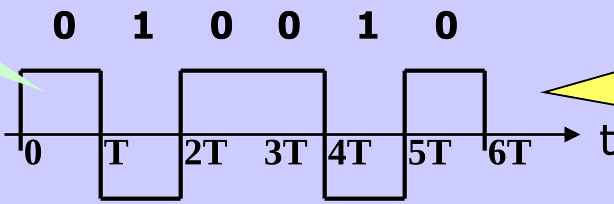
Modulation and Multiplexing

How to send data fast and far?

- 2-Values & Multi-Values Encoding, and Baud Rate & Bit Rate
- Nyquist Theorem – Relationship between Speed & Bandwidth
- Shannon Theorem – Relationship between Speed & Noise
- Digital Encoding
- Carrier, Modulation, Demodulation and Modem
  - Digital Modulations: FSK, ASK, PSK, QAM
- Multiplexing and Demultiplexing
  - FDM (Frequency Division Multiplexing)
  - TDM (Time Division Multiplexing)
  - WDM (Wave Division Multiplexing)
  - CDMA (Code Division Multiple Access)

Increase Digital Signal Transmission Speed

Pulse (2-values)
M=2, interval=T

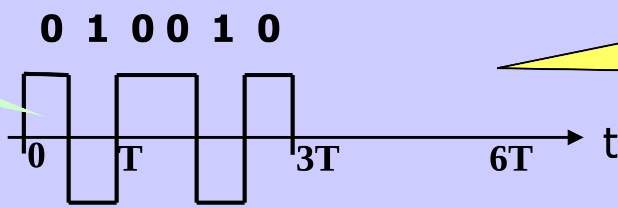


bit rate = 1/T
unit: **bps**
bits per second

baud rate:
pulses per sec.
→ **Baud**
= **bps** if M=2

...010010 → Encoder Sender → Transmission System/Channel → Decoder Receiver →

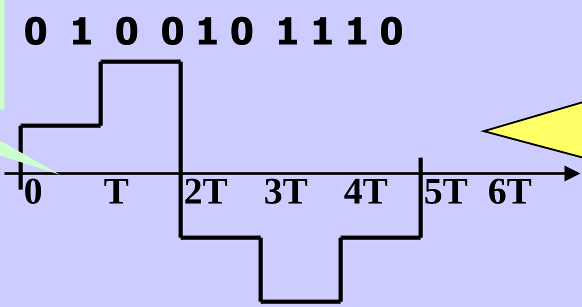
Pulse (2-values)
M=2, half T



Increase bit rate by reducing T

Minimum T?

Pulse (4-values)
M=4, interval=T



Increase bit rate by increasing $M=2^n$
M-values encoding
1 pulse = $\log_2 M$ bits
= n bits

Maximum M?

1 Baud = n***bps**

Harry Nyquist

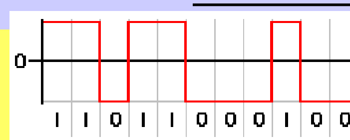
Born: February 7, 1889, Sweden
Died: April 4, 1976, Texas, USA
Institutions: Bell Laboratories, AT&T
Known for
-- Nyquist sampling theorem
-- Nyquist rate
-- Johnson–Nyquist noise
-- Nyquist stability criterion
-- Nyquist ISI criterion
-- Nyquist filter

Basic Question:

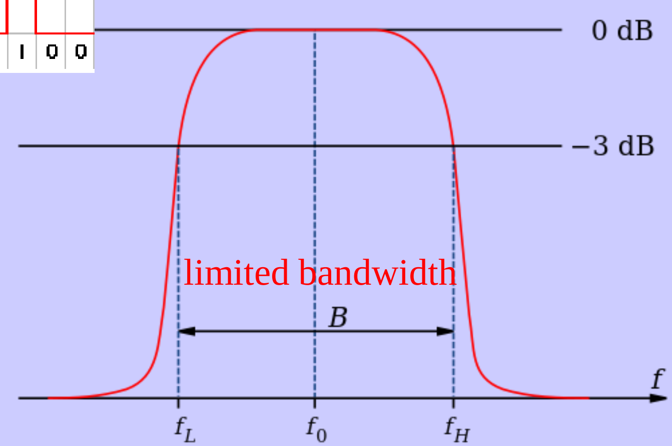
-- How many pulses could be transmitted per second, and recovered, through a channel/system of limited bandwidth B?

Nyquist's Paper:

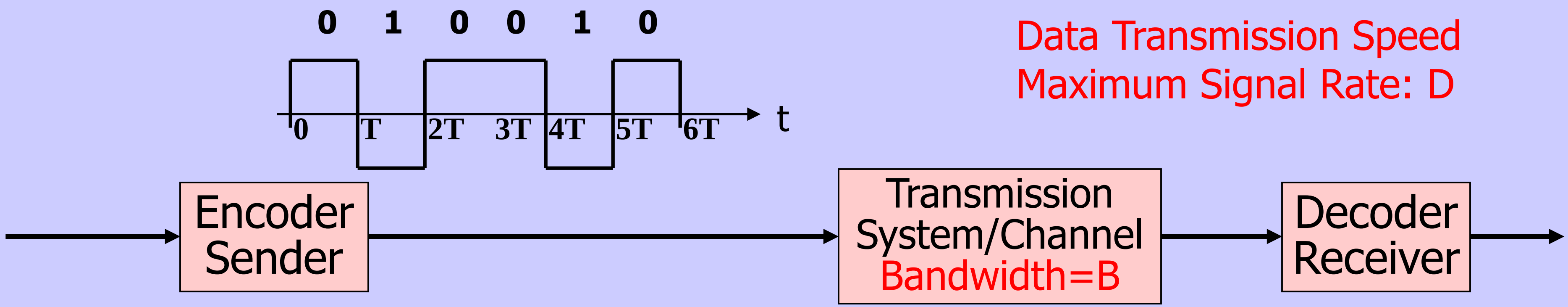
-- Certain topics in telegraph transmission theory, Trans. AIEE, vol. 47, Apr. 1928



Transmission System/Channel



Nyquist Theorem
Relationship between Transmission Speed and System Bandwidth



Nyquist Theorem:

1) Given a system/channel bandwidth B, the minimum **T=1/2B**, i.e., the maximum signal rate

D=2B pulses/sec (baud rate, Baud) = 2B$\log_2$M bits/sec (bit rate, bps)

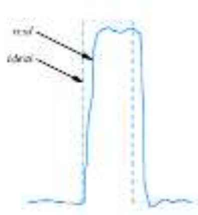
2) To transmit data in bit rate D, the minimum bandwidth of a system/channel must be

B>=D/2$\log_2$M (Hz)

Maximum M?

Explanations:

A hardware cannot change voltages so fast because of its physical limitation



$T\downarrow \Longrightarrow F\uparrow$

Questions:

1) Assume a telephone channel bandwidth B=3000Hz and M=1024, what's its maximum rate?

2) Can we use the above channel to send a TV signal in real time? Why?

Claude Shannon

Born: April 30, 1916, Michigan
Died: February 24, 2001, Massachusetts
Fields: Mathematics & electronic engineering
Institution: Bell Laboratories
Known for
-- Information theory
-- Shannon–Fano coding
-- Noisy channel coding theorem
-- Computer chess, Cryptography
. . . . . .

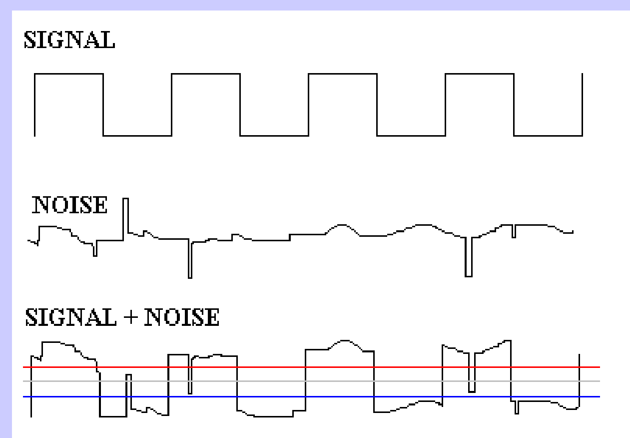
Basic Question:

-- How do bandwidth and noise affect the transmission rate at which information can be transmitted over an channel?

