The Link Layer

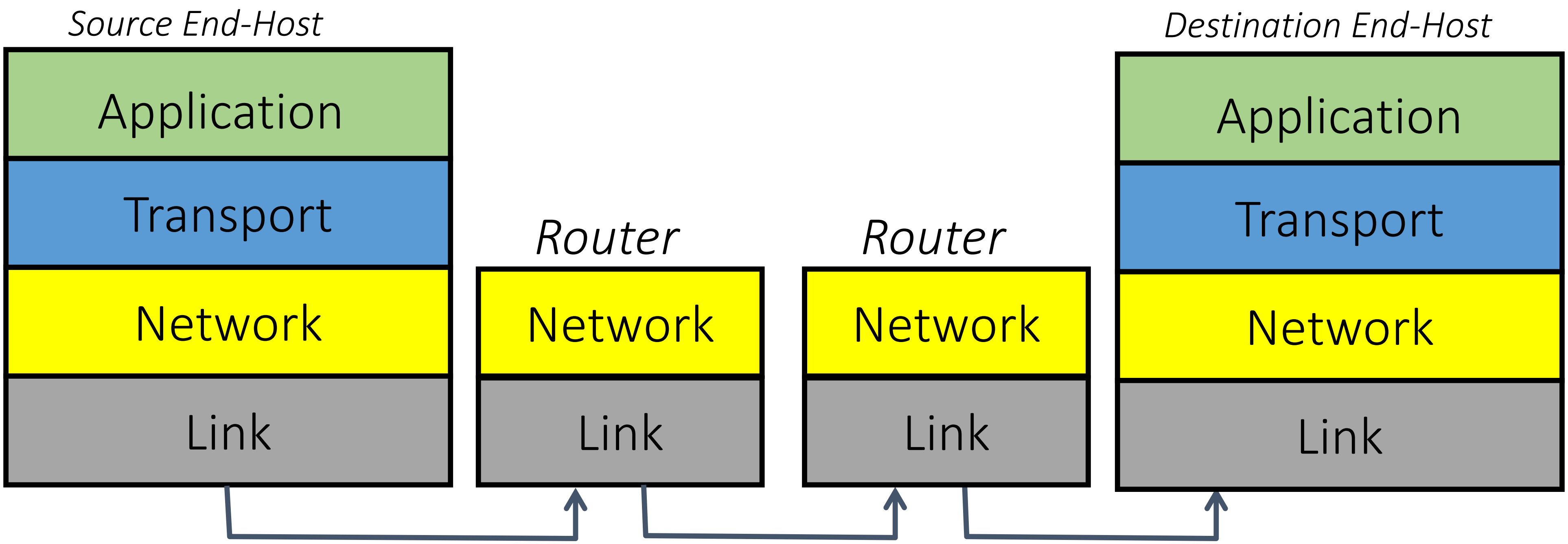
aka *Physical Layer*

Goals for today & Wednesday

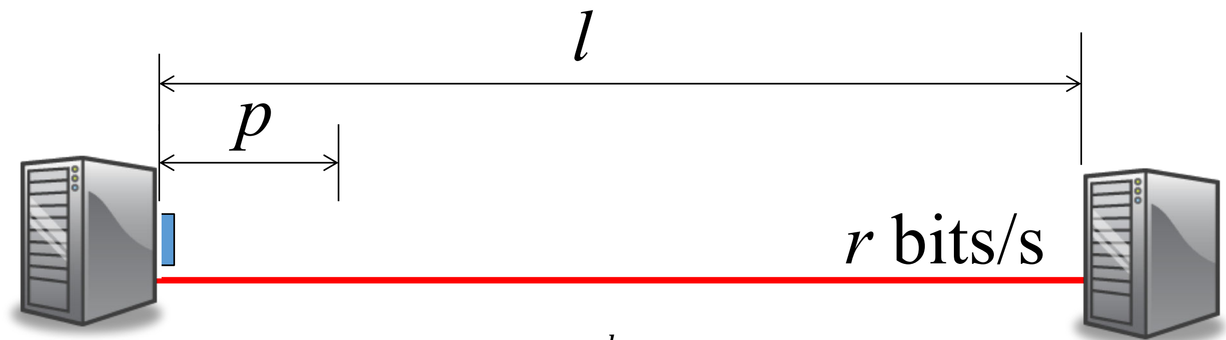
1. **Capacity**:
   What determines the maximum data rate of a link?
   - How can we get close to the maximum capacity?

2. **Clocks**: Two communicating entities cannot have exactly the same clock or frequency. How can they communicate?

The 4 Layer Internet Model

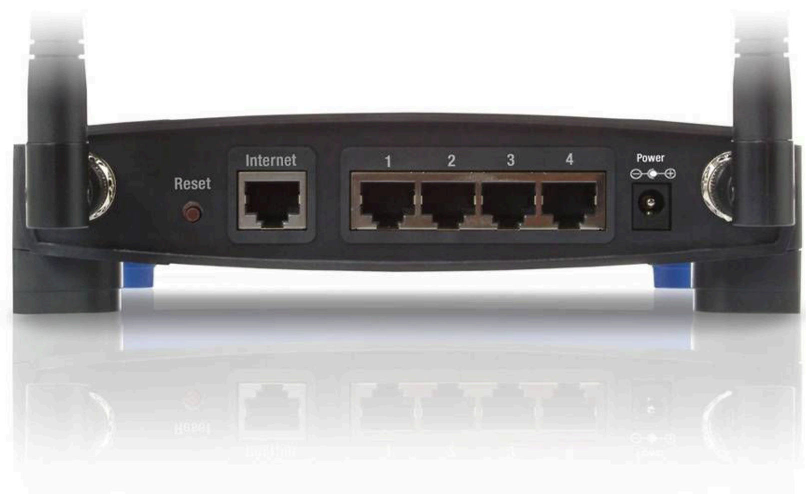


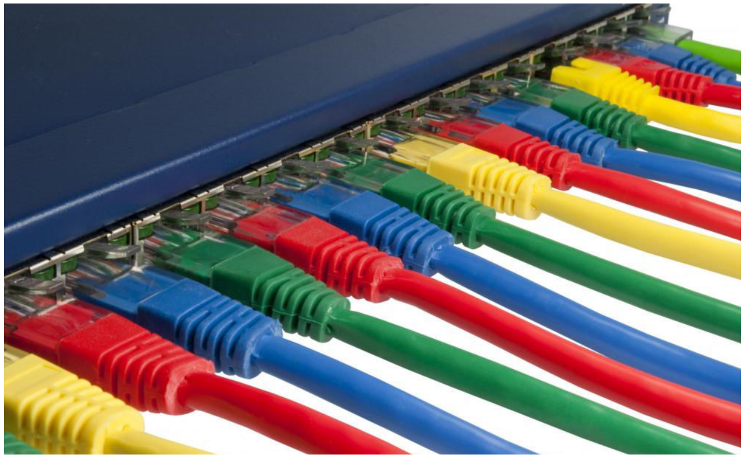
Total time to send a packet across a link: The time from when the first bit is transmitted until the last bit arrives.

