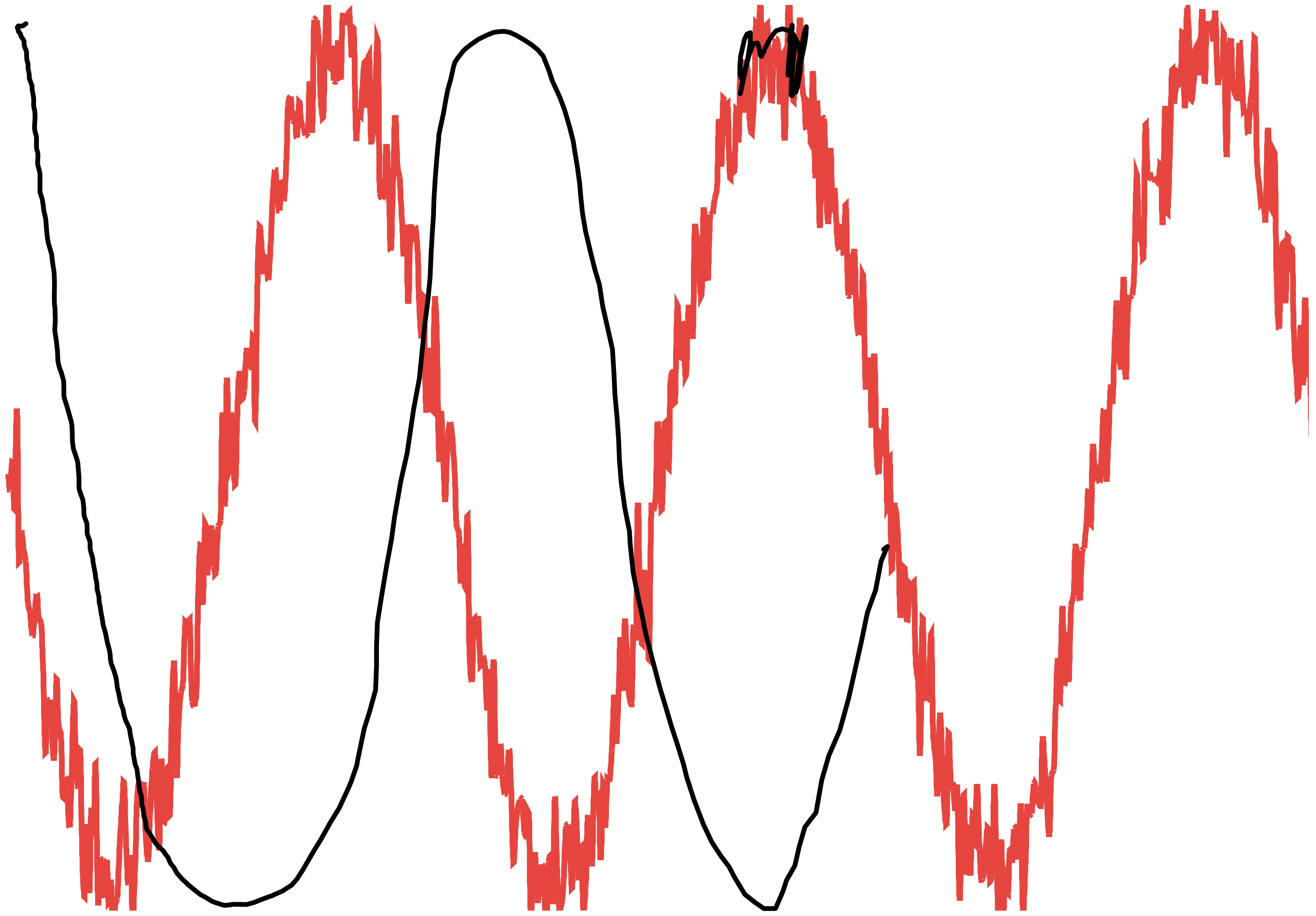
Physical Layer: Bit Errors and Coding

Signal to Noise Ratio (SNR)

