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CA169
Networks & Internet

Physical Layer

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This Week: Physical Layer

- Digital Modulation
- Fundamental Limits
- Network Performance Measures

The Physical Layer

- The physical layer is the **foundation** on which other layers build
  - The properties of the different media (wires, fiber optics or wireless) **limit** what the network can do

- The key problem addressed by the physical layer is to send (digital) bits using only (analog) signals
  - This process is called **modulation**

Digital Modulation

Digital Modulation

- Wires and wireless channels carry analog signals such as continuously varying voltage, sound intensity or light intensity

- To send digital information, we must devise analog signals to represent a bit

- The process of converting between bits and signals that represent them is called **digital modulation**

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Digital Modulation

- There are a number of different schemes for converting bits into a signal
- Schemes that directly convert bits into a signal result in what is called **baseband transmission**
  - In this scheme the signal uses the entire bandwidth of the signal
- Scheme that regulate the amplitude, phase, or frequency of a carrier signal to convert bits into a signal result in what is called **passband transmission**
  - In these schemes the signal occupies a band of frequencies around the frequency of the carrier signal

1- Baseband Transmission

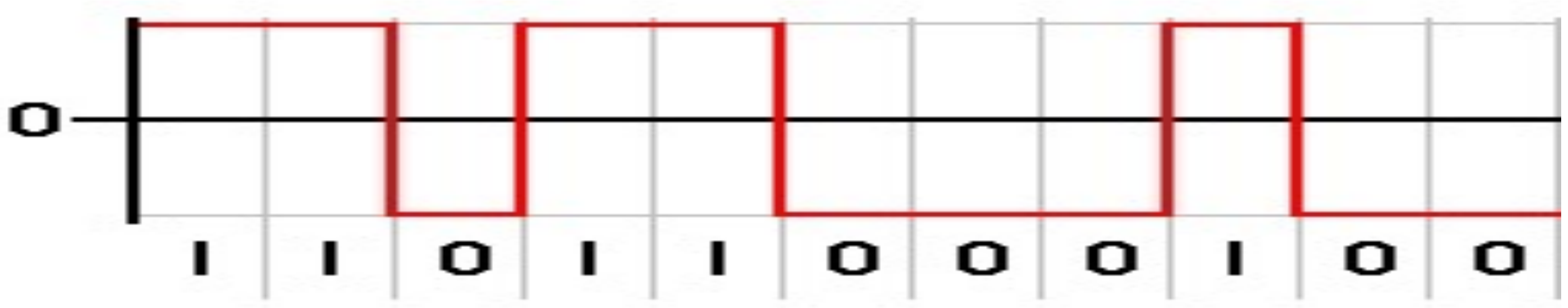
- The most straightforward form of digital modulation is to use two signal levels:
    - a positive voltage to represent a 1
    - and a negative voltage to represent a 0

- For an optical fiber, the presence of light might represent a 1 and the absence of light might represent a 0

- This scheme is called **NRZ (Non-Return-to-Zero)**.

Non Return to Zero

- Once sent, the NRZ signal travels down the wire
- At the other end, the receiver converts it into bits by sampling the signal at regular intervals of time



Non Return to Zero

- This signal will not look exactly like the signal that was sent
- It will be attenuated and distorted by the channel and noise at the receiver
- To decode the bits, the receiver maps the signal samples to the closest symbols
- For NRZ:
  - a **positive voltage** will be taken to indicate that a **1** was sent
  - a **negative voltage** will be taken to indicate that a **0** was sent.

Clock Skew with NRZ

- For schemes that encode bits into symbols, the receiver must know when one symbol ends and the next symbol begins to correctly decode the bits.

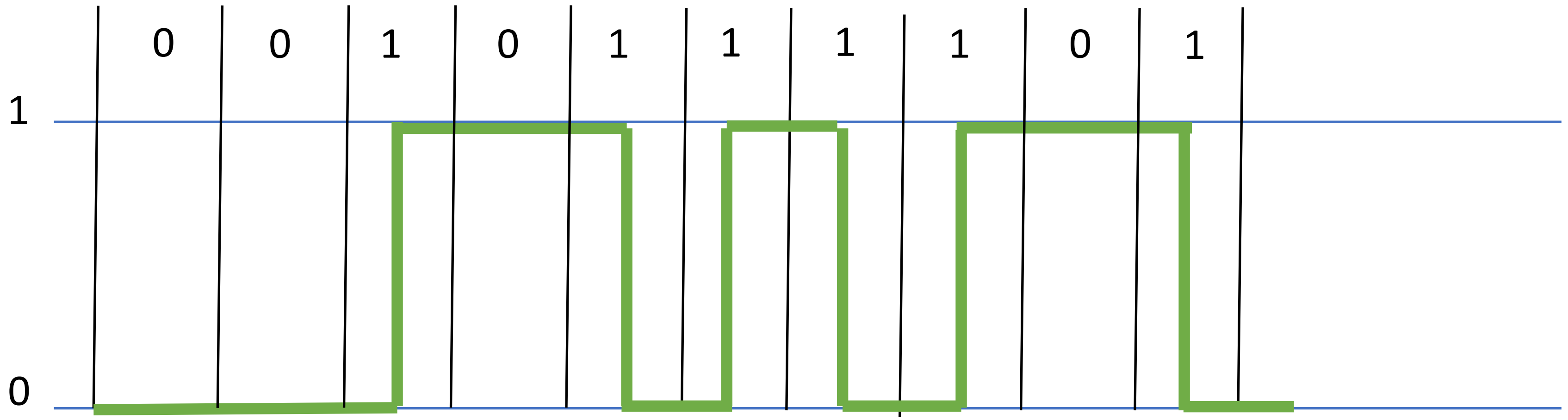
- With NRZ, in which the symbols are simply voltage levels, a long run of 0s or 1s leaves the signal unchanged.

