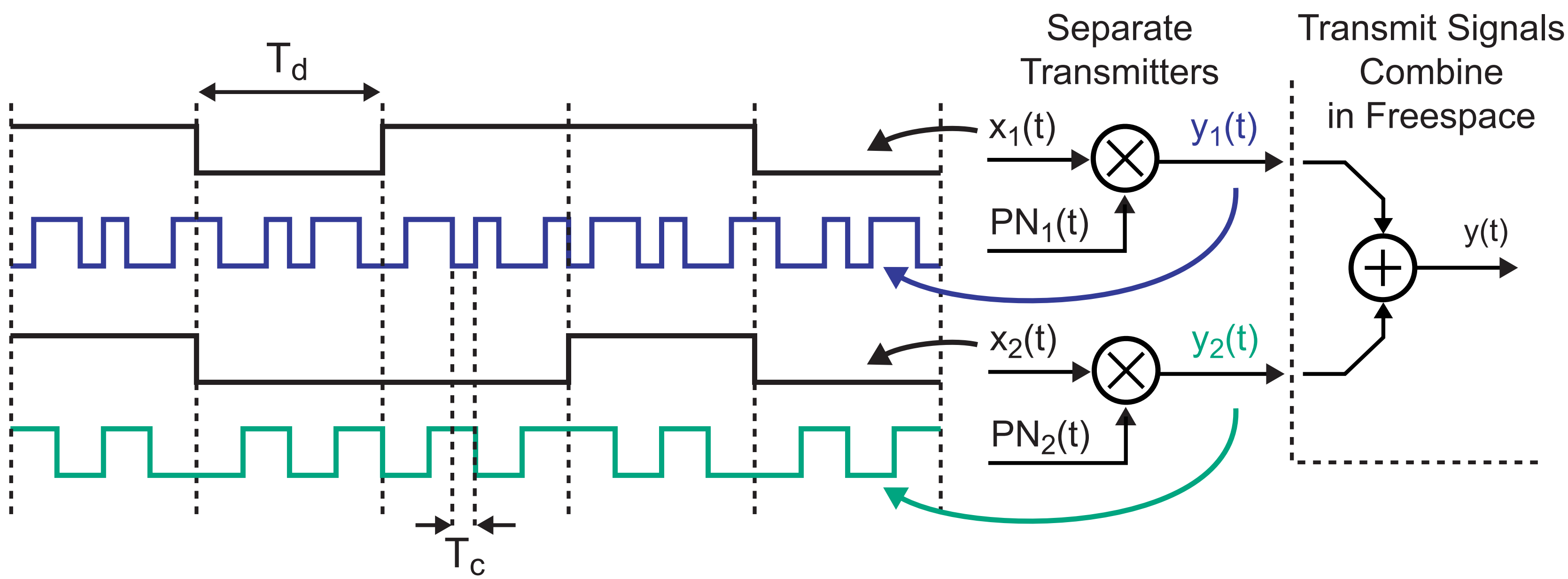
- **Place users into different time slots**
  - **A given time slot repeats according to time frame period**
- **Often combined with FDMA**
  - **Allows many users to occupy the same frequency channel**

Channel Partitioning Using (Nearly) "Orthogonal Coding"



