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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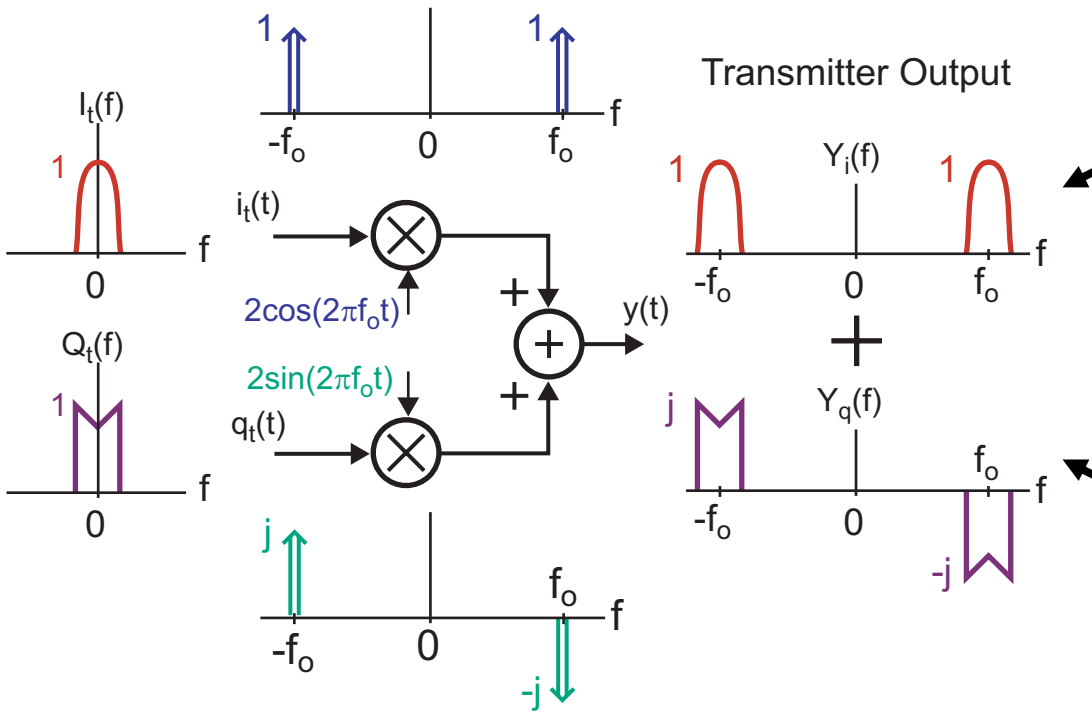
Review of Analog I/Q Modulation

