CS6458
Systems for programmable optical interconnects

Lecture 3

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How many bits can a signal carry?

Hartley's Law:

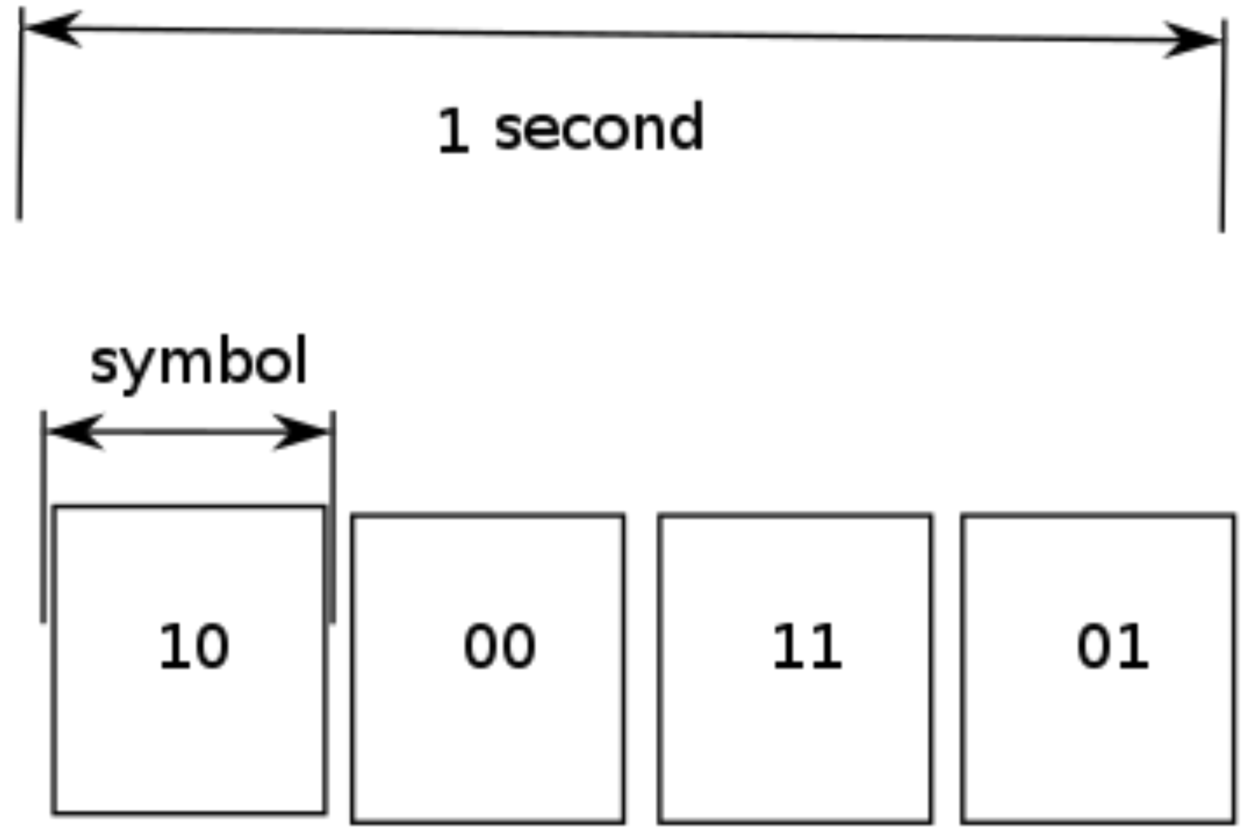
$R = f_p log_2 M$

Where,

R = data rate, bit rate in bits/second

f_p = symbol rate or baud rate in symbols/second

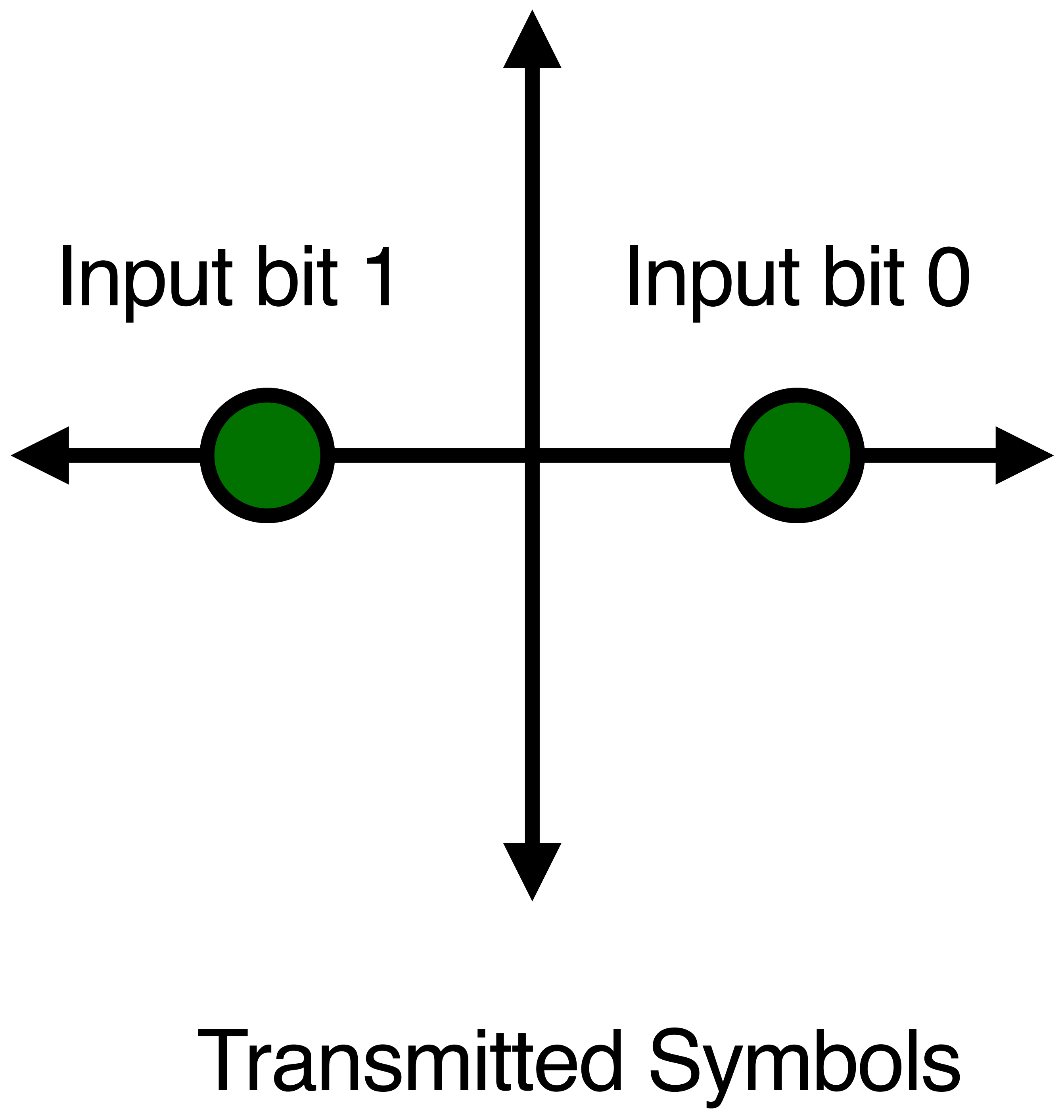
M = number of levels in a given symbol



Baud rate = 4, N = 2

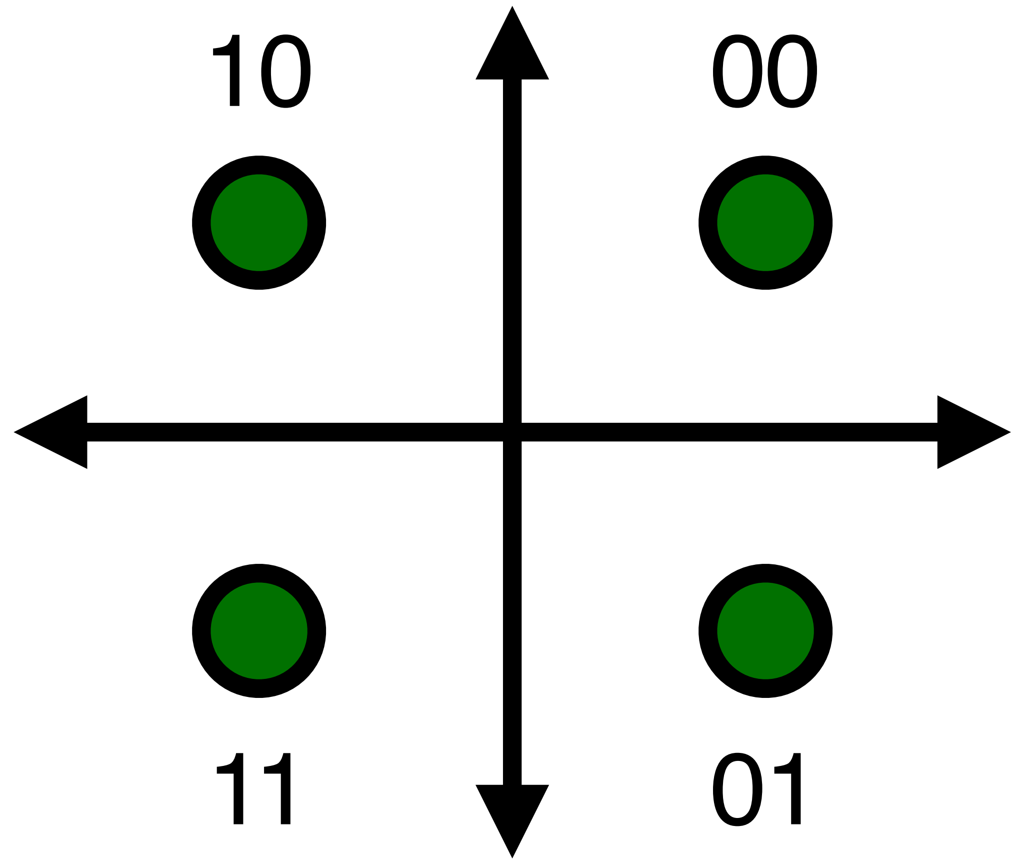
Example signal modulation

1. Simple modulation format:
    1. One symbol to represent “1”
    2. One symbol to represent “0”
2. Modify the phase of the signal to encode
    1. Phase = 0 to encode input bit 0
    2. Phase = 180 to encode input bit 1
3. This modulation is called *binary phase shift keying (BPSK)*
4. Number of bits encoded per symbol $N = log_2 M$
    1. *BPSK* encodes 1 bit per symbol