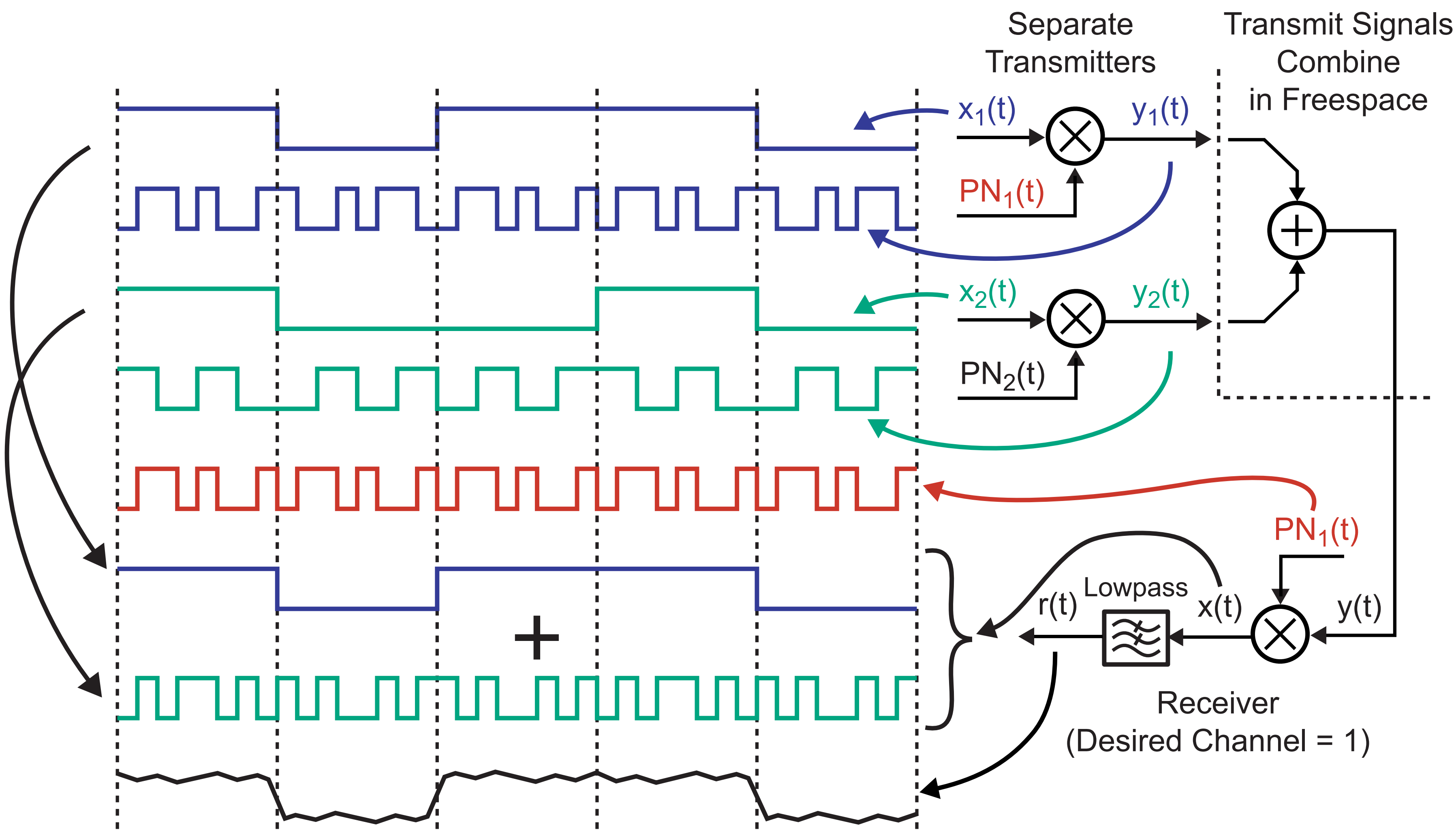
- Consider two correlation cases
  - Two independent random Bernoulli sequences
    - Result is a random Bernoulli sequence
  - Same Bernoulli sequence
    - Result is 1 or -1, depending on relative polarity

Code-Division Multiple Access (CDMA)