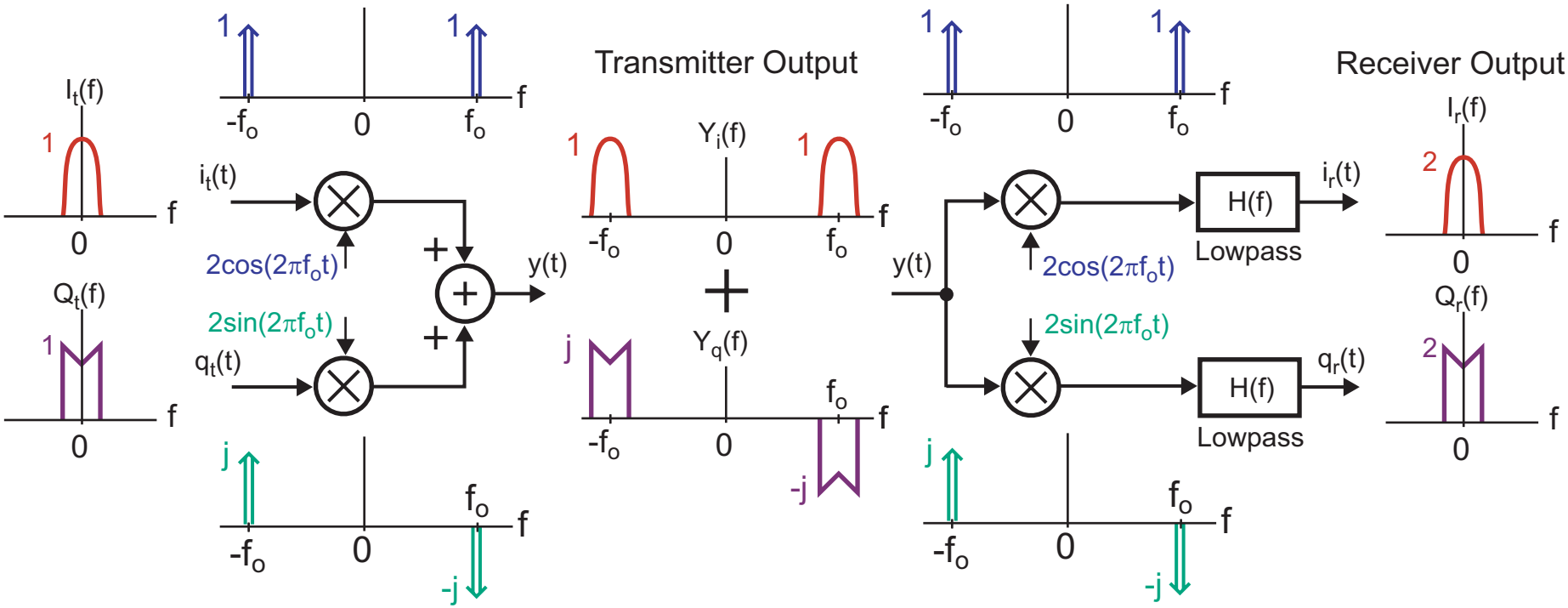


I stands for *in-phase* component

Q stands for *quadrature* component

- 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

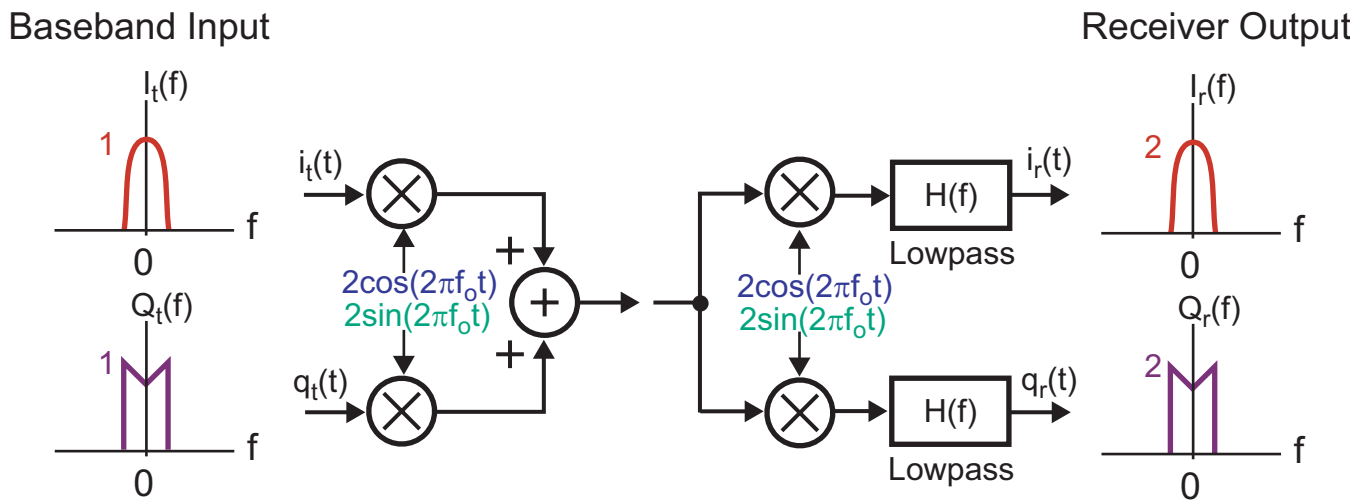
Review of Analog I/Q Demodulation



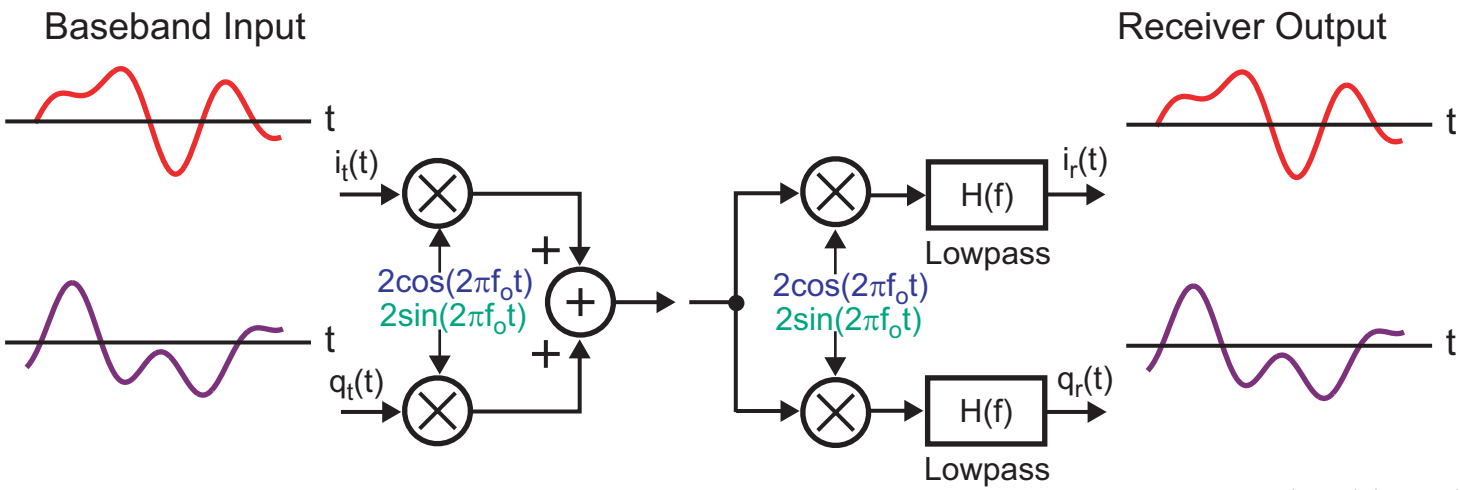
- Demodulate with *both* a cosine and sine wave
  - Both I and Q channels are recovered!
- I/Q modulation allows twice the amount of *information* to be sent compared to basic AM modulation with same *bandwidth*

Summary of Analog I/Q Demodulation

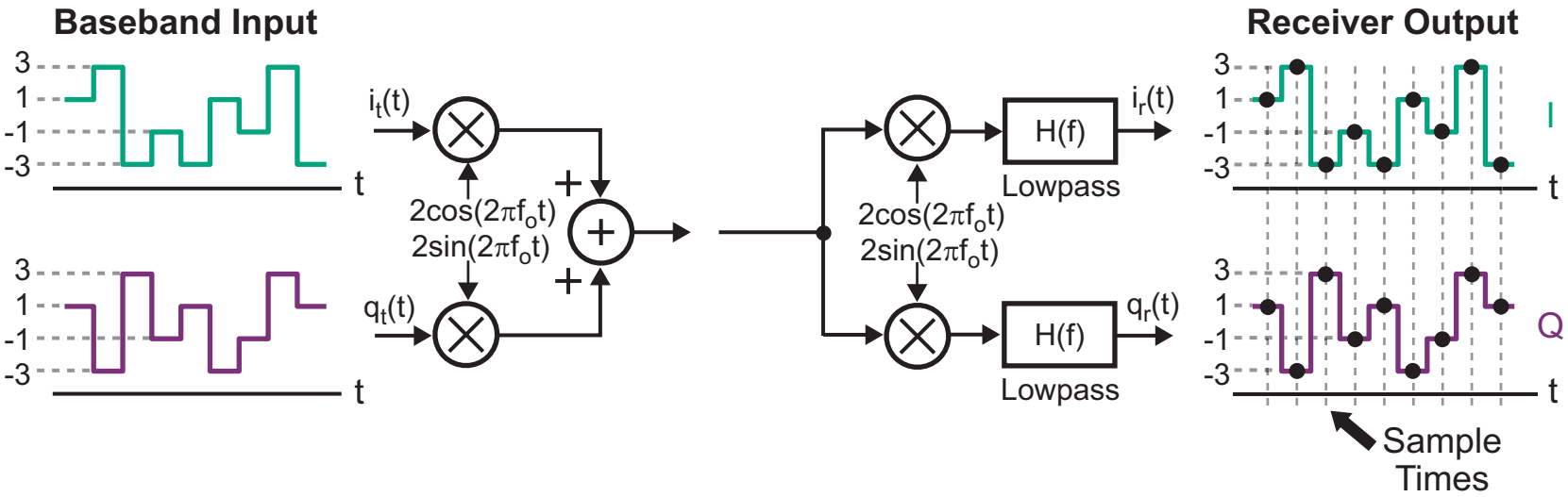
- **Frequency domain view**



- **Time domain view**



Digital I/Q Modulation

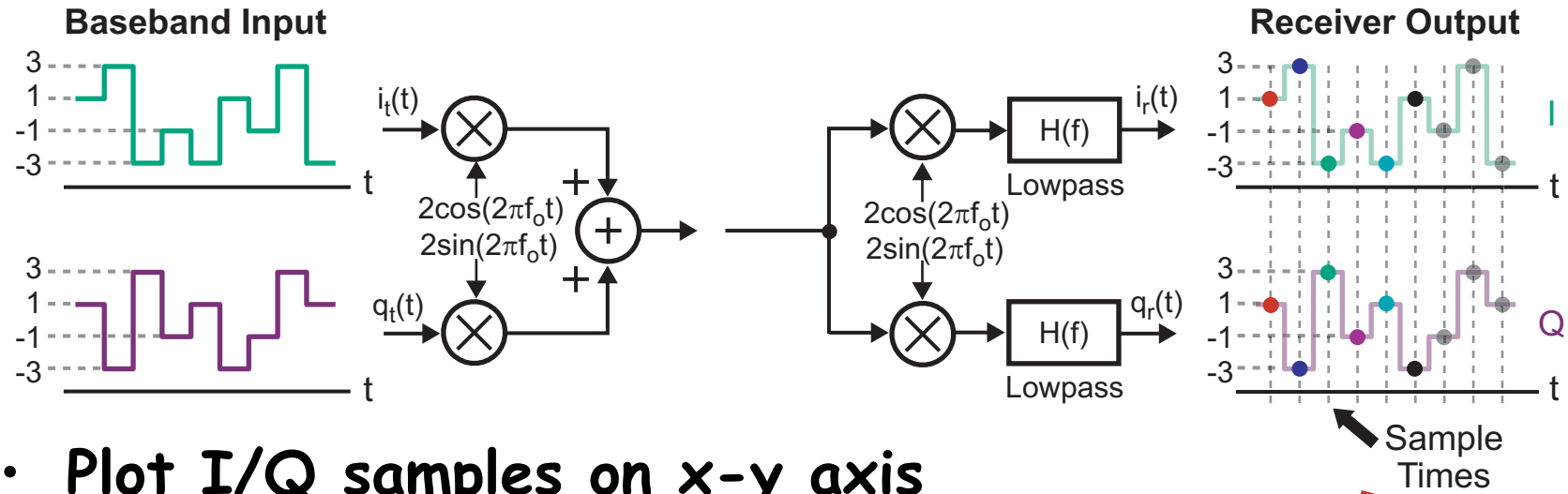


- Leverage *analog communication channel* to send *discrete-valued symbols*
  - Example: send symbol from set {-3,-1,1,3} on both I and Q channels each *symbol period*
- At receiver, sample I/Q waveforms every symbol period
  - Associate each sampled I/Q value with symbols from set {-3,-1,1,3} on both I and Q channels