- After a while it is hard to tell the bits apart:
  - 15 successive zeros look much like 16 zeros
  - 15 successive ones look much like 16 ones

Clock Skew!

Non Return to Zero Invert

- Non return to zero invert (NRZI) is a special case of NRZ where changes to the level of the signal called **transitions** are used to represent a 1 and no change to represent a 0



Clock Skew with NRZI

- With NRZI:
  - A long run of 1s always change the signal (solves this issue of NRZ)
  - But, a long run of 0s or leaves the signal unchanged

- After a while it is hard to tell the bits apart:
  - 15 successive zeros look much like 16 zeros
- unless you have a very accurate clock

Clock Skew!

Clock Recovery

- Accurate clocks would help with this problem, but they are an **expensive** solution for equipment that will be very common

- A possible solution is to send a **separate clock signal**
  - The receiver then only has to keep time with the clock signal

- The clock signal changes the level of the signal at regular intervals
  - These changes are called **transitions**

- This however requires an extra cable which could be used to carry data
- A clever way is to mix the clock signal with the data signal by **XORing** them together so that no extra line is needed

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XOR Operation

A	B	XOR (A, B)
0	0	0
0	1	1
1	0	1
1	1	0

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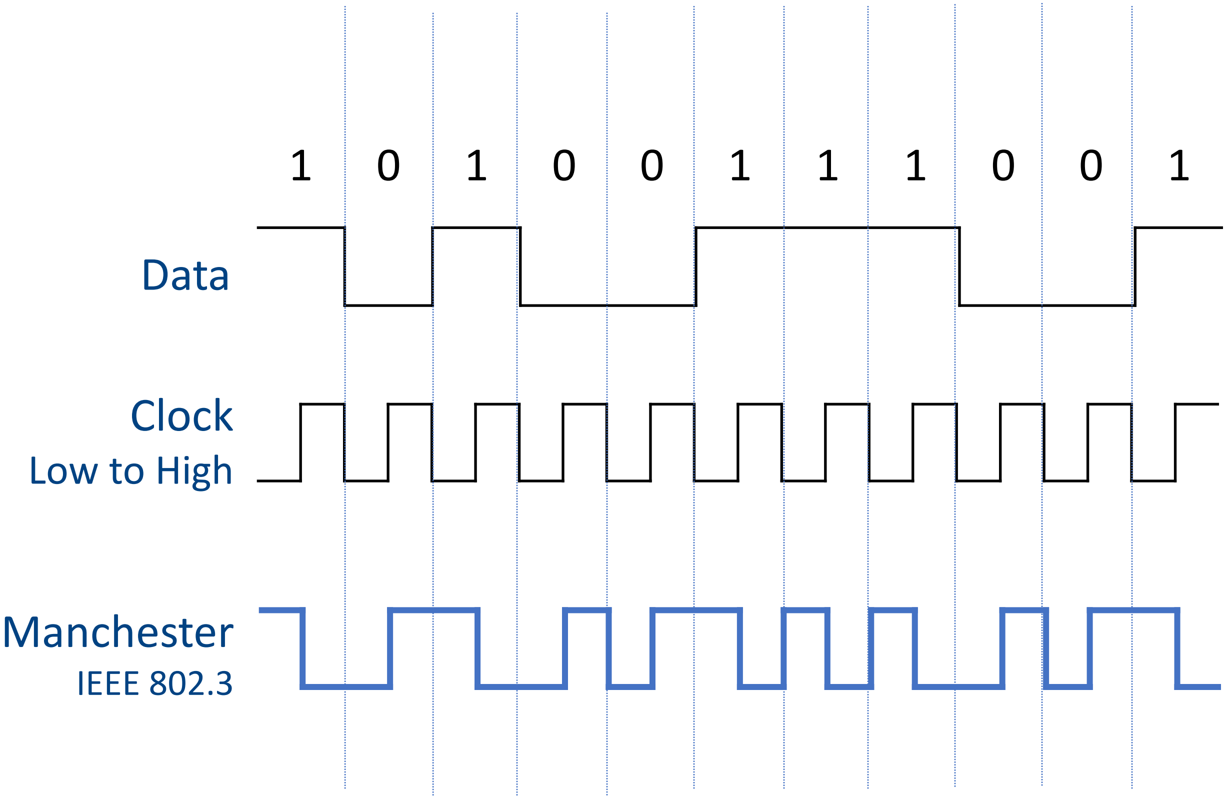
Manchester Encoding