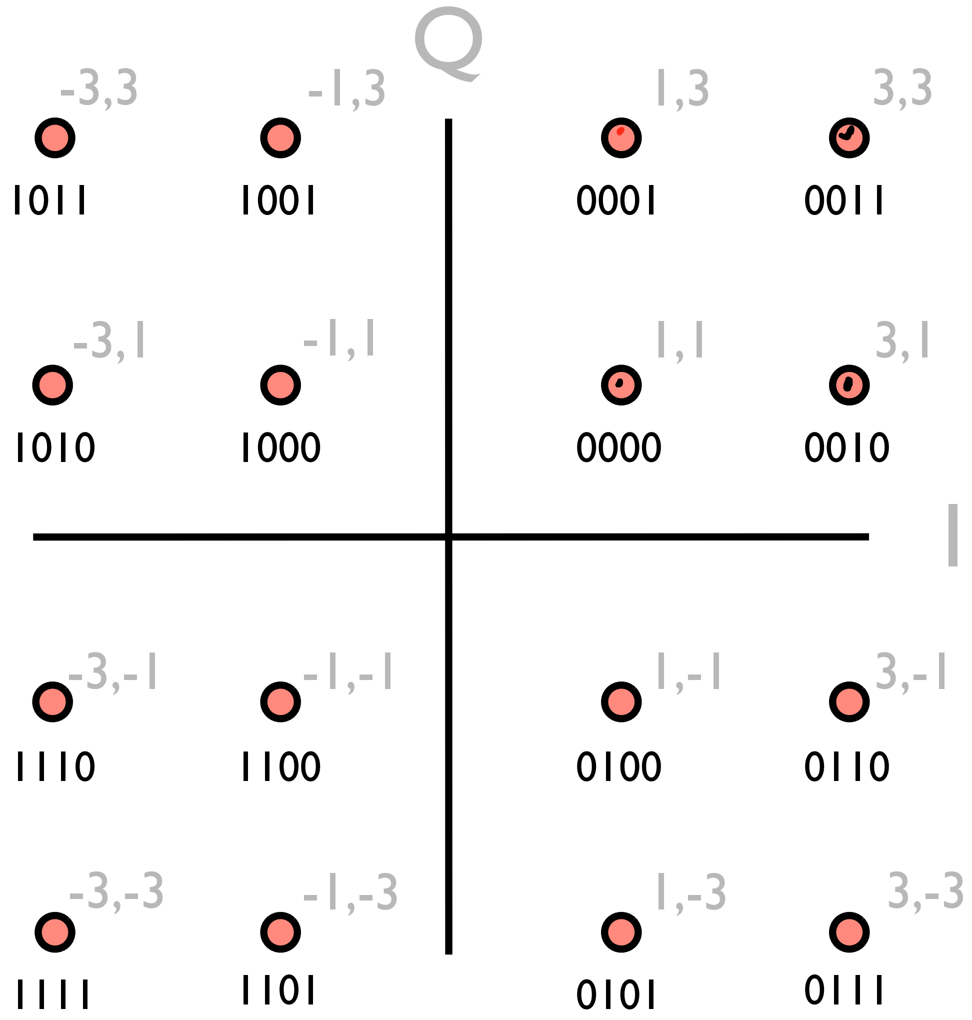
- Shannon limit = $B \log_2(1 + S/N)$
- B is Bandwidth, S is Signal strength, N is Noise
  - Possible data rate bounded by the signal to noise ratio (SNR)
  - Just a limit! Don't necessarily know how to achieve it
  - Bandwidth typically fixed
- Stronger signal means you can transmit data faster
  - Shorter symbols
  - More bits per symbol (denser constellation)