Shannon's Paper:

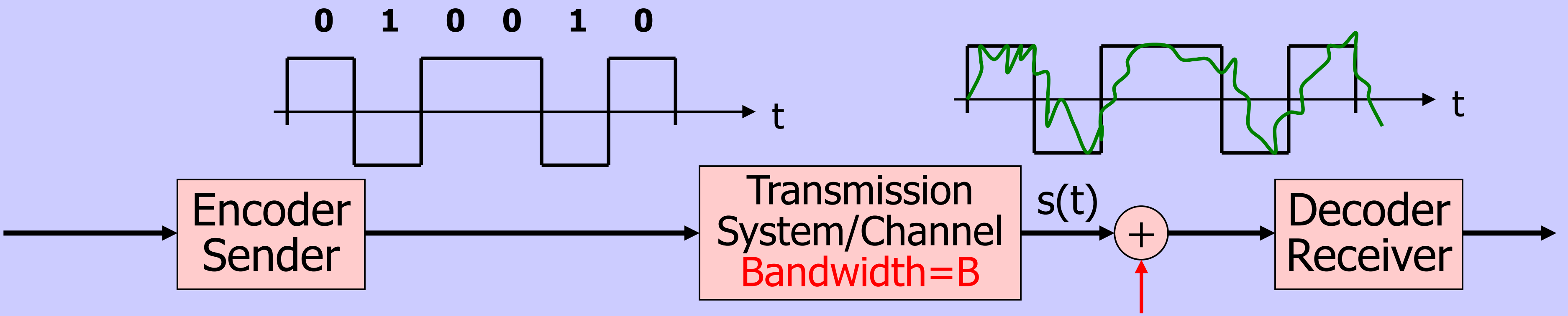
-- Communication in the presence of noise. Proc. Institute of RE. vol. 37, 1949

Transmission System/Channel



Shannon Theorem

Relationship between Transmission Speed and Noise



Maximum Signal Rate
Data Transmission Speed
Channel Capacity

$S/N = s^2(t)/n^2(t)$
$= 10\log_{10} S/N$ (dB, decibel)
called signal-to-noise ratio

Shannon Theorem:

1) Given a system/channel bandwidth B and signal-to-noise ratio S/N, the maximum value of M = (1+S/N) when baud rate equals B, and its channel capacity is,

$C = B\log_2(1+S/N)$ bits/sec (bps, bite rate)

2) To transmit data in bit rate D, the channel capacity of a system/channel must be

$C >= D$

Two theorems give upper bounds of bit rates implement-able without giving implemental method.

Channel Capacity

Nyquist-Shannon theorem $C = B\log_2(1+S/N)$ shows that the maximum rate or channel Capacity of a system/channel depends on bandwidth, signal energy and noise intensity. Thus, to increase the capacity, three possible ways are

1) increase bandwidth; 2) raise signal energy; 3) reduce noise

Examples

1. For an extremely noise channel $S/N \rightarrow 0$, $C \rightarrow 0$, cannot send any data regardless of bandwidth

2. If $S/N=1$ (signal and noise in a same level), $C=B$

3. The theoretical highest bit rate of a regular telephone line where B=3000Hz and S/N=35dB.

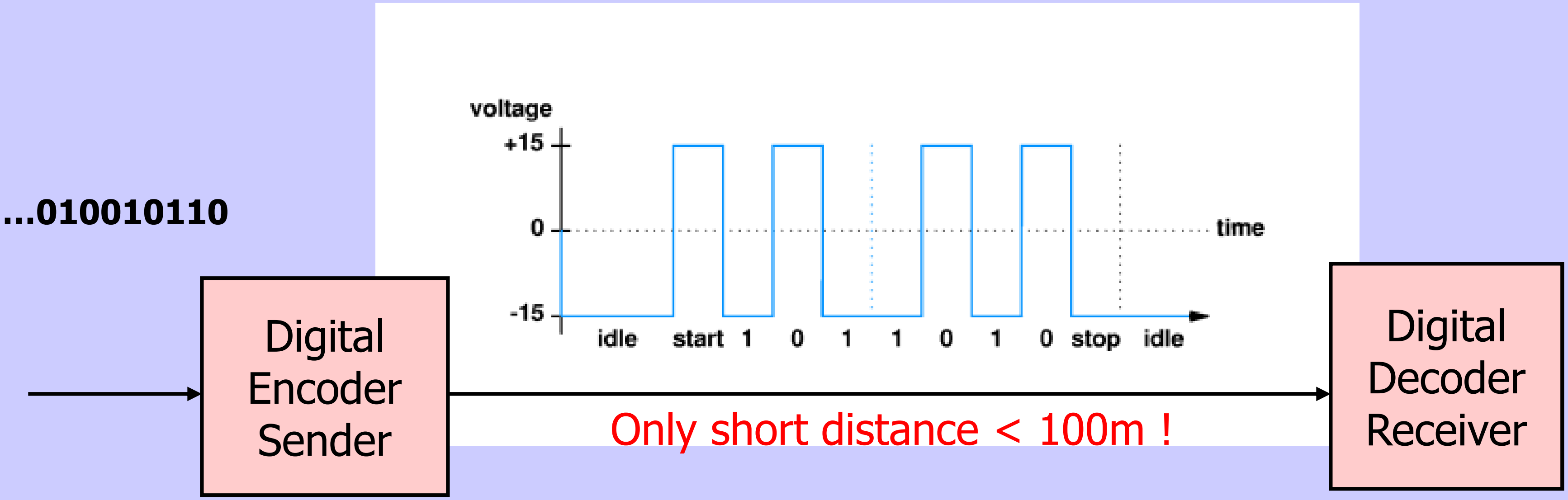
$$10\log_{10}(S/N)=35 \rightarrow \log_2(S/N)= 3.5\text{x} \log_2 10$$

$$C= B\log_2(1+S/N) \approx B\log_2(S/N) =3000\text{x}3.5\text{x} \log_2 10=34.86 \text{ Kbps}$$

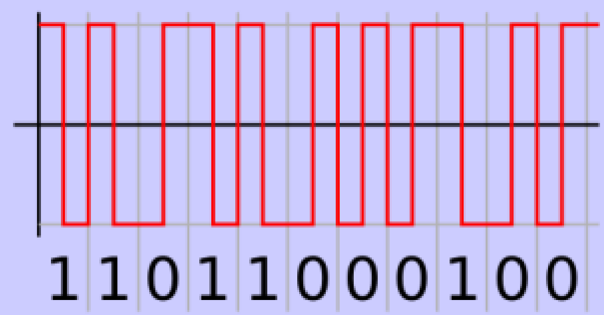
If B is fixed, we have to increase signal-to-noise ration for increasing transmission rate.

Shannon theorem tell us that we cannot send data faster than the channel capacity, but we can send data through a channel at the rate near its capacity. However, it has not told us any method to attain such transmission rate of the capacity.