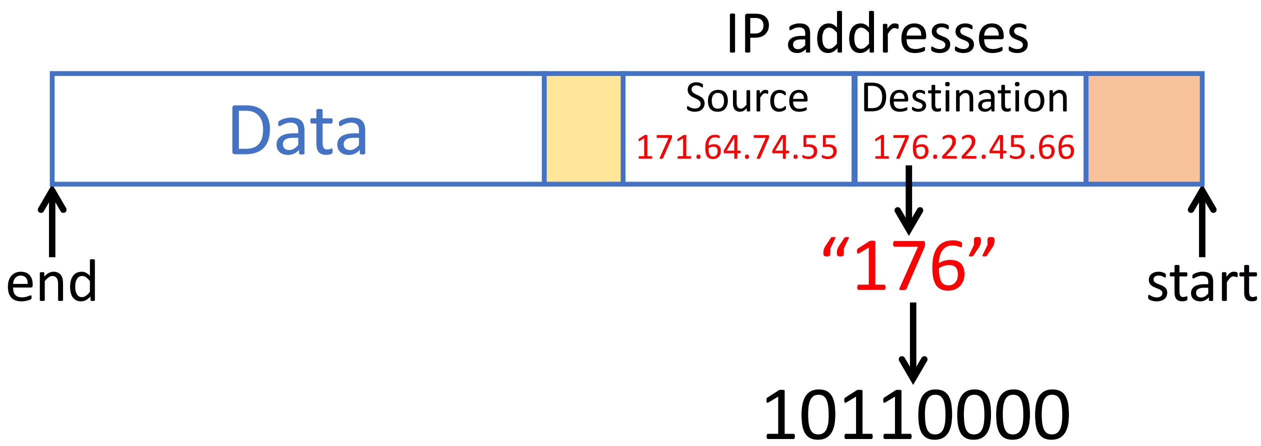


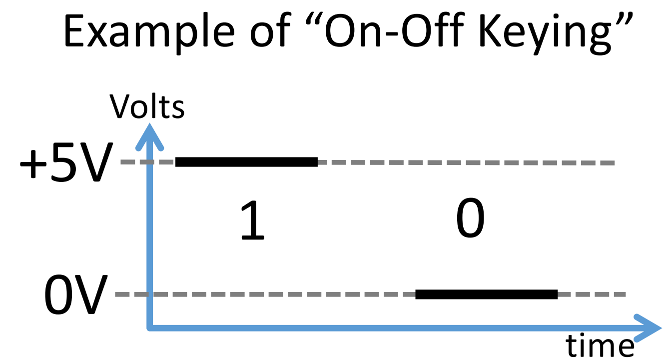
$$t = t_p + t_l = \frac{p}{r} + \frac{l}{c}$$

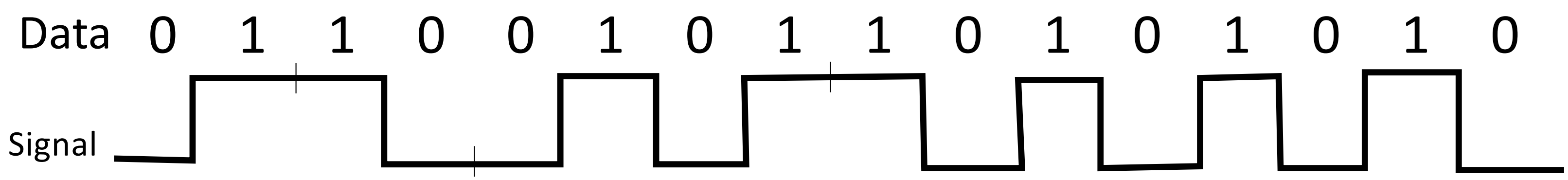
<u>Example</u>: A 100bit packet takes 10 + 5 = 15μs to be sent at 10Mb/s over a 1km link.

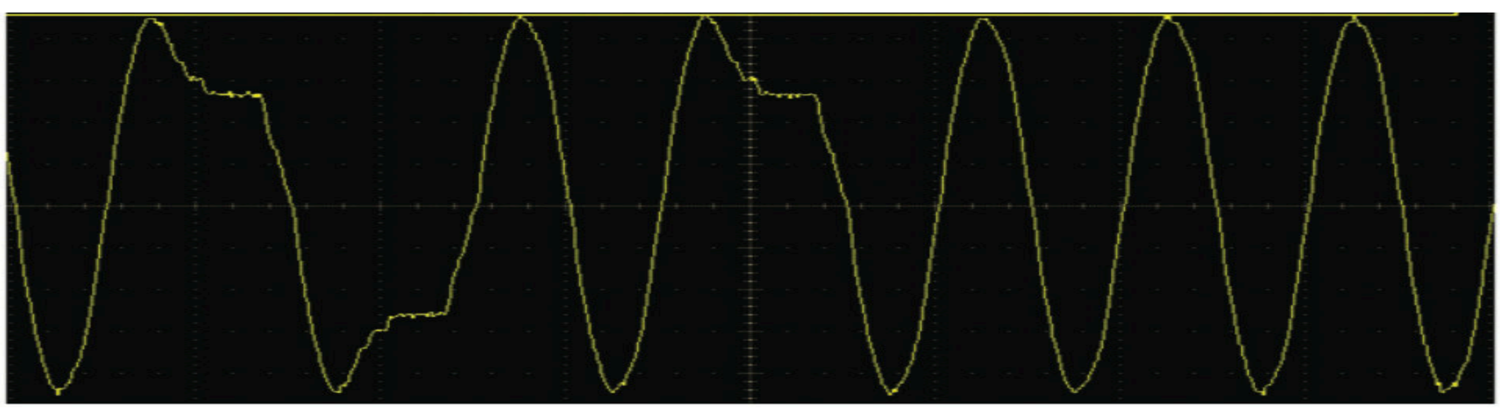

LINKSYS
Wireless-G
Broadband Router

Reset
Internet
1
2
3
4
Power

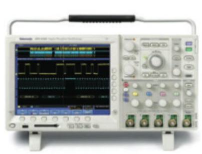



IP addresses
Data
Source
171.64.74.55
Destination
176.22.45.66
end
start
"176"
10110000


Example of "On-Off Keying"
Volts
+5V
0V
1
0
time

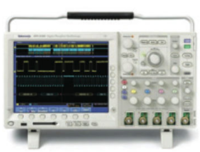

Data 0 1 1 0 0 1 0 1 1 0 1 0 1 0 1 0
Signal





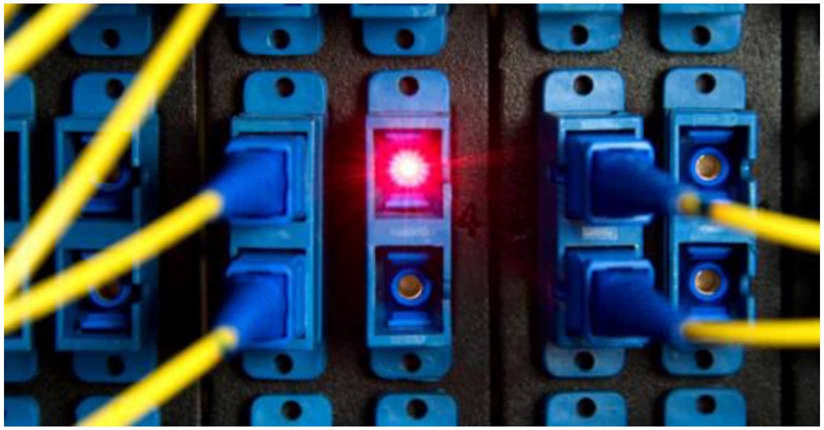
What determines the data rate?

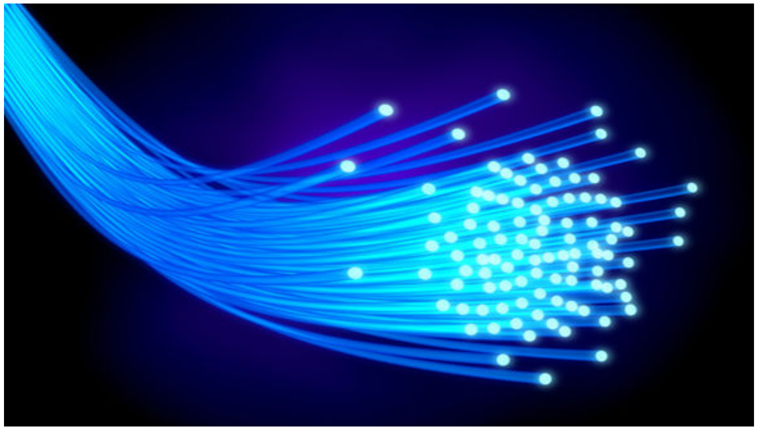
Q: What determines the steepness (i.e. rate) of this change?
Q: How does the rate of change affect the data rate?



Fiber-optic links

Packets are sent by turning a **laser** on and off very fast





Each fiber is smaller than a human hair

Used for very long, very fast communications (e.g. 100 Gb/s and 200km)

What determines the maximum data rate of a cable, fiber, wireless link, etc?

Q: What happens if we put the “bits” closer and closer together?

Q: If we can’t put them closer together, how can we increase the number bits of information transmitted per second?

Q: What other factors limit the number of bits per second we can transmit?