Signal with Noise

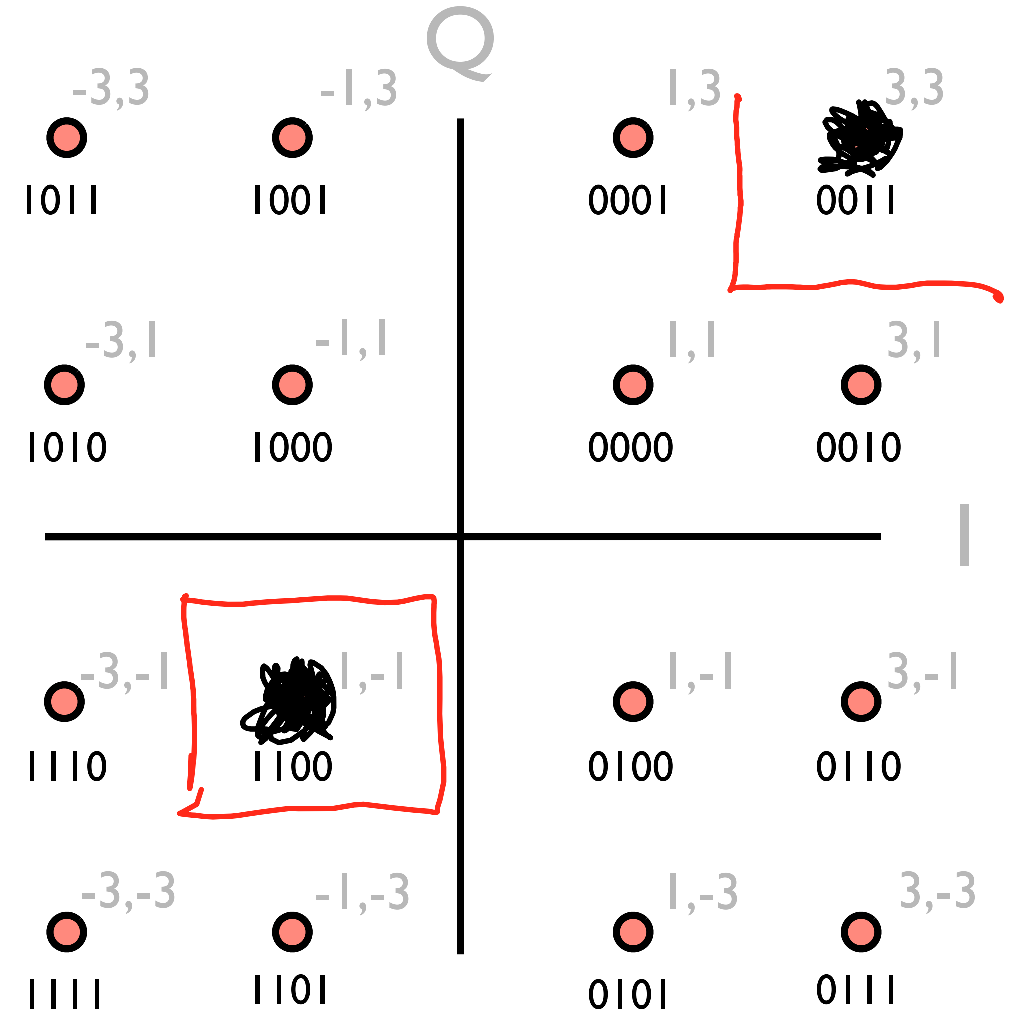


Example: 16-QAM

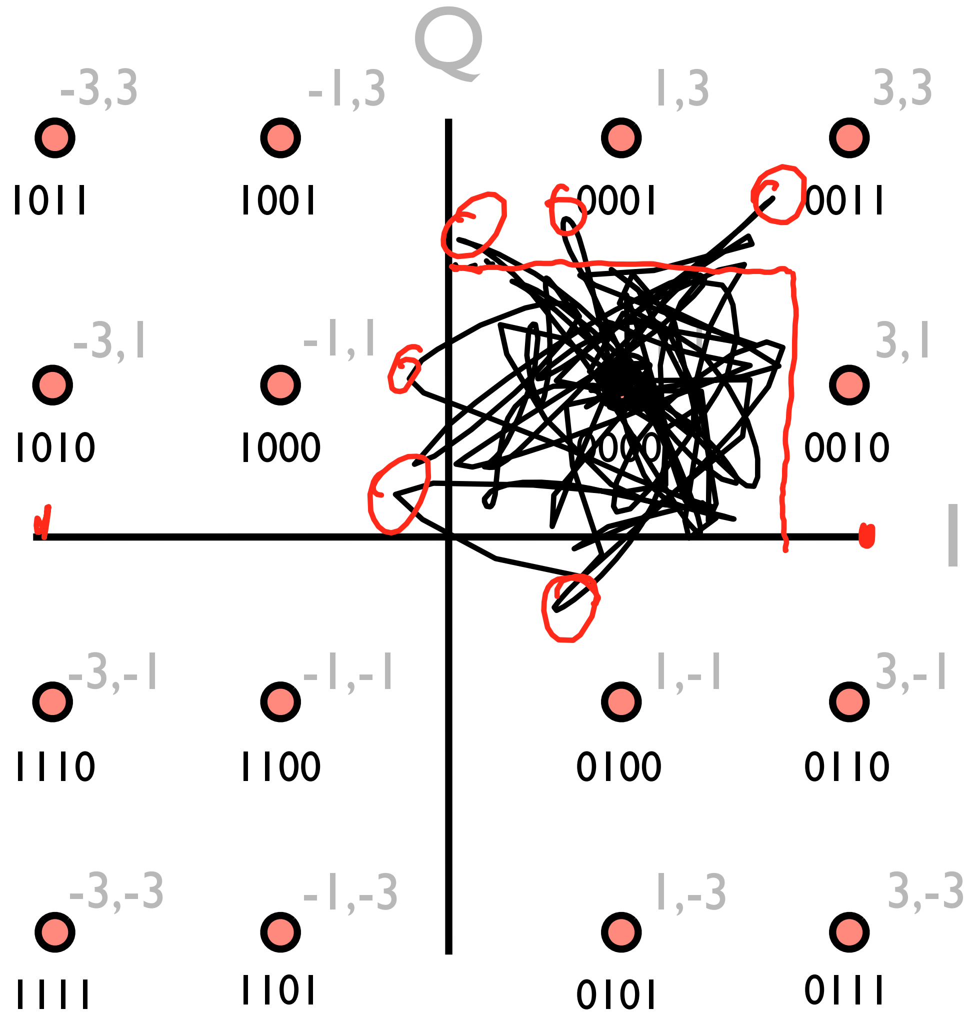
(constellation used in HSPDA)