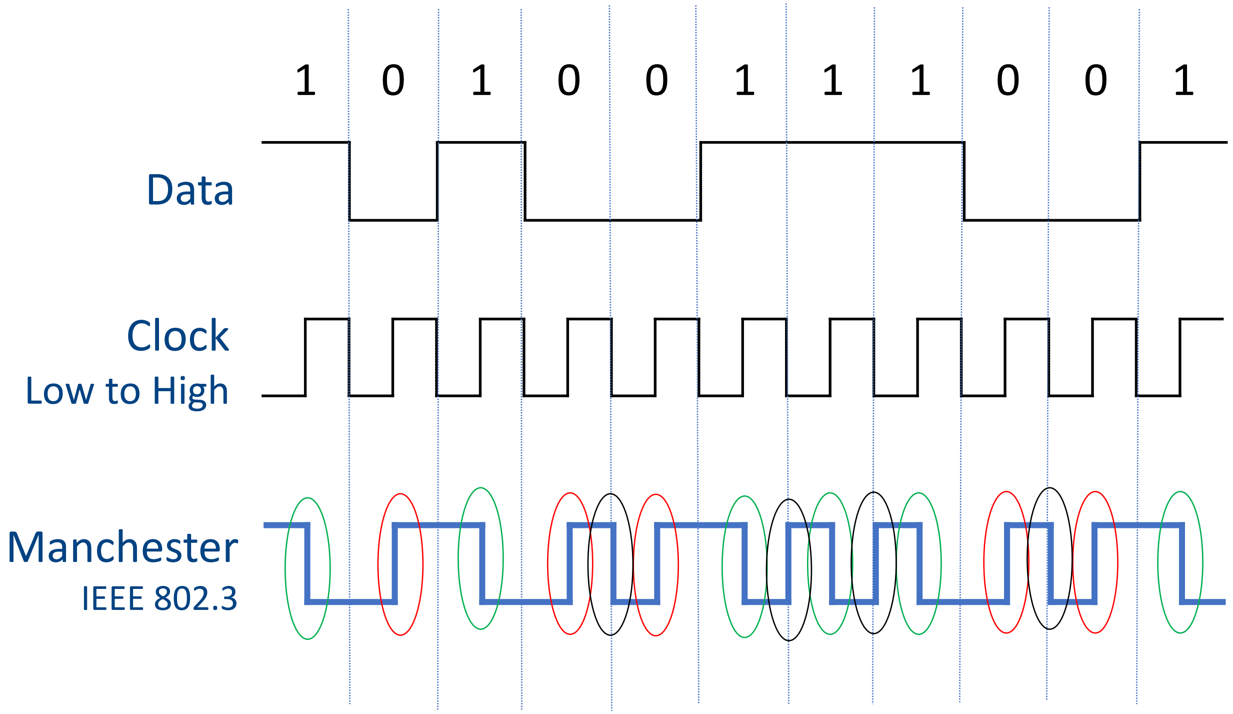
- The clock makes a “clock transition” in every bit time, so it runs at twice the bit rate

- XOR(clock, 0) makes a low-to-high transition (i.e., similar to the clock)
  - This transition is a logical 0
- When it is XORed with the 1 makes a high-to-low transition (inverse of the clock)
  - This transition is a logical 1



Manchester Encoding

- The downside of Manchester encoding is that it requires twice as much bandwidth as NRZ because of the clock



These High to low transitions signify a '1' in data!

These Low to High transitions signify a '0' in data!

These Remaining transitions do not signify data and are considered overhead

Manchester Encoding

- The downside of Manchester encoding is that it requires twice as much bandwidth as NRZ because of the clock

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Breaking Consecutive 0s

- A different strategy is based on the idea that we should code the data to ensure that there are enough transitions in the signal

Remember clock skew!

- NRZ will have clock skew problems for long runs of 0s and 1s
- NRZI will have clock skew problem only for long runs of 0s
- If there are frequent transitions, it will be easy for the receiver to stay synchronized with the in-coming stream of symbols

- To really fix the problem of NRZI we can break up runs of 0s by mapping small groups of bits to be transmitted so that groups with successive 0s are mapped to slightly longer patterns that do not have too many consecutive 0s

4B/5B

- A well known code to breaking up sequences of 0s is called 4B/5B
- Every possible combination of 4 bits is mapped to a sequence of 5 bits
- The 5 bit sequences are chosen so there will never be more than 3 consecutive 0s
- At the receiver the codes are converted back to their original values

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4B/5B Mappings

Data 4B	Codeword 5B	Data 4B	Codeword 5B
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

4B/5B

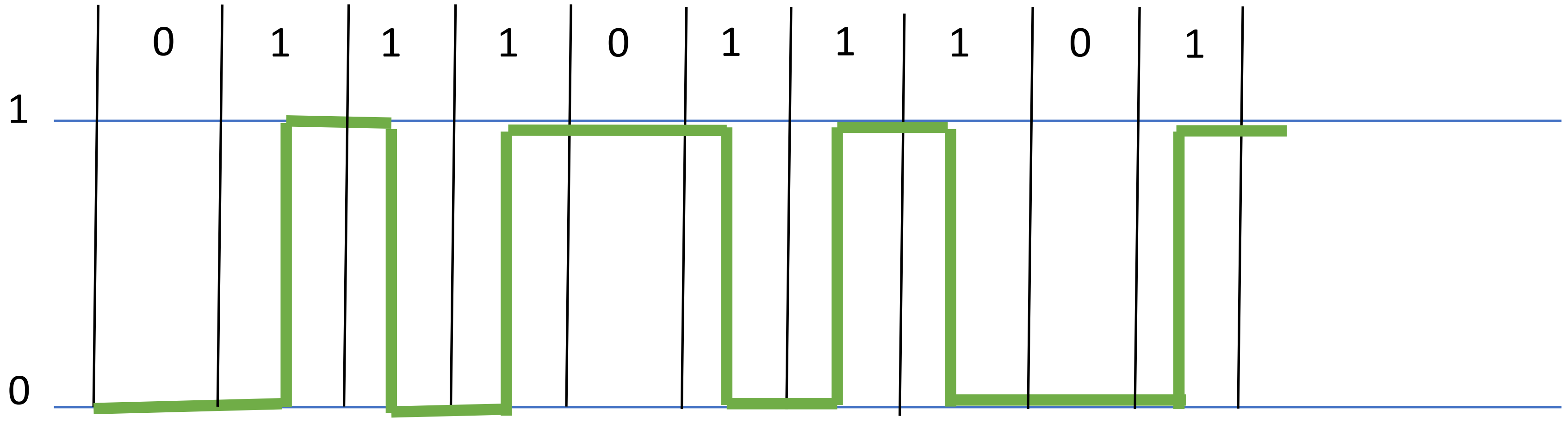
- Since there are 16 (2^4) input combinations and 32 (2^5) output combinations, some of the output combinations are not used