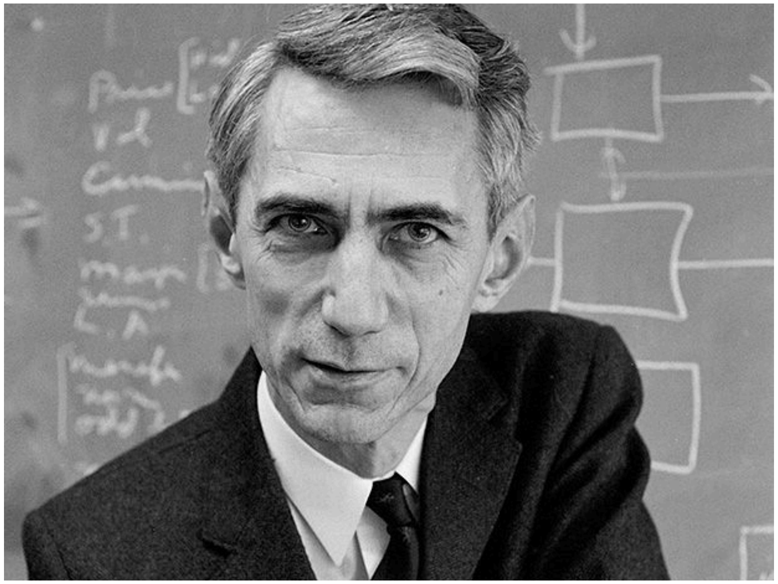
Q: Are there any other factors other than “Bandwidth” and “Noise” that determine the maximum data rate of a channel?

Claude Shannon

1937: MS Thesis proposed using Boolean algebra for digital circuit design.

1948: “A Mathematical Theory of Communication” led to the field of Information Theory and Shannon Capacity

(Juggling Machines!)



Claude Shannon (1916 – 2001)
Mathematician, Electrical Engineer

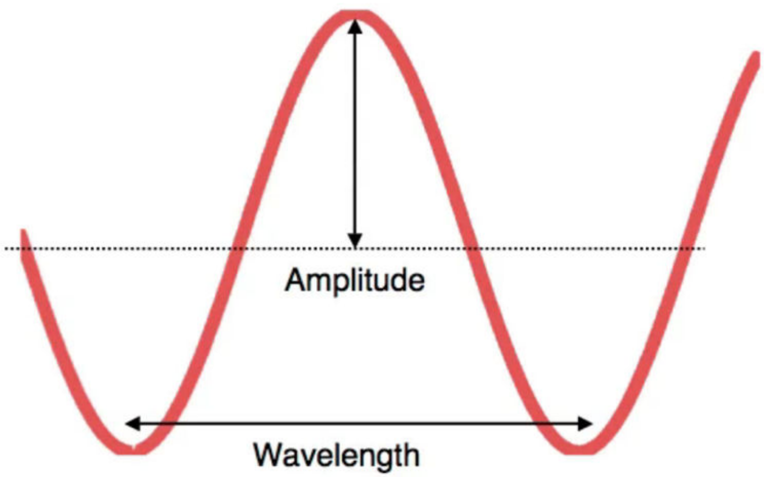
Shannon Capacity

- Shannon capacity represents the maximum error-free rate we can transmit through a channel
- The maximum data rate.
- Under some mild assumptions:

$$\text{Shannon Capacity} = \text{B}\ log_2\left(1 + \frac{S}{N}\right)$$

- In other words, it depends only on Bandwidth and Signal-to-Noise ratio!
- EE376A: Information Theory. Wow.

Analog signals



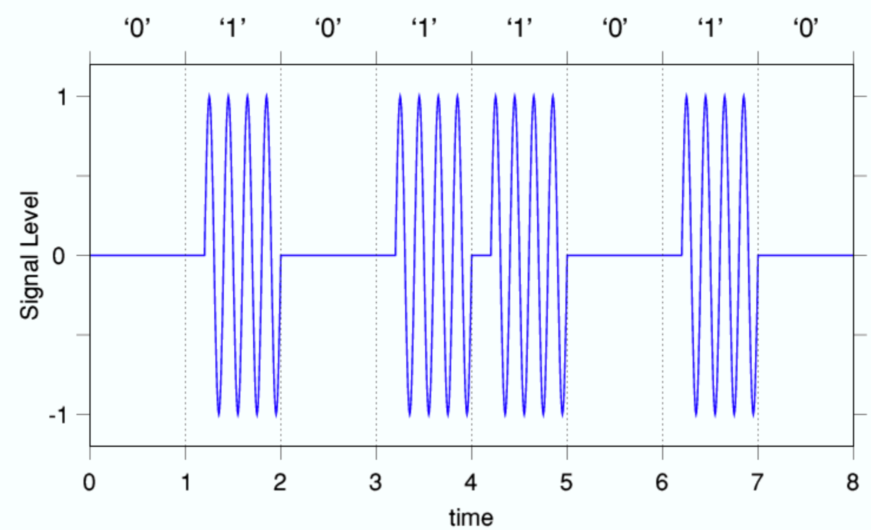


Figure 19.1 Simple on/off binary keying.

Frequency = 1/wavelength
Bandwidth: size of frequency range
Phase: location of peak within the wavelength

On-Off Keying (OOK)

- One frequency
- 2 amplitudes

Sending 0s and 1s

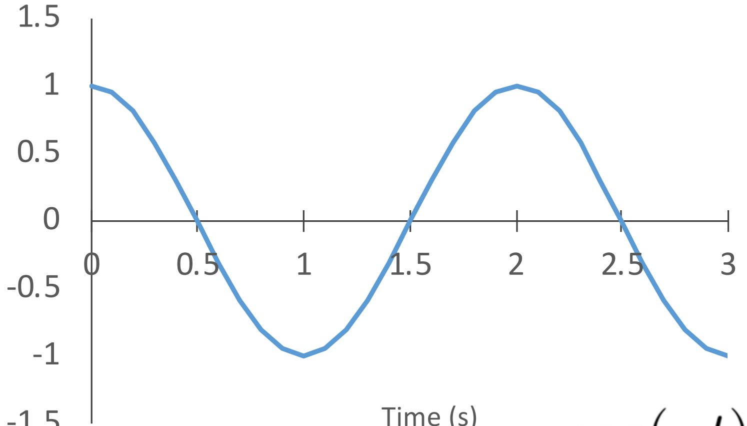
Frequency Shift Keying (FSK)

Amplitude Shift Keying (ASK)

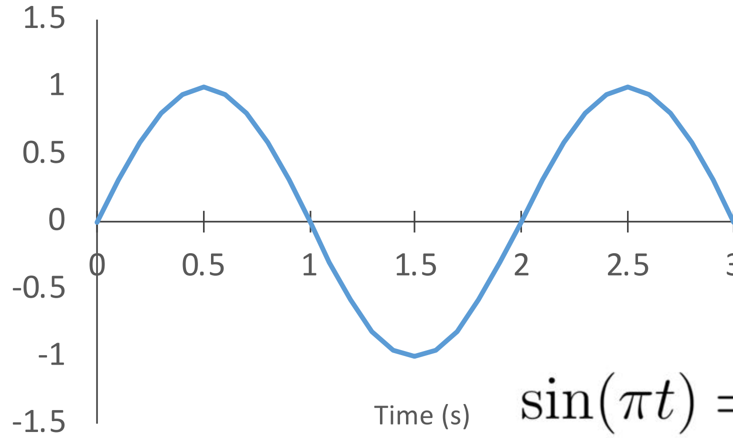
Phase Shift Keying (PSK)

- For the same frequency + amplitude, vary the phase
- No variation in power (amplitude) or wavelength (frequency)