Digital Encoding



Encoding Schemes:
- RZ (Return to Zero)
- NRZ (Non-Return to Zero)
  - # NRZ-I, NRZ-L (RS-232, RS-422)
  - # AMI (ISDN)
- Biphase
  - # Manchester & D-Manchester (LAN)
  - # B8ZS, HDB3



Manchester encoding

Carrier and Modulation

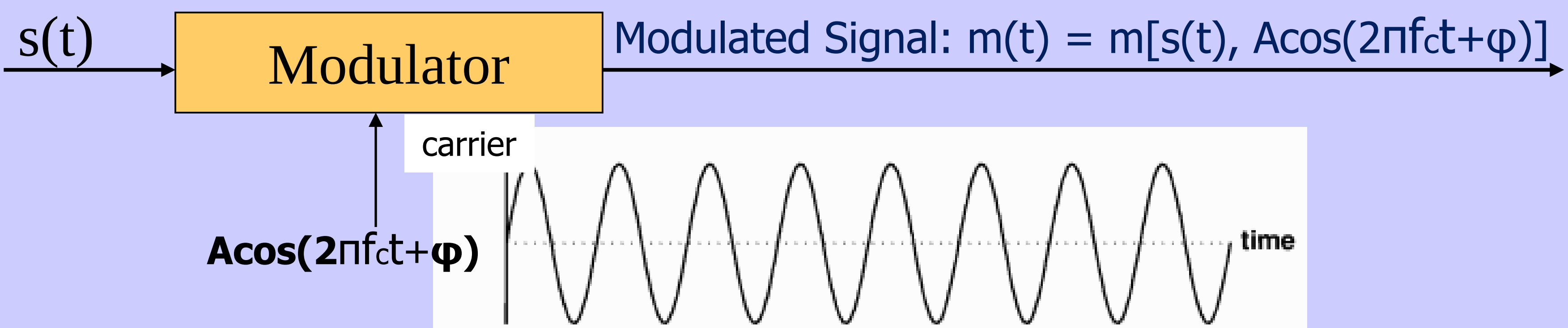
Important facts:

- The **RS-232** connects two devices in a **short distance** (<15m).
- It cannot be propagated far because its **signal energy rapidly becomes weak** with the increase of transmission distance.
- A **sine wave can propagate farther**. The sine wave is an analogy signal.
- A signal can be **carried by the sine wave**, called **carrier**, **for long distance**.

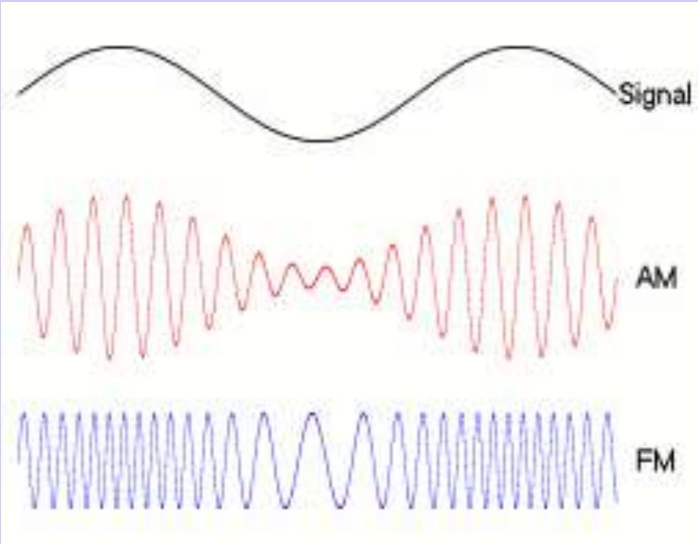
Carrier: **$A\cos(2\pi f_c t+\varphi)$** where f_c is called **carrier frequency**

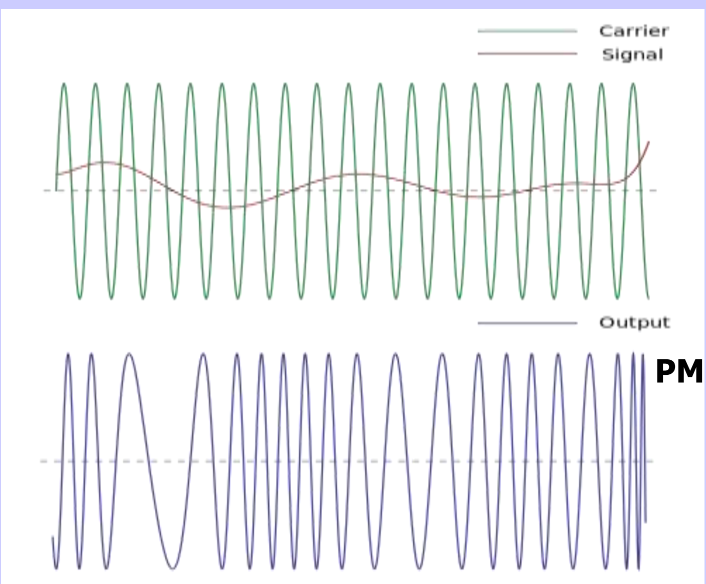
Modulation: change or modify values of **A,** f_c, **φ** according to input signal **s(t)**

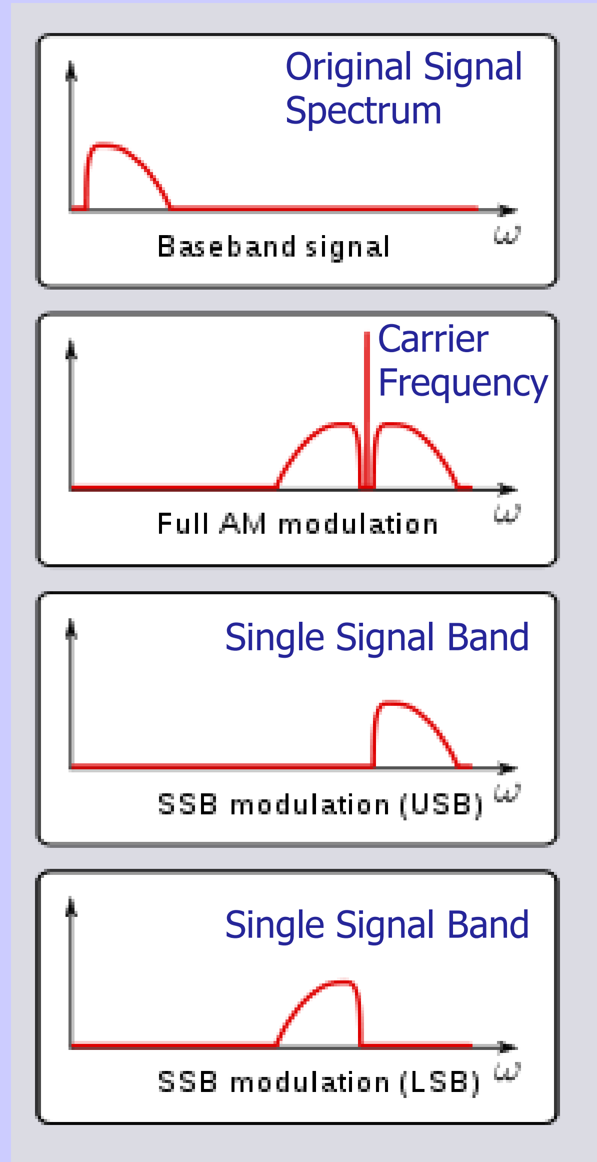
- **modify A → A[s(t)]: A**mplitude **M**odulation **(AM)**
- **modify** f_c → f_c**[s(t)]: F**requency **M**odulation **(FM)**
- **modify φ → φ[s(t)]: P**hase **M**odulation **(PM)**