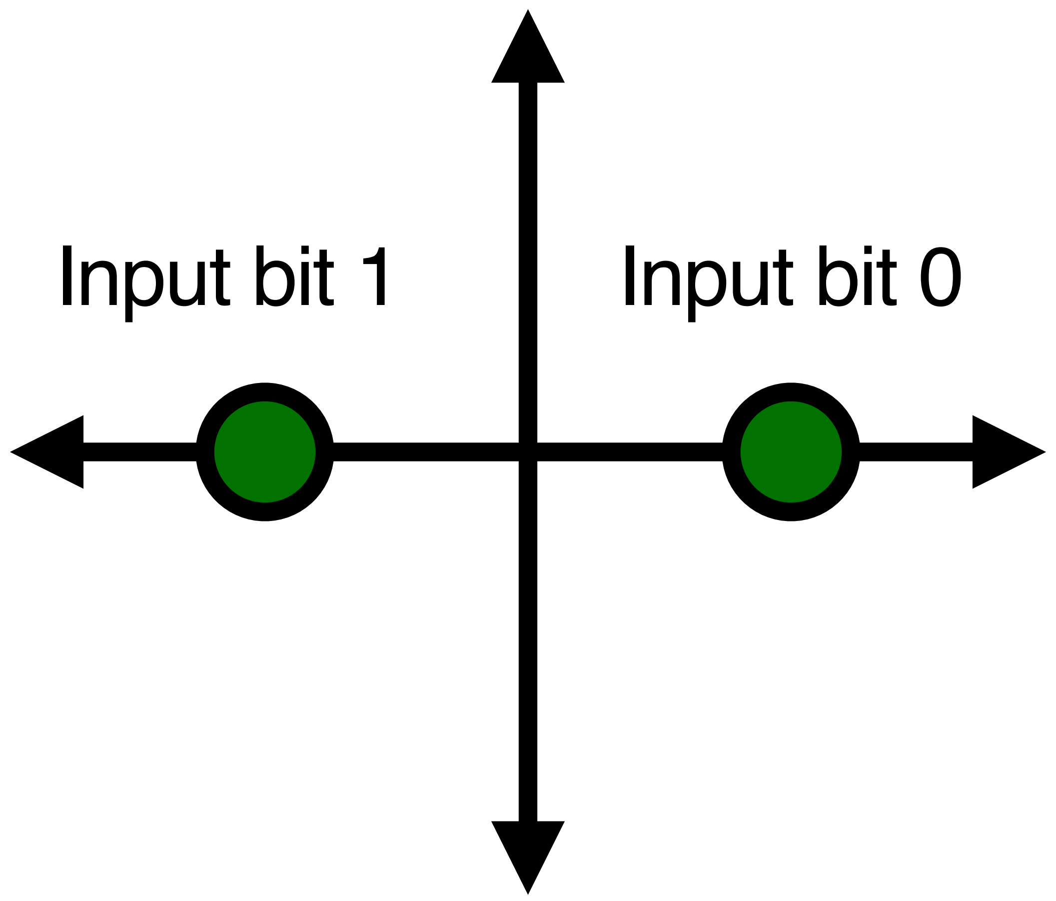
Example signal modulation

1. Quadrature phase shift keying (QPSK)
   1. Four symbols
   2. 2 bits per symbol



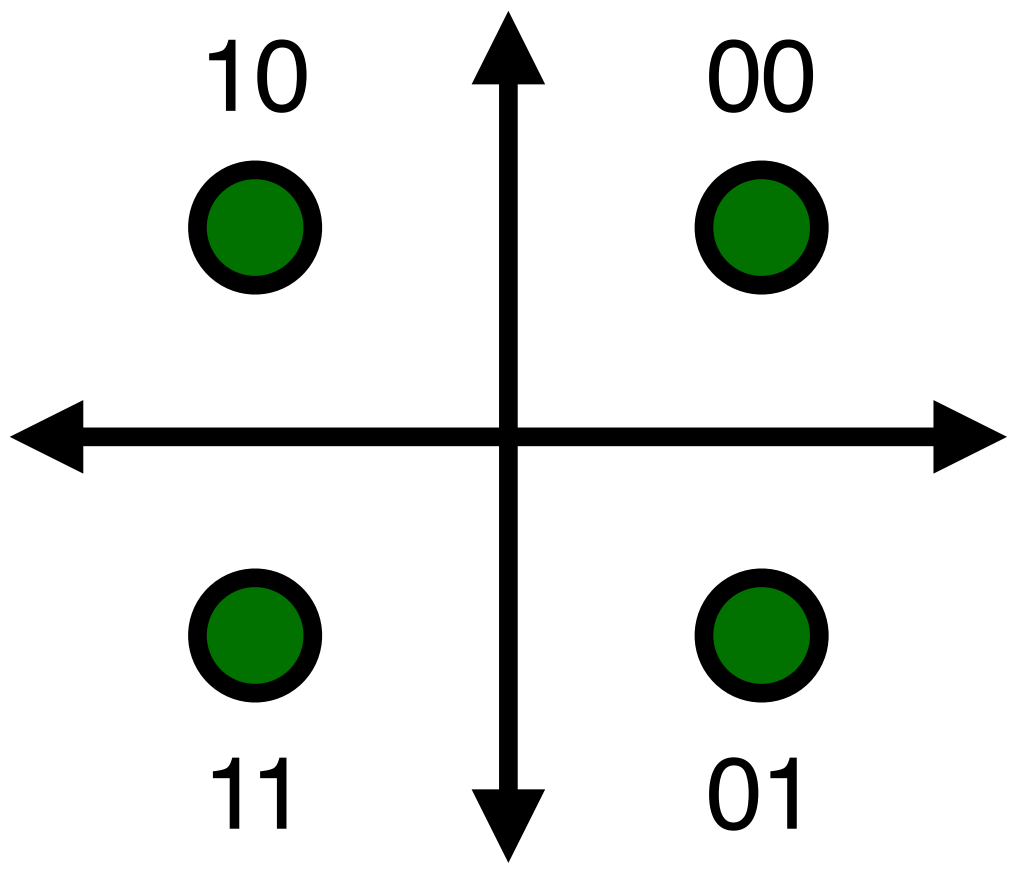
Transmitted Symbols

Signal modulation



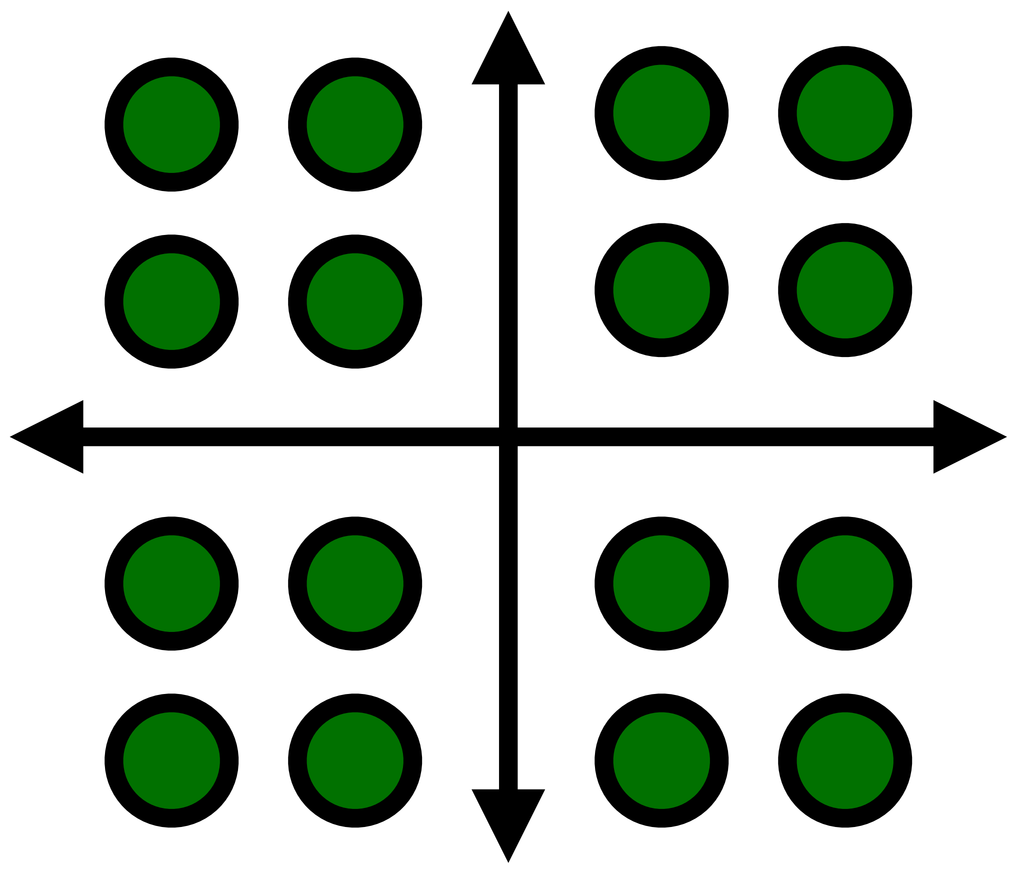
BPSK

1 bit per symbol



QPSK

2 bits per symbol



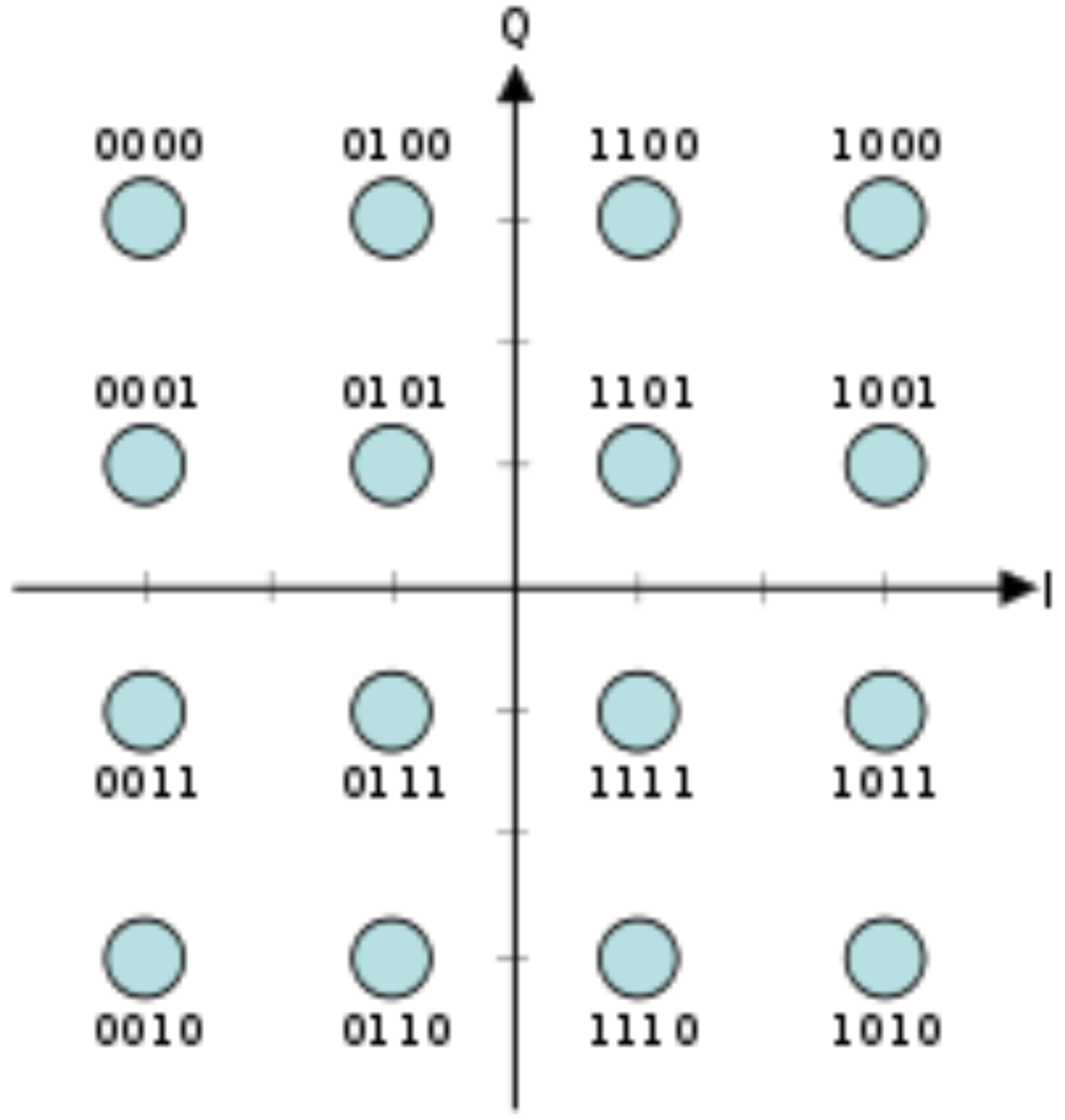
16-QAM

4 bits per symbol

Packing more bits per symbol with different modulation formats