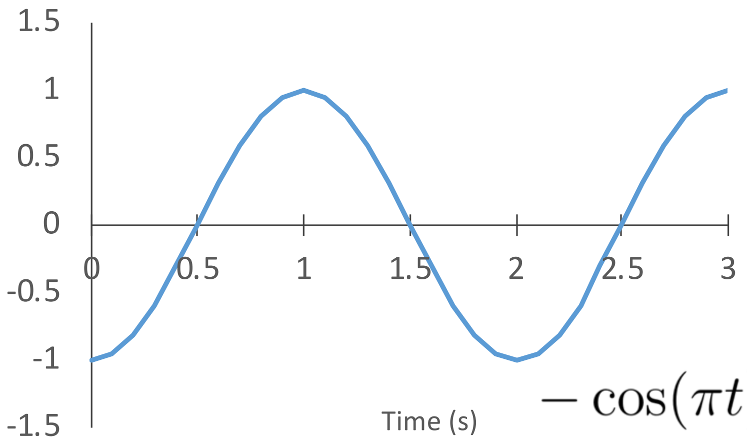
Phase in Analog signals



$$\cos(\pi t)$$



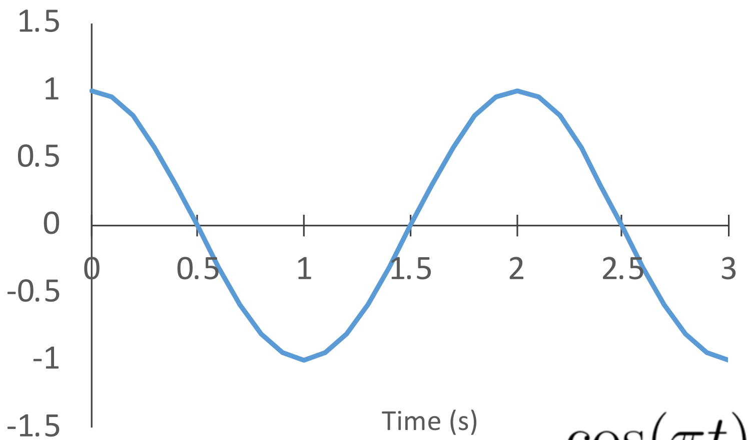
$$\sin(\pi t) = \cos(\pi t \overbrace{- \tfrac{\pi}{2}}^{(-90^\circ)})$$



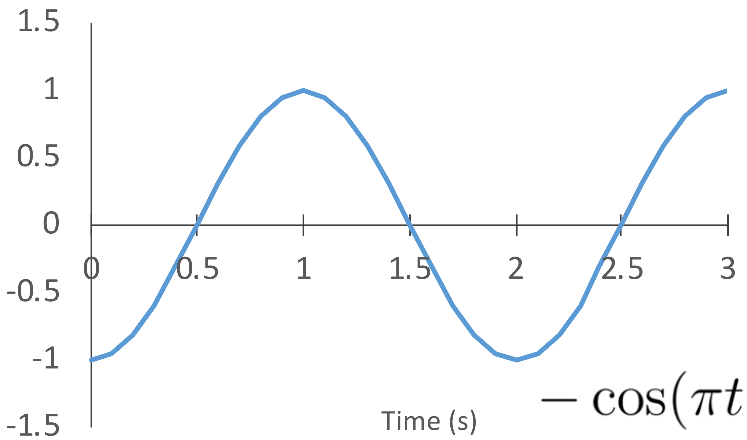
$$-\cos(\pi t) = \cos(\pi t \overbrace{- \pi}^{(-180^\circ)})$$

- Same frequency
- Same amplitude
- Different phase

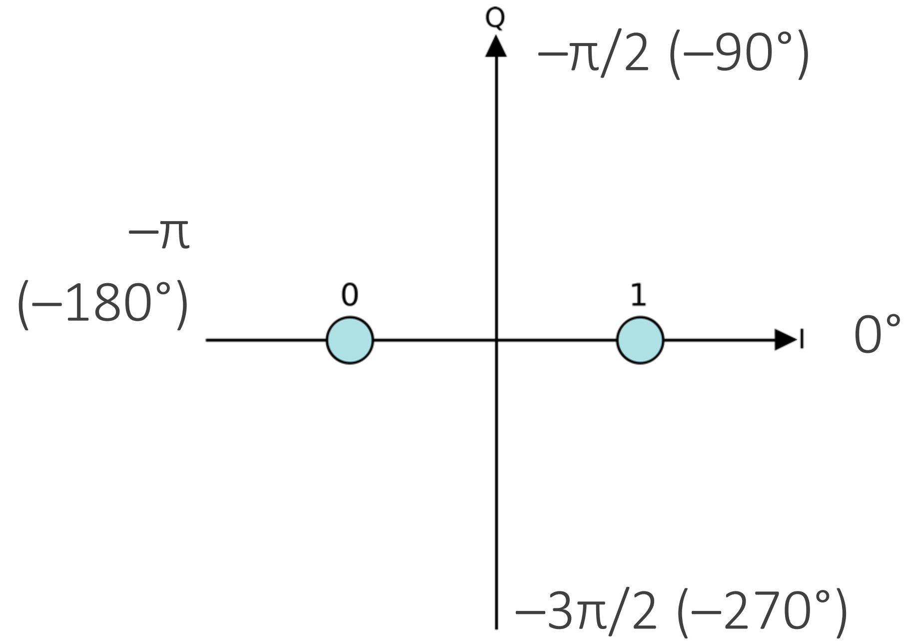
Phase in Analog signals



$$\cos(\pi t)$$



$$-\cos(\pi t) = \cos(\pi t \overbrace{- \pi}^{(-180^\circ)})$$

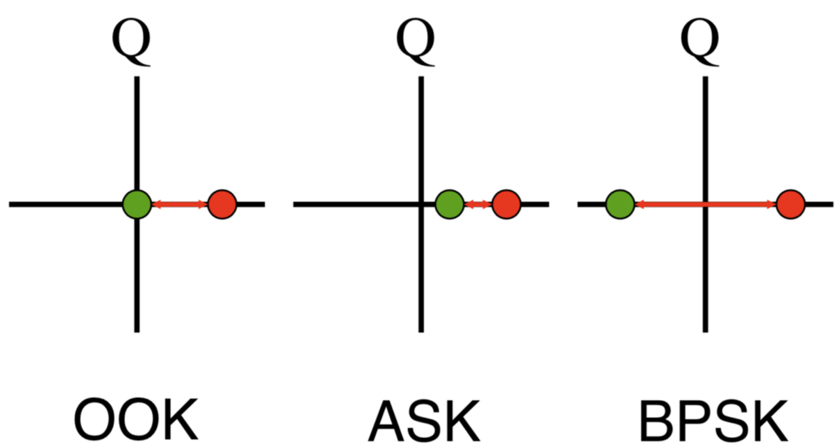


- Same frequency
- Same amplitude
- Different phase

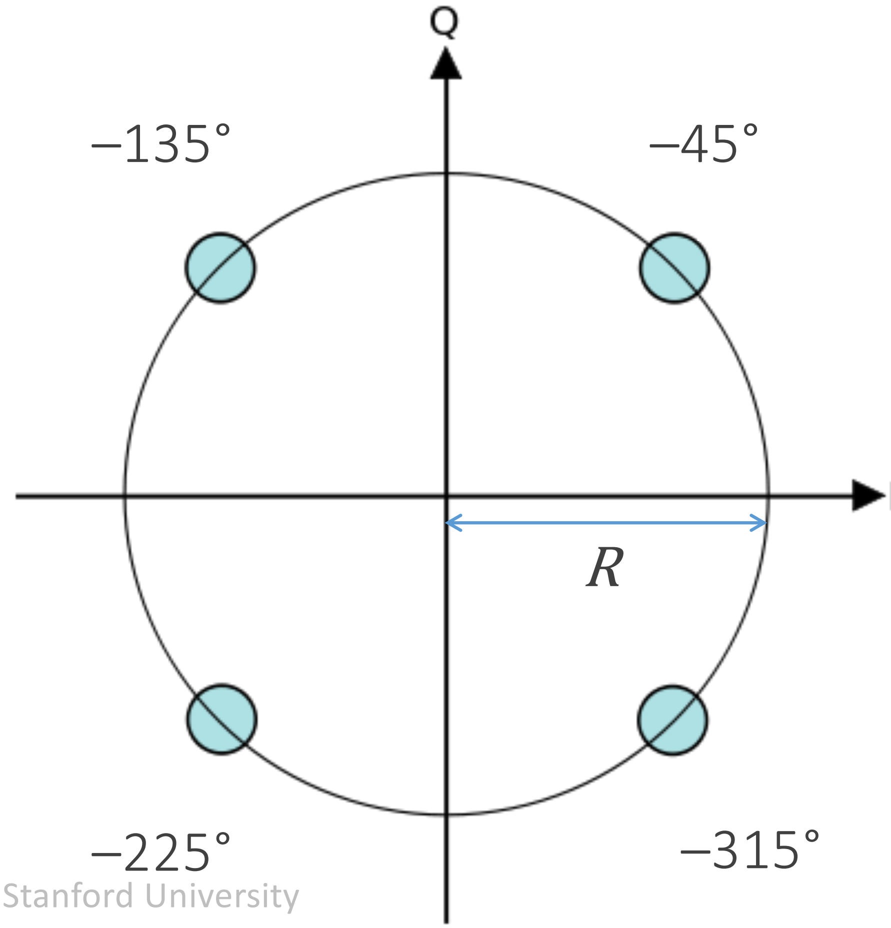
I/Q constellations

For the same frequency:

- What <u>I/Q constellation</u> (amplitude, phase) should I select?
- How should I assign a symbol (amplitude, phase) = to bits?

