Computer Networks

The Physical Layer: Signals & Media

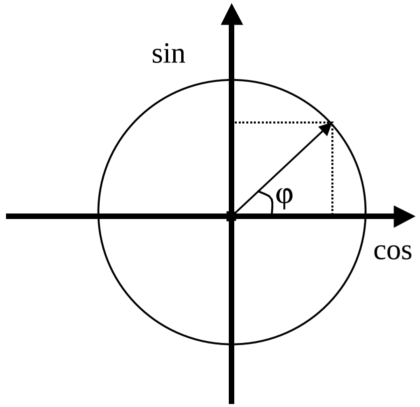
Signals

- Question: What does a 0 or a 1 actually look like when it travels through a wire?
- Electronic data transmission over a communications medium is modelled by *signals*
- Signals model variations and are mathematically represented as functions of one or more independent variables
- Information can be transmitted on wires by varying some physical property such as voltage or current. By representing the value of this property as a function of time *f(t),* we can model the behaviour of the signal and analyse it mathematically.
- Analog vs Digital Signals

Analog Signals

- Continuous-time signal formed by continuously varying voltage levels.
- Typically represented by their characteristic sinusoidal function
- Characterised by:
  - Period (*T*): the signal is periodic if it repeats a pattern continuously. The period is the time to complete a pattern once.
  - Frequency (*f*): the number of times the signal oscillates per unit of time. (cycles per second or Hz) $f=1/T$
  - Amplitude: the values between the signal oscillates
  - Phase

Analog Signals

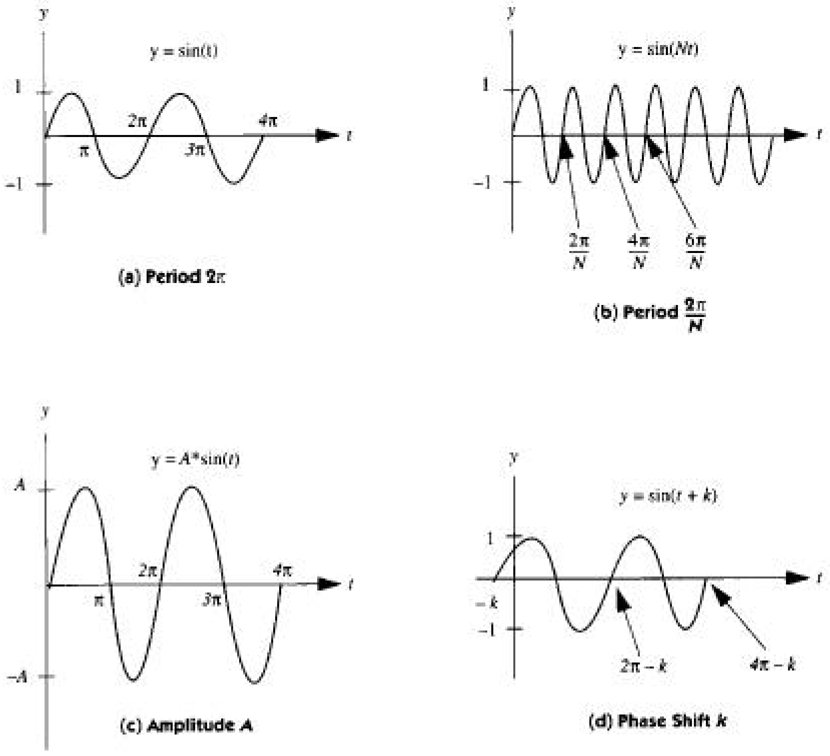


- $f(t)= a \sin (wt + \varphi)$
- $\varphi/t=w$ *rad/sec* (angular velocity)

where $radians=(degrees * \pi)/180$

- $2\pi/T$ = mean angular velocity $= w_0$
- $f_0 = 2\pi / w_0$ = <u>fundamental frequency</u> Hz (number of complete cycles per second)