Exercise: signal modulation

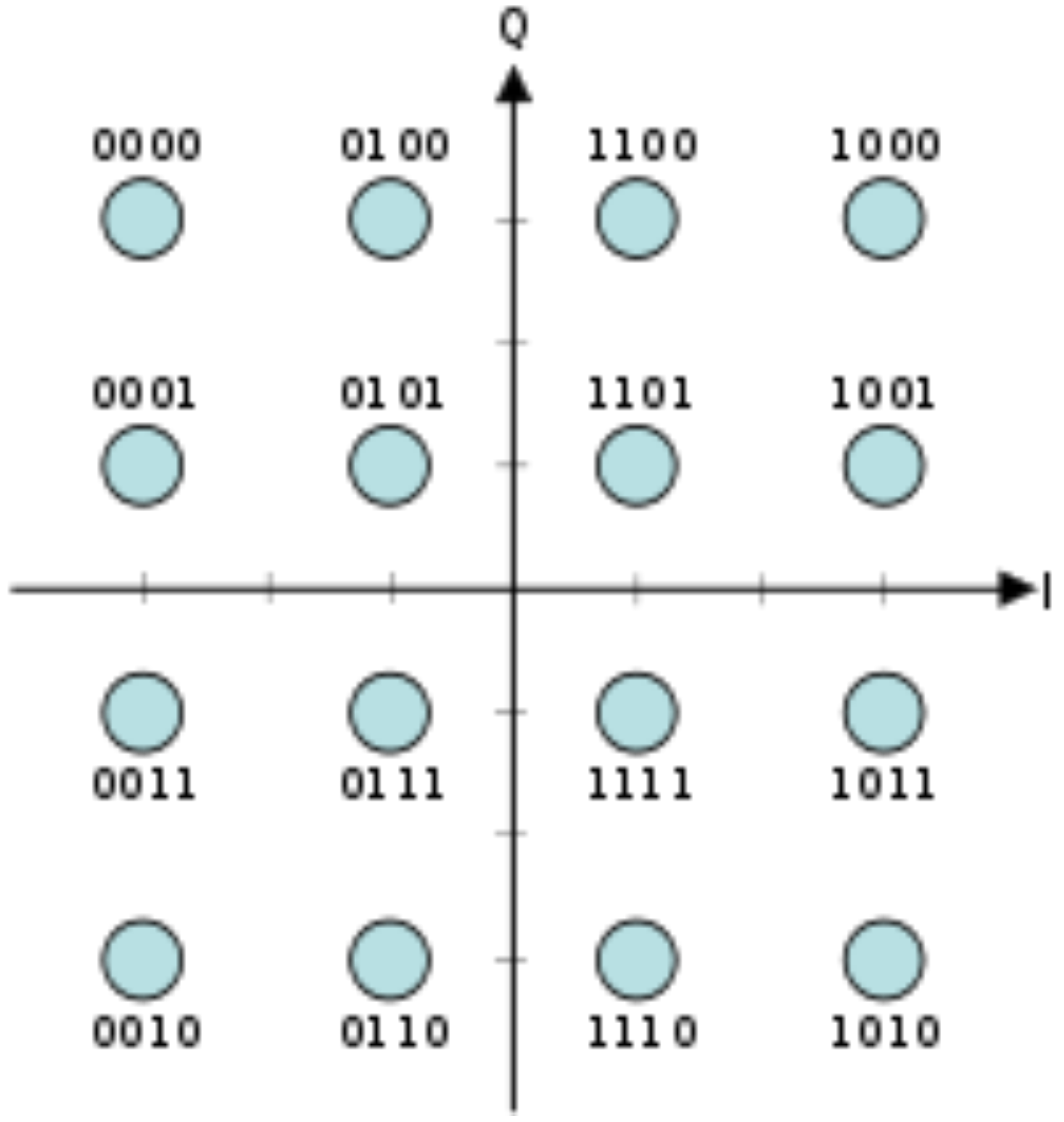
QAM: quadrature amplitude modulation uses a mix of different amplitude levels and phase shifts to create different symbols (see right).



Constellation Diagram of 16-QAM

Exercise: signal modulation

QAM: quadrature amplitude modulation uses a mix of different amplitude levels and phase shifts to create different symbols (see right).