- Some are not used because there are too many successive 0s

- Others non-data codes are used to represent physical layer control signals

4B/5B

- If we wish to send the number 0110 1111
- First we convert it to codewords
  - 01110 11101



2- Passband Transmission

- Often, we want to use a range of frequencies that do not start at zero to send information across a channel

- For wireless channels, it is not practical to send very low frequency signals because the size of the antenna needs to be a fraction of the signal wavelength, which becomes large

- Even for wires, placing a signal in a given frequency band is useful to let different kinds of signals coexist on the channel

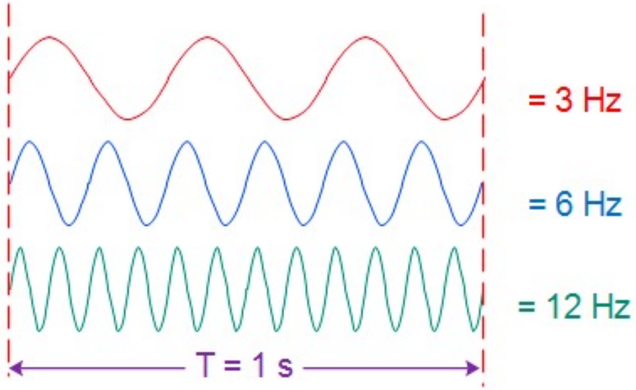
- This kind of transmission is called **passband transmission**

Carrier Signals

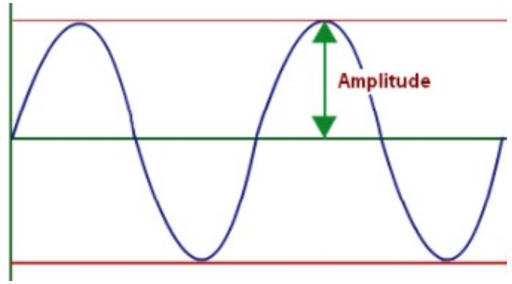
- A carrier is simply a signal oscillating at a desired frequency

- We can modulate it by changing the **amplitude** (size of the signal), **frequency** (speed of oscillation) or **phase** (position of the cycle)

Frequency



Amplitude



Phase

Passband Transmission

- Digital modulation is accomplished with passband transmission by regulating or modulating a carrier signal that sits in the passband
- We can modulate the amplitude, frequency, or phase of the carrier signal
- Each of these methods has a corresponding name
  - In **ASK (Amplitude Shift Keying)**, two different amplitudes are used to represent 0 and 1
  - With **FSK (Frequency Shift Keying)**, two or more different tones are used
  - In the simplest form of **PSK (Phase Shift Keying)**, the carrier wave is systematically shifted 0 or 180 degrees at each symbol period

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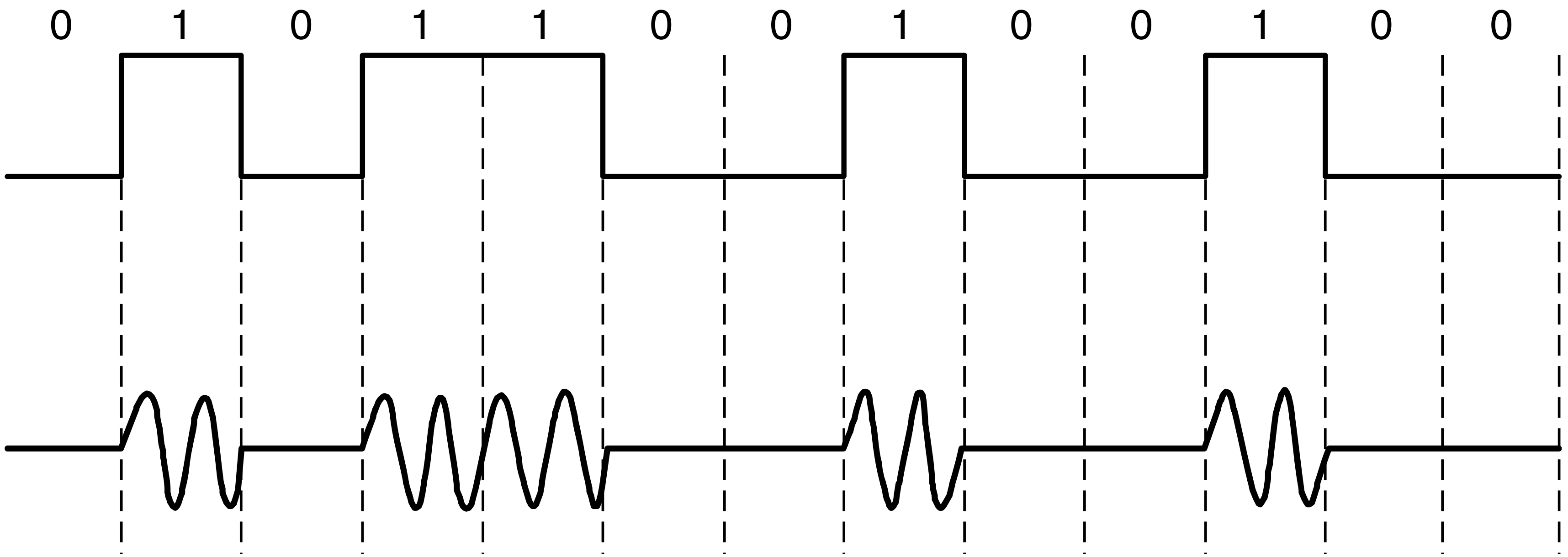
Amplitude Shift Keying

