Physical Layer

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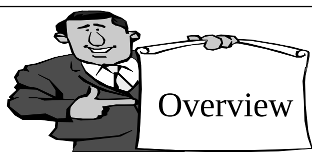
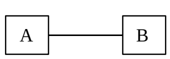
Based in part upon the slides of Prof. Raj Jain (OSU)



- ***The physical layer problem***
- ***Theory***: Frequency vs time domain, Information theory, Nyquist criterion**,** Shannon's theorem
- ***Link characteristics***: bandwidth, error rate, attenuation, dispersion
- ***Transmission Media:***
  - UTP, Coax, Fiber
  - Wireless: Satellite

The physical layer problem

- Two nodes communicating on a "link or medium". What does it take to get "bits" across the "link or medium" ?



- This means understanding the physical characteristics (aka parameters) and limitations of the link, and developing techniques and components which allow cost-effective bit-level communications.

What is information, mathematically ?

- Answer given by Shannon's Information Theory
- ***Information is created when you reduce uncertainty***
  - So, can we ***quantify information ?***
  - If X is a discrete random variable, with a range R = {x_1, x_2, …}, and p_i = P{X = x_i}, then:
  - $\sum_{i>=1}$ ***(- p_i log p_i) = a measure of "information"*** provided by an observation of X.
    - This is called the "***entropy***" function.
    - The entropy function also happens to be a measure of the ***"uncertainty" or "randomness" in X.***

Time Domain vs Frequency Domain

Frequency domain is useful in the analysis of linear, time-invariant systems.

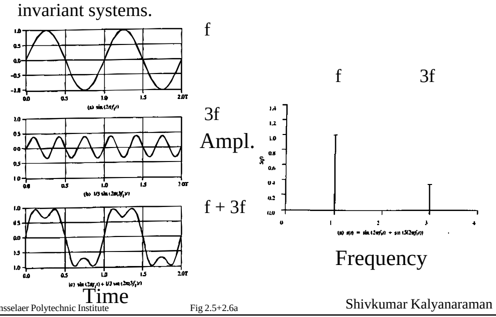


 Fig 2.5+2.6a

Why Frequency Domain ?
Ans: Fourier Analysis

- Can write any periodic function g(t) with period T as:
  - **g(t) = 1/2 c + Σ a_n sin (2πnft) + Σ b_n cos (2πnft)**
  - f = 1/T is the fundamental frequency
  - a_n and b_n amplitudes can be computed from g(t) by integration
- You find the component frequencies of sinusoids that it consists of…
  - The range of frequencies used = ***"frequency spectrum"***
  - Digital (DC, or ***baseband***) signals require a large spectrum
  - Techniques like ***amplitude, frequency or phase modulation*** use a sinusoidal carrier and a smaller spectrum
  - The *width* of the spectrum (*band*) available: ***"bandwidth"***

Bits/s vs Baud vs Hertz

- Data rate vs signal rate vs Bandwidth
- Information is first coded using a "***coding***" scheme, and then the code (called "signal") is mapped onto the available bandwidth (Hz) using a modulation scheme.
- ***Signal rate*** (of the code) is the number of ***signal element*** (voltage) ***changes*** per second. This is measured in "***baud***." The signal rate is also called "***baud-rate***".
- Each baud could encode a variable number of bits. So, the "***bit rate***" of the channel (measured in ***bits/sec***) is the maximum number of bits that that be coded using the coding scheme and transmitted on the available available bandwidth.
  - ***The bit-rate is a fundamental link parameter.***

Modulation techniques

A Sin(2πft+θ)

ASK

FSK

PSK

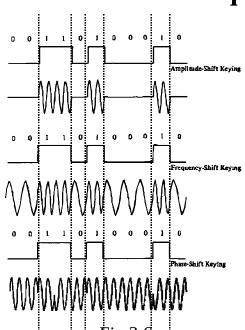


Fig 3.6

Application: 9600 bps Modems

- 4 bits ⇒ 16 combinations
- 4 bits/element ⇒ 1200 baud
- 12 Phases, 4 with two amplitudes