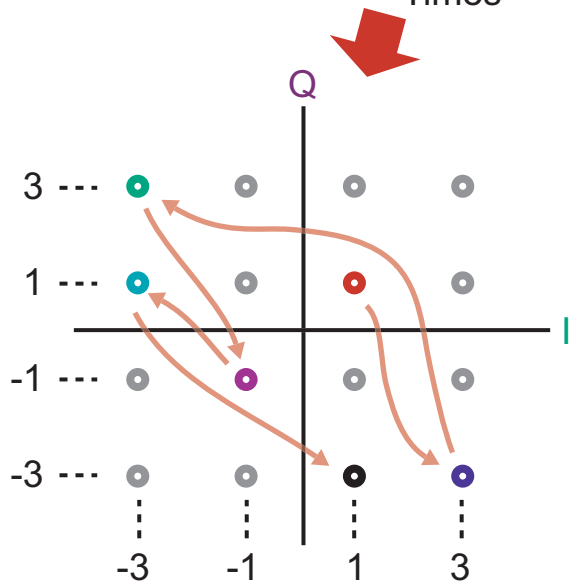
Advantages of going Digital

- 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

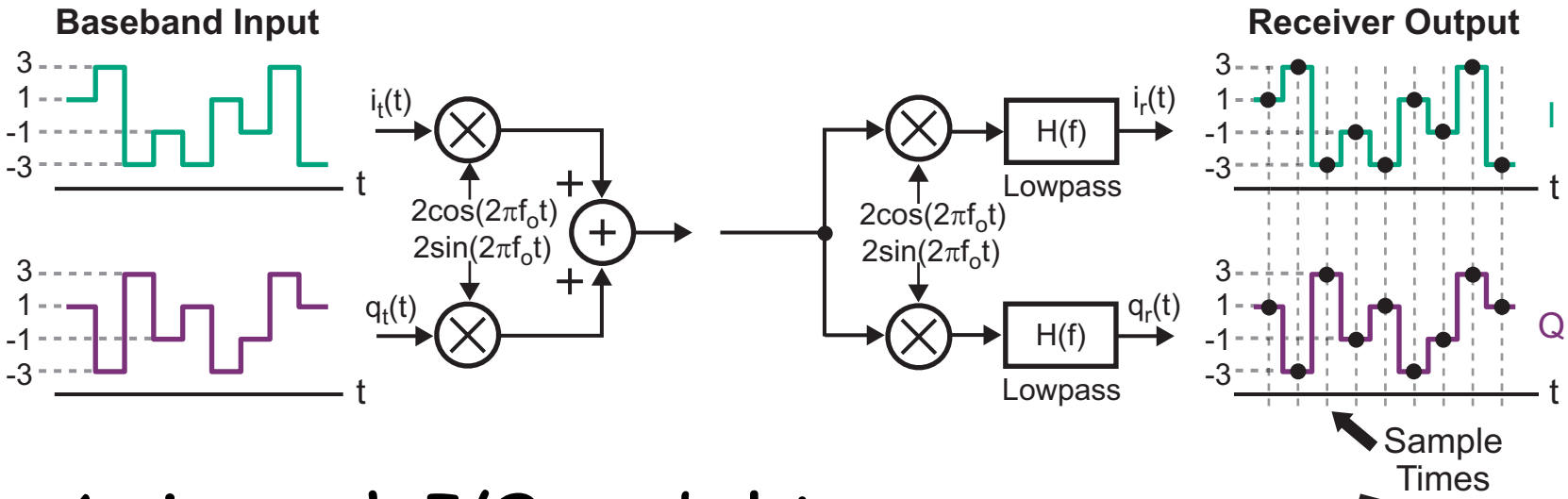
Constellation Diagrams



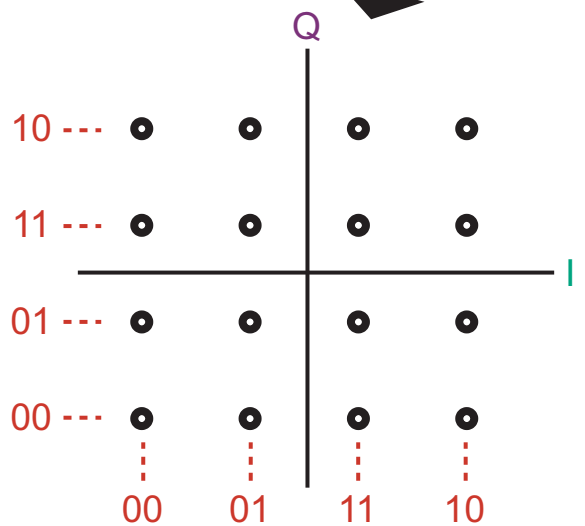
- Plot I/Q samples on x-y axis
  - Example: sampled I/Q value of {1,-3} forms a dot at x=1, y=-3
  - As more samples are plotted, constellation diagram eventually displays all possible symbol values
- Constellation diagram provides a sense of how easy it is to distinguish between different symbols



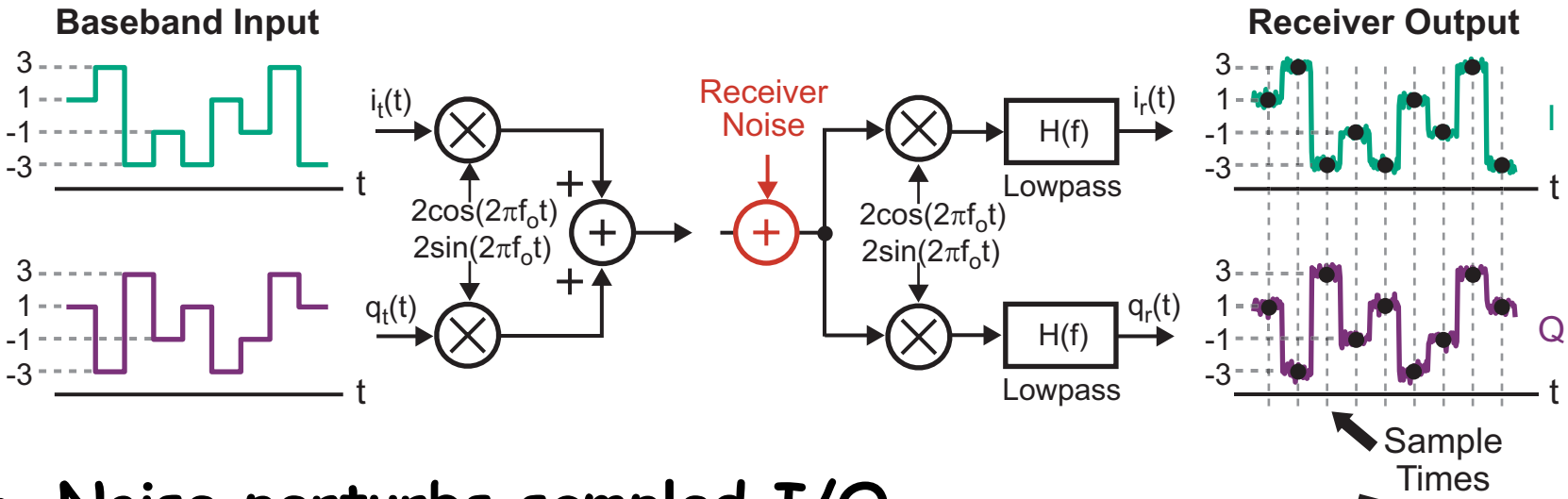
Sending Digital Bits



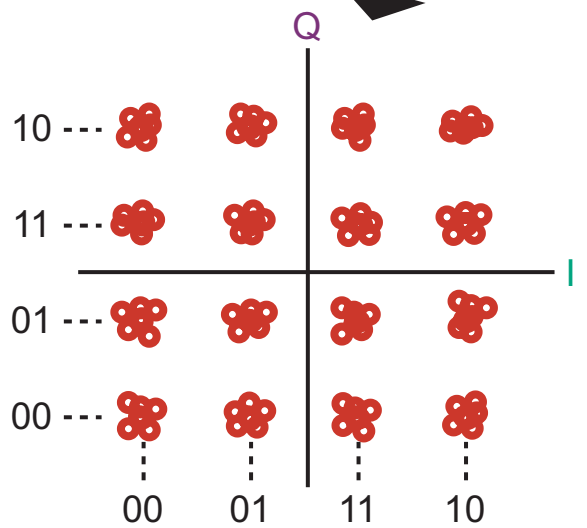
- **Assign each I/Q symbol to a set of digital bits**
  - Example: I/Q = {1,3} translates to bits of 1110
  - *Gray coding minimizes bit errors* when symbol errors are made
    - Example: I/Q = {1,1} translates to bits of 1010
      - Only one bit change from I/Q = {1,3}