Constellation Diagram of 16-QAM

Exercise: If the baud rate of the transmission is 50 Gbaud, what is the data rate of a wavelength modulated with 16-QAM modulation?

Exercise: signal modulation

QAM: quadrature amplitude modulation uses a mix of different amplitude levels and phase shifts to create different symbols (see right).

Hartley's Law

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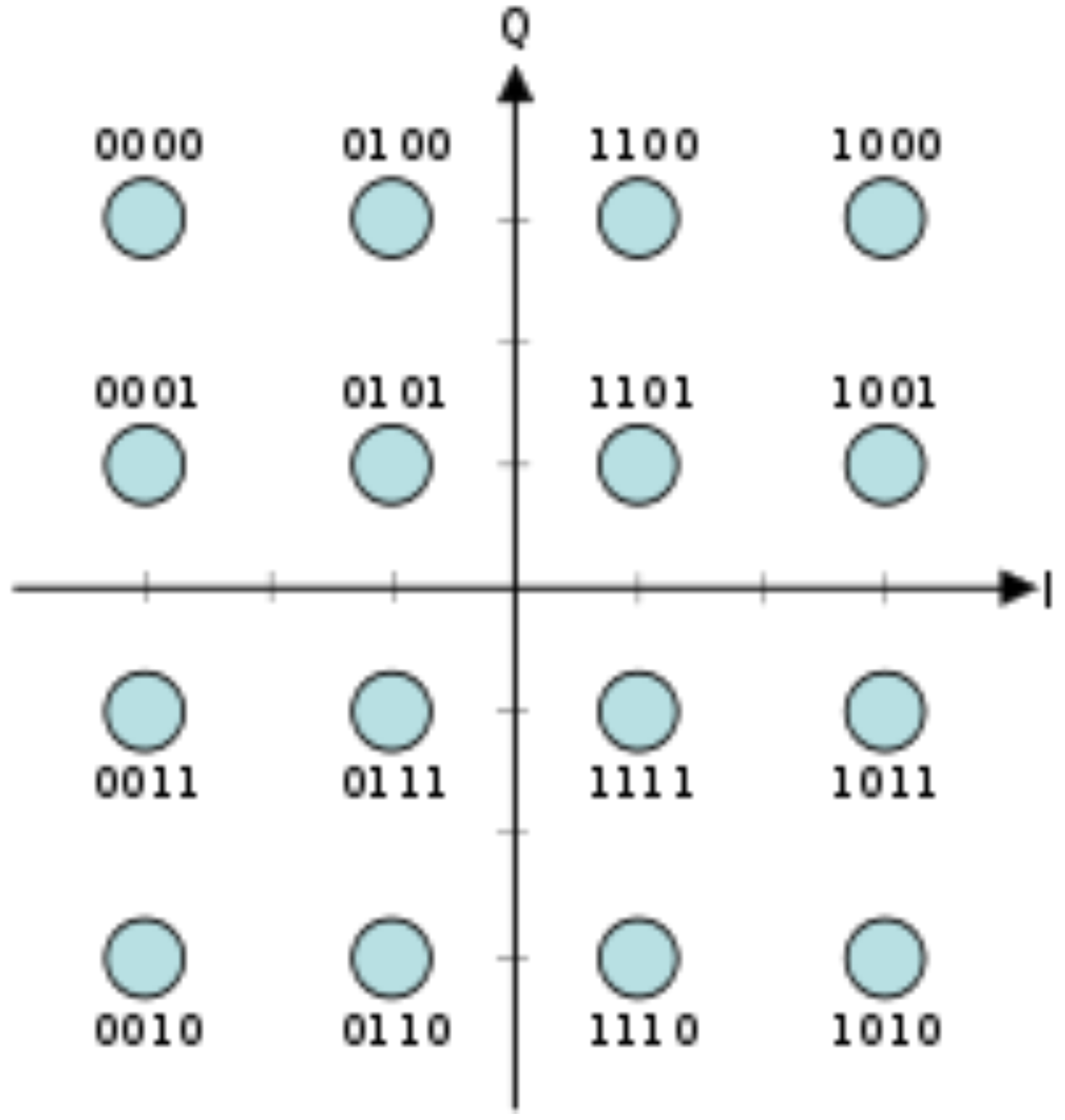