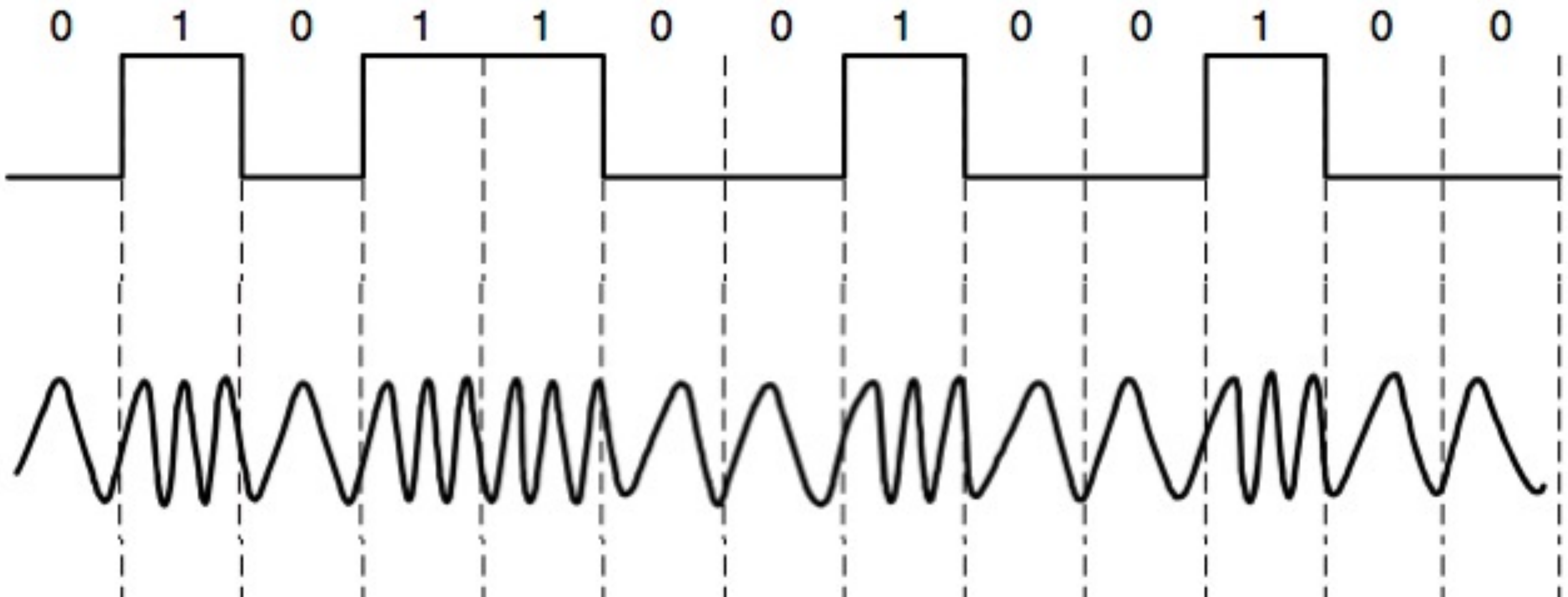
- In **ASK** two different amplitudes are used to represent 0 and 1

- In this example one of the amplitudes used is 0



Frequency Shift Keying

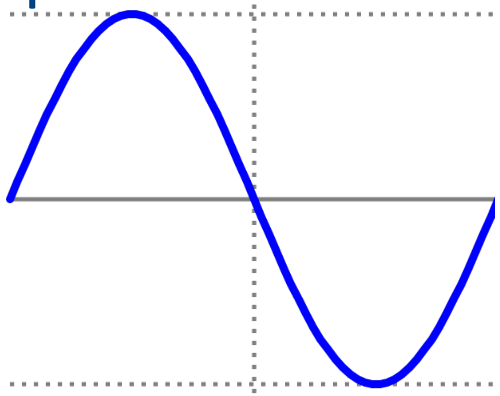
- In **FSK** two different frequencies are used to represent 0 and 1
- In this example a lower frequency is used for 0 and a higher frequency for 1



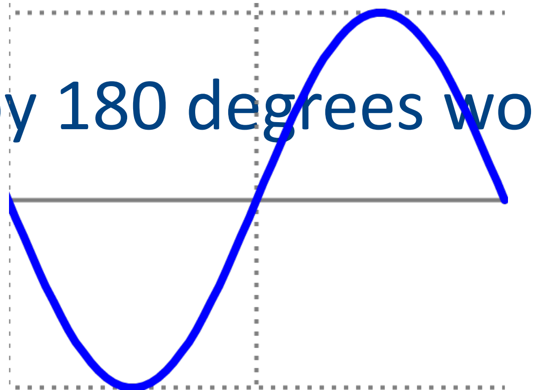
Phase

- Phase in a carrier signal refers to the position of the cycle within the time period