Modulated Wave/Signal and Spectrum

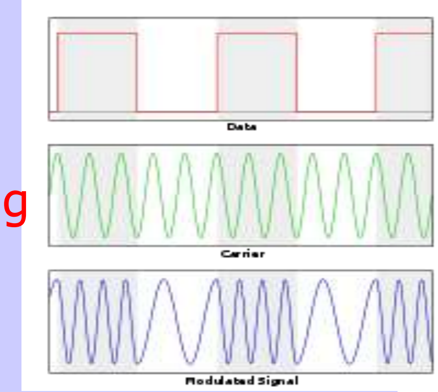






Digital Modulation

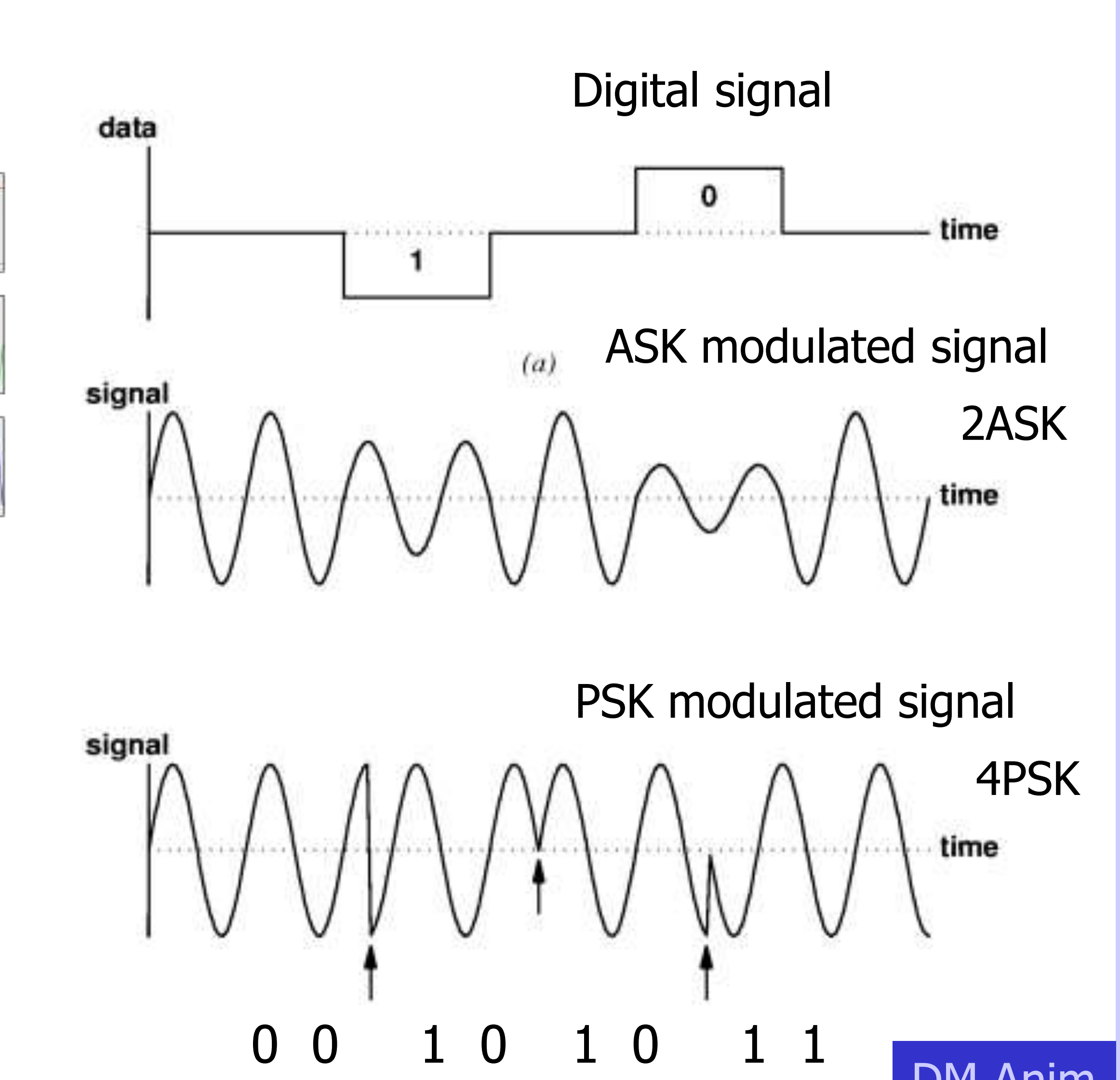
Digital Modulation
input: digital signal
output: analogy signal



FSK – Frequency Shift Keying

ASK – Amplitude Shift Keying
2-ASK
0: $A_1\cos 2\pi f_c t$
1: $A_2\cos 2\pi f_c t$

PSK – Phase Shift Keying
4-PSK
00: $A\cos(2\pi f_c t + 0)$
01: $A\cos(2\pi f_c t + \pi/2)$
10: $A\cos(2\pi f_c t + \pi)$
11: $A\cos(2\pi f_c t + 3\pi/2)$



DM Anim

QAM – Quadrature Amplitude Modulation

QAM: a combinational modulation of amplitude and phase

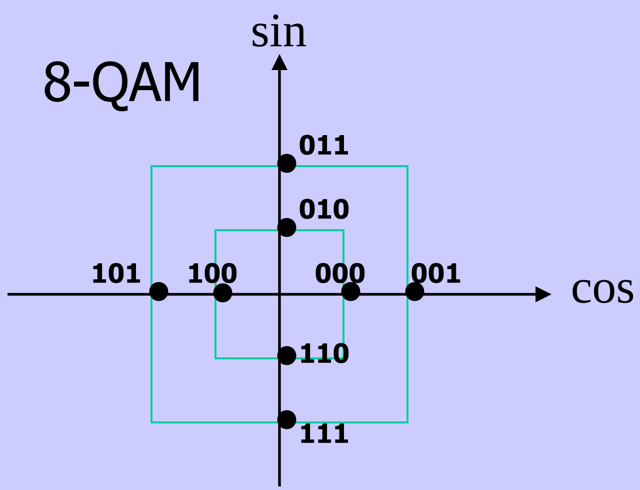
$$m(t) = A[s(t)] \cos\{2\pi f_c t+\varphi[s(t)]\} = p(t) \cos(2\pi f_c t) + q(t) \sin(2\pi f_c t)$$

π/4 (90°) phase difference between cos(x) and sin(x), called quadrature

QAM is currently more common in digital communications

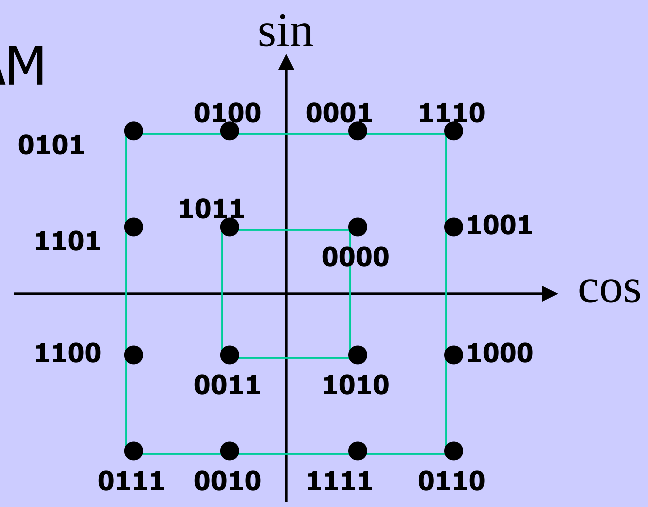
4-QAM, 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM, 256-QAM, 512-QAM, …