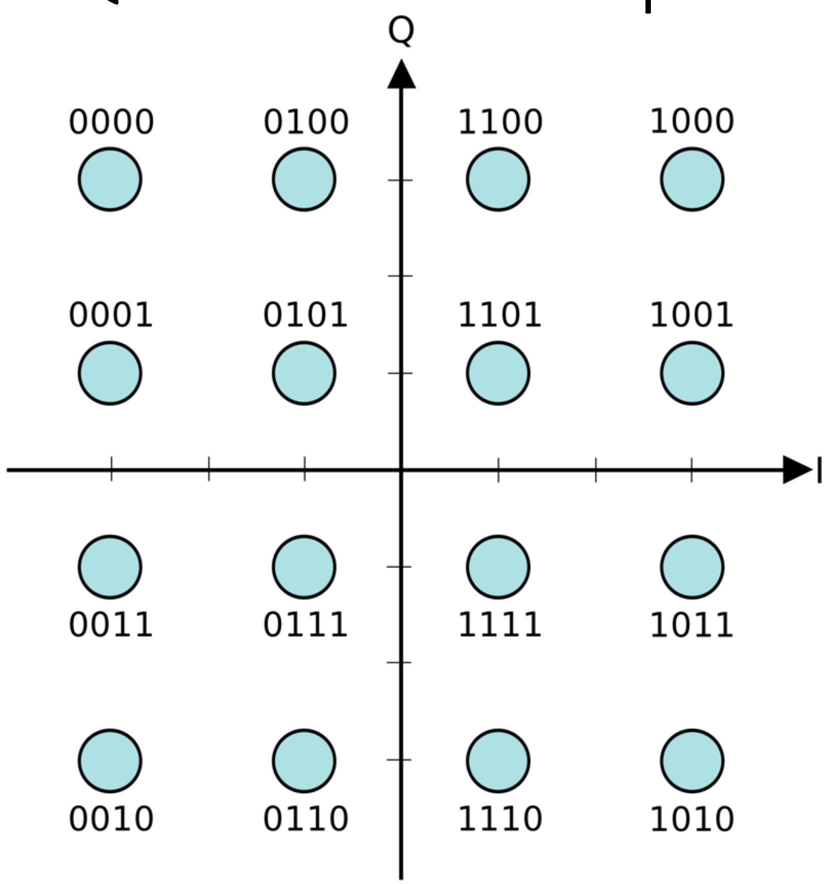


Quadrature Phase Shift Keying (QPSK)



1. For each symbol:
   - What is the amplitude?
   - What is the phase?
2. Represent each symbol as a bit (or bits).

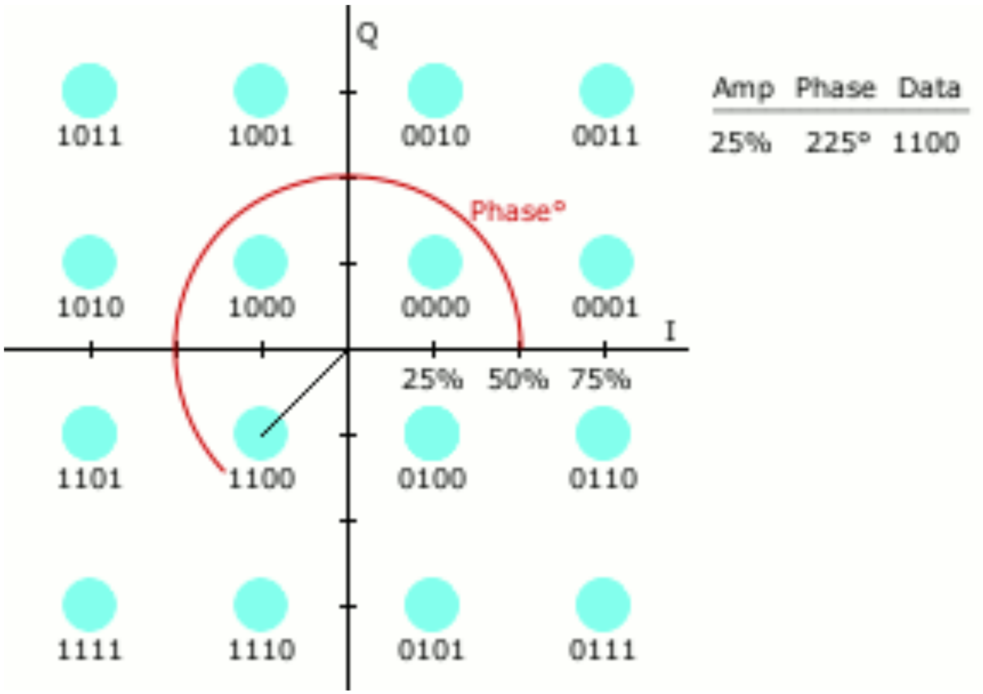
Quadrature Amplitude Modulation (16-QAM)



1. How many symbols?
2. How many amplitude variations?
3. How many phase variations?
4. How many bits per symbol?

Example 32 bit word transmission using 16-QAM

1100 1001 0100 1110 1100 0110 1100 1111
0 1 2 3 4 5 6 7

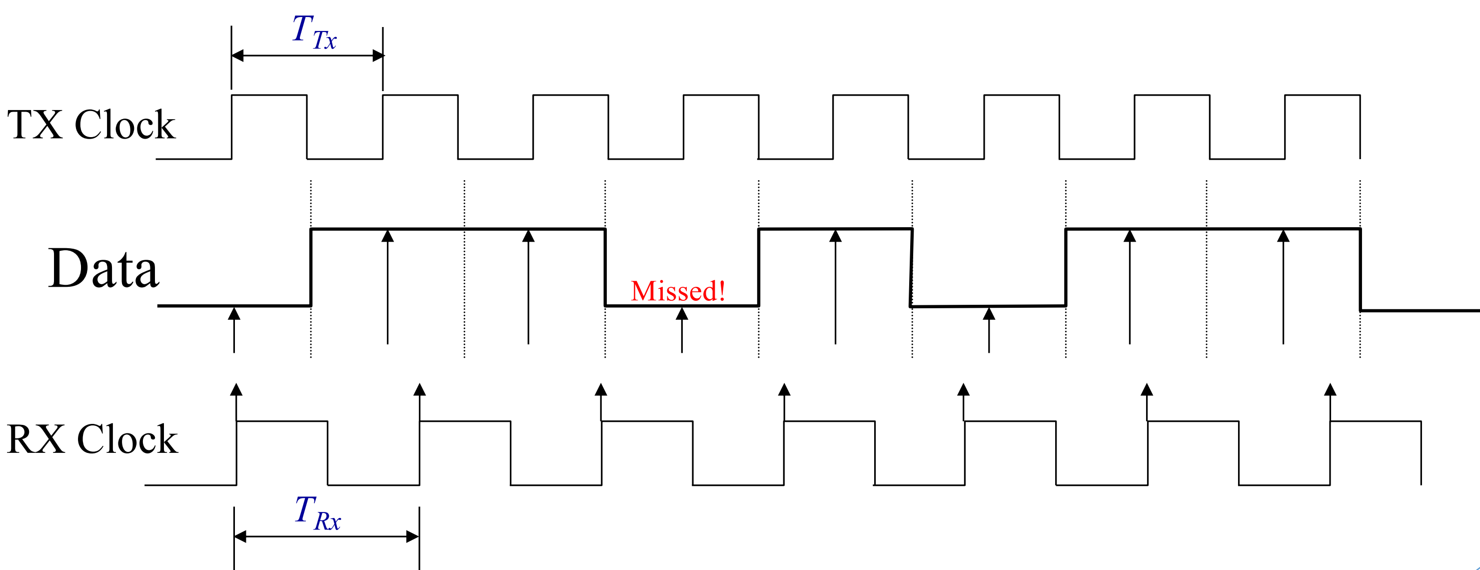


Examples today

ASK/OOK: Wired Ethernet
FSK: Bluetooth
BPSK: 802.11 abgn
QPSK: 802.11 abgn, LTE
16-QAM: 802.11abgn, LTE
64-QAM: 802.11 abgn, LTE, 5G
256-QAM: 5G
1024-QAM: Home powerline communication
32768-QAM: ADSL (digital data over long telephone cables)