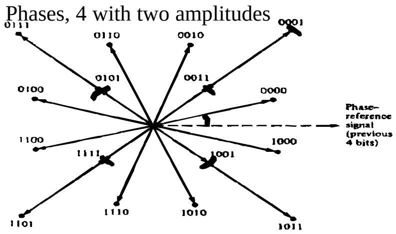
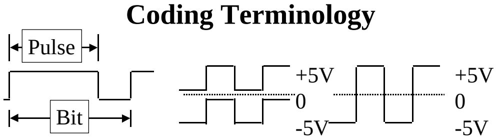


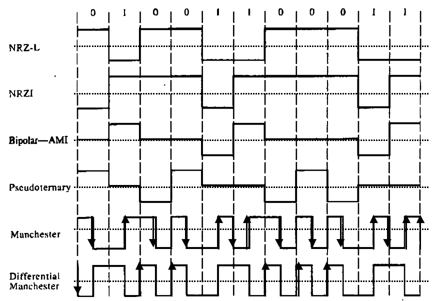
Fig 3.8

Coding Terminology



- Signal element: Pulse
- Signal Rate: 1/Duration of the smallest element
  =Baud rate
- Data Rate: Bits per second
- Data Rate = F(Bandwidth, encoding, ...)
  - Bounds given by Nyquist and Shannon theorems…
- Eg signaling schemes: Non-return to Zero (NRZ), Manchester coding etc

Coding Formats



Coding Formats

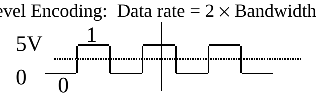
- **Nonreturn-to-Zero-Level (NRZ-L)**
  0= **high** level
  1= **low** level
- **Nonreturn to Zero Inverted (NRZI)**
  0= ***no transition at beginning*** of interval (one bit time)
  1= ***transition at beginning*** of interval
- **Manchester**
  0=***transition*** from ***high to low in middle*** of interval
  1= ***transition*** from ***low to high in middle*** of interval
- **Differential Manchester**
  Always a transition in middle of interval
  0= ***transition at beginning*** of interval
  1= ***no transition at beginning*** of interval

Limits of Coding: Nyquist's Theorem

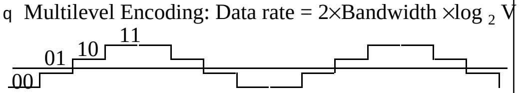
- Says that you cannot stretch bandwidth to get higher and higher data rates indefinitely. There is a limit, called the Nyquist limit (Nyquist, 1924)
- If bandwidth = H; signaling scheme has V discrete levels, then:
  - ***Maximum Date Rate = 2 H log_2 V bits/sec***
- ***Implication 1:*** A noiseless 3 kHz channel cannot ***transmit*** binary signals at a rate exceeding 6000 bps
- ***Implication 2:*** This means that binary-coded signal can be completely ***reconstructed*** taking only 2 H samples per second

Nyquist's Theorem (Cont)

- **Nyquist Theorem**: Bandwidth = H
  Data rate $\leq$ 2 H $\log_2 V$
- Bilevel Encoding: Data rate = 2 $\times$ Bandwidth



- Multilevel Encoding: Data rate = 2$\times$Bandwidth $\times \log_2$ V



Example: V=4, Capacity = 4 $\times$ Bandwidth

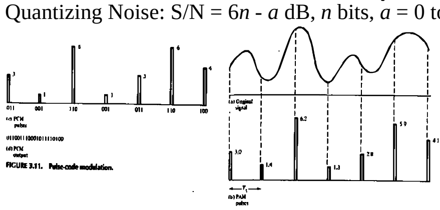
So, can we have V -> infinity to extract infinite data rate out of a channel ?