8-QAM



bit_rate = 3 x baud _rate

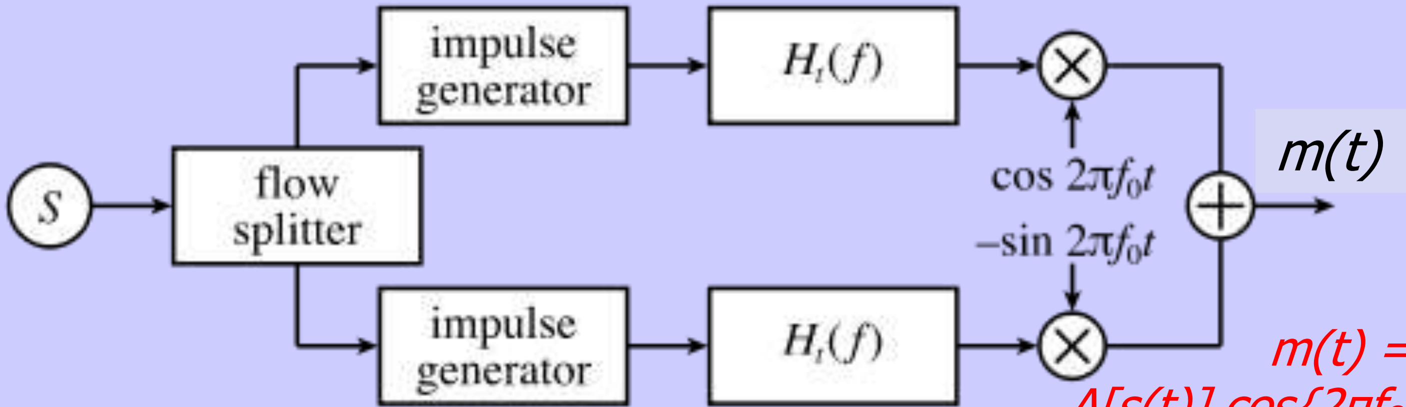
16-QAM



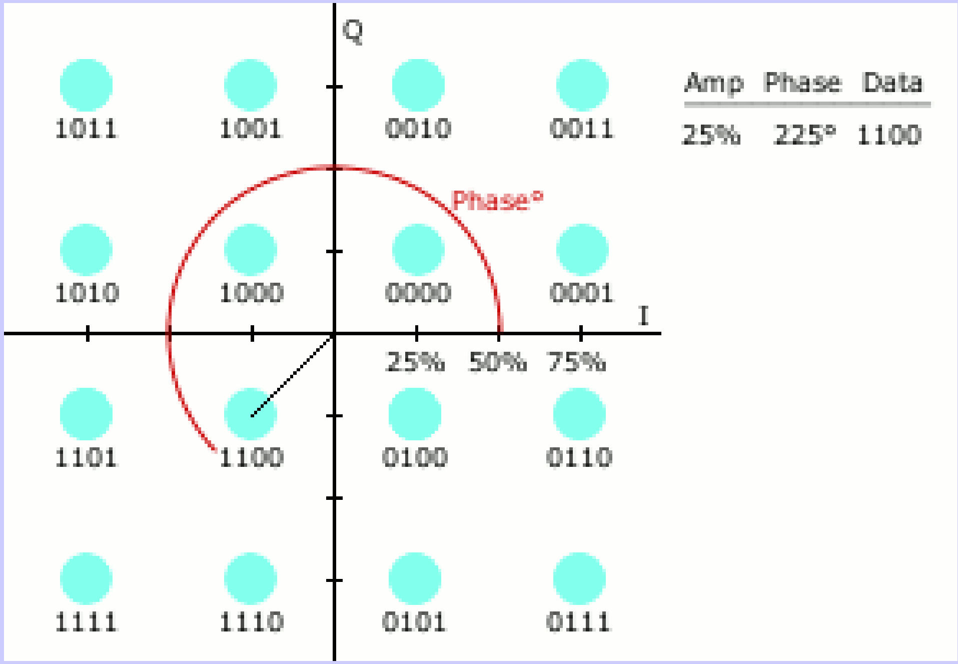
bit_rate = 4 x baud _rate

QAM Vid

QAM Transmitter and Demo



m(t) =
A[s(t)] cos{2πfct+φ[s(t)]}

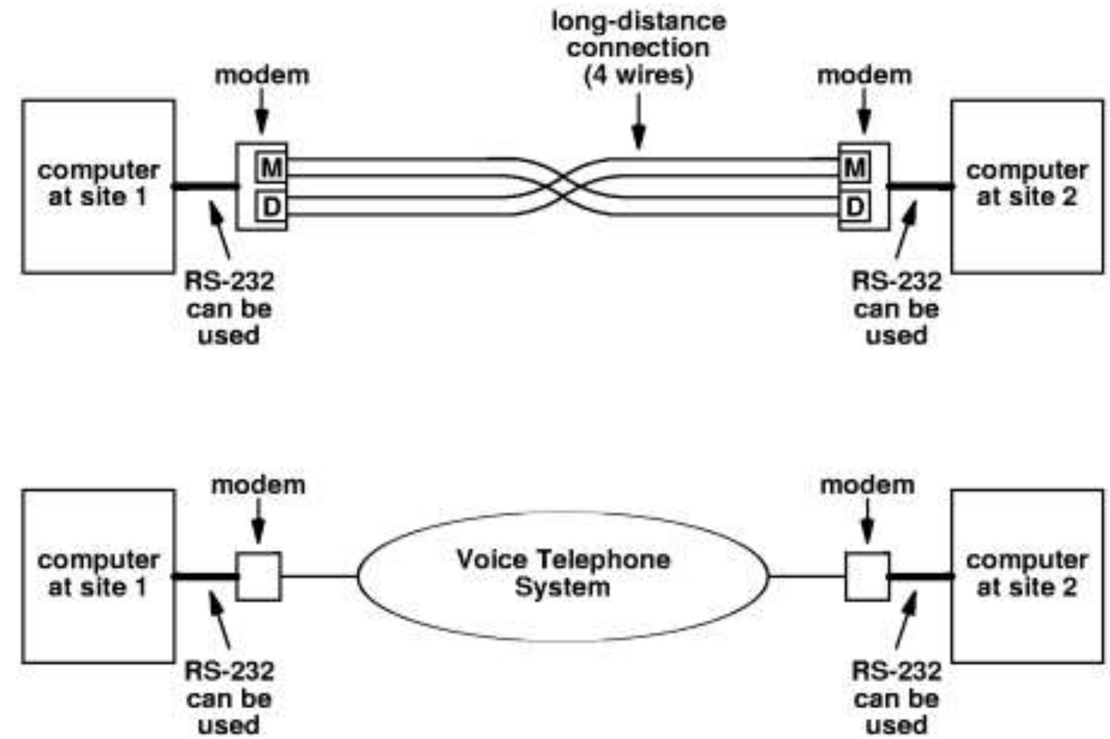


Modulator, Demodulator and Modem

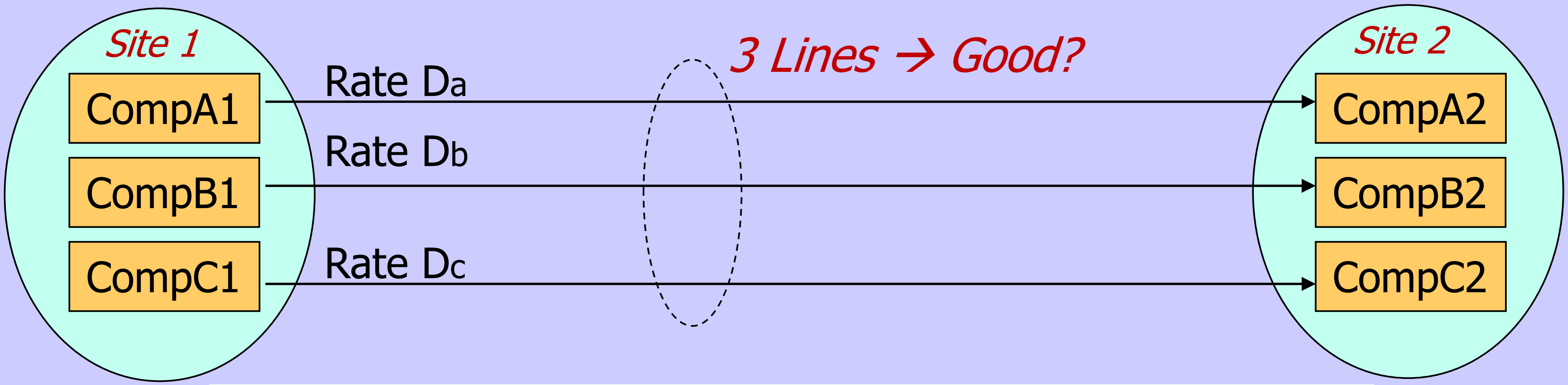
Modulator: accept bit sequence and modulate a carrier