Clocks

If we don't know the sender's (TX) clock

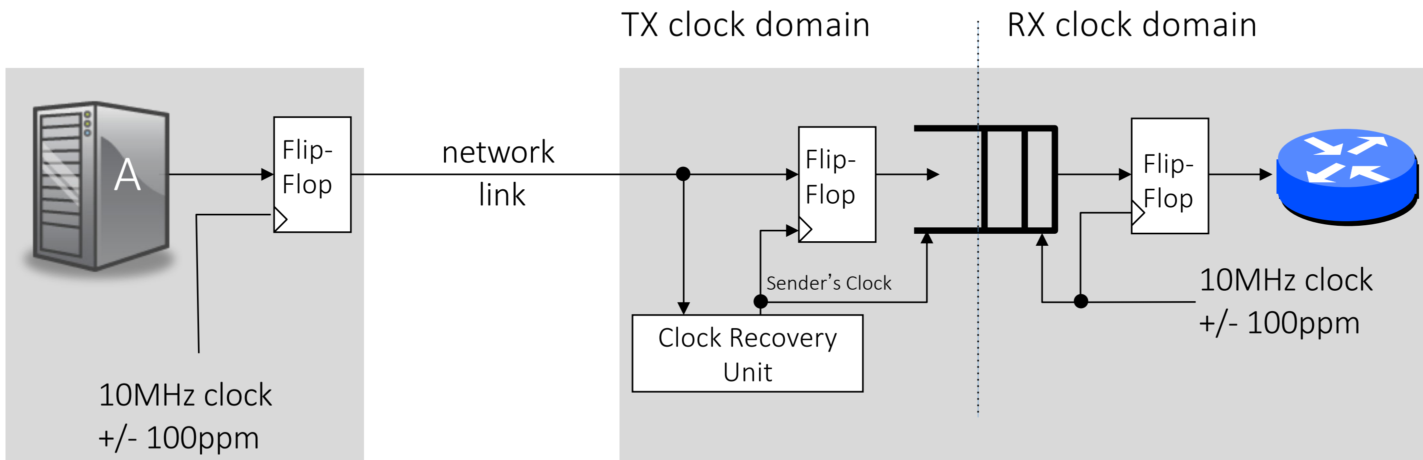


Usually expressed in parts per million (ppm) rather than percentage

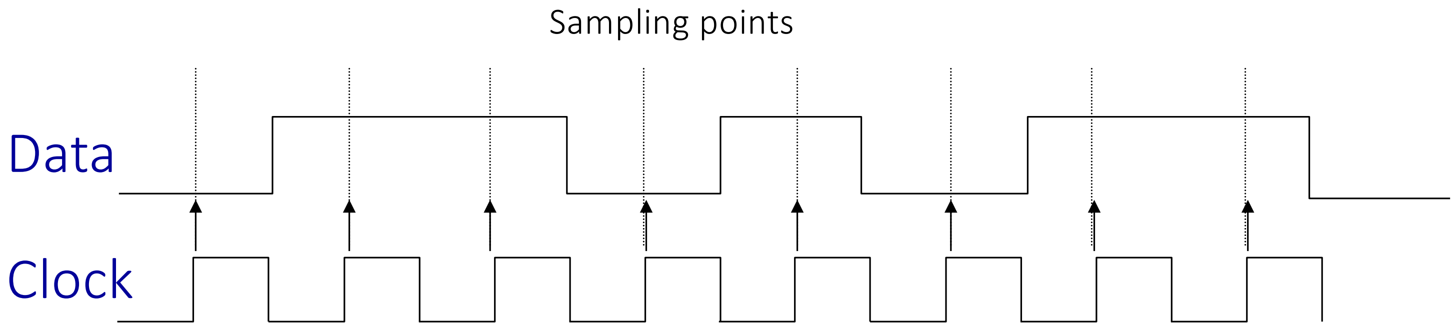
If the RX clock is p% slower than the TX clock, then: $T_{RX} = T_{TX}\left(1 + \frac{p}{100}\right)$

After $\frac{0.5}{10^{-2}p}$ bit times, the RX clock will miss a bit completely.

Synchronous communication on network links



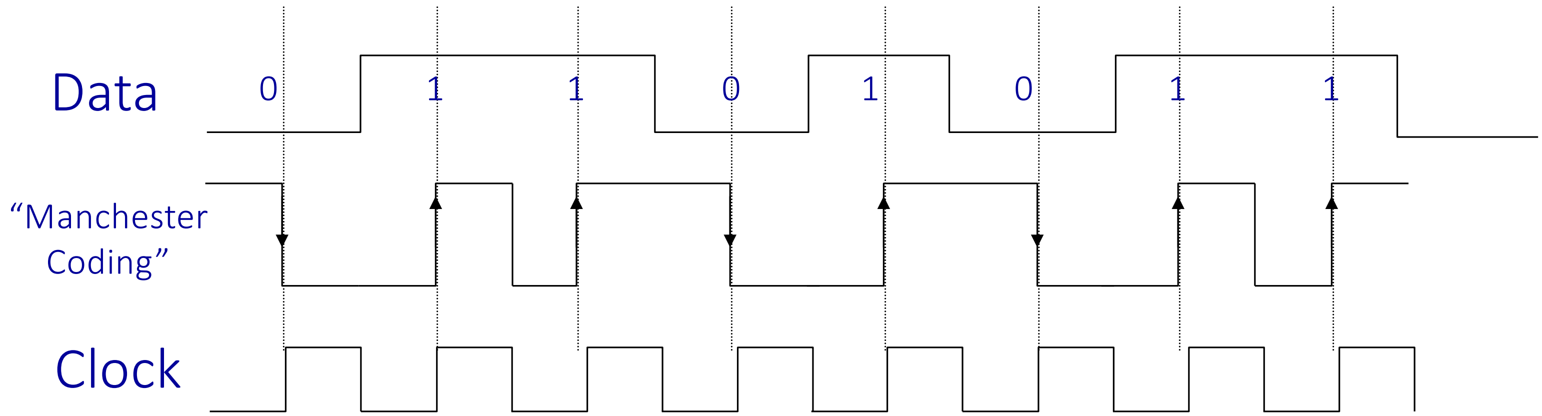
Encoding for clock recovery



If the clock is not sent separately, the data stream must have sufficient transitions so that the receiver can determine when to sample the arriving data.