Low-Noise Reception

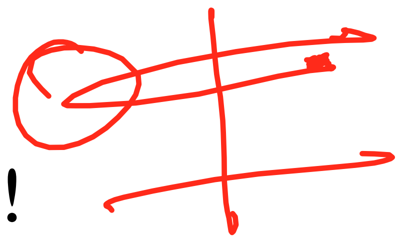


High Noise Reception



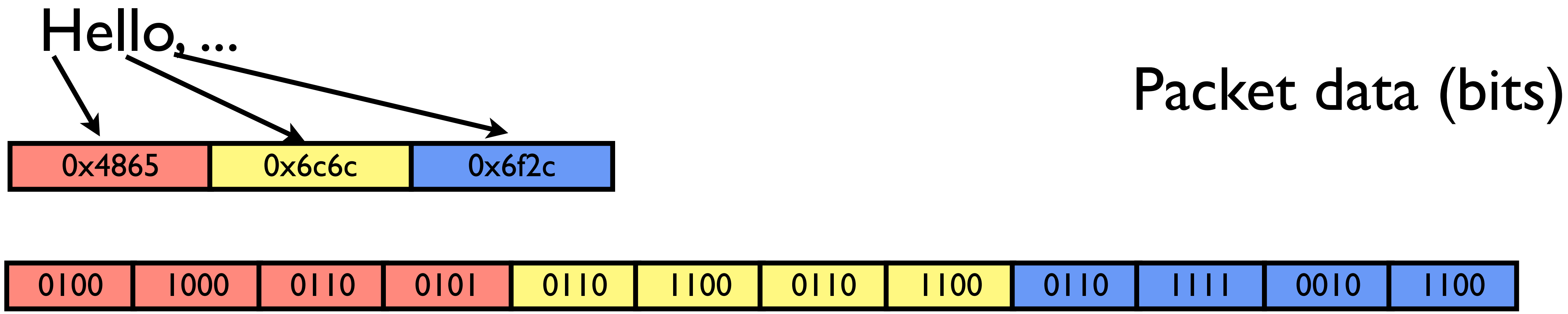
SNR/BER Curves

- For a given modulation scheme and signal-to-noise ratio, you can compute the expected bit error rate
  - Making some mathematical assumptions about noise
  - Bedrock principle of RF communication theory
- Bit error rate can become arbitrarily low, but never reaches zero!