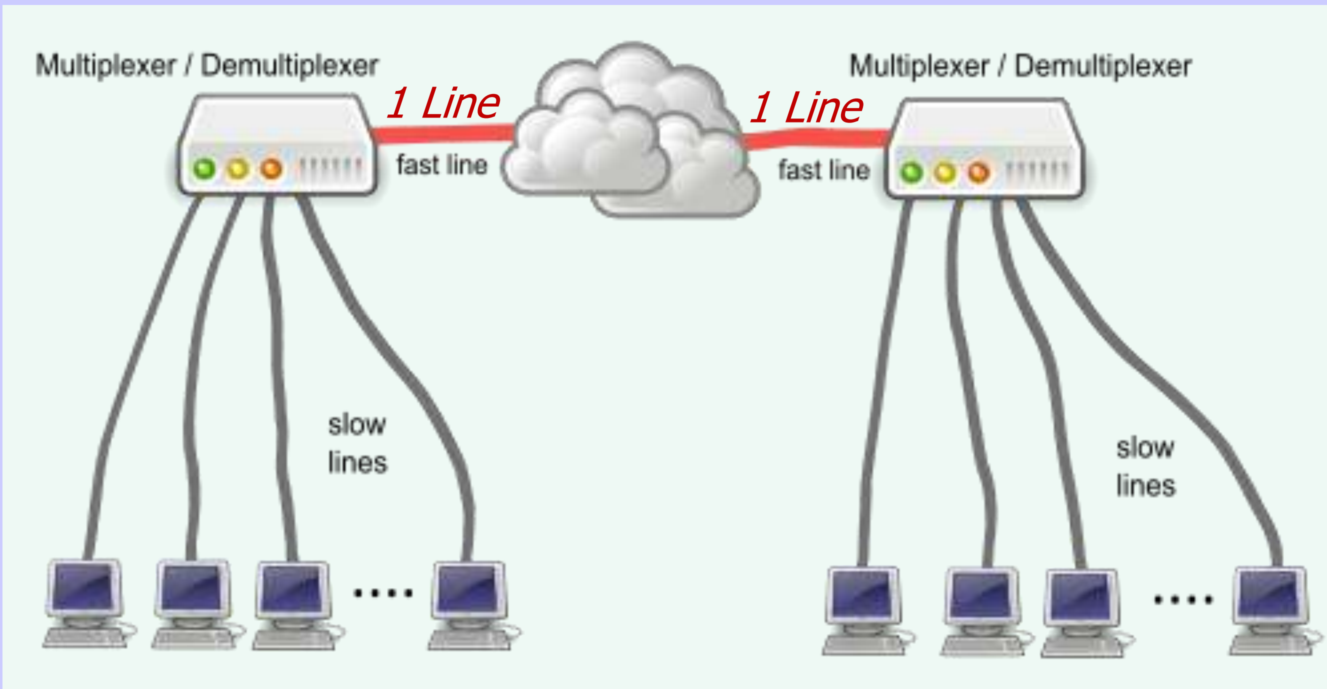
Demodulator: accepted a modulated signal, and recreated bit sequence

Modem: a single device = modulator + demodulator



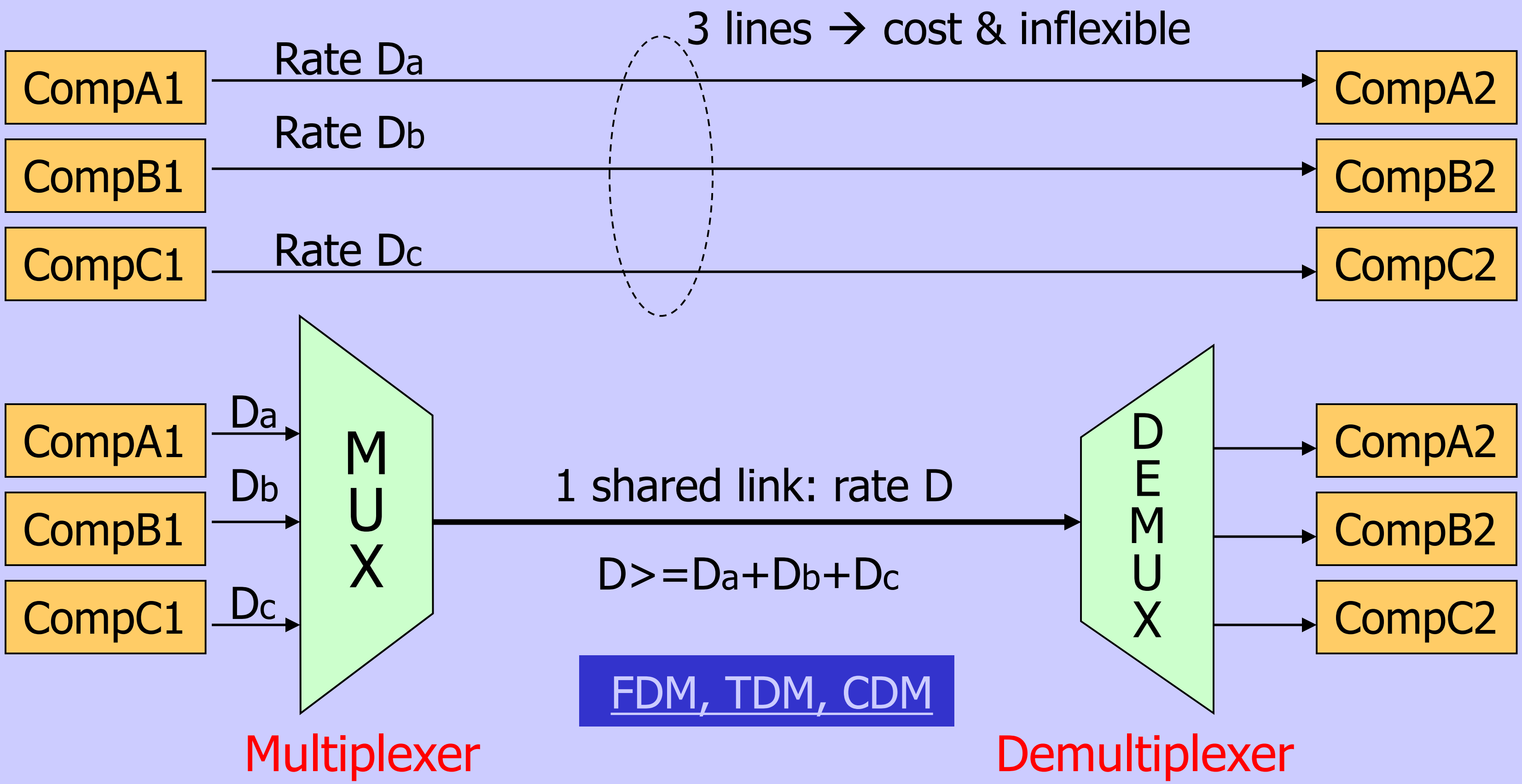
How to send data efficiently?