Constellation Diagram of 16-QAM

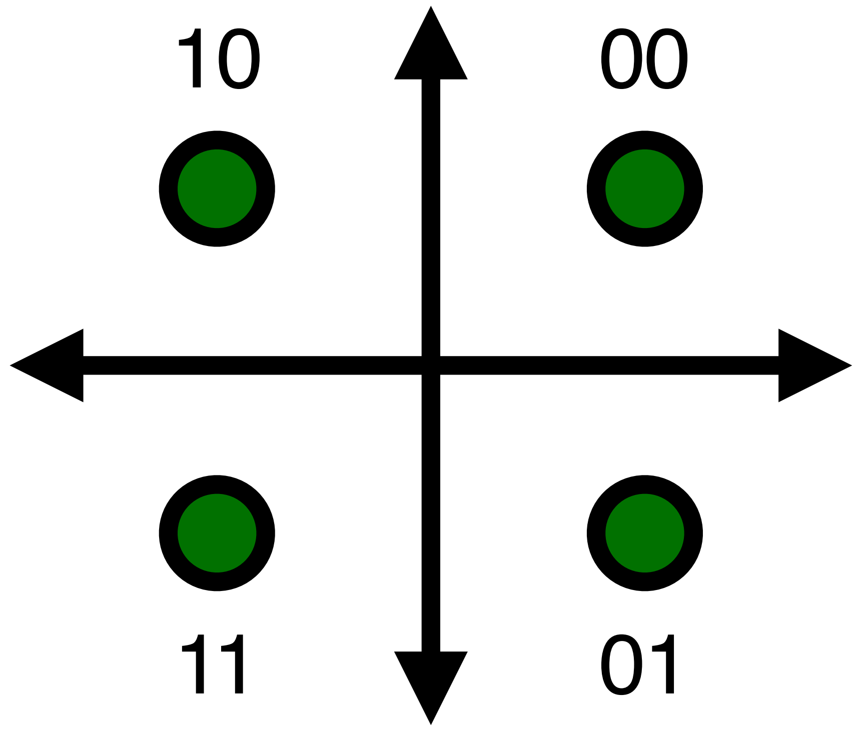
Exercise: If the baud rate of the transmission is 50 Gbaud, what is the data rate of a wavelength modulated with 16-QAM modulation?

Hint: 16-QAM has 16 levels per symbol

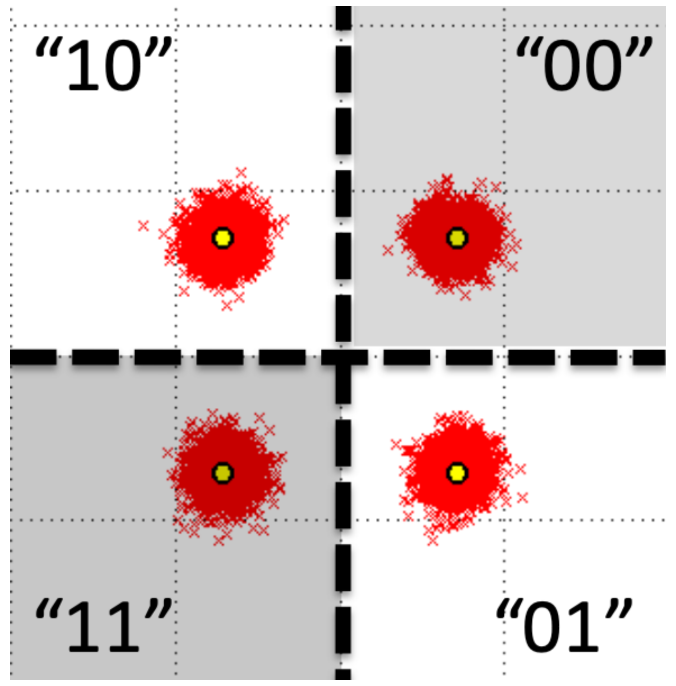
$Answer = 50 * log_2 16 = 200 Gbps$

Noisy channels

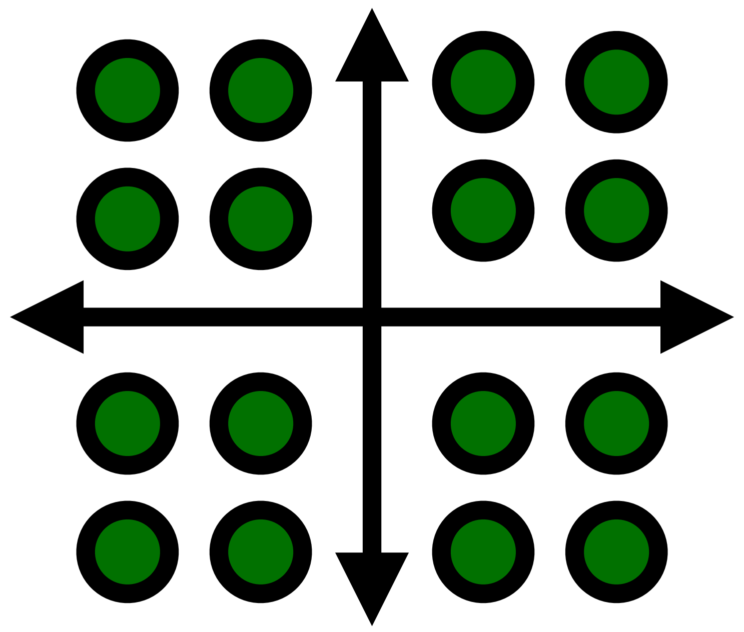
1. All media add some noise to the signal
    1. Fiber adds noise to the transmitted signal
    2. The received symbols are a result of the transmission + noise
2. Sustaining a modulation format for transmission
    1. Depends on the noise in the media
3. High noise => harder to decode bits from symbols



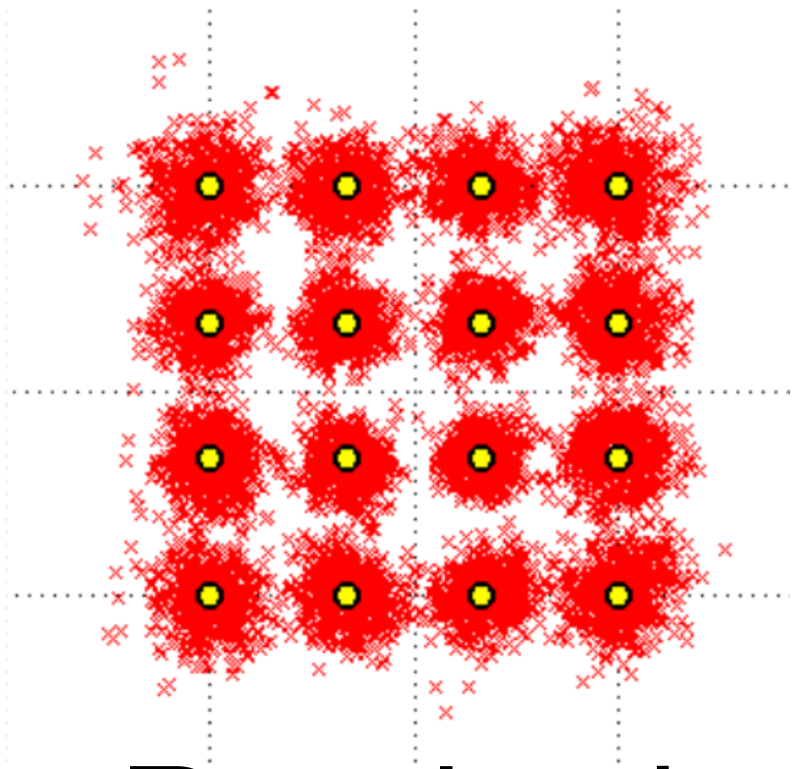
Transmitted



Received



Transmitted



Received

Channel noise

1. Hartley's law assumes an "error-less" channel
   - Computes an upper-bound on channel capacity
   - In reality, fiber adds noise
2. Signal-to-noise ratio
   - Measures the ratio of signal power to noise power in the channel
   - *Signal power* is the power of the data signal that encodes bits
   - *Noise power* is the power of the noise on fiber
   - $SNR = \frac{P_{signal}}{P_{noise}}$
3. SNR is often measured in decibels (dB): $SNR_{db} = 10log_{10}(SNR)$
   - $10log_{10}$ of a quantity makes the unit decibels