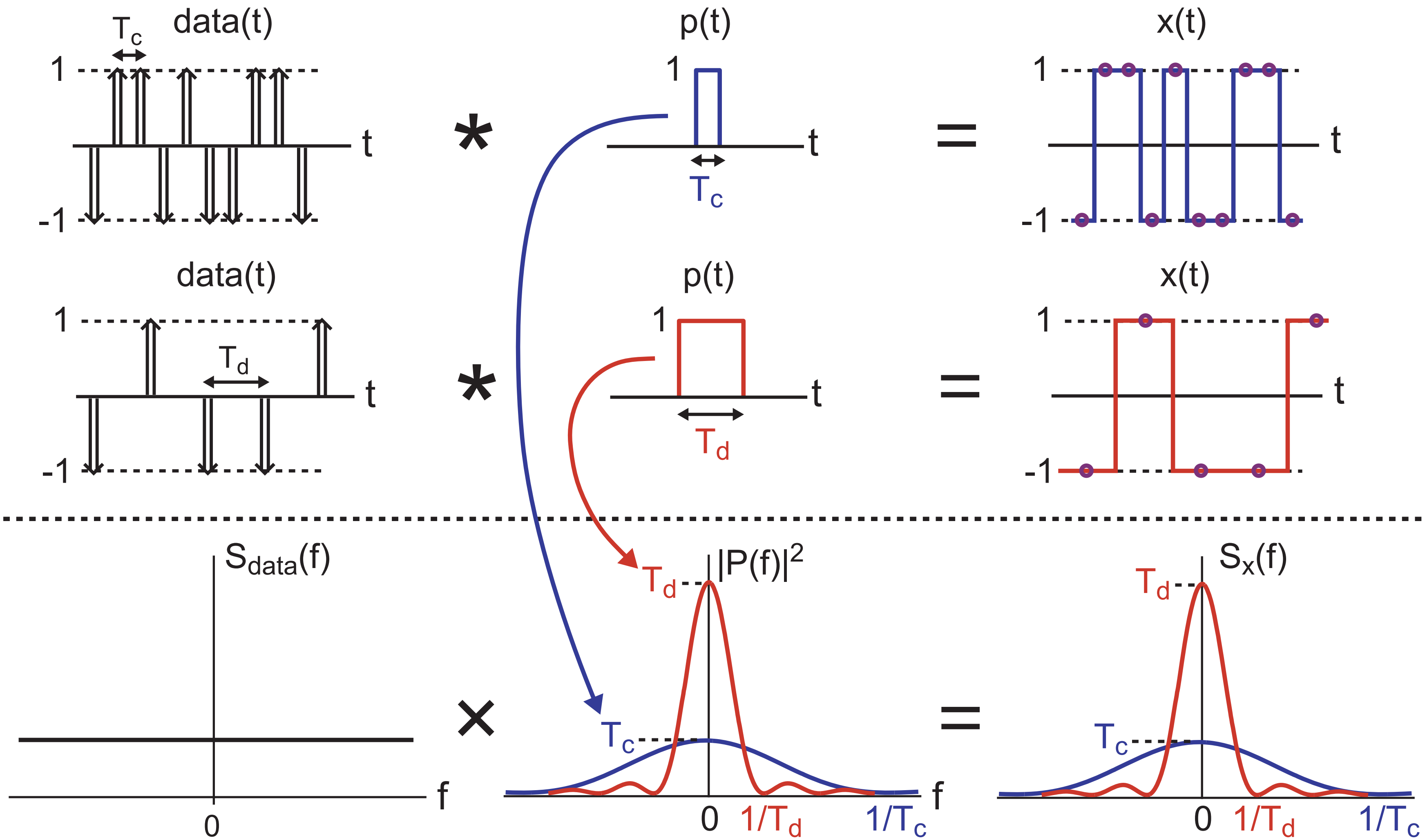
- **Assign a unique code sequence to each transmitter**
- **Data values are encoded in transmitter output stream by varying the polarity of the transmitter code sequence**
  - **Each pulse in data sequence has period T_d**
    - Individual pulses represent binary data values
  - **Each pulse in code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