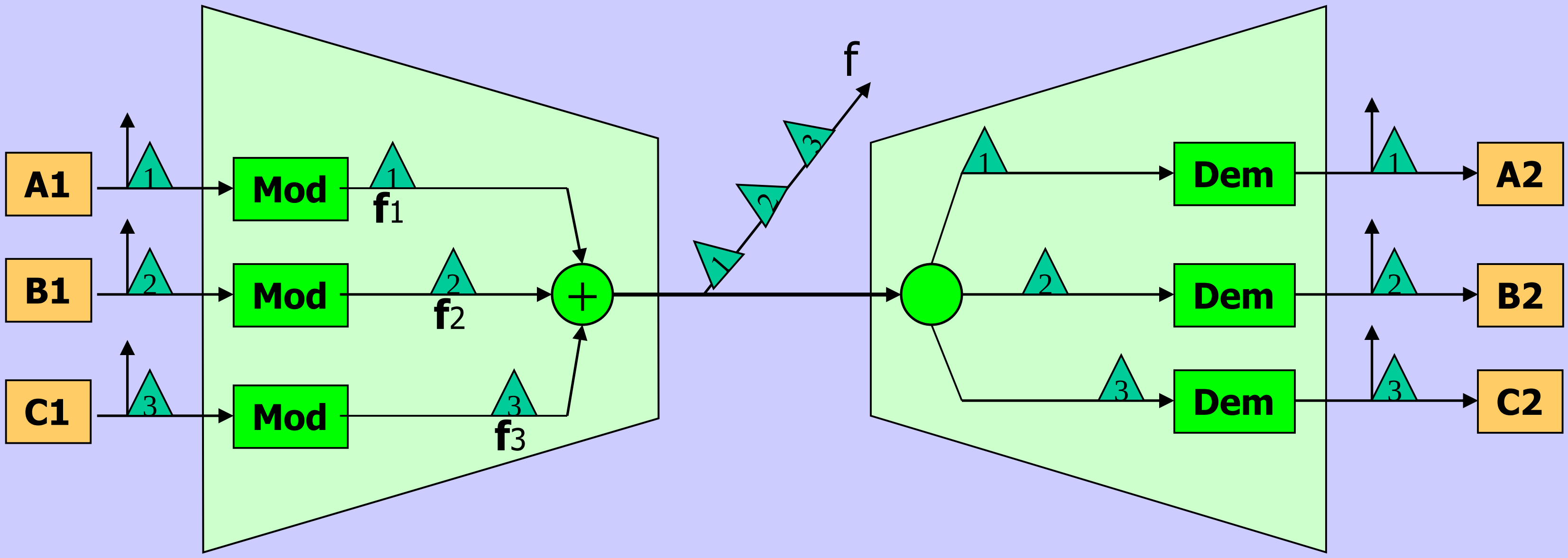
Multiplexing, Multiplexer and Demultiplexer

Multiplexing is the set of techniques that allows simultaneous transmissions of multiple signals across a single data link.



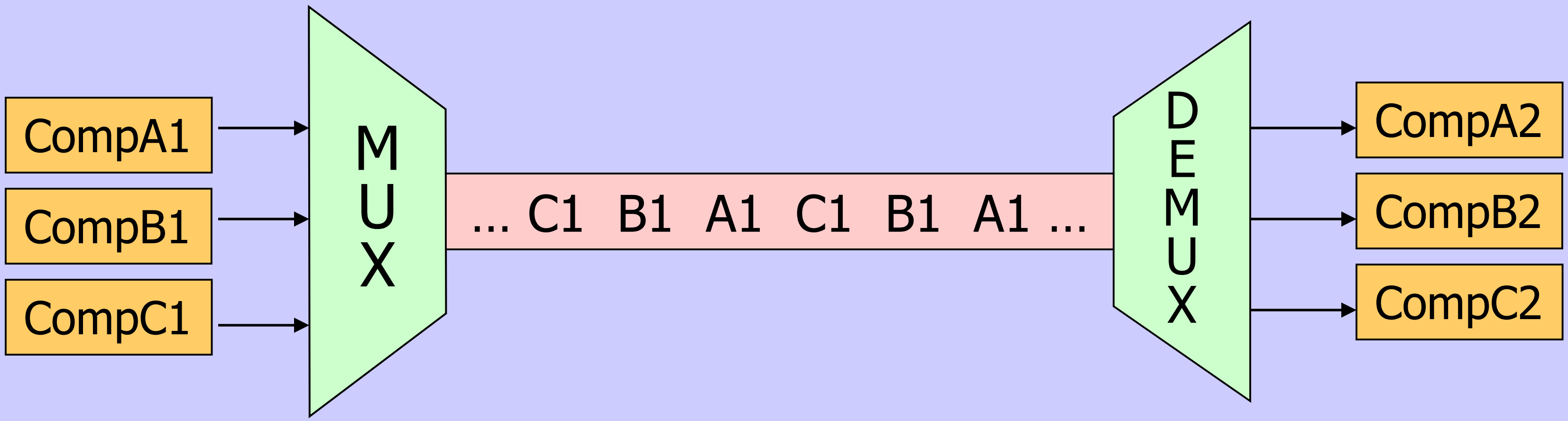
FDM – Frequency Division Multiplexing

FDM: - A set of signals are put in different frequency positions of a link/medium
- Bandwidth of the link must be larger than a sum of signal bandwidths
- Each signal is modulated using its own carrier frequency
- Examples: radio, TV, telephone backbone, satellite, …