- If we think of the original signal as

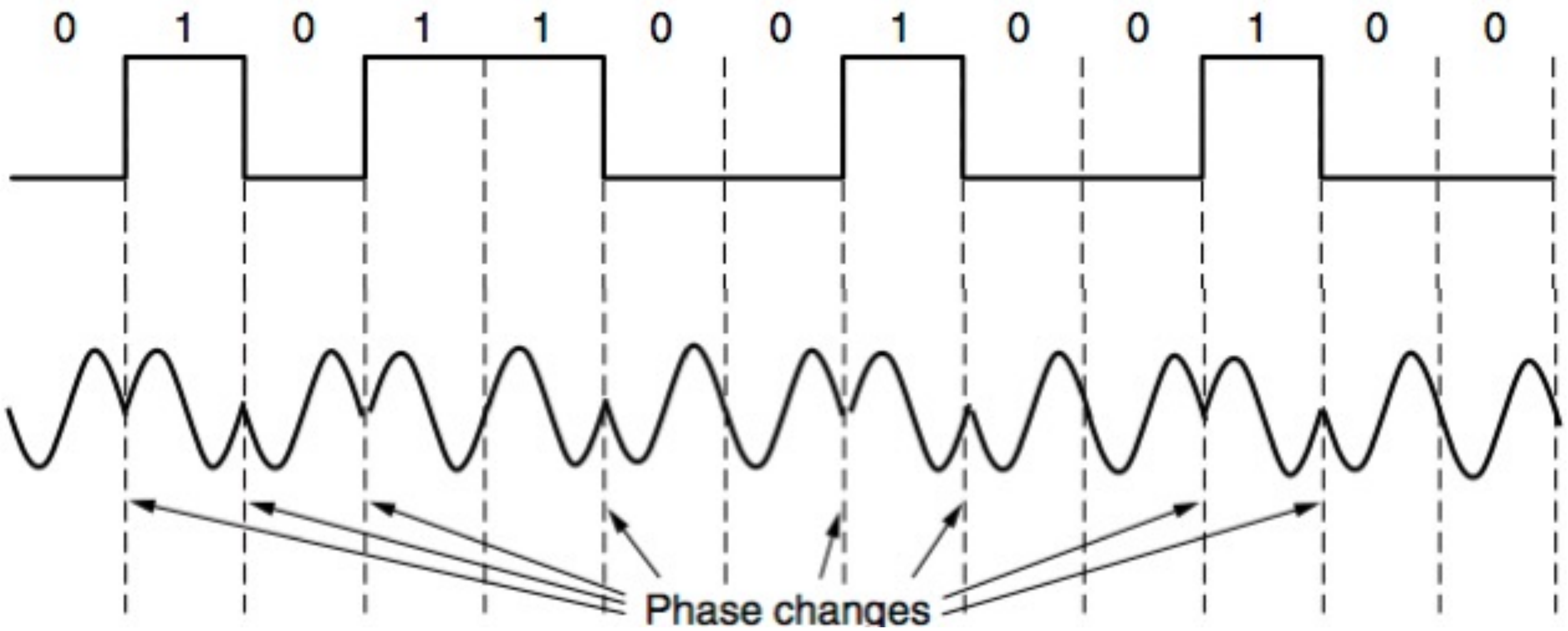


- Then one with a the phase shifted by 180 degrees would be



Phase Shift Keying

- In the simplest form of **PSK (Phase Shift Keying)**, the carrier wave is systematically shifted 0 or 180 degrees at each symbol period



Passband Transmission

- We can combine these schemes and use more levels to transmit more bits per symbol
- Only one of frequency and phase can be modulated at a time because they are related, with frequency being the rate of change of phase over time
- Usually, amplitude and phase are modulated in combination

Fundamental Limits

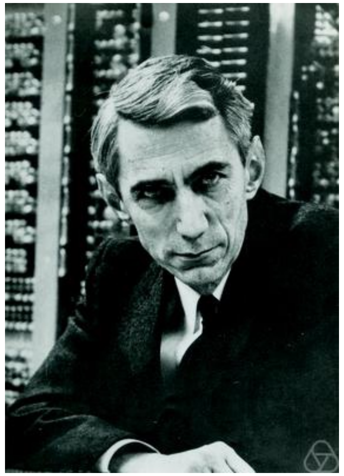
Fundamental Limits

- How fast can we send information over a link?

- There are two limits which have been calculated that give us an idea
  - The Nyquist limit
    - Discovered in 1924
  - The Shannon Capacity
    - Discovered in 1948

- Both of these limits determine how much information it is possible to send over a link

Harry Nyquist
American-Swedish Engineer



Claude Shannon
American Mathematician
Electrical Engineer

Key Channel Properties

- There are three key properties of communication channels that are represented in both calculations

- These are
  - Bandwidth (B)
  - Signal Strength (S)
  - Noise (N)

Bandwidth

- Bandwidth is the difference between the upper and lower frequencies in a continuous set of frequencies.
  - It is typically measured in hertz
- A key characteristic of bandwidth is that any band of a given width can carry the same amount of information, regardless of where that band is located in the frequency spectrum
  - It doesn’t matter if we use the frequencies 0 – 3 KHz or 12 – 15 KHz
- Bandwidth limits how fast we can change between states

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Signal Strength and Noise

- **Signal Strength** is the strength of the signal at the receiver
- **Noise** is also the amount of noise in a signal as measured at the receiver
- Signal Strength and Noise determine how many signal levels we can distinguish