Receiver Selects Desired Transmitter Through Its Code



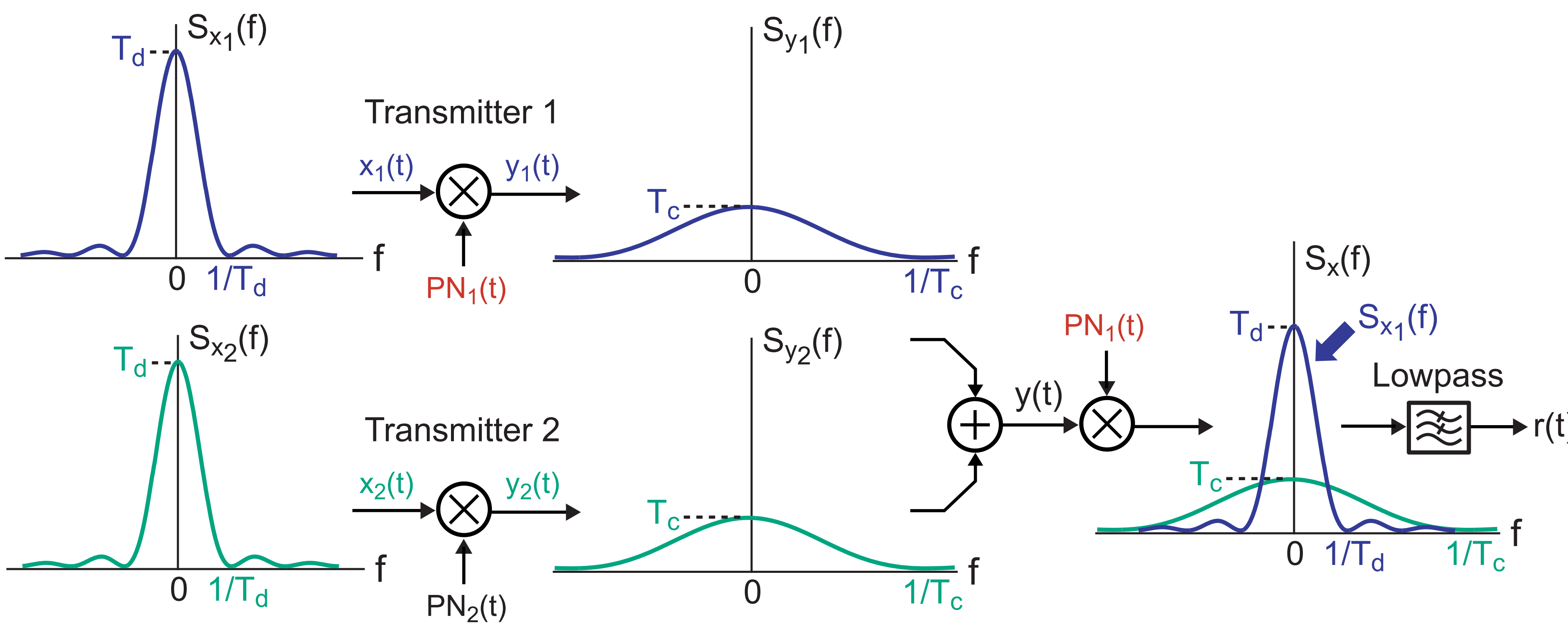
- Receiver correlates its input with desired transmitter code
  - Data from desired transmitter restored
  - Data from other transmitter(s) remains randomized