Encoding for clock recovery

Example #1: 10Mb/s Ethernet

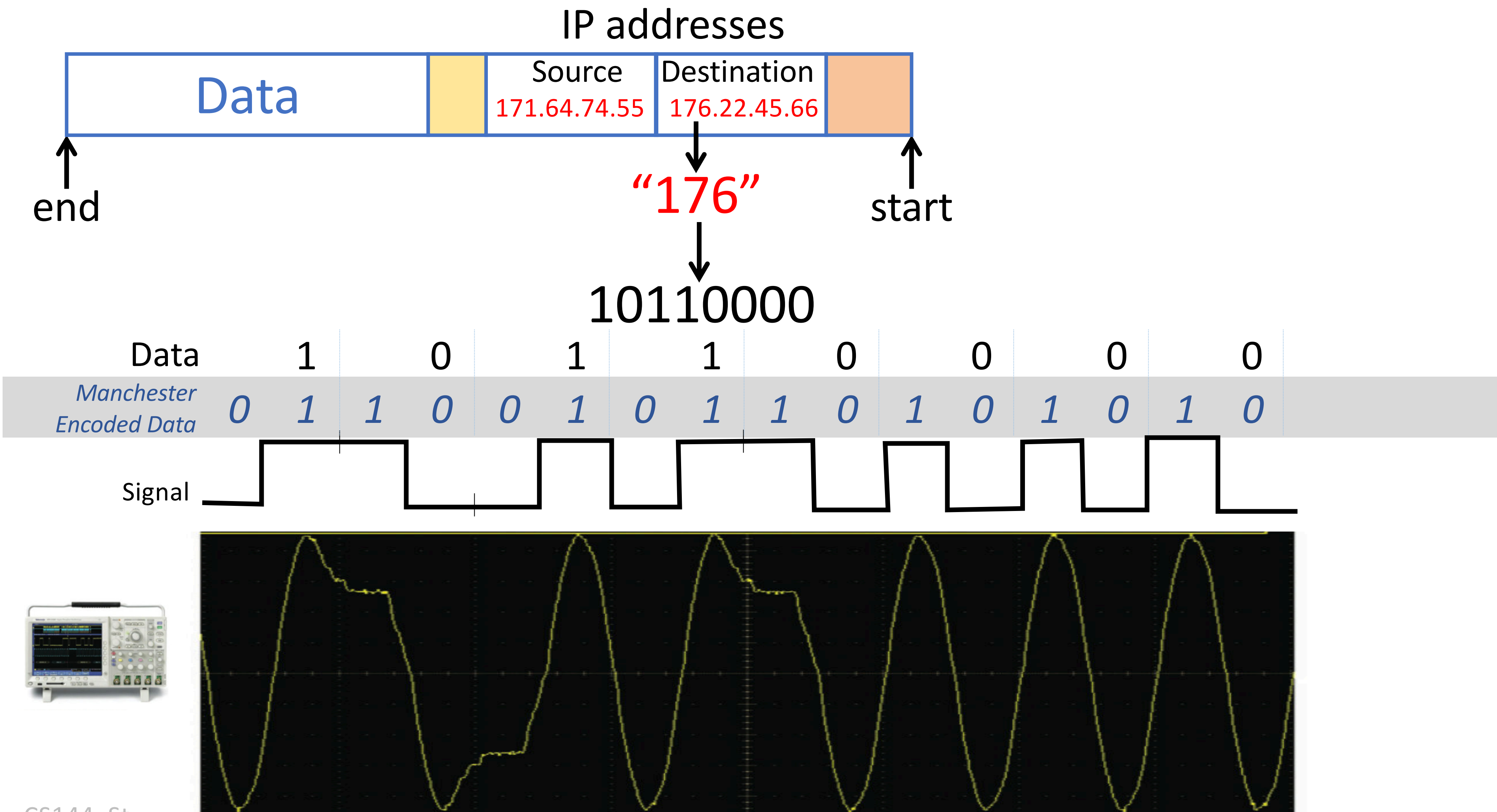


Advantages of Manchester encoding:

- Guarantees one transition per bit period.
- Ensures d.c. balance (i.e. equal numbers of hi and lo).

Disadvantages

- Doubles bandwidth needed in the worst case.


IP addresses
Data
Source
171.64.74.55
Destination
176.22.45.66
end
start
"176"
10110000
Data
1 0 1 1 0 0 0 0
Manchester
Encoded Data
0 1 1 0 0 1 0 1 1 0 1 0 1 0 1 0
Signal

Encoding for clock recovery

Example #2: 4b/5b encoding

4-bit data	5-bit code
0000	11110
0001	01001
0010	10100
…	…

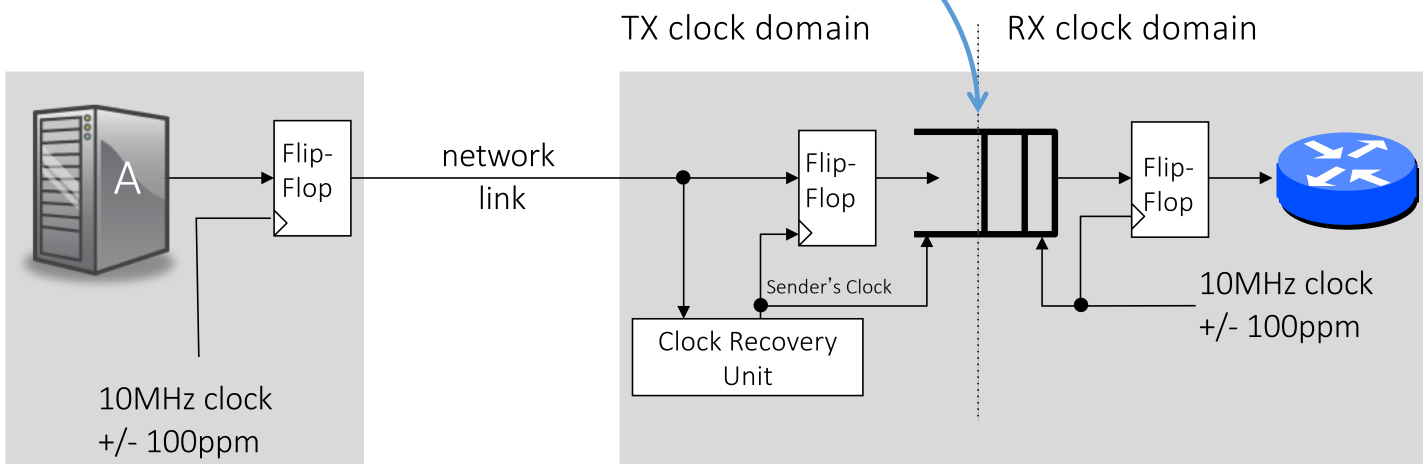
Advantages of 4b/5b encoding:

- More bandwidth efficient (only 25% overhead).
- Allows extra codes to be used for control information.

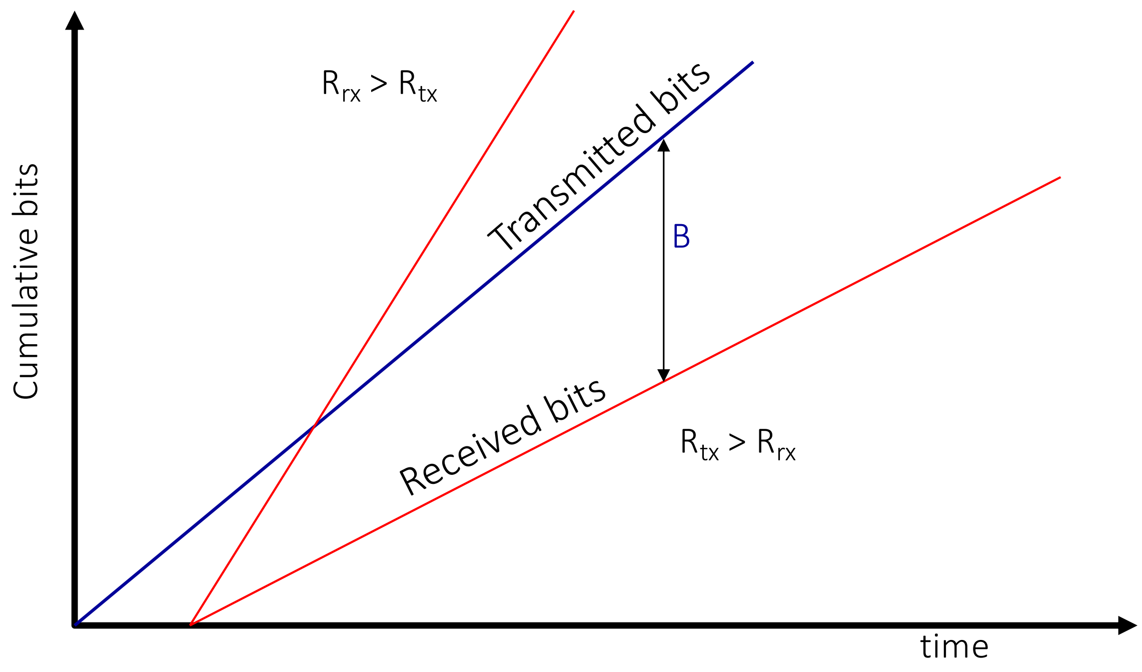
Disadvantages

- Fewer transitions makes clock recovery a little harder.