Shannon capacity

Shannon-Hartley Law states the max. rate at which information can be transmitted over a noisy channel

$$R = B \cdot log_2(1 + SNR)$$

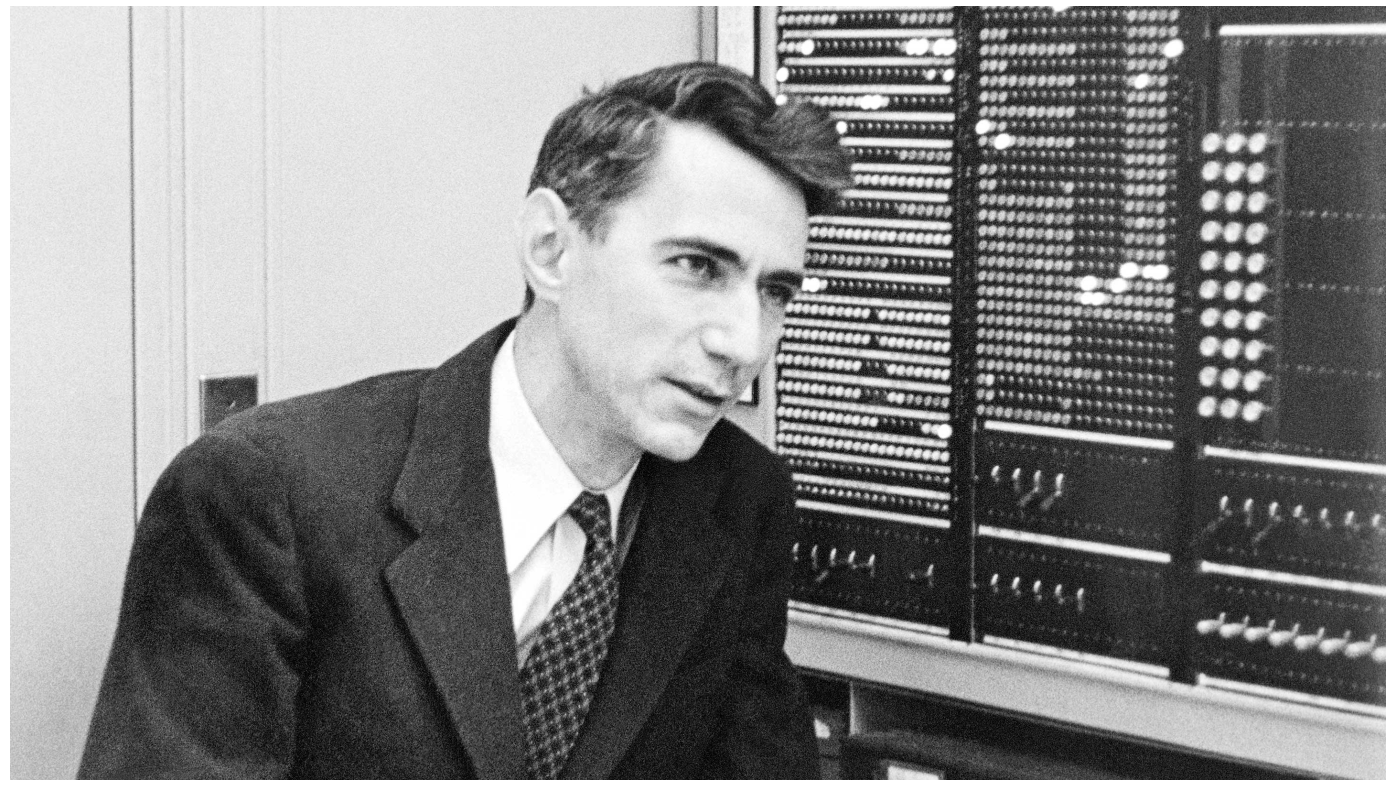
Where,

R = data rate, bit rate in bits/second

B = bandwidth in Hz of the channel

SNR = signal to noise ratio (measures signal quality)

$$R \approx 0.332 \cdot B \cdot SNR$$



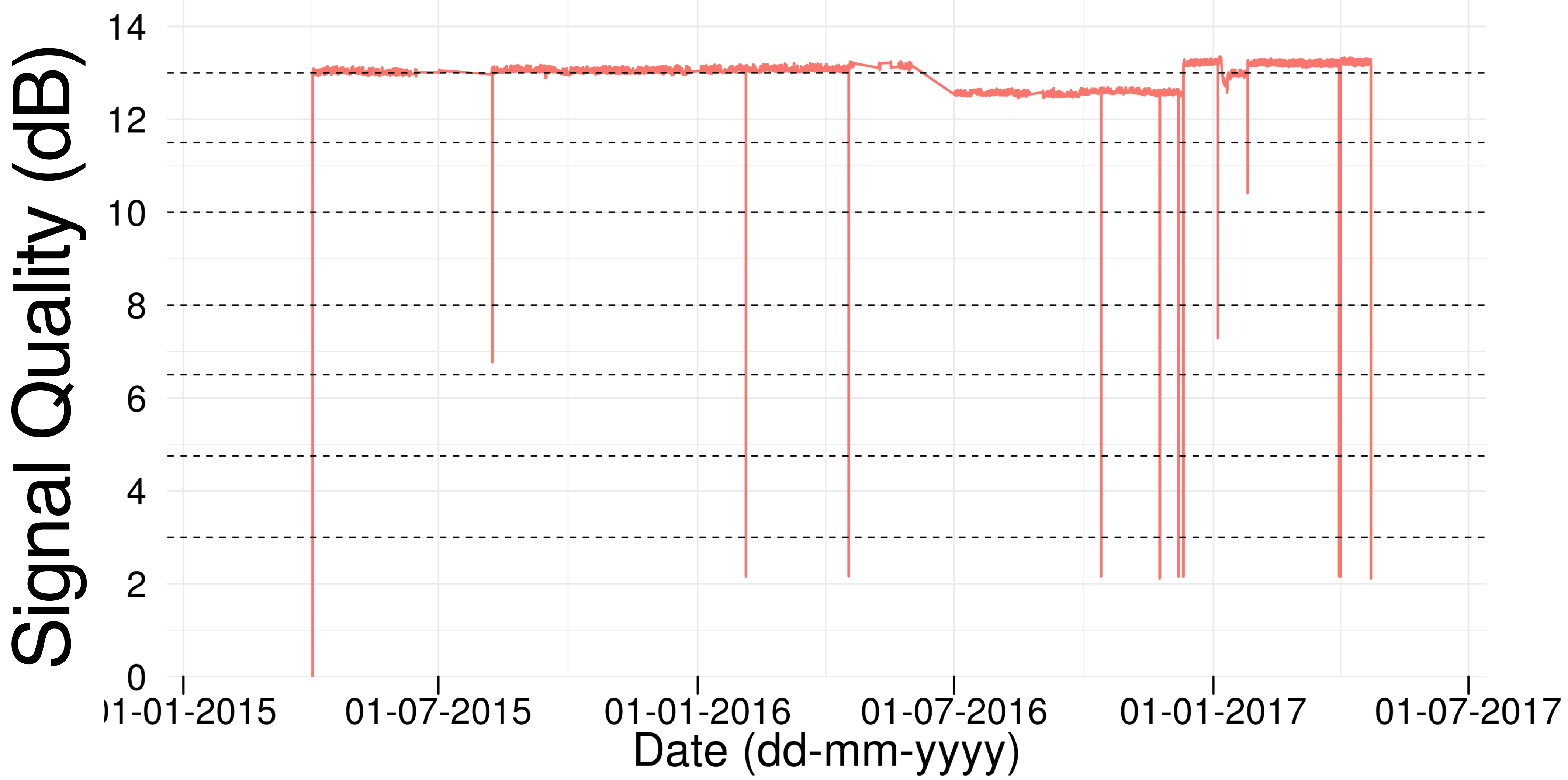
Claude Shannon

Shannon capacity

1. Shannon–Hartley Law
    1. $R \approx 0.332 \cdot B \cdot SNR$
2. Fundamental limit on the capacity of a channel
3. Cannot pack more bits by
    1. Increasing modulation format
    2. Increasing symbol rate