Frequency Domain View of Chip Vs Data Sequences



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

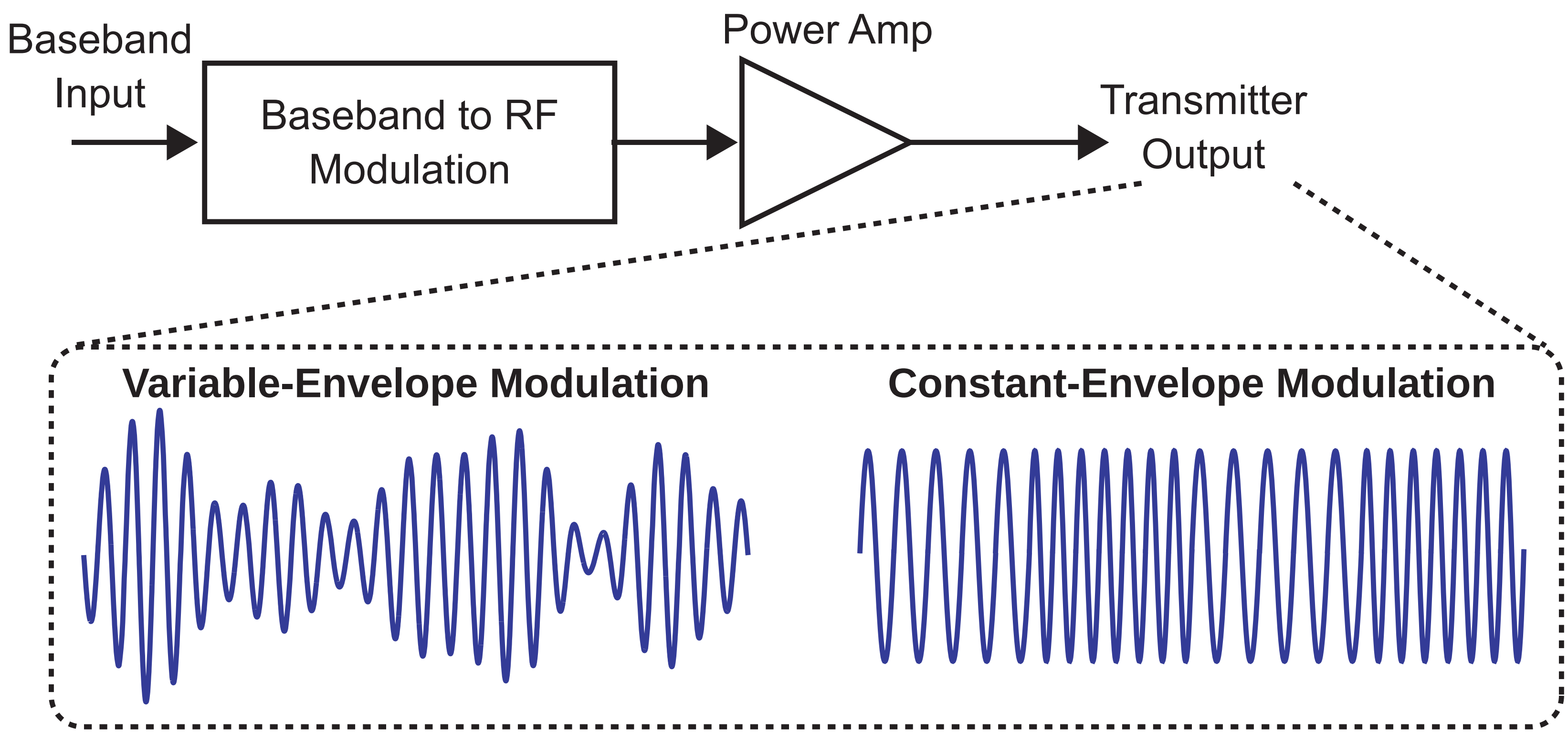
Frequency Domain View of CDMA



- **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

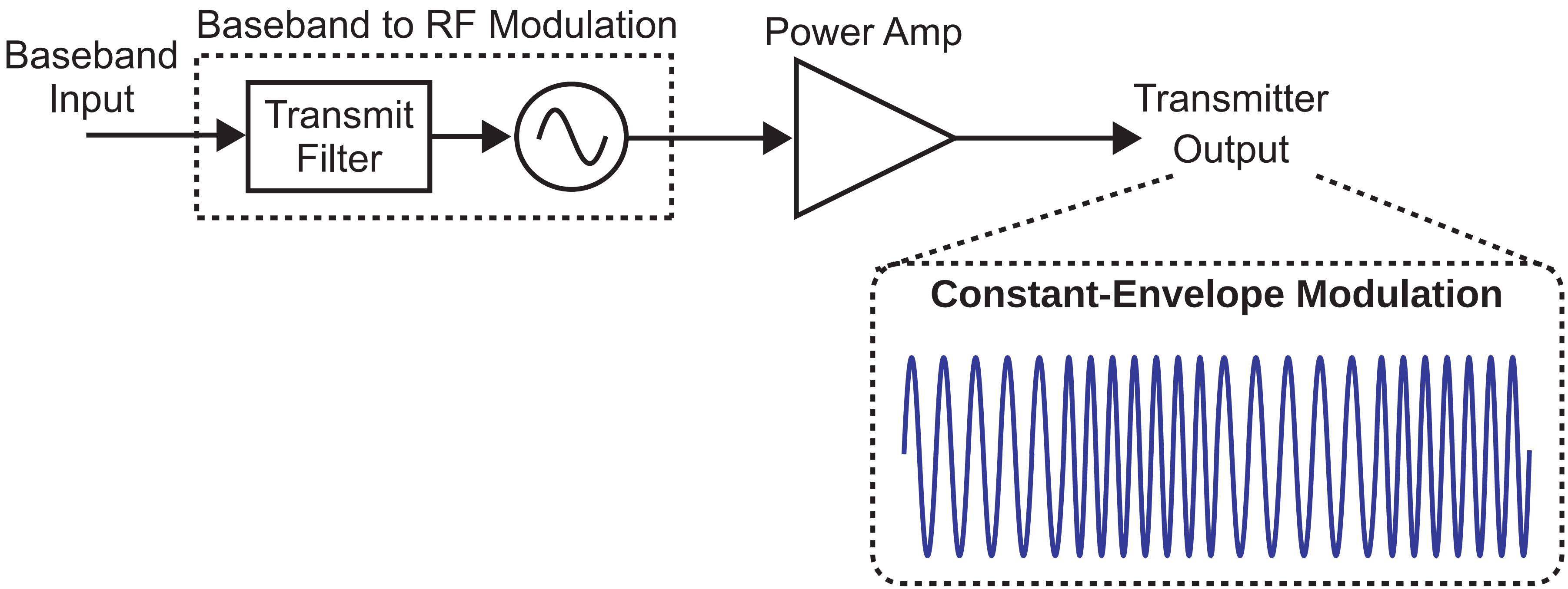
Constant Envelope Modulation