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Nyquist Limit

- The Nyquist limit determines the maximum symbol rate for a communication link without noise
- A symbol is a wave that can represent a number of bits
- If we have a bandwidth of B the maximum symbol rate is 2B
- If we have V signal levels the maximum bit rate R is

$$R = 2B \log_2 V \quad bits/second$$

- E.g., a noiseless 3-kHz channel transmitting Binary signals (i.e., two levels)
  - cannot exceed a bit rate of 2 x 3000 x $\log_2(2)$ = 6000 bps

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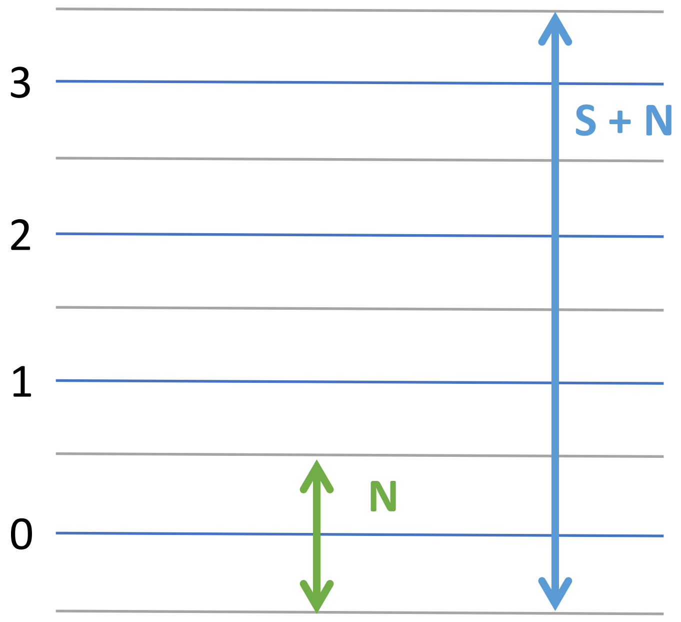
Shannon Capacity

- Shannon capacity tells us the maximum information carrying rate of a channel

- It is calculated based on the noise and signal strength
  - We calculate what is called the signal-to-noise ratio (SNR)

- SNR is given on a log-scale in decibels (dB) :
  - $SNR_{dB} = 10.\log_{10}(\frac{S}{N})$



Shannon Capacity

- The Shannon limit for capacity (C)
  - This is the maximum information carrying rate of the channel

- $C = B \log_2(1 + \frac{S}{N})$ bits/s

- Information cannot be transferred any faster than this rate

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Network Performance Measures

Network Performance Measures

In order to understand if a communication link is being fully use we have a number of performance measures

1. **Propagation delay**
   - The amount of time it takes a single bit to travel along the communication link
   - Measured in seconds
2. **Transmission time**
   - How long it takes to get a packet of data onto the communication link?
   - Measured in seconds
3. **Throughput**
   - How fast data can pass a certain point?
   - Measured in bits per second or packets per second
4. **Efficiency**
   - How well the communication link is being used?
   - Measured in percent

Network Performance Measures

- These measures are calculated based on a number of variables
  - Length of the signal path in the communication link **l**
    - Measured in meters
  - Signal propagation speed in the communication link **v**
    - Measured in meters per second
  - Average length of a frame or packet **L**
    - Measured in bits
  - Transmission rate **C**
    - Measured in bits per second

Propagation Delay

- **Length of the signal path** in the communication link **l**
- **Signal propagation speed** in the communication link **v**
- Average length of a frame or packet L
- Transmission rate C

- Propagation delay is calculated by dividing the length of the signal path in the communication link by the signal propagation speed

- Propagation delay = l / v

Transmission Time

- Length of the signal path in the communication link l
- Signal propagation speed in the communication link v
- **Average length of a frame or packet L**
- **Transmission rate C**

- Transmission time is calculated by dividing the average length of a packet by the transmission rate

- Transmission time = L / C

Throughput

- Throughput can be calculated for a single node in the network or for the whole network

- For a single node:
  - throughput is the number of packets it can transmit in a second multiplied by the length of the packet

- For the whole network:
  - throughput is the sum of the throughput of each node in the network

Efficiency

- The efficiency of a network is calculated based on the throughput
- Efficiency is measured as:
  - the current data throughput
  - a percentage of the maximum capacity of the network

Example 1

Consider an optical fiber 3000 km long with a transmitter transmitting at 1.5 Gbps (1 Giga bit per second = 1 000 000 000 bit per second).

The signal propagation speed in optical fiber is approximately 200 000 km/sec.

Suppose packet switching is being used with a packet length of 2000 bits.

- What is the propagation delay along the fiber?

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Example 1

Consider an optical fiber 3000 km long with a transmitter transmitting at 1.5 Gbps (1 Gbps = 1 000 000 000 bps). The signal propagation speed in optical fiber is approximately 200 000 km/sec. Suppose packet switching is being used with a packet length of 2000 bits.

- What is the propagation delay along the fiber?
  - propagation delay = l / v
  - propagation delay = 3 000 000 (m) / 200 000 000 (m/sec)
  - propagation delay = 0.015 (s) = (15 ms)
- What is the packet transmission time?

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Example 1

Consider an optical fiber 3000 km long with a transmitter transmitting at 1.5 Gbps (1 Gbps = 1 000 000 000 bps). The signal propagation speed in optical fiber is approximately 200 000 km/sec. Suppose packet switching is being used with a packet length of 2000 bits.