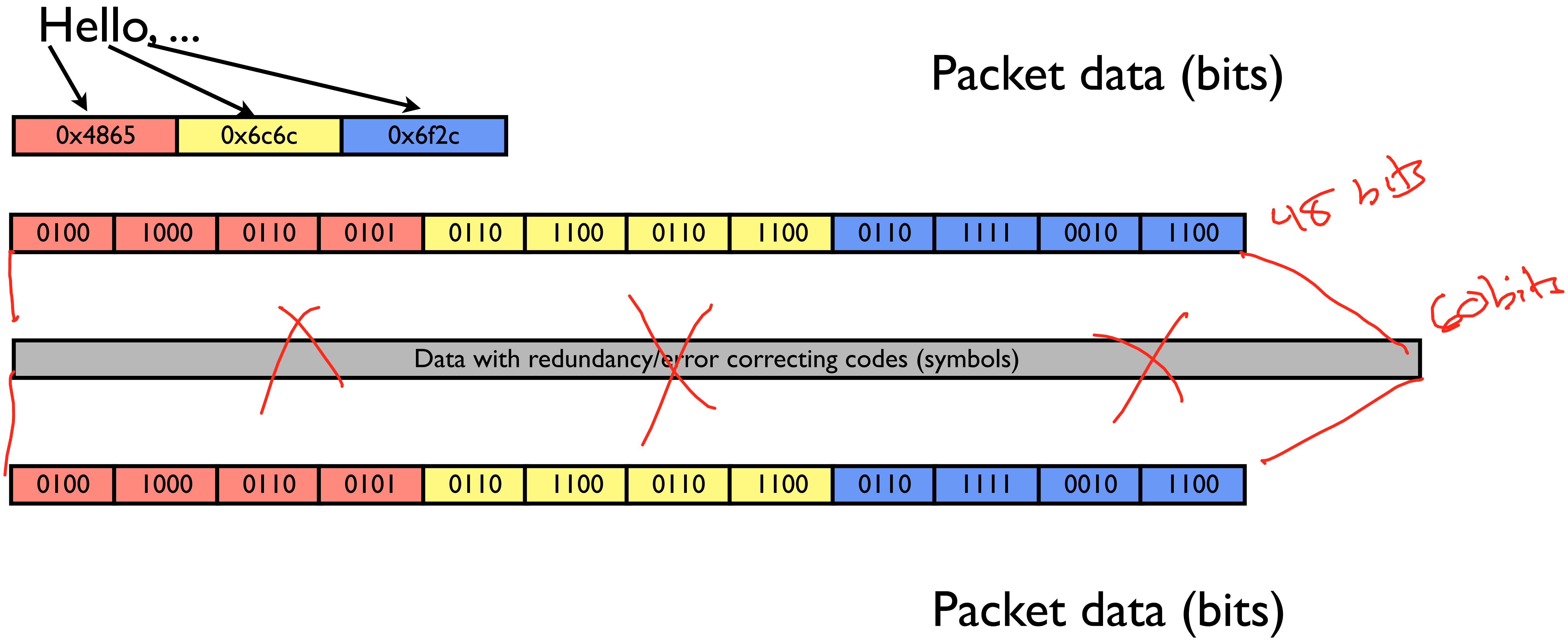


- In practice, the math works out that sending packets as raw bits is very inefficient
  - Expected data throughput is far, far below Shannon limit

Bits vs. Symbols



Bits vs. Symbols



Coding

- Adding a little redundancy at the physical layer can greatly improve link layer throughput
  - Both in theory and in practice
- *Coding gain*: the ratio of bits at link layer to bits at physical layer
  - 1/2 code: each link layer bit is 2 physical layer bits
  - 3/4 code: each 3 link layer bits are 4 physical layer bits

n bits

2n bits

3n bits

4n bits

Example: 802.15.4 (QPSK)

Zigbee

Symbols: Bits	Chips
0000	1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0
0001	1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0
0010	0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0
0011	0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1
⋮	
1111	1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0

4 bits 2^4

16 chips (QPSK symbols)

Calculating Data Rate

bitrate = bits/symbol * symbol rate * coding rate

Example: 802.15.4

Bitrate: 250kbps

Coding rate: 16 chips of 2 bits = 4 bits

32 bits → 4

1/8 code

8 · 250 kbps = 2 Mbps

1 Million symbols/s

1 μs

Example: 802.11n

MCS Index	Spatial Streams	Modulation	Coding	Data Rate (Mbps) 20MHz Channel 800ns GI	20MHz Channel 400ns GI	40 MHz Channel 800ns GI	40 MHz Channel 400ns GI
0	1	BPSK	1/2	6.5	7.2	13.5	15.0
1	1	QPSK	1/2	13.0	14.4	27.0	30.0
2	1	QPSK	3/4	19.5	21.7	40.5	45.0
3	1	16-QAM	1/2	26	28.9	54.0	60.0
4	1	16-QAM	3/4	39	43.3	81.0	90.0
5	1	64-QAM	2/3	52	57.8	108.0	120.0
6	1	64-QAM	3/4	58.5	65.0	121.5	135.0
7	1	64-QAM	5/6	65	72.2	135.0	150.0

Overview

- Chips (physical layer) versus bits (link layer)
- Physical layer must deal with noise, which can cause chip errors
  - Denser modulation provides higher throughput
  - Sparser modulation has fewer errors
- Translating between link layer bits and physical layer bits
  - 1:1 mapping is rarely the most efficient data representation
  - Coding gain: L2/L1 ratio, so can be robust to some chip errors
- Example: 802.11n