Digitization & quantization in telephony

- The Nyquist result is used in digitization where a voice-grade signal (of bandwidth 4 kHz) is sampled at 8000 samples/s.
  - The inter-sample time (125 usec) is a well-known constant in telephony.
- Now each of these analog sample is digitized using 8 bits
  - These are also called ***quantization levels***
  - This results in a 64kbps voice circuit, which is the basic unit of multiplexing in telephony.
    - T-1/T-3, ISDN lines, SONET etc are built using this unit
- If the quantization levels are *logarithmically spaced* we get better resolution at low signal levels. Two ways:
  - ***m-law*** (followed in US and Japan), and ***A-law*** (followed in rest of world) => all international calls must be remapped.

Telephony digitization: contd

- Sampling Theorem: 2 × Highest Signal Frequency
- 4 kHz voice = 8 kHz sampling rate
  8 k samples/sec × 8 bits/sample = 64 kbps
- Quantizing Noise: S/N = 6*n* - *a* dB, *n* bits, *a* = 0 to 1



Nonlinear Encoding

- Linear: Same absolute error for all signal levels
- Nonlinear:More steps for low signal levels

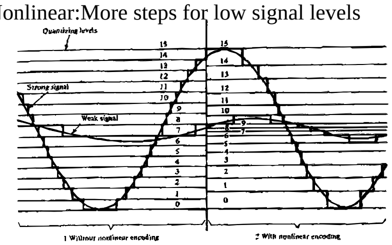


Fig 3.13

Effect of Noise: Shannon's Theorem

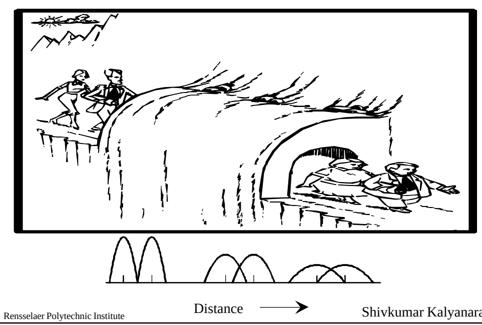
- Bandwidth = H Hz
  Signal-to-noise ratio = S/N
  - ***Maximum data rate = H*** $\boldsymbol{\log_2}$ ***(1+S/N)***
- Example: Phone wire bandwidth = 3100 Hz
  S/N = 1000
  Maximum data rate = 3100 $\log_2$ (1+1000)
  = 30,894 bps

This is an *absolute limit*. In reality, you can't get very close to the Shannon limit.

Decibels

- Attenuation = $\log_{10} \frac{P_{in}}{P_{out}}$ Bel
- Attenuation = $10 \log_{10} \frac{P_{in}}{P_{out}}$ deciBel
- Attenuation = $20 \log_{10} \frac{V_{in}}{V_{out}}$ deciBel Since $P=V^2/R$
- **Example 1**: Pin = 10 mW, Pout=5 mW
  Attenuation = $10 \log_{10} (10/5) = 10 \log_{10} 2 = 3$ dB
- **Example 2**: S/N = 30 dB => $10 \log_{10}$ S/N = 30, or,
  $\log_{10}$ S/N = 3.
  S/N = 10^3

Other link issues: Attenuation, Dispersion



Real Media: Twisted Pair

- Unshielded Twisted Pair (UTP)
  - Category 3 (Cat 3): Voice Grade. Telephone wire. Twisted to reduce interferece
  - Category 4 (Cat 4)
  - Category 5 (Cat 5): Data Grade. Better quality. More twists per centimeter and Teflon insulation

  100 Mbps over 50 m possible
- Shielded Twisted Pair (STP)

Coaxial Cable

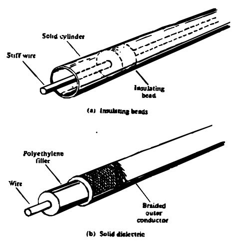


Fig 2.20

Baseband Coaxial Cable

- Better shielding
  ⇒ longer distances and higher speeds
- 50-ohm cable used for digital transmission
- Construction and shielding
  ⇒ high bandwidth and noise immunity
- For 1 km cables, 1-2 Gbps is feasible
- Longer cable ⇒ Lower rate