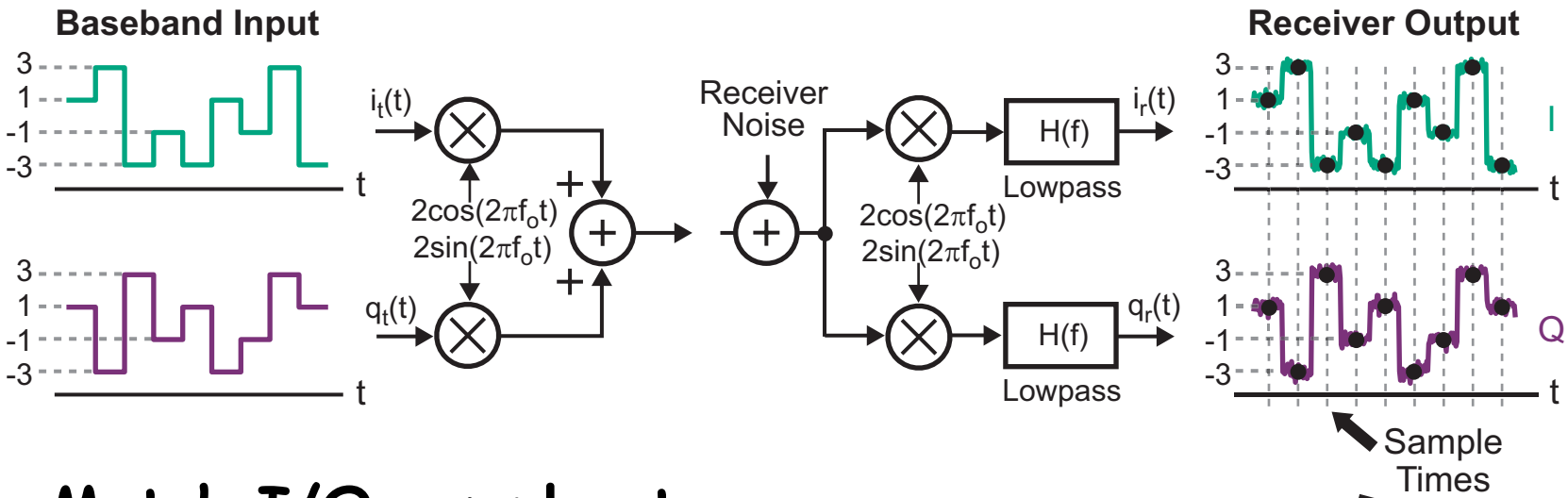
The Impact of Noise



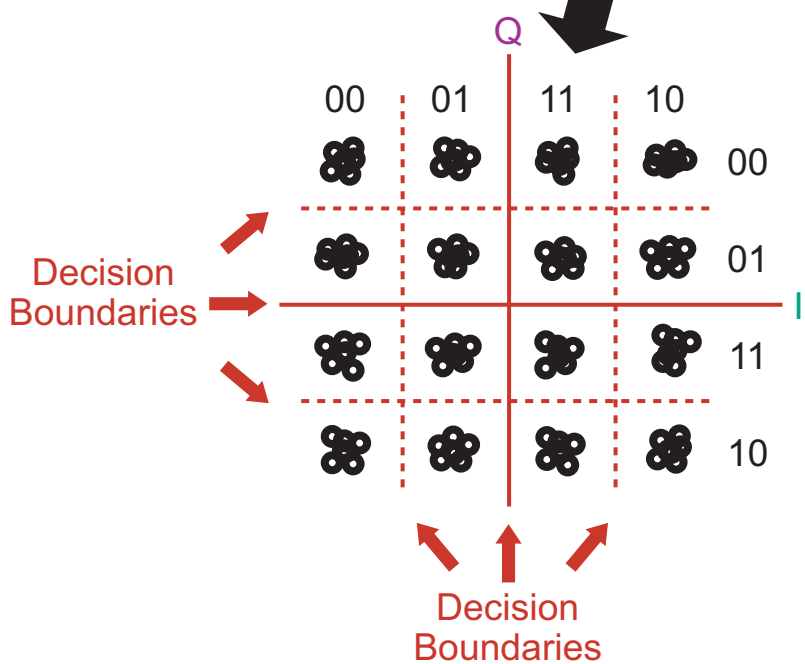
- Noise perturbs sampled I/Q values
  - Constellation points no longer consist of single dots for each symbol
- Issue: what is the best way to match received I/Q samples with their corresponding symbols?



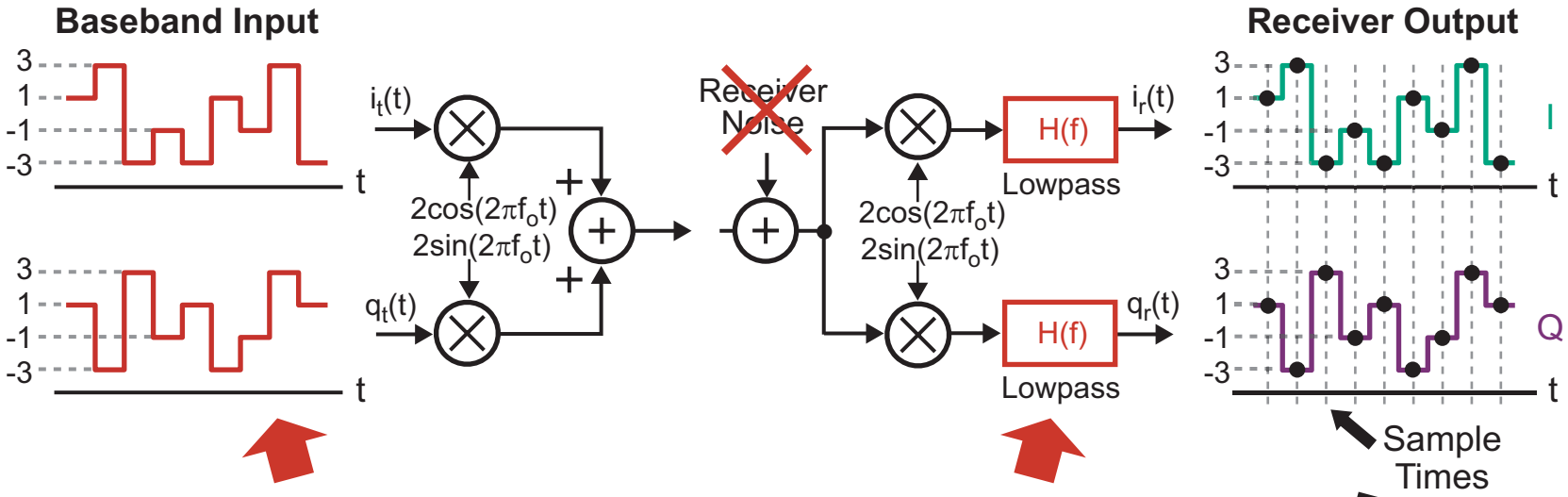
Symbol Selection Based on Slicing

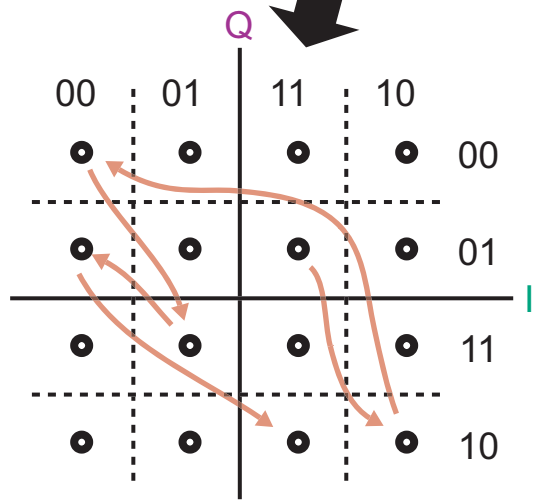


- Match I/Q samples to their corresponding symbols based on decision regions
  - Choose decision regions to minimize symbol errors
  - Decision boundaries are also called slicing levels