Analog Signals



Digital Signals

- A constant voltage value for short time and then changes to a different voltage value
- Digitally encoded data ⇔digital signals (0,1 - low, high voltage)
- Digital Encoding Schemes:
  - Non-Return-to-Zero (NRZ)
  - Manchester Encoding
- Unipolar (0⟶V) vs Bipolar (-V⟶+V)

NRZ Encoding

- A 0 is transmitted by raising the voltage level to high and a 1 by bringing it down to low
- The name NRZ refers to the fact the the voltage does not return to zero, it changes only when the bit value changes
- Problem: constant signal values cannot synchronize the communicating devices

FIGURE 2.29 NRZ Encoding

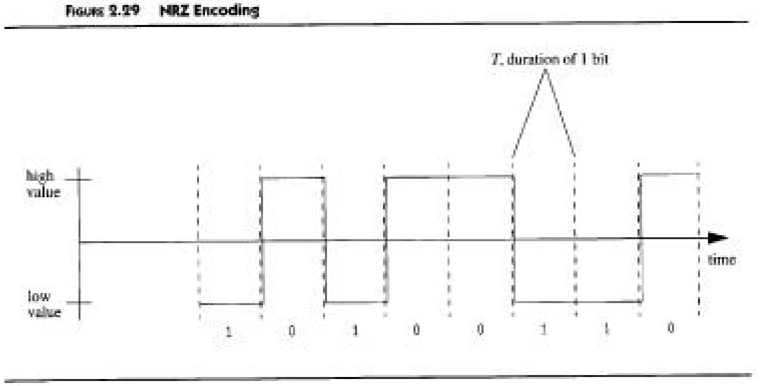
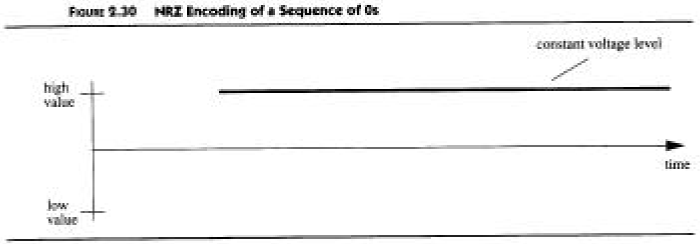


FIGURE 2.30 NRZ Encoding of a Sequence of 0s



Manchester Encoding

- Uses signal changes to transmit a bit and achieves synchronisation without reference to an external clock
- Problem: Twice the bandwidth of NRZ is required
- Variation: Differential Manchester Encoding
  - 0s and 1s are distinguished by whether there is a change in the signal at the beginning of the bit interval (only 0 cause changes)

FIGURE 2.31 Manchester Encoding

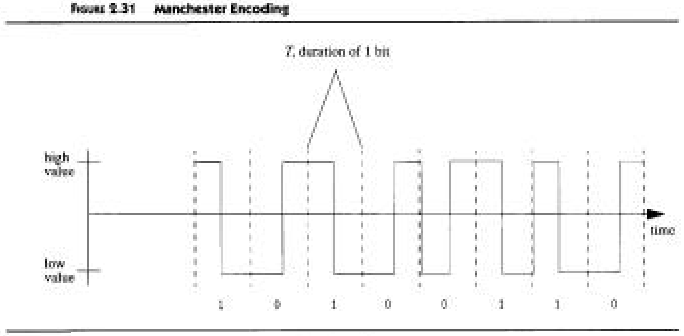
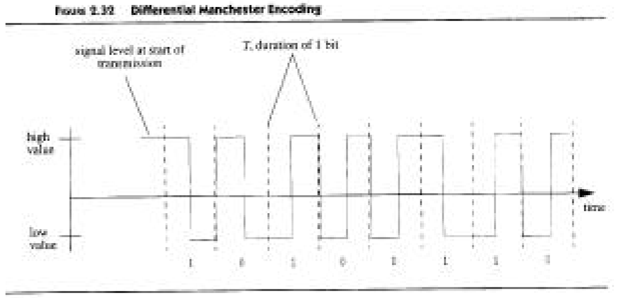


FIGURE 2.32 Differential Manchester Encoding



Fourier Analysis

- Jean Baptiste Fourier: Any periodic signal is made up of an infinite series of sinusoidal frequency components. The period of the signal determines the <u>fundamental frequency</u>. The other components have frequencies which are multiples of this and are known as the <u>harmonics</u> of the fundamental.

$$v(t) = \frac{a_o}{2} + \sum_{i=1}^{\infty}\left[a_i \cdot \cos\left(\frac{\text{it}2p}{\text{T}}\right) + b_i \cdot \sin\left(\frac{\text{it}2p}{\text{T}}\right)\right]$$

$$a_o = \frac{1}{T}\int_0^T s(t)dt$$

$$a_i = \frac{2}{T}\int_0^T s(t)\cos\left(\frac{it2p}{T}\right)dt$$

$$b_i = \frac{2}{T}\int_0^T s(t)\sin\left(\frac{it2p}{T}\right)dt$$

- Where
  - α_0 is the mean of the signal over the period T and is known as the DC component
  - α_i and b_i are the Fourier coefficients

Fourier Analysis

- An alternative form of the Fourier Series is:

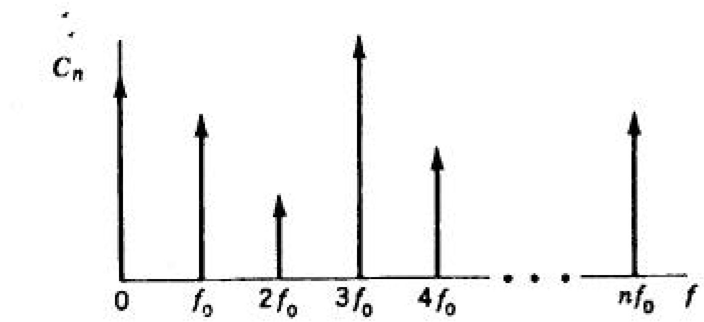
$$v(t) = C_0 + \sum_{i=1}^{\infty} C_i \cos\left(\frac{it2p}{T} - j_i\right)$$

$$C_0 = a_o$$

$$c_i = \sqrt{a_i^2 + b_i^2}$$

$$j_i = \tan^{-1}\frac{a_i}{b_i}$$

- The coefficients C_n are called spectral amplitudes. They represent the energy transmitted at the corresponding frequency.

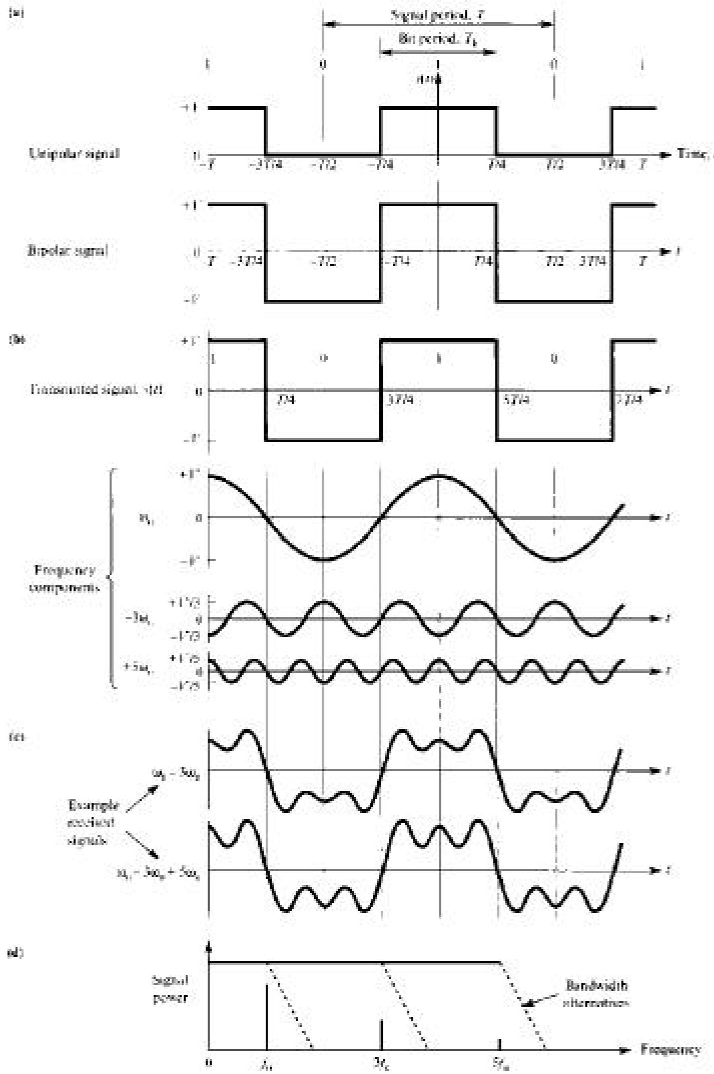


Fourier Analysis of Digital Signals

- Digital signals:
  - A digital signal is the sum of analog signals with different amplitudes and frequencies
  - Only odd harmonic components are present
  - The amplitude diminishes with increasing frequency

$$\text{Unipolar}\quad v(t) = \frac{V}{2} + \frac{2V}{p}\left\{\cos w_o t - \frac{1}{3}\cos 3w_o t + \frac{1}{5}\cos 5w_o t - \ldots\right\}$$

$$\text{Bipolar}\quad v(t) = \frac{4V}{p}\left\{\cos w_o t - \frac{1}{3}\cos 3w_o t + \frac{1}{5}\cos 5w_o t - \ldots\right\}$$



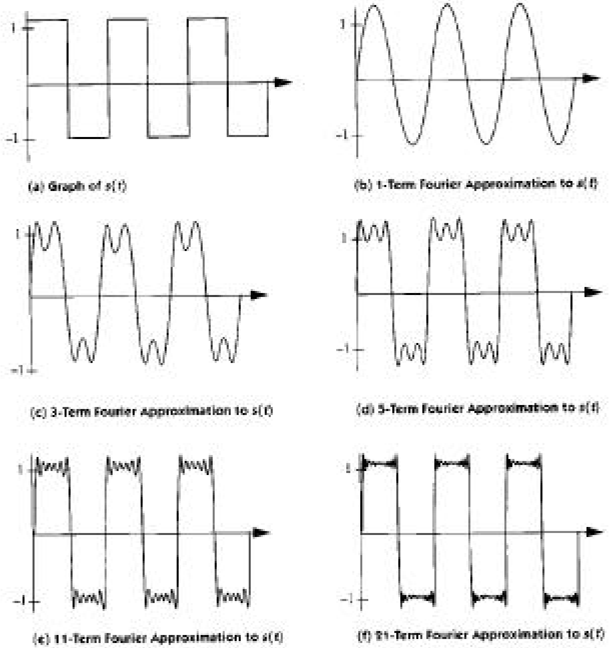
An Example

- Consider the signal:

$$v(t) = \begin{Bmatrix} 1 \text{ for } 0p \le t \le p \text{ ; } 2p \le t \le 3p \text{ ; } 4p \le t \le 5p \text{ ; etc.} \\ -1 \text{ for } p \le t \le 2p \text{ ; } 3p \le t \le 4p \text{ ; } 5p \le t \le 6p \text{ ; etc.} \end{Bmatrix}$$

- The fourier analysis gives $\alpha_i = 0$ and

$$b_i = \begin{Bmatrix} 0 \text{ if } i \text{ is even} \\ \dfrac{4}{ip} \text{ if } i \text{ is odd} \end{Bmatrix}$$



Proof

$$a_0 = \frac{2}{T}\left[\int_0^{\frac{T}{2}} 1 \cdot \cos\left(\frac{0t2p}{T}\right)dt + \int_{\frac{T}{2}}^{T} (-1) \cdot \cos\left(\frac{0t2p}{T}\right)dt\right] \Rightarrow$$

$$a_0 = \frac{2}{T}\left[\int_0^{\frac{T}{2}} cos(0t)dt - \int_{\frac{T}{2}}^{T} cos(0t)dt\right] \Rightarrow$$

$$a_0 = \frac{2}{T}(\sin 0 - \sin 0) = 0$$

$$a_1 = \frac{2}{T}\left[\int_0^{\frac{T}{2}} cos\left(\frac{t2p}{T}\right)dt - \int_{\frac{T}{2}}^{T} cos\left(\frac{t2p}{T}\right)dt\right] \Rightarrow$$

$$a_1 = \frac{2}{T}\left[\int_0^{\frac{T}{2}} cos\left(\frac{t2p}{T}\right)dt - \int_{\frac{T}{2}}^{T} cos\left(\frac{t2p}{T}\right)dt\right] \Rightarrow$$

$$a_1 = \frac{2}{T}\left(\sin\frac{t2p}{T}\Big]_0^{\frac{T}{2}} - \sin\frac{t2p}{T}\Big]_{\frac{T}{2}}^{T}\right) \Rightarrow$$

$$a_1 = \frac{2}{T}\left[(\sin p - \sin 0) - (\sin 2p - \sin p)\right] \Rightarrow$$

$$a_1 = \frac{2}{T}\left[(0-0) - (0-0)\right] = 0$$

$$b_1 = \frac{2}{T}\left[\int_0^{\frac{T}{2}} 1\cdot\sin\left(\frac{1t2p}{T}\right)dt + \int_{\frac{T}{2}}^{T}(-1)\cdot\sin\left(\frac{1t2p}{T}\right)dt\right] \Rightarrow$$

$$b_1 = \frac{2}{T}\left[\int_0^{\frac{T}{2}}\sin\left(\frac{t2p}{T}\right)dt - \int_{\frac{T}{2}}^{T}\sin\left(\frac{t2p}{T}\right)dt\right]\Rightarrow$$

$$b_1 = \frac{2}{T}\left(\left[-\frac{T}{2p}\cos\left(\frac{t2p}{T}\right)\right]_0^{\frac{T}{2}} - \left(-\frac{T}{2p}\cos\left(\frac{t2p}{T}\right)\right)_{\frac{T}{2}}^{T}\right)\Rightarrow$$

$$b_1 = \frac{2}{T}\cdot\frac{T}{2p}\left[-\left(\cos\left(\frac{2p\frac{T}{2}}{T}\right)-\cos\left(\frac{2p\,0}{T}\right)\right)+\left(\cos\left(\frac{T2p}{T}\right)-\cos\left(\frac{2p\frac{T}{2}}{T}\right)\right)\right]$$

$$b_1 = \frac{1}{p}(-\cos p + \cos 0 + \cos 2p - \cos p) = \frac{1}{p}(-2\cos p + \cos 2p + \cos 0)$$

$$b_1 = \frac{1}{p}(-2\cdot(-1)+1+1)\Rightarrow b = \frac{1}{p}4 \Rightarrow b_1 = \frac{4}{p}$$

$$b_2 = \frac{2}{T}\left(\left[-\frac{T}{4p}\cos\left(\frac{t4p}{T}\right)\right]_0^{\frac{T}{2}} - \left(-\frac{T}{4p}\cos\left(\frac{t4p}{T}\right)\right)_{\frac{T}{2}}^{T}\right)\Rightarrow$$

$$b_2 = \frac{2}{T}\left(\left[-\frac{T}{4p}\cos\left(\frac{t4p}{T}\right)\right]_0^{\frac{T}{2}} - \left(-\frac{T}{4p}\cos\left(\frac{t4p}{T}\right)\right)_{\frac{T}{2}}^{T}\right)\Rightarrow$$

$$b_2 = \frac{2}{T}\cdot\frac{T}{4p}\left[-\left(\cos\left(\frac{4p\frac{T}{2}}{T}\right)-\cos\left(\frac{4p\,0}{T}\right)\right)+\left(\cos\left(\frac{T4p}{T}\right)-\cos\left(\frac{4p\frac{T}{2}}{T}\right)\right)\right]$$

$$b_2 = \frac{1}{2p}(-\cos 2p + \cos 0 + \cos 4p - \cos 2p)\Rightarrow$$

$$b_2 = \frac{1}{2p}(-2\cos 2p + \cos 4p + \cos 0) = \frac{1}{2p}(-2\cdot 1+1+1)\Rightarrow b_2 = 0$$

Bandwidth

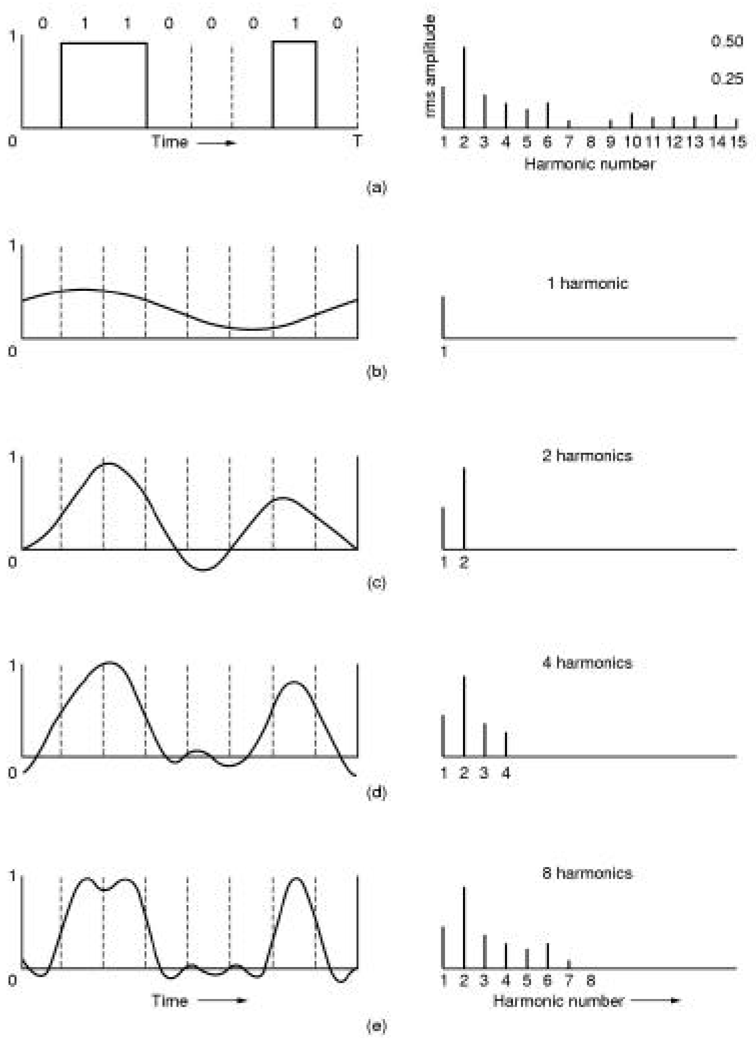
- Question: So, how is Fourier analysis related to bandwidth (and computer networks!?)
- Bandwidth: the band (range) of sinusoidal frequency components that can be transmitted by the channel (Hz) . This is a physical property of the channel (medium)
- Transmitting a complex signal over a channel is the same as approximating the function using some of the Fourier harmonics
- Question: But bandwidth is measured in bps (bits per second). No?
- No! This is the **data rate**. However, an important result in communications theory relates bandwidth with data rate. Simply put, the higher the bandwidth the higher the data rate. This relation is so strong that many people often use the terms interchangeably.
- It is Nyquist Theorem that relates bandwidth with data rate.

Nyquist Theorem

- Baud: The number of signal changes per second (=the frequency with which the signal components change)
- data rate = baud rate * n (n=bits per component)
  - n is determined by the modulation technique used. This will be discussed in subsequent lectures in the context of modulation techniques (WAN Technologies)
- If f is the maximum frequency that the medium can transmit, the receiver can completely reconstruct a signal by sampling it $2*f$ times per second (or twice the period - baud rate). (Nyquist, 1920s).
- Since each sample conveys n bits:
  - *Maximum data rate = 2*f*n = 2*f*log2V*, where f is the maximum frequency transmitted and V is the number of different signal components.
- Practically, the fundamental frequency f_0 is enough to reconstruct a signal.

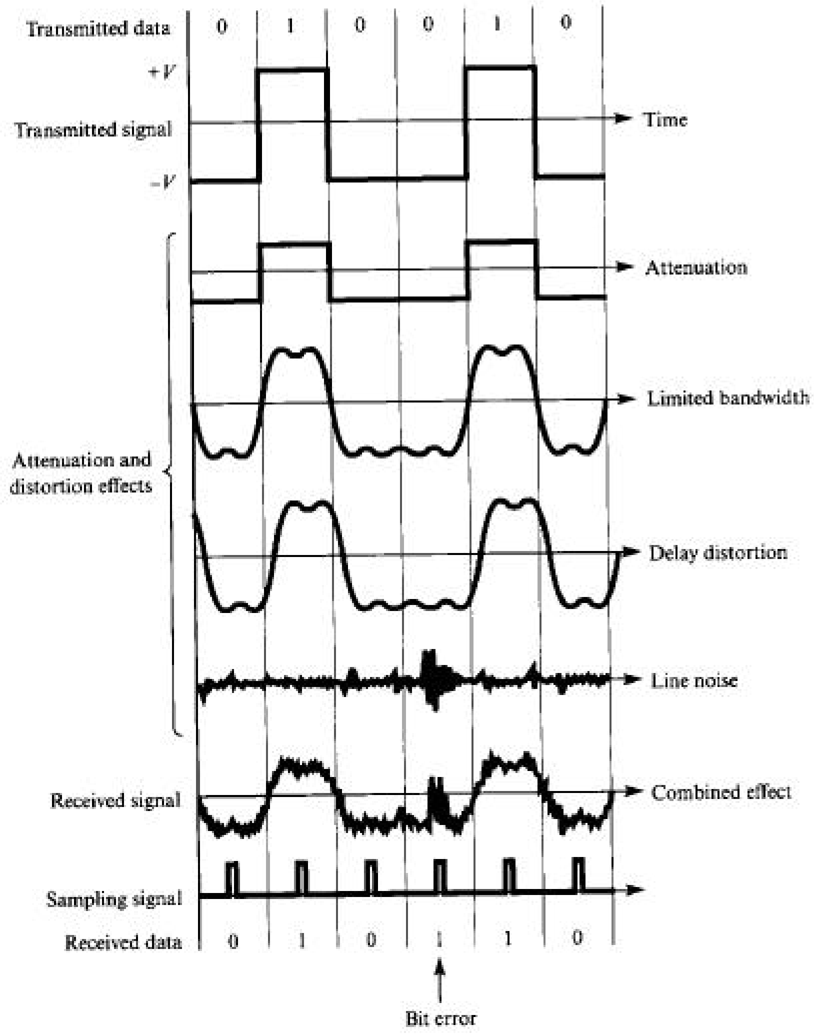
Data Rate and Harmonics

- Example:
  - Assuming a voice-grade link (cut-off frequency ~3000Hz), baud rate b, and one bit per bound. The time to transmit 8 bits is 8/b sec (the period T) so the frequency of the fundamental harmonic is b/8. The number of the highest harmonic passed through is 3000/(b/8) or 24.000/b



Shannon's Result

- Given the maximum frequency, is there an upper bound for data rate (i.e. can $n \rightarrow \infty$)?
- Yes (No)!, There is a limit imposed by:
  - Signal Attenuation
  - Noise (Signal-to-Noise-Ratio SNR)
- Max. $n = f * log2(1+S/N)$ (Shannon, 1940s)

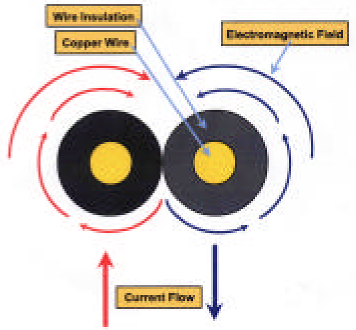


Noise

- ***Near-end crosstalk (NEXT):*** When two wires are near each other and untwisted, energy from one wire can wind up in an adjacent wire and vice versa. This can cause noise at both ends of a terminated cable.
  - Termination technology, strict adherence to standard termination procedures, use of quality twisted pair cables.
- ***Thermal Noise:*** Due to the random motion of electrons. Unavoidable but relatively small.
- ***AC Power/Reference Ground Noise:*** the chassis of a computing device serves as the signal reference ground, and as the AC power line ground. Long neutral and ground wires that lead to electrical outlet act as antennas for electrical noise which interferes with the digital signals.
- ***Electromagnetic/Radio Frequency interference (EMI/RFI).*** Wires act like antennas absorbing electrical signals from electrical sources outside the cable (most LANs use frequencies 1-100MHz frequency region similar to FM Radio signals, TV signals etc)

Dealing with EMI/RFI

- Increase the size of the conductor wires. cancellation
- Improve the type of insulating material used.
- BUT: such changes increase the size and cost of the cable faster than they improve its quality.
- Alternative techniques:
  - *Shielding* : Metal braid (foil) surrounds each group of wire pairs. This shielding acts as a barrier to any interfering signals. Increases the diameter of the cable and the cost as well.
  - *Cancellation*. In wire pairs magnetic fields can cancel each other out. Twisting the wires can enhance this cancellation effect.



Bandwidth Requirements

- Current network bandwidths cannot handle the accelerating need for bandwidth for very long
- The combined exponential growths in computing power and the nonlinear growth in intercommunications create an overall demand for data communications growth that is greater than exponential

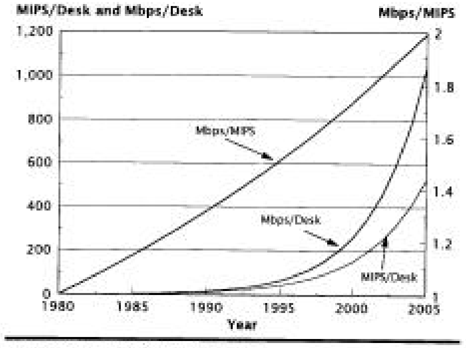


Figure 1.4 Accelerating Bandwidth Principle

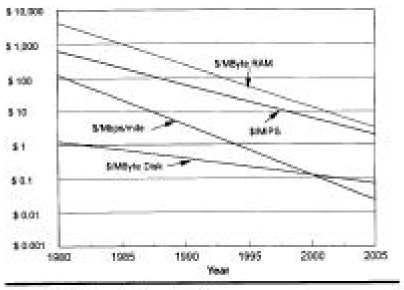


Figure 1.5 Technology Cost Trends over Time