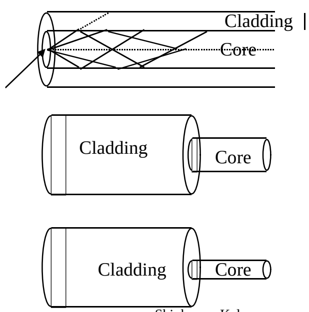
Broadband Coaxial Cable (Cont)

- 75-ohm cable used for analog transmission (standard cable TV)
- Cables go up to 450 MHz and run to 100 km because they carry analog signals
- System is divided up into multiple channels, each of which can be used for TV, audio or converted digital bitstream
- Need analog amplifiers to periodically strengthen signal

- Dual cable systems have 2 identical cables and a head-end at the root of the cable tree
- Other systems allocate different frequency bands for inbound and outbound communication, e.g. subsplit systems, midsplit systems

Optical Fiber

- Index=Index of referection =Speed in Vacuum/ Speed in medium Modes
- Multimode
- Single Mode



Fiber Optics

- With current fiber technology, the achievable bandwidth is more than 50,000 Gbps
- 1 Gbps is used because of conversion from electrical to optical signals
- Error rates are negligible
- Optical transmission system consists of light source, transmission medium and detector

- Pulse of light indicates a 1-bit and absence 0-bit
- Detector generates electrical pulse when light falls on it
- Refraction traps light inside the fiber
- Fibers can terminate in connectors, be spliced mechanically, or be fused to form a solid connection
- LEDs and semiconductor lasers can be used as sources
- Tapping fiber is complex ⇒ topologies such as rings or passive stars are used

Wavelength Bands

- 3 wavelength bands are used

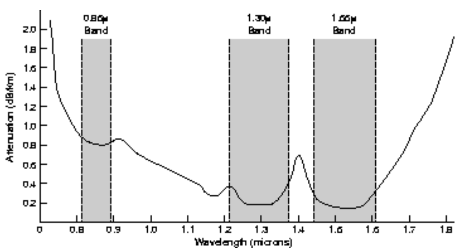


Fig 2-6

Wireless Transmission

- The Electromagnetic Spectrum
- Radio Transmission
- Microwave Transmission
- Infrared and Millimeter Waves
- Lightwave Transmission
- Satellite Transmission

Electromagnetic Spectrum

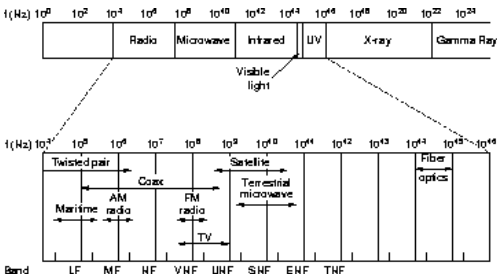


Fig 2-11

Low-Orbit Satellites

- As soon as a satellite goes out of view, another replaces it
  - May be the technology that breaks the local loop barrier

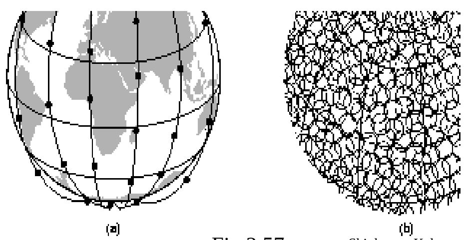


Fig 2.57

Summary

- Link characteristics:
  - Bandwidth, Attenuation, Dispersion
- Theory:
  - Frequency domain and time domain
  - Nyquist theorem and Shannon’s Theorem
  - Coding, Bit, Baud, Hertz
- Physical Media: UTP, Coax, Fiber, Satellite