The Issue of Power Efficiency



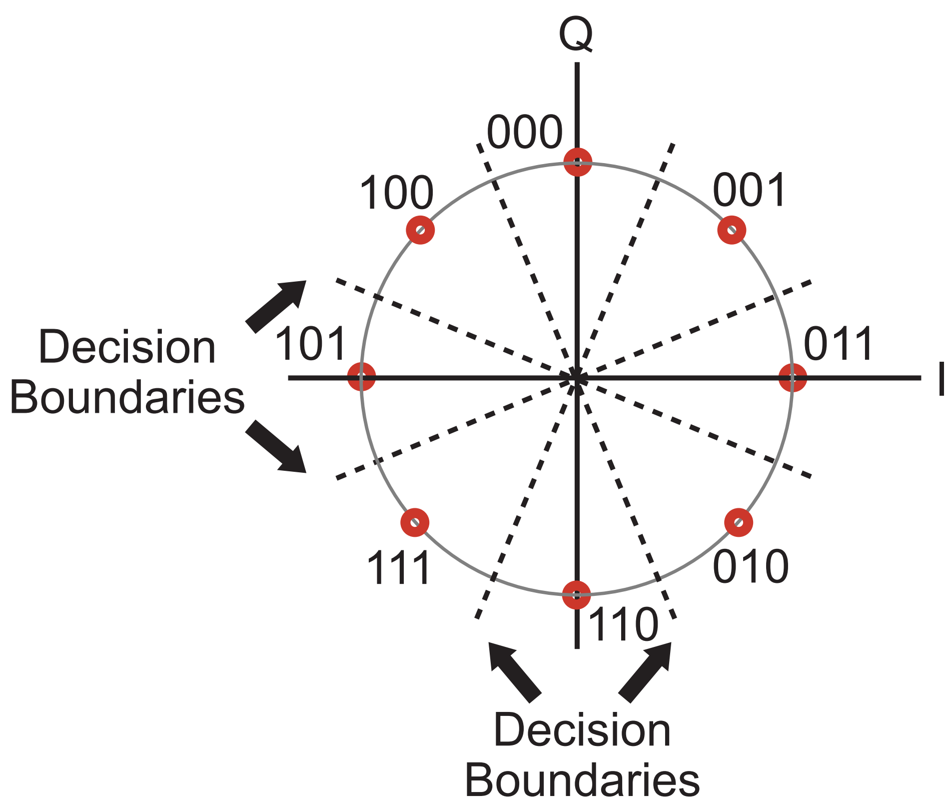
- **Power amp dominates power consumption for many wireless systems**
  - **Linear power amps more power consuming than nonlinear ones**
- **Constant-envelope modulation allows nonlinear power amp**
  - **Lower power consumption possible**

