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

$$0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 0$$

**Encoder**

Sender

Transmission System/Channel

Decoder Receiver

**bit rate** = \(1/T\)  
unit: bps

bits per second

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

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

$$0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 0$$

Increase bit rate by reducing T.

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

$$0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 0 \quad 1 \quad 1 \quad 1 \quad 0$$

Increase bit rate by increasing M=2^n.

M-values encoding
1 pulse = \(\log_2 M\) bits  
= n bits

1 Baud = n*bps
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

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
Nyquist Theorem
Relationship between Transmission Speed and System Bandwidth

0 1 0 0 1 0

Data Transmission Speed
Maximum Signal Rate: \(D\)

Encoder
Sender

Transmission System/Channel
Bandwidth = \(B\)

Decoder
Receiver

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 \(B \geq D/2 \log_2 M\) (Hz)

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

Questions:
1) Assume a telephone channel bandwidth \(B = 3000\)Hz and \(M = 1024\), what’s its maximum rate?

2) Can we use the above channel to send a TV signal in real time? Why?
Basic Question:
-- How do bandwidth and noise affect the transmission rate at which information can be transmitted over a channel?

Shannon’s Paper:
-- Communication in the presence of noise. Proc. Institute of RE. vol. 37, 1949

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

Transmission System/Channel
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,

\[
C = \text{Blog}_2(1+S/N) \text{ bits/sec (bps, bite rate)}
\]

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

Two theorems give upper bounds of bit rates implement-able without giving implemental method.
Nyquist-Shannon theorem \( C = \text{Blog}_2(1+S/N) \) 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 \( S/N \to 0, \) \( C \to 0, \) cannot send any data regardless of bandwidth.

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

3. The theoretical highest bit rate of a regular telephone line where \( B=3000\text{Hz} \) and \( S/N=35\text{dB} \).
   \[
   10\log_{10}(S/N)=35 \quad \Rightarrow \quad \log_{2}(S/N)= 3.5 \times \log_{2}10 \\
   C= \text{Blog}_2(1+S/N) \approx \text{Blog}_2(S/N) =3000 \times 3.5 \times \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.
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

...010010110

Manchester encoding

Only short distance < 100m!
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: \( \text{Acos}(2\pi f_c t + \phi) \) where \( f_c \) is called carrier frequency

Modulation: change or modify values of \( A, f_c, \phi \) according to input signal \( s(t) \)
- modify \( A \rightarrow A[s(t)] \): Amplitude Modulation (AM)
- modify \( f_c \rightarrow f_c[s(t)] \): Frequency Modulation (FM)
- modify \( \phi \rightarrow \phi[s(t)] \): Phase Modulation (PM)
Modulated Wave/Signal and Spectrum

- Original Signal Spectrum
- Carrier Frequency
- Single Signal Band (USB)
- Single Signal Band (LSB)
Digital Modulation

Input: digital signal
Output: analogy signal

**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: $A \cos(2\pi f_c t + 3\pi/2)$

**FSK** – Frequency Shift Keying

2FSK

Digital signal

ASK modulated signal

2ASK

PSK modulated signal

4PSK

DM Anim
QAM – Quadrature Amplitude Modulation

QAM: a combinational modulation of amplitude and phase

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

\( \pi/4 \) (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

16-QAM

\[\text{bit}\_\text{rate} = 3 \times \text{baud}\_\text{rate}\]

\[\text{bit}\_\text{rate} = 4 \times \text{baud}\_\text{rate}\]
QAM Transmitter and Demo

\[ m(t) = A[s(t)] \cos\{2\pi f_c t + \varphi[s(t)]\} \]
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?

Site 1
- CompA1
- CompB1
- CompC1

Rate $D_a$
Rate $D_b$
Rate $D_c$

3 Lines $\rightarrow$ Good?

Site 2
- CompA2
- CompB2
- CompC2

Multiplexer / Demultiplexer
!

1 Line

Multiplexer / Demultiplexer

1 Line

slow lines

fast line

slow lines

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

3 lines → cost & inflexible

1 shared link: rate D

D >= Da + Db + Dc

FDM, TDM, CDM
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
Examples of FDM and TDM

FDM

TDM

Mux

Demux

Conversaion A

Conversaion B

Conversaion C

Conversaion D

Conversaion E

Schutzbander

10 kH

20 kHz
Lecture 2

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 are controlled by a pseudorandom 0/1 sequence (code)
- The signal is represented in code-domain

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

\[ s(t) \]

\[ \text{Code Mod} \]

\[ \text{Digital Mod} \]

\[ \ldots 0011001001010 \ldots \]

Pseudorandom code

\[ A \cos 2 \pi f_c t \]

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

= Codes with different spreading, giving 8-500 kbps
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.