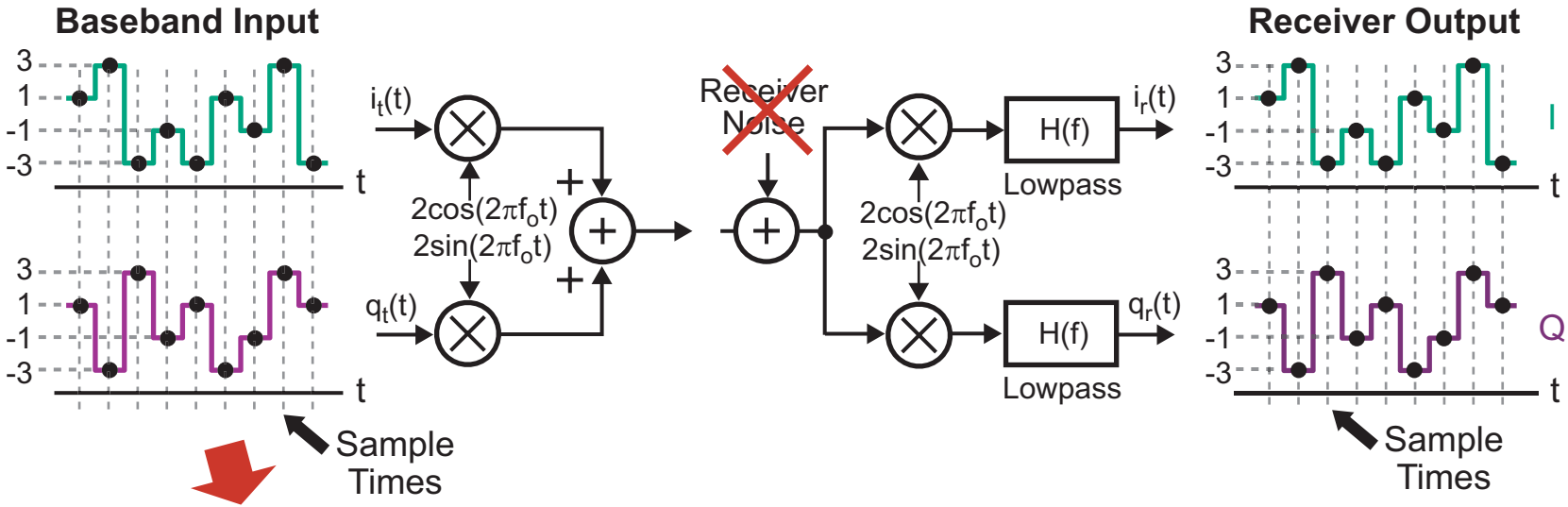
Transitioning Between Symbols

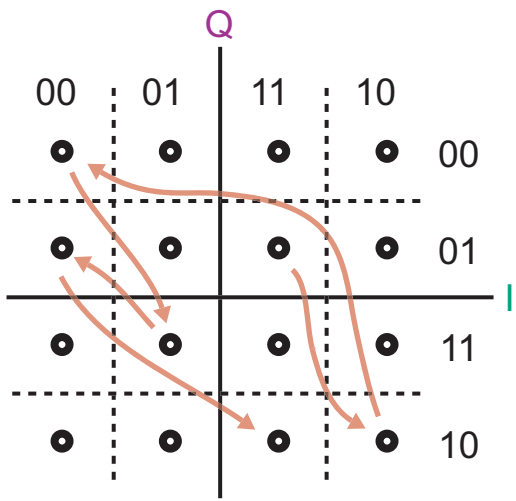




- Transition behavior between symbols is influenced by both transmit I/Q input waveforms and receive filter
  - We will focus on impact of transition behavior at transmitter today
  - Ignore the impact of noise for this analysis

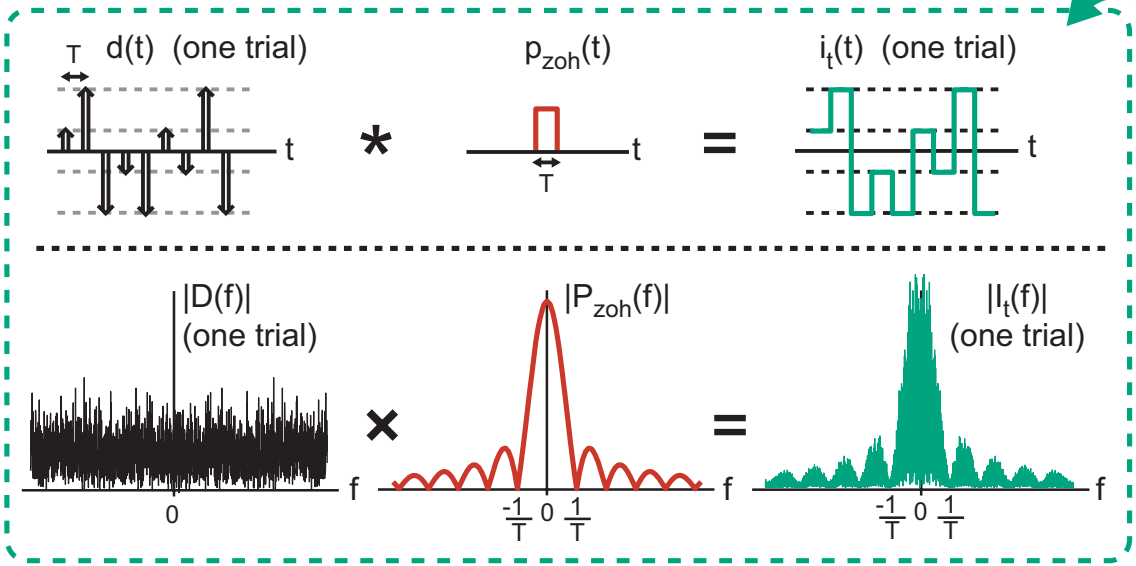
Influence of Transitions at Transmitter

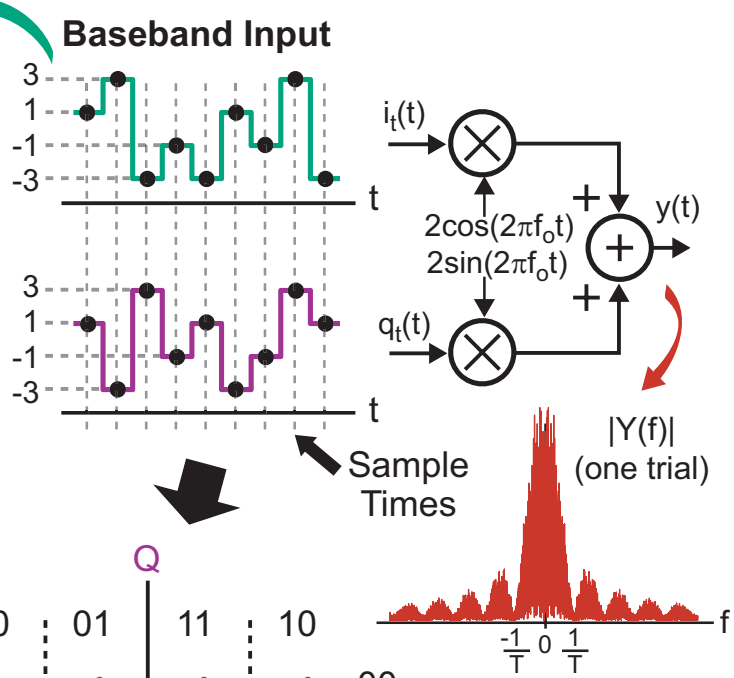


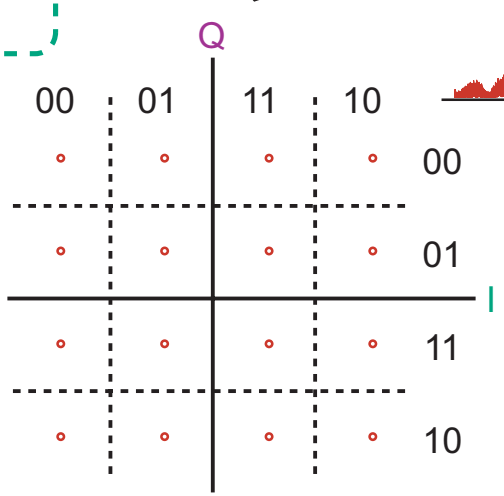


- *Ideal* analog communication channel simply transports the transmitter I/Q signals to the receiver
- Constellation diagram can be constructed at *transmitter* to evaluate its performance
  - Bad constellation at transmitter implies bad one at receiver