Signal quality

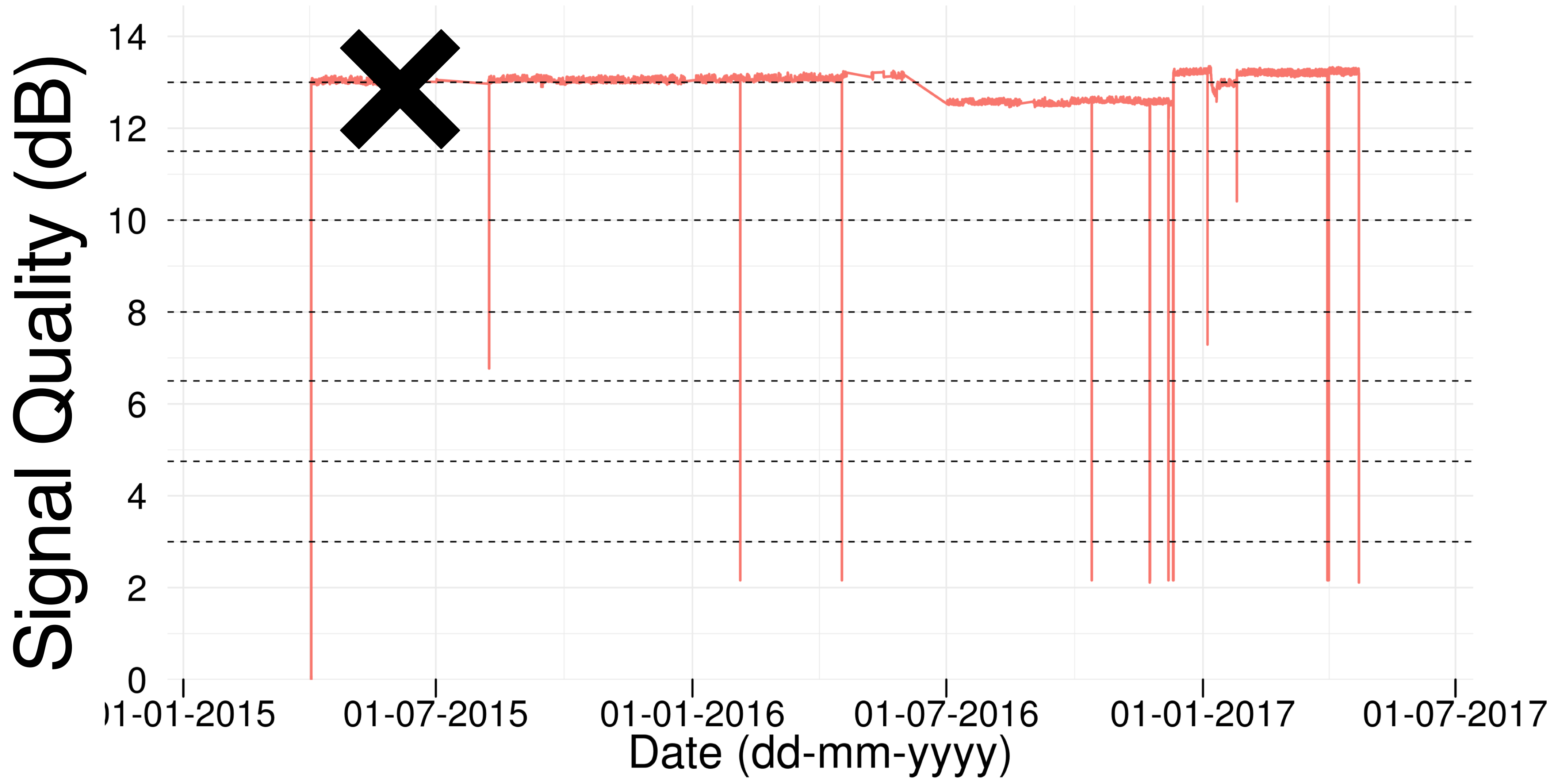
1. Measure signal quality on a fiber over time
2. Signal quality of a wavelength on fiber over time undergoes changes



Signal quality of a wavelength on fiber in North America

Shannon capacity

Exercise: What is the maximum data rate that could be supported by this wavelength at the time shown by the cross if the bandwidth of the wavelength is 50GHz?



$R \approx 0.332 \cdot B \cdot SNR$

$R \approx 0.332 \cdot 50 \cdot 13$

$= 215$ Gbps

$R = B \cdot log_2(1 + SNR)$

Where,

R = data rate, bit rate in bits/second

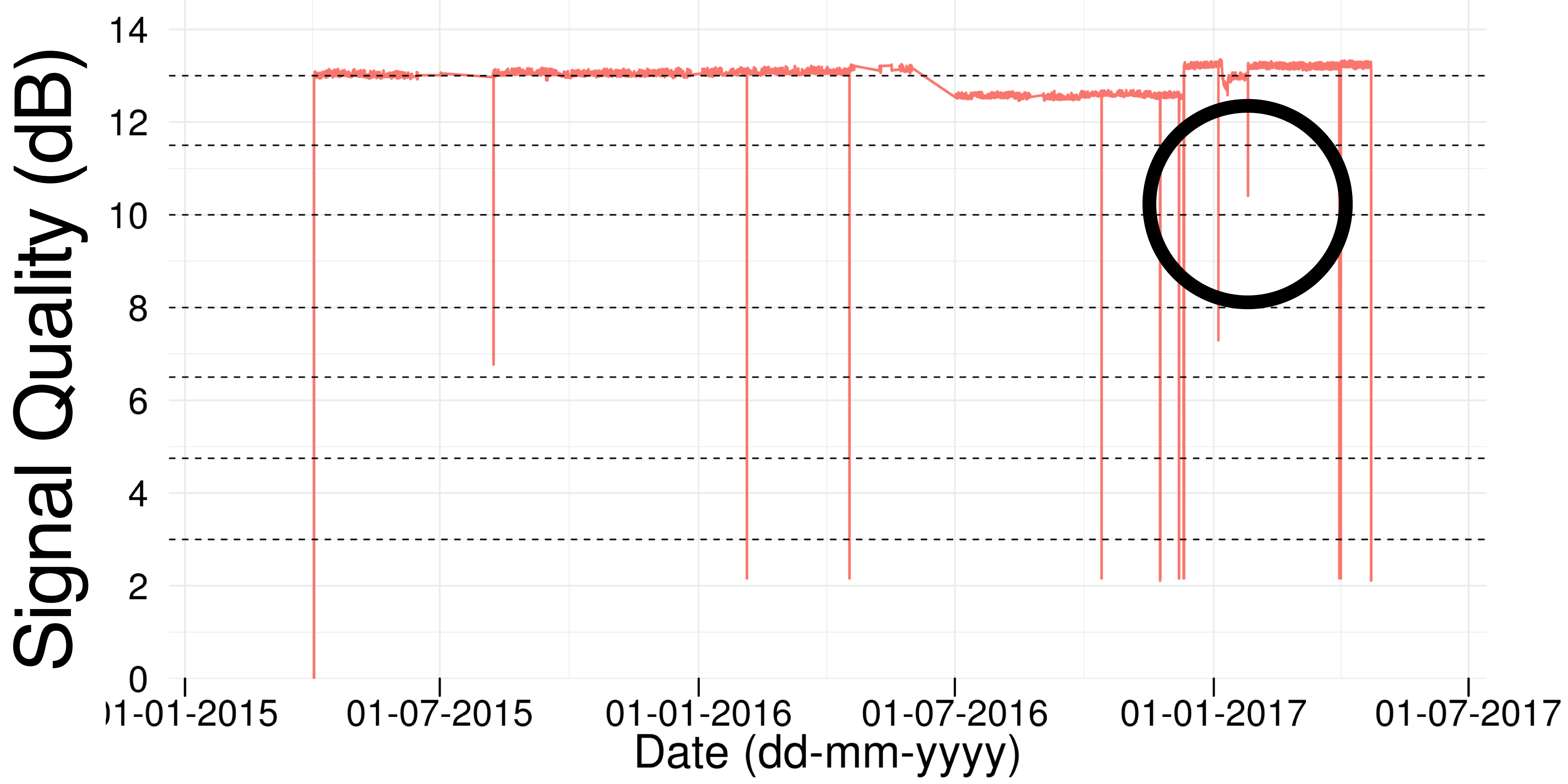
B = bandwidth in Hz of the channel

SNR = signal to noise ratio (measures signal quality)

$R \approx 0.332 \cdot B \cdot SNR$

Shannon capacity

Exercise: What is the maximum data rate that could be supported by this wavelength at the time shown by the cross if the bandwidth of the wavelength is 50GHz?



$R \approx 0.332 \cdot B \cdot SNR$

$R \approx 0.332 \cdot 50 \cdot 10$

$= 166$ Gbps

$R = B \cdot log_2(1 + SNR)$

Where,

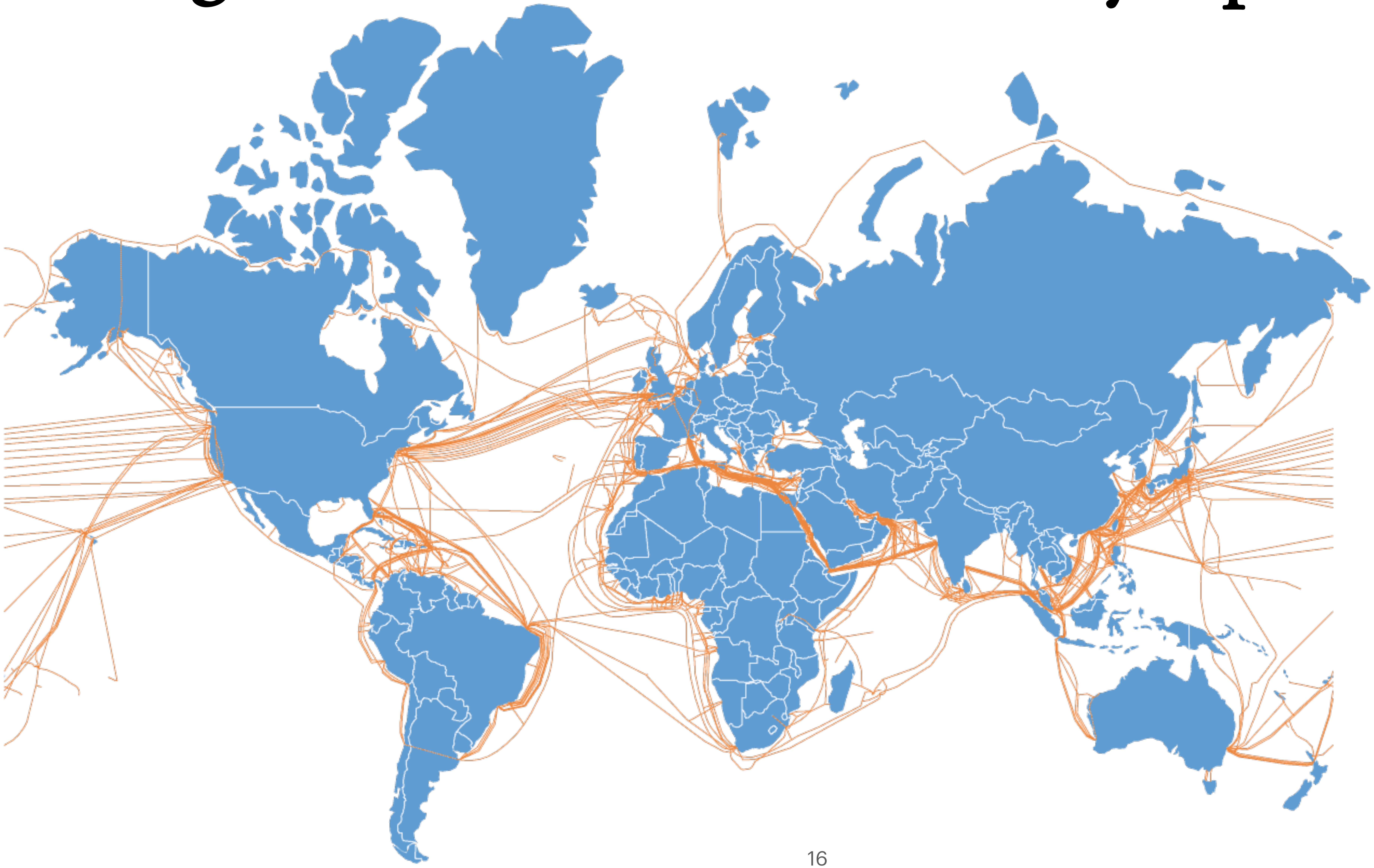
R = data rate, bit rate in bits/second

B = bandwidth in Hz of the channel

SNR = signal to noise ratio (measures signal quality)

$R \approx 0.332 \cdot B \cdot SNR$

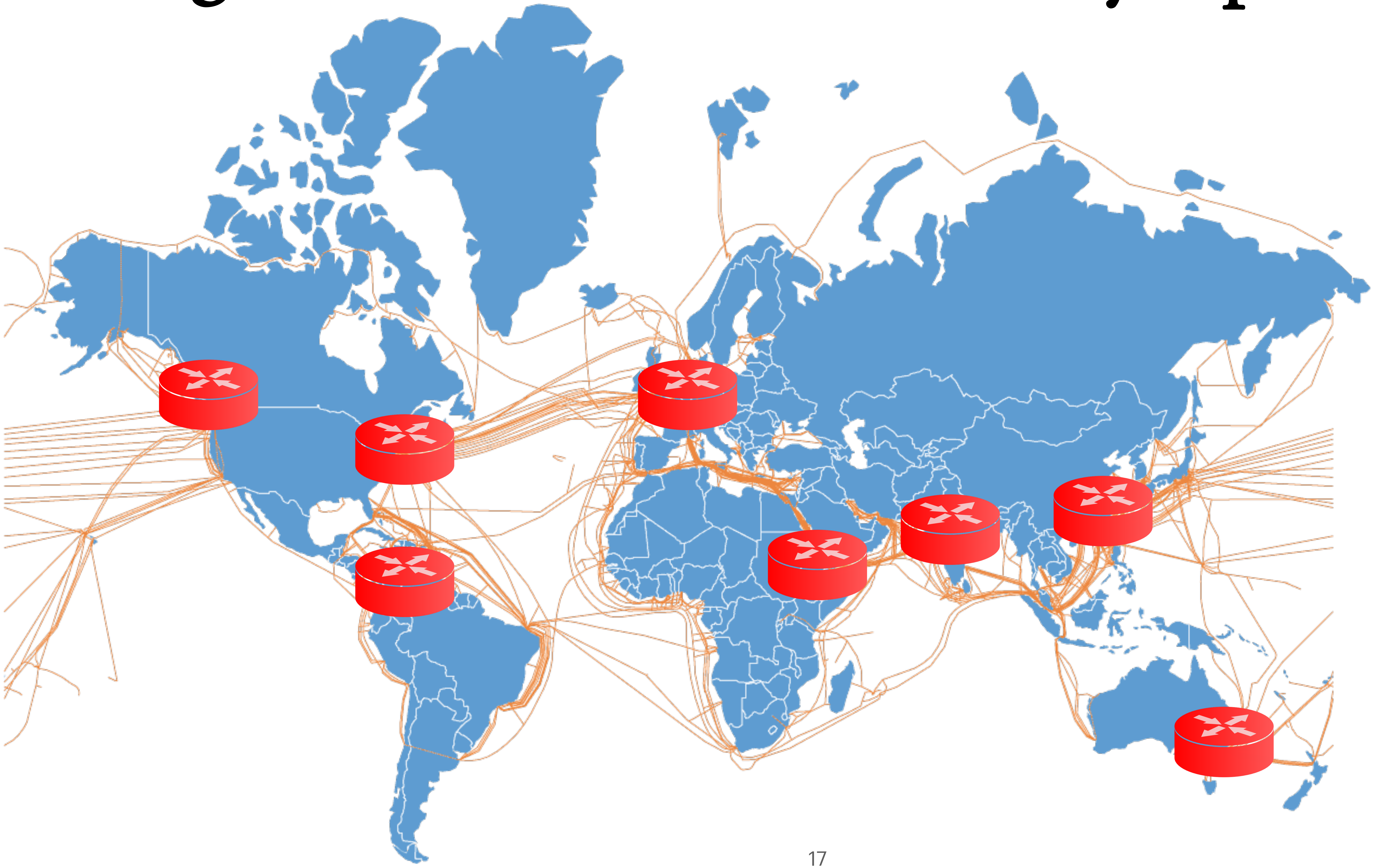
Long-haul network connectivity: optical fiber



Under-sea fiber

Terrestrial fiber

Long-haul network connectivity: optical fiber



Under-sea fiber

Terrestrial fiber