- What is the propagation delay along the fiber?
    - propagation delay = l / v
    - propagation delay = 3 000 000 (m) / 200 000 000 (m/sec)
    - propagation delay = 0.015 (s) = (15 ms)

- What is the packet transmission time?
    - packet transmission time = L / C
    - packet transmission time = 2 000 (bit) / 1 500 000 000 (bit/s)
    - packet transmission time = 0.0000013333 (s) = 1.3333 (µs)

Example 1

Consider an optical fiber 3000 km long with a transmitter transmitting at 1.5 Gbps (1 Gbps = 1 000 000 000 bps). The signal propagation speed in optical fiber is approximately 200 000 km/sec. Suppose packet switching is being used with a packet length of 2000 bits.

- How many packets have been transmitted and are propagating over the fiber when the first bit reaches the destination ?

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Example 1

Consider an optical fiber 3000 km long with a transmitter transmitting at 1.5 Gbps (1 Gbps = 1 000 000 000 bps). The signal propagation speed in optical fiber is approximately 200 000 km/sec. Suppose packet switching is being used with a packet length of 2000 bits.

- How many packets have been transmitted and are propagating over the fiber when the first bit reaches the destination ?
  - # propagated packets = propagation delay / packet transmission time
  - # propagated packets = 0.015 (s) / 1.3333 x 10^{-6} (s) = 11 250 packets
    - Note that this is 22 500 000 bits

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Example 2

Consider a route in a store-and-forward network going through 8 intermediate nodes.

The packets contain 1000 bits and are transmitted at 64 kbps.

Assume propagation delays over the links are 0.

As a packet travels along the route, it encounters an average of 5 packets when it arrives at each node.

- How long does it take for the packet to get to the receiver if the nodes transmit on a “first come first served” basis ?

Example 2

At each intermediate node, 6 packets must be transmitted in order for “our” packet to be transmitted: our packet finds 5 packets ahead of it, which will be transmitted first due to the “first come first served” policy.

- The packet transmission time at every node is
  - packet transmission time = L / C
  - packet transmission time = 1 000 (bit) / 64 000 (bit/s) =
  - packet transmission time = 0.015625 (s) = 15.625 (ms)

- The total travel time for our packet through the network is the transmission time at the sender plus 8 times the delay at each intermediate node
  - total travel time = packet transmission time + [number of intermediate nodes x number of packets x packet transmission time] = 750 milliseconds
  - total travel time = 0.015625 (s) + [8 x 6 x 0.015625 (s)]
  - total travel time = 0.765625 (s) = 765.625 (ms)

Example 2

- Note that the “pure” transmission delays only account for
  - pure transmission delay = packet transmission time + [8 x packet transmission time]
  - pure transmission delay = 0.015625 (s) + [8 x 0.015625 (s)]
  - pure transmission delay = 0.140625 (s) = 140.625 (ms)

- Our packet must endure a queuing delay at each intermediate node of
  - node queueing delay = 5 x packet transmission time
  - node queueing delay = 5 x 0.015625 (s) = 0.078125 (s) = 78.125 (ms)

- Because there are 8 intermediate nodes, the total queuing delay is
  - total queueing delay = 8 x node queueing delay =
  - total queueing delay = 8 x 0.078125 (s) = 0.625 (s) = 625 (ms)

- This represents just over 80% of the total travel time

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Queuing Delay

- Queuing delay can account for a substantial “extra” delay experienced by packets in the network.
- One way to reduce this queuing delay form some packets would be to use a different policy in the intermediate nodes, rather than first-come-first-served.
- This could result in some “higher-priority” packets getting to their receivers much quicker, while “lower-priority” packets would experience longer delays.

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Example 3

- 150 nodes are connected to a 1000 meter length of coaxial cable. Using “some protocol”, each node can transmit 70 packet/second, where each packet is 1000 bits long. The transmission rate at each node is 100 Mbps.

- What is the per-node throughput?

Example 3

- 150 nodes are connected to a 1000 meter length of coaxial cable. Using some protocol, each node can transmit 70 packet/second, where each packet is 1000 bits long. The transmission rate at each node is 100 Mbps.

- What is the per-node throughput?
  - node throughput = 70 (packet/s) x 1000 (bit) = 70 000 bps

- What is the total throughput (of the 150 nodes)?

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- What is the per-node throughput?
  - node throughput = 70 (packet/s) x 1000 (bit) = 70 000 bps

- What is the total throughput (of the 150 nodes)?
  - Total throughput = 150 x node throughput = 10 500 000 bps = 10.5 Mbps

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Example 3

- 150 nodes are connected to a 1000 meter length of coaxial cable. Using some protocol, each node can transmit 70 packets/second, where each packet is 1000 bits long. The transmission rate at each node is 100 Mbps.

- What is the total throughput (of the 150 nodes)?
  - Total throughput = 150 x node throughput = 10 500 000 bps = 10.5 Mbps

- What is the efficiency of this protocol?
  - efficiency = total throughput (bps) x bit transmission time (s)
  - = 10 500 000 x (1 / 100 000 000) = 0.105 or 10.5%

Network Efficiency

- What would give us 100% efficiency, and why is the efficiency so far below 100% in our example?
- To reach 100% efficiency there would always have to be someone transmitting “data” all of the time
- However the protocol used to decide who's turn it is to transmit introduces some delays
  - This is either because it permits collisions to occur, which must be recovered from; or because some “permission to transmit” token must be passed
- These delays result in a drop in efficiency