Transitions and the Transmitted Spectrum

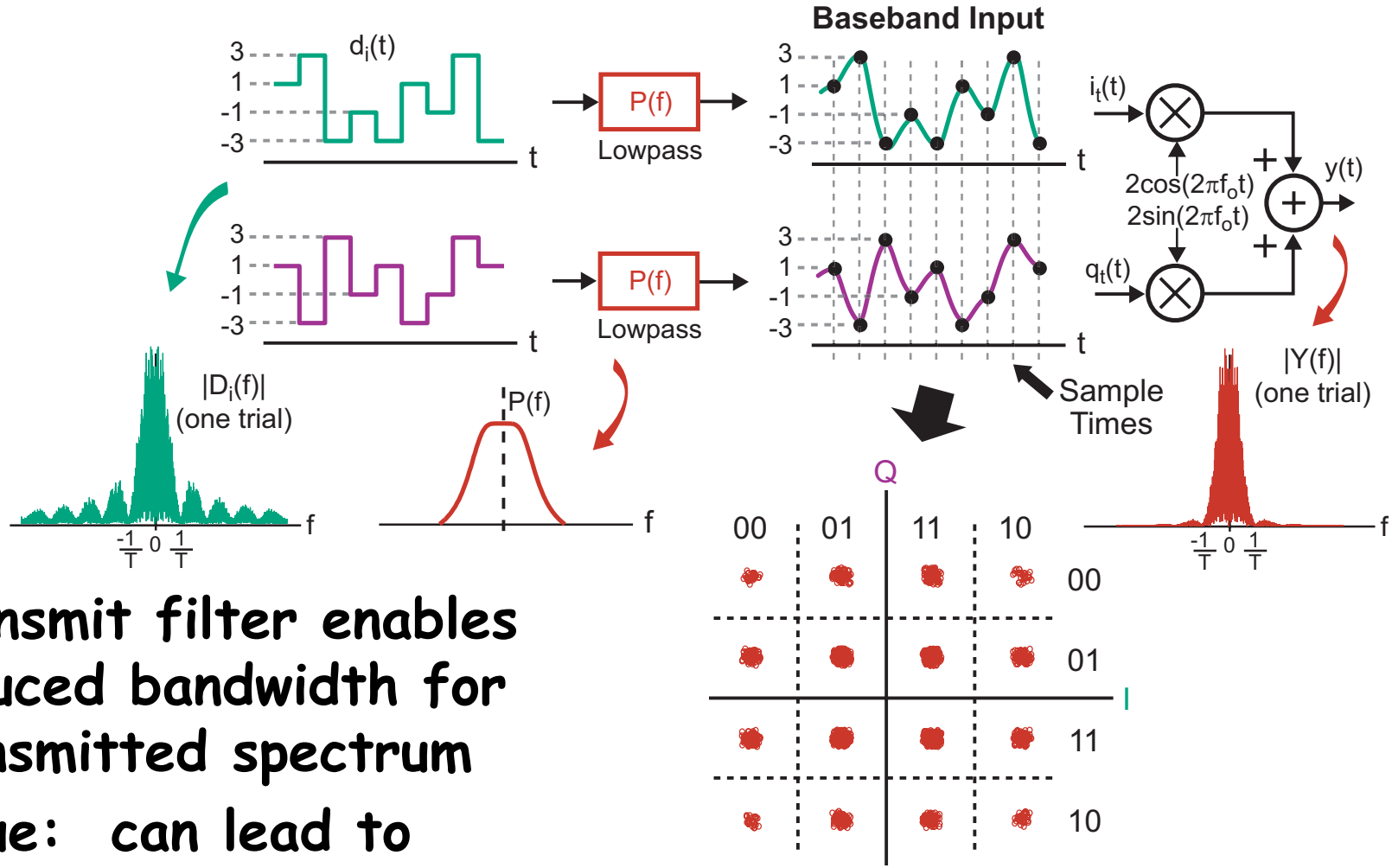






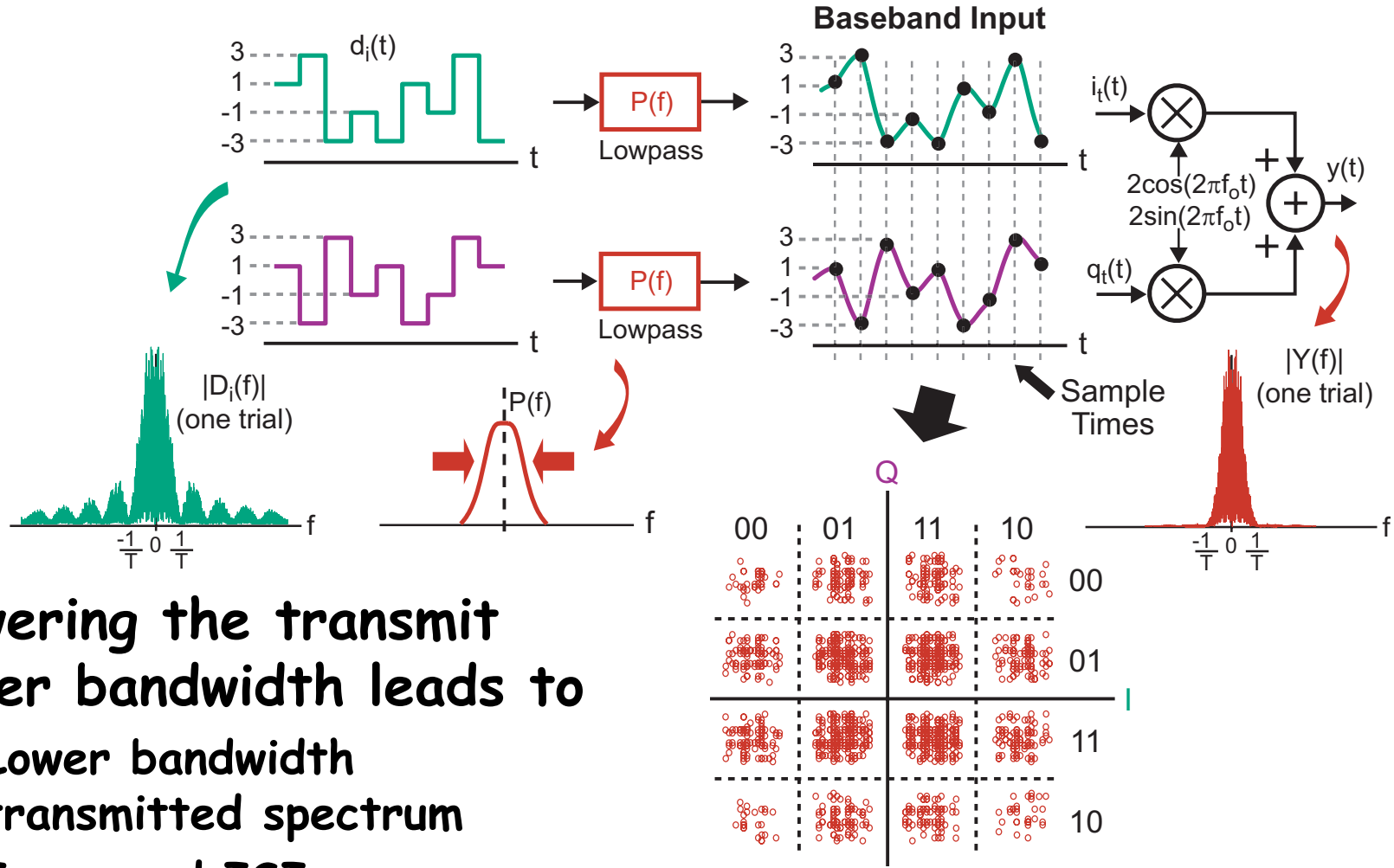
- Want transmitted spectrum with minimal bandwidth
  - Wireless communication channels are a *shared* resource
- Issue: sharply changing I/Q waveforms lead to a *wide bandwidth* spectrum