Simplified Implementation for Constant-Envelope



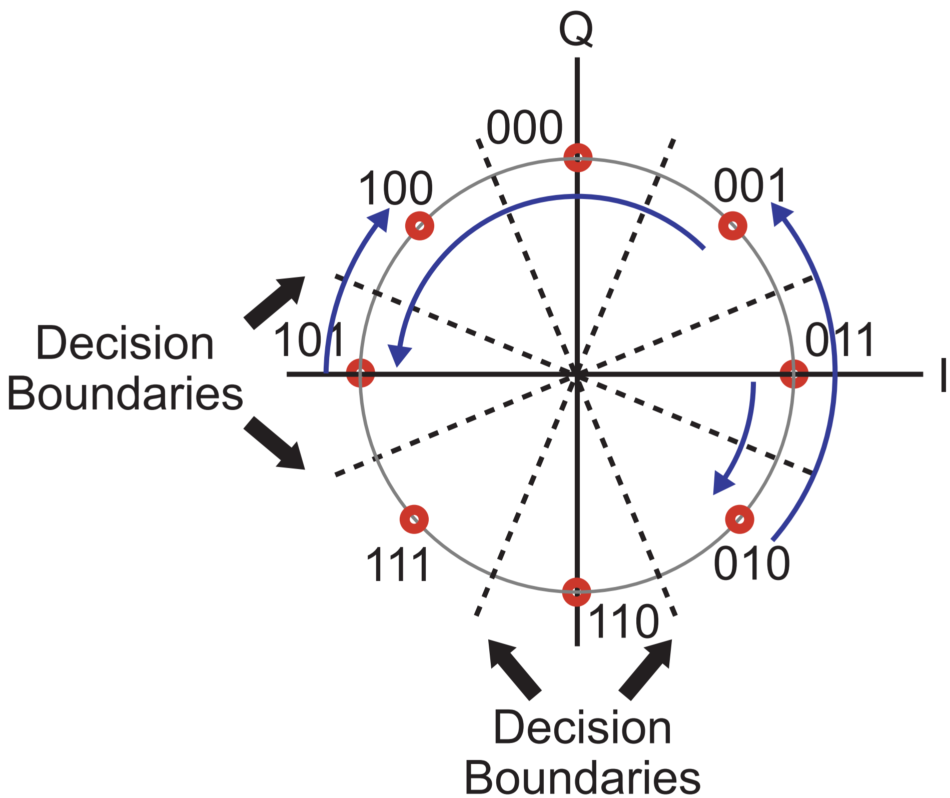
- **Constant-envelope modulation limited to phase and frequency modulation methods**
- **Can achieve both phase and frequency modulation with ideal VCO**
  - **Use as model for analysis purposes**
  - **Note: phase modulation nearly impossible with practical VCO**

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**

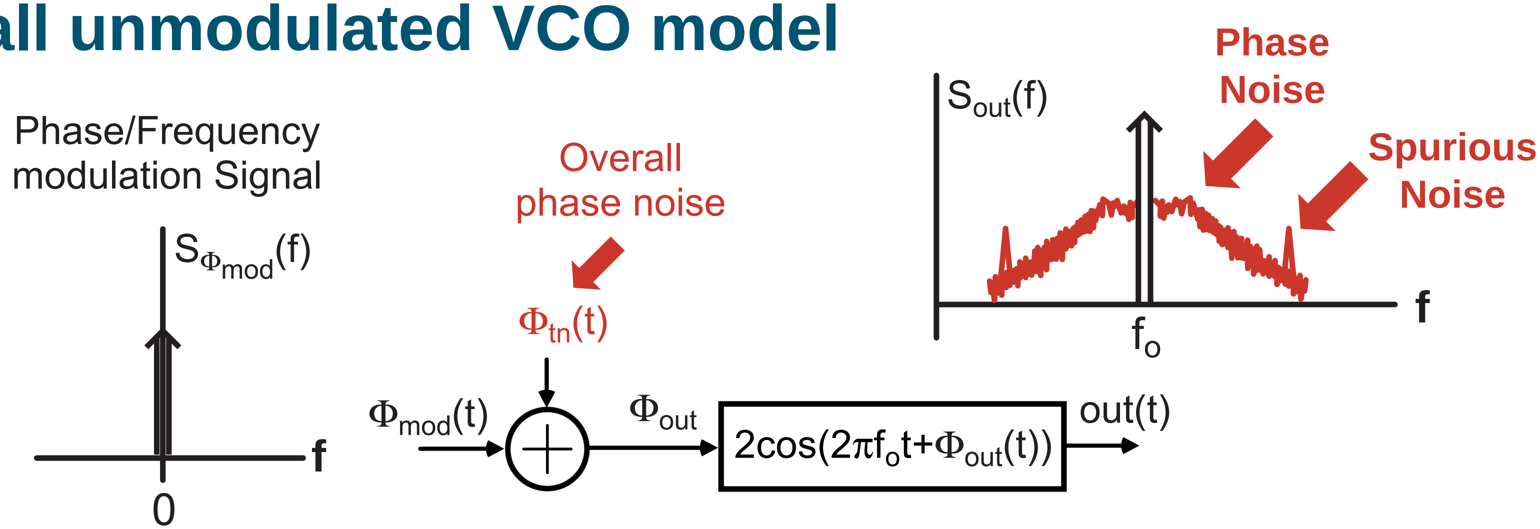
Transitioning Between Constellation Points