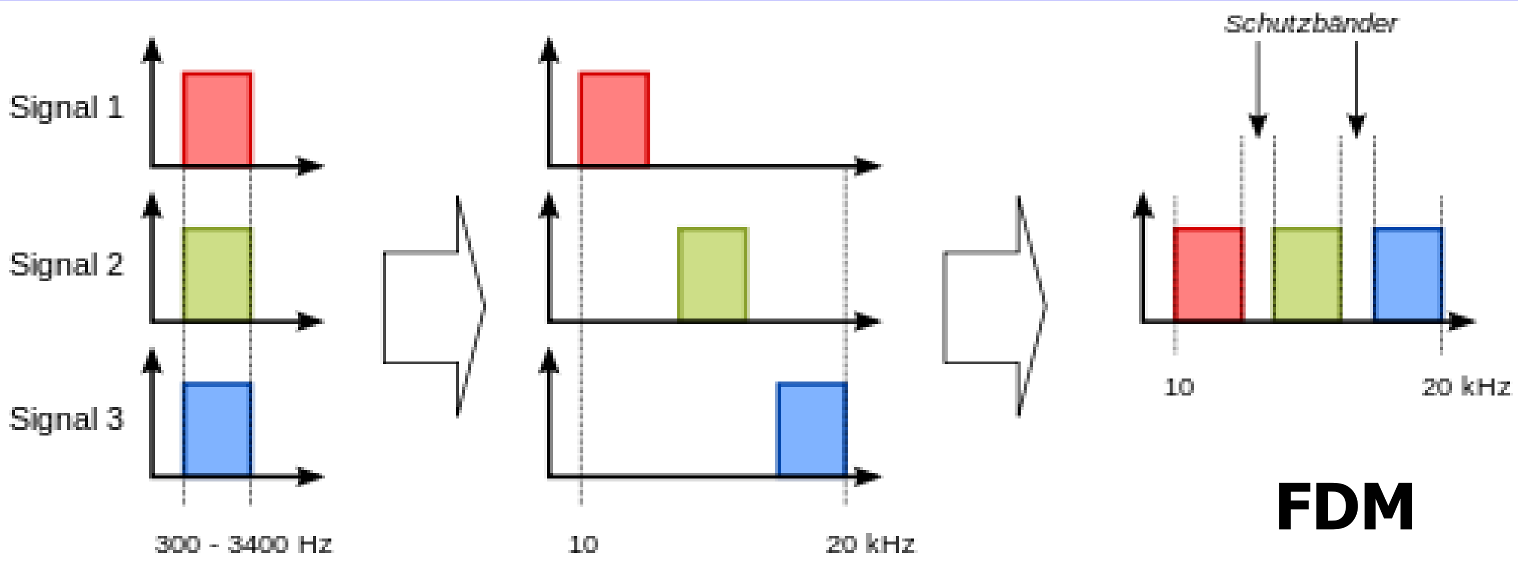
TDM – Time Division Multiplexing

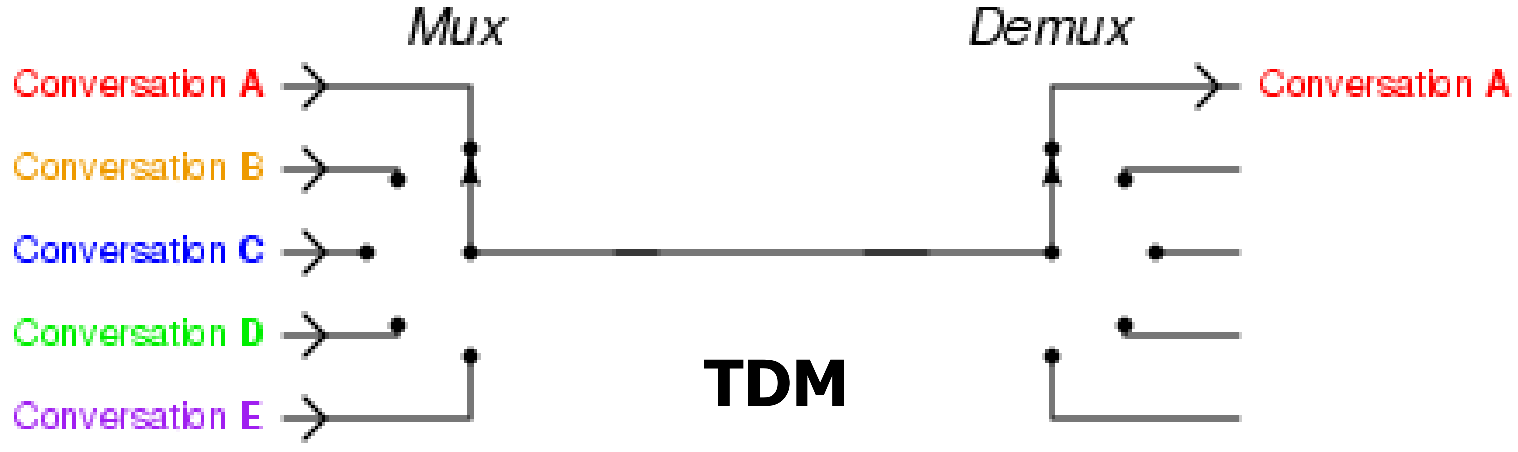
TDM:
- Multiple data streams are sent in different time in single data link/medium
- Data rate of the link must be larger than a sum of the multiple streams
- Data streams take turn to transmit in a short interval
- widely used in digital communication networks



Anim1, Anim2

Examples of FDM and TDM

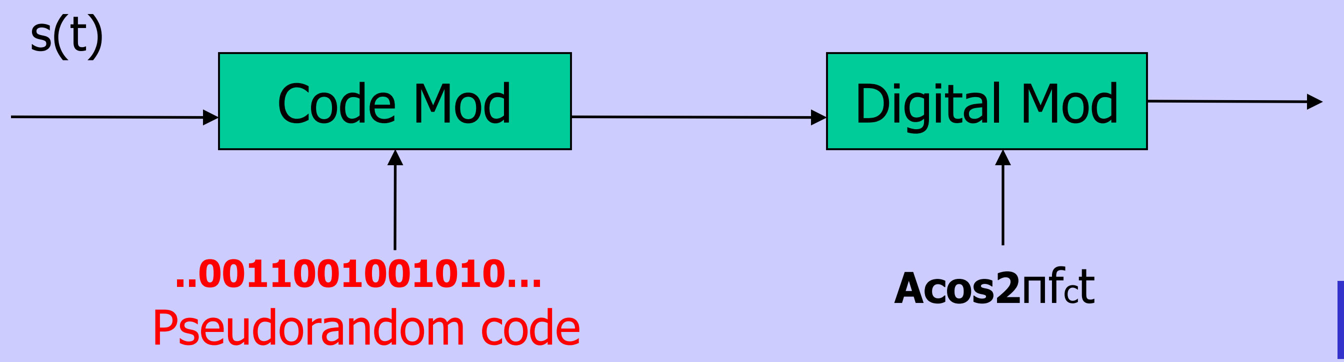




Wave Division Multiplexing (WDM) and Spread Spectrum

WDM: - conceptually the same as FDM
- using visible light signals (color division multiplexing)
- sending multiple light waves across a single optical fiber

Spread Spectrum:
- spread the signal over a wider bandwidth for reliability and security
- its carrier frequency is not fixed and dynamically changed
- such changes is controlled by a pseudorandom 0/1 sequence (code)
- the signal is represented in code-domain

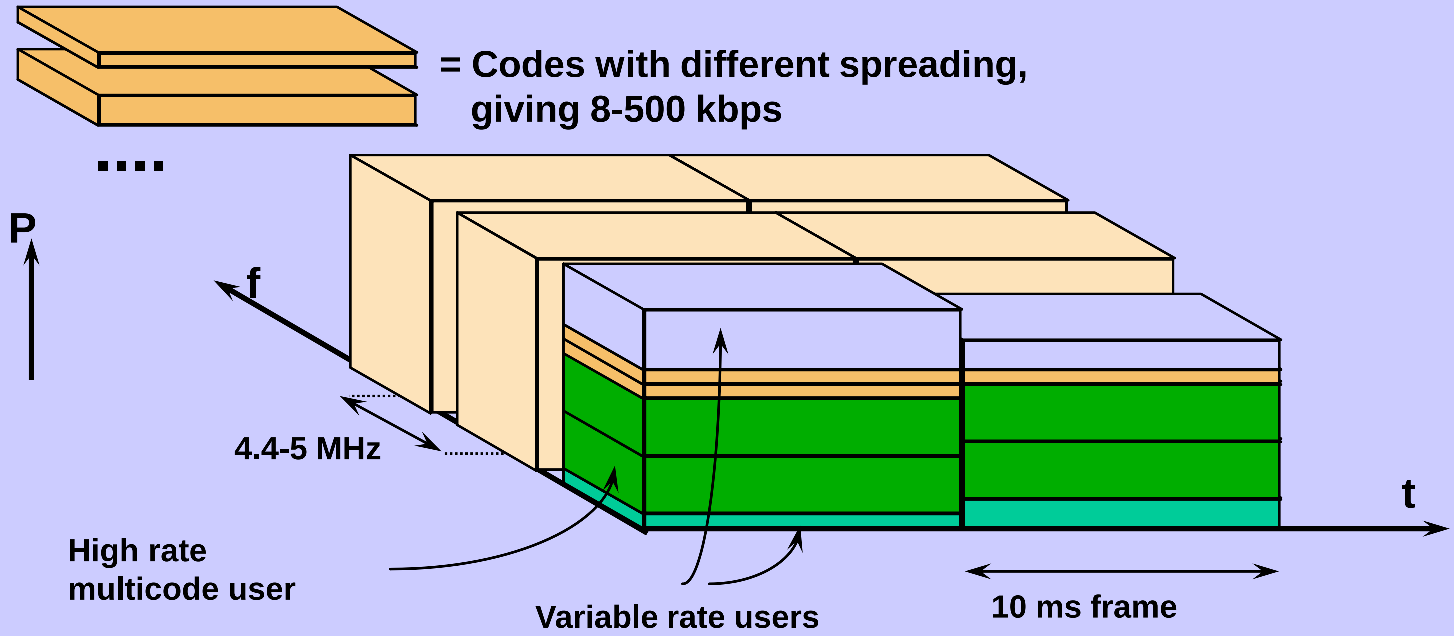


CDMA More

CDMA (Code Division Multiple Access): different codes for different signals

WIDEBAND CDMA (3G, NTT)

- **The W-CDMA concept:**
  - **4.096 Mcps Direct Sequence CDMA**
  - **Variable spreading and multicode operation**
  - **Coherent in both up-and downlink**



Exercise 2

1. Use Nyquist's Theorem to determine the maximum rate in bits per second at which data can be send across a transmission system that has a bandwidth of 4000 Hz and use four values of voltage to encode information. What's the maximum rate when encoding the information with 16 values of voltage?

2. Is it possible to increase a number of the encoded values without limit in order to increase transmission speed of system? Why? Assume a bandwidth of a system is 4000 Hz and a signal-to-noise ratio S/N=1023, What's the maximum rate of the system?

3. (True/false) A digital modulator using ASK, PSK or QAM is a digital-to-digital system.

4. (1) If the bit rate of 4-PSK signal is 2400bps, what's its baud rate?
   (2) If the baud rate of 256-QAM is 2400 baud, what's its bit rate?

5. The bite rate of one digital telephone channel is 64Kbps. If a single mode optical fiber can transmit at 2 Gbps, how many telephone channel can be multiplexed to the fiber. Assume TDM is used.