Impact of Transmit Filter



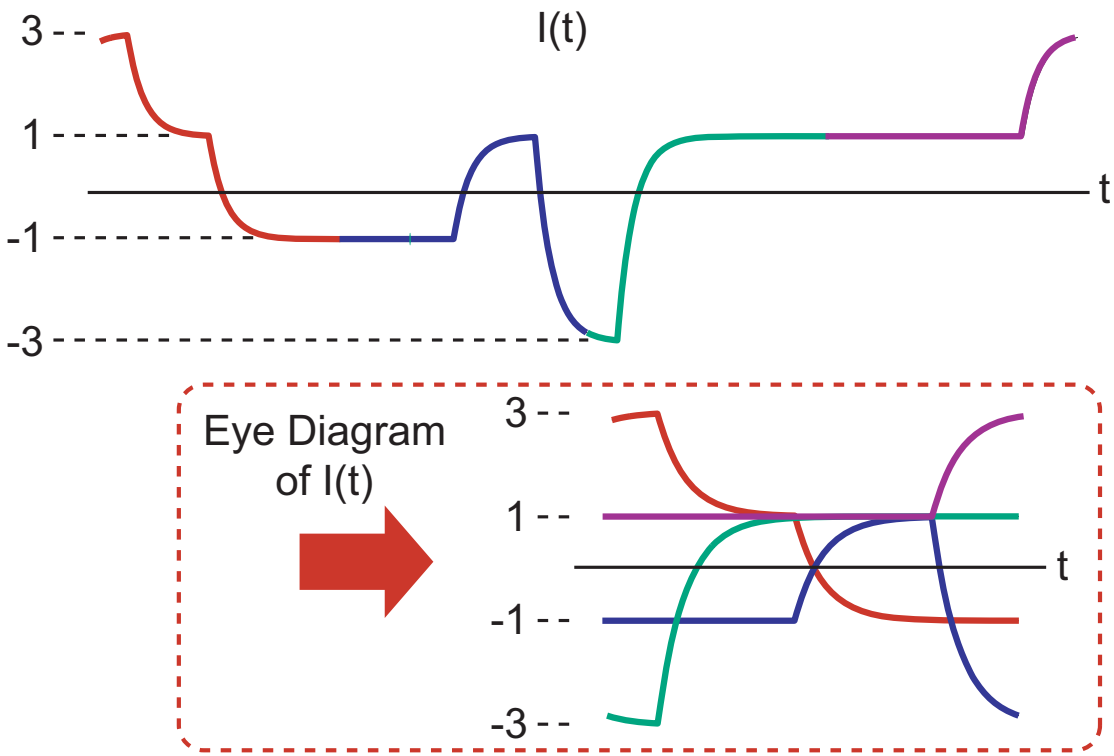
- Transmit filter enables reduced bandwidth for transmitted spectrum
- Issue: can lead to *intersymbol interference (ISI)*
  - Constellation diagram displays vulnerability to making bit errors

Impact of Low Bandwidth Transmit Filter



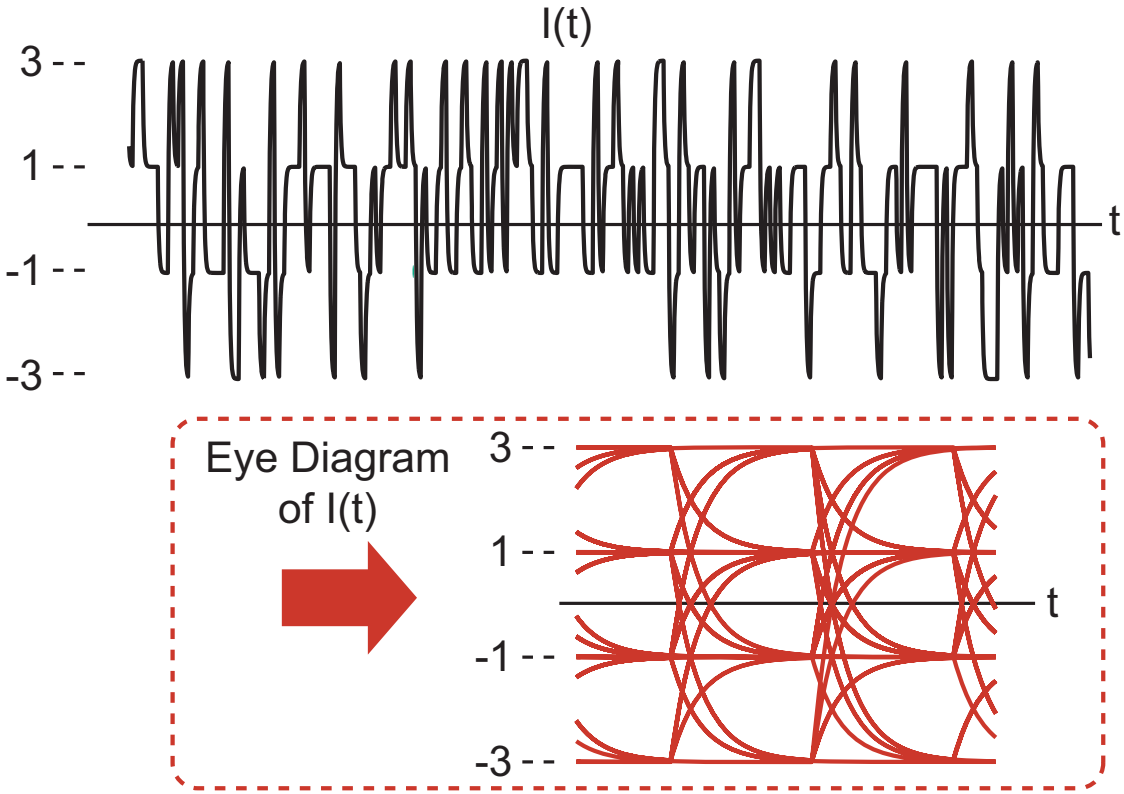
- Lowering the transmit filter bandwidth leads to
  - Lower bandwidth transmitted spectrum
  - Increased ISI
- Eye diagrams allow ISI to be intuitively examined

Eye Diagrams



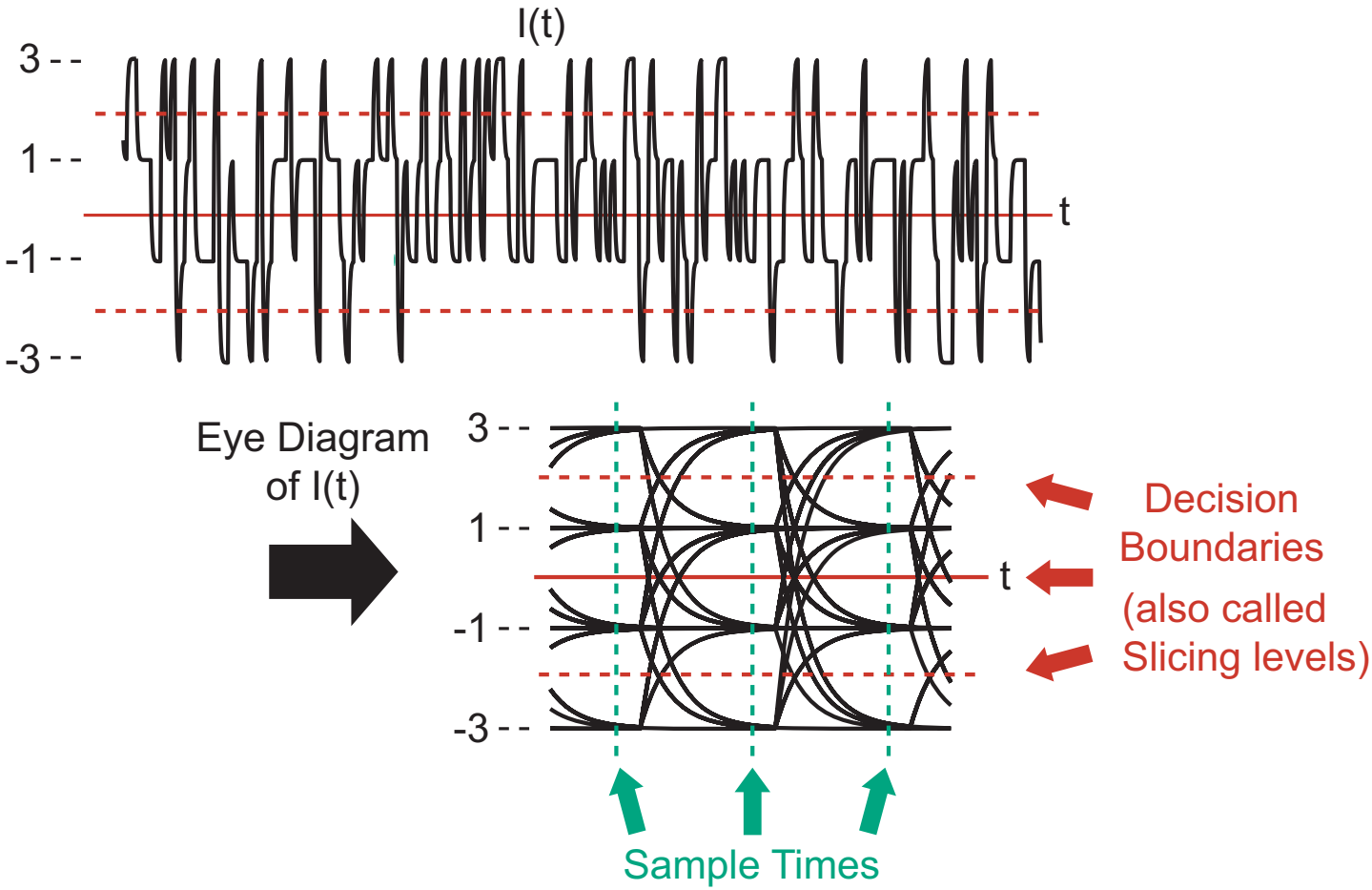
- **Key idea: wrap signal back onto itself in periodic time intervals and retain all traces**
  - **Similar to action of oscilloscope**