- **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**

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

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**

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

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

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

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)**

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

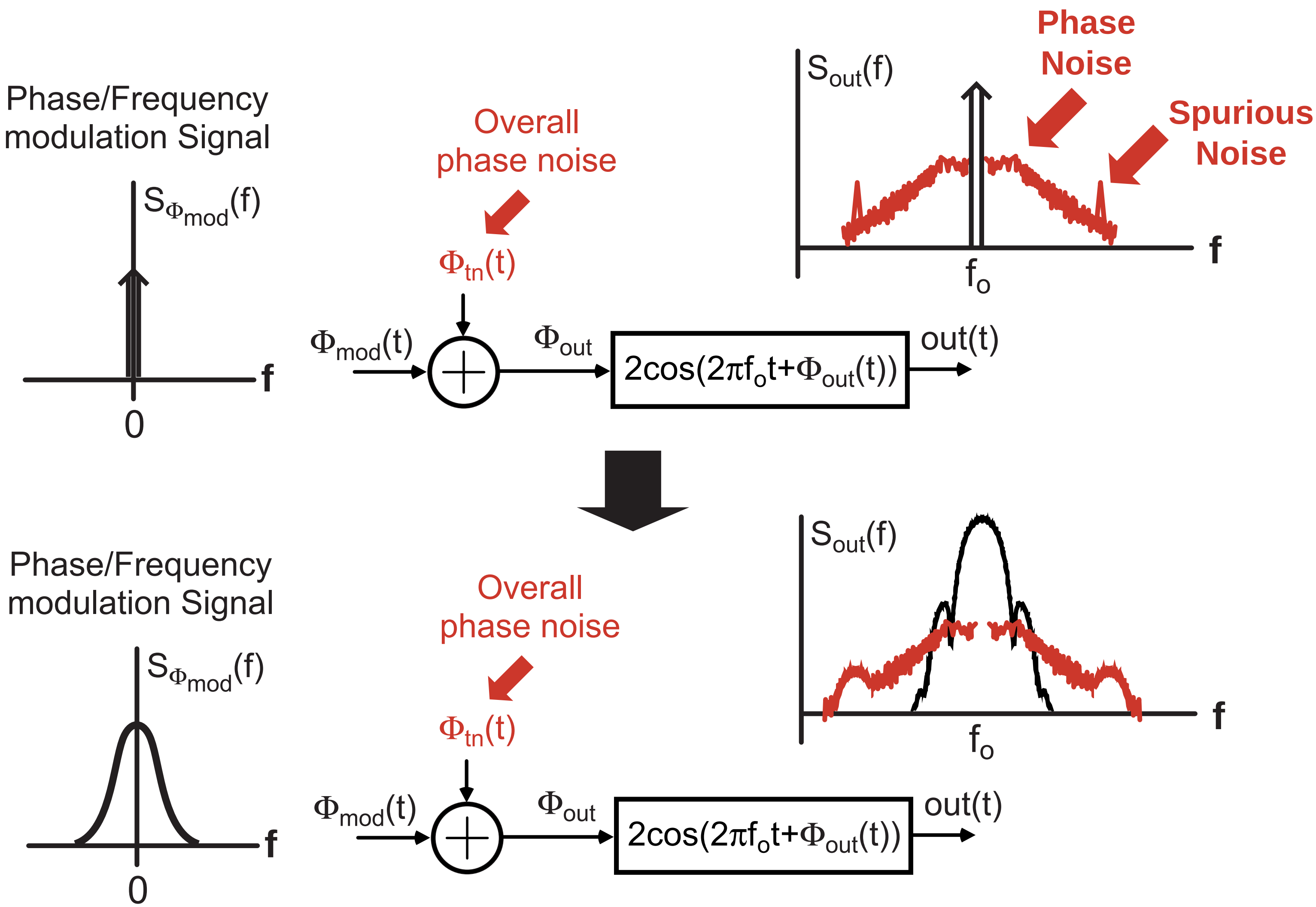
- **Output spectral density (Fourier transform of autocorrelation)**

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

  - **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

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

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