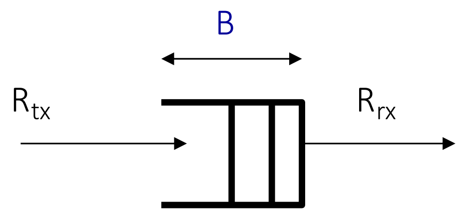
Elasticity Buffer



Sizing an elasticity buffer

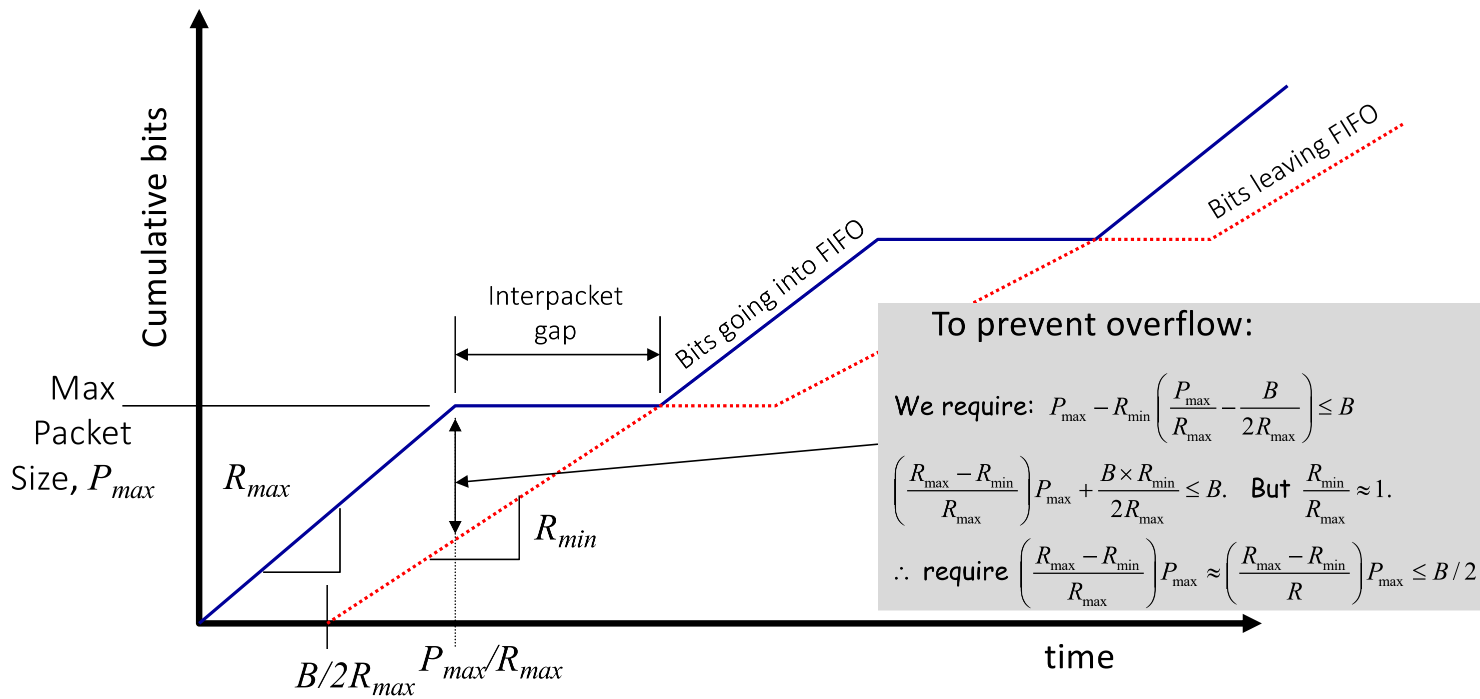


Sizing an elasticity buffer



1. Hold buffer nominally at B/2.
   - At start of new packet, allow buffer to fill to B/2.
   - Or, make sure buffer drains to B/2 before new packet.
2. Size buffer so that it does not overflow or underflow before packet completes.
3. ($R_{tx} > R_{rx}$): Given inter packet gap, size B/2 for no overflow.
4. ($R_{rx} > R_{tx}$): Given max length packet, pick B/2 for no underflow.

Preventing overflow



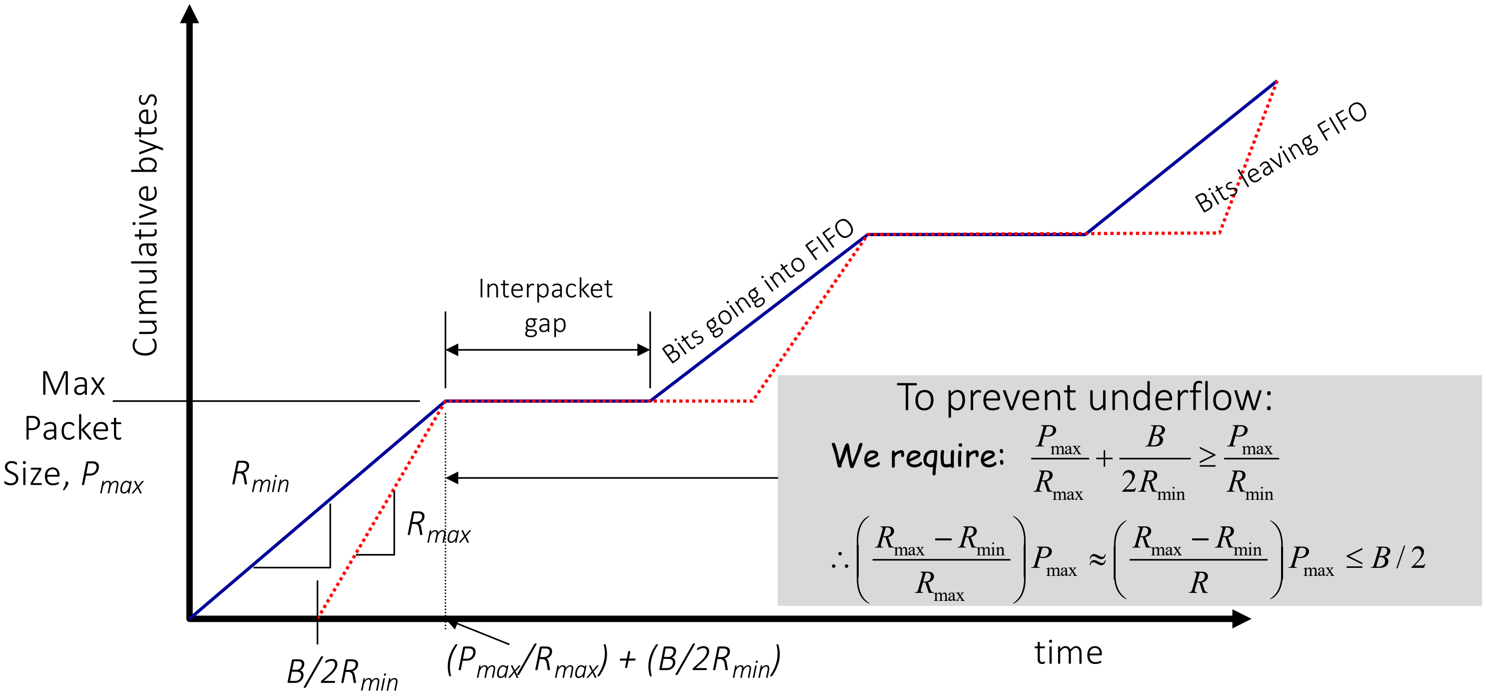
To prevent overflow:

We require: $P_{\max} - R_{\min}\left(\frac{P_{\max}}{R_{\max}} - \frac{B}{2R_{\max}}\right) \le B$

$\left(\frac{R_{\max} - R_{\min}}{R_{\max}}\right)P_{\max} + \frac{B \times R_{\min}}{2R_{\max}} \le B.$ But $\frac{R_{\min}}{R_{\max}} \approx 1.$

$\therefore$ require $\left(\frac{R_{\max} - R_{\min}}{R_{\max}}\right)P_{\max} \approx \left(\frac{R_{\max} - R_{\min}}{R}\right)P_{\max} \le B/2$

Preventing underflow



To prevent underflow:

We require: $$\frac{P_{\max}}{R_{\max}} + \frac{B}{2R_{\min}} \geq \frac{P_{\max}}{R_{\min}}$$

$$\therefore \left(\frac{R_{\max} - R_{\min}}{R_{\max}}\right) P_{\max} \approx \left(\frac{R_{\max} - R_{\min}}{R}\right) P_{\max} \leq B/2$$

Sizing an elasticity buffer
Example

Maximum packet size 4500bytes

Clock tolerance +/- 100ppm

$$\left(\frac{R_{\max} - R_{\min}}{R}\right) = 200 \times 10^{-6}$$

$$\therefore B \geq 2(4500 \times 8 \times 200 \times 10^{-6}) = 14 bits$$

Therefore,
1. Elasticity buffer needs to be at least 14 bits
2. Wait for at least 7 bits before draining buffer
3. Inter-packet gap at least 7 bits