Looking at Many Symbols



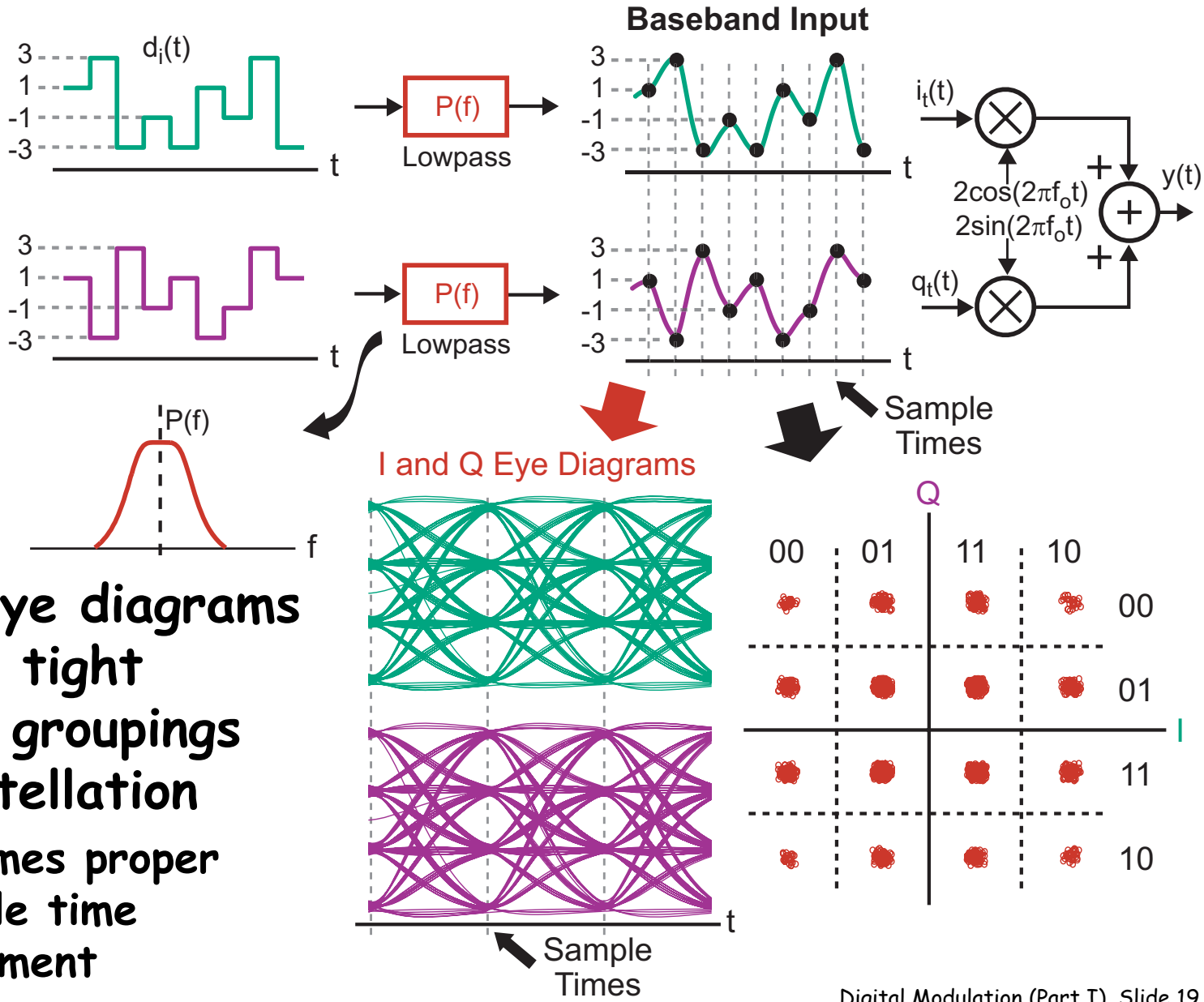
- Increasing the number of symbols eventually reveals all possible symbol transition trajectories
  - Intuitively displays the impact of filtering on ISI

Assessing the Quality of an Eye Diagram



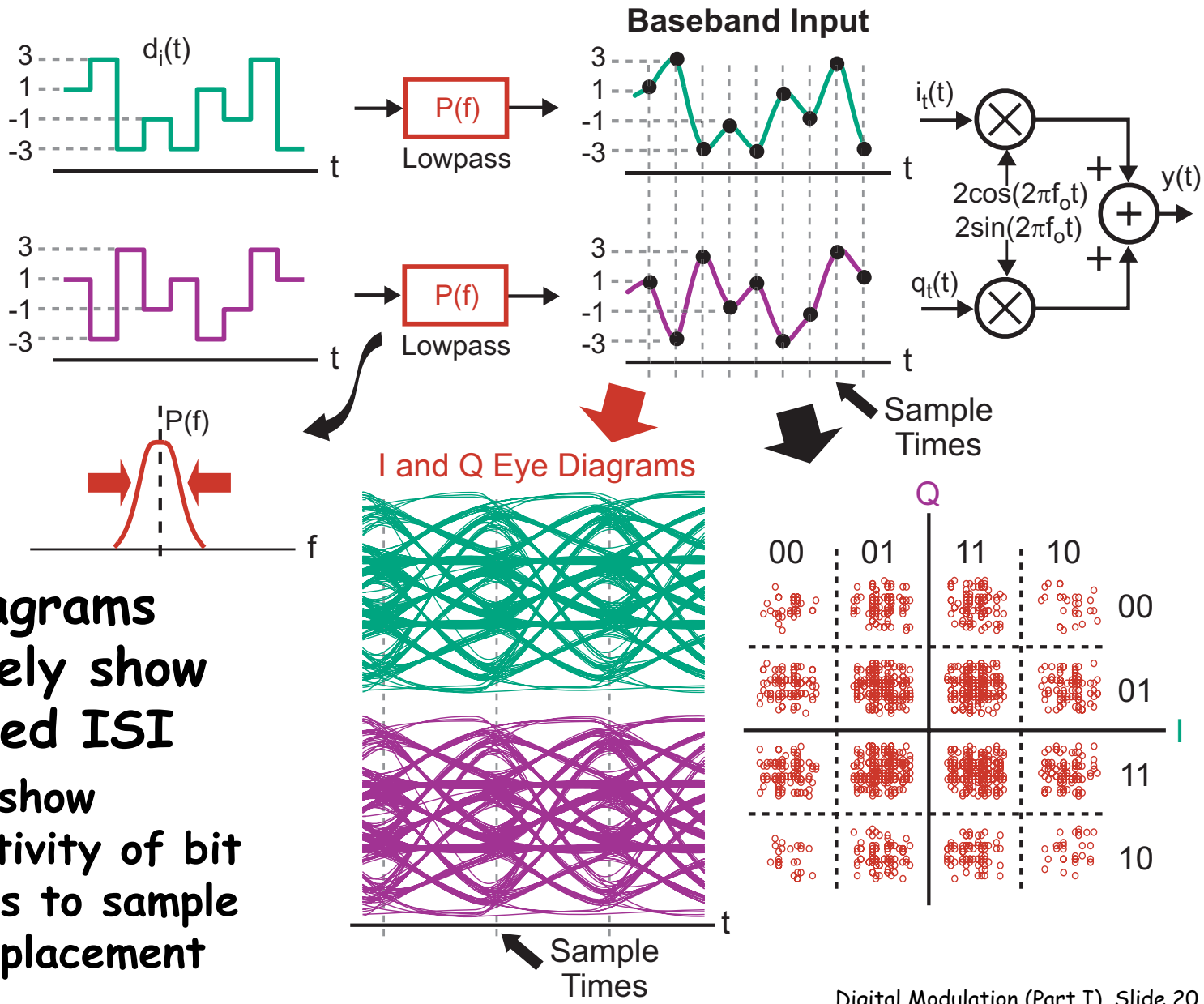
- Eye diagram allows visual inspection of the impact of sample time and decision boundary choices
  - Large *eye opening* implies less vulnerability to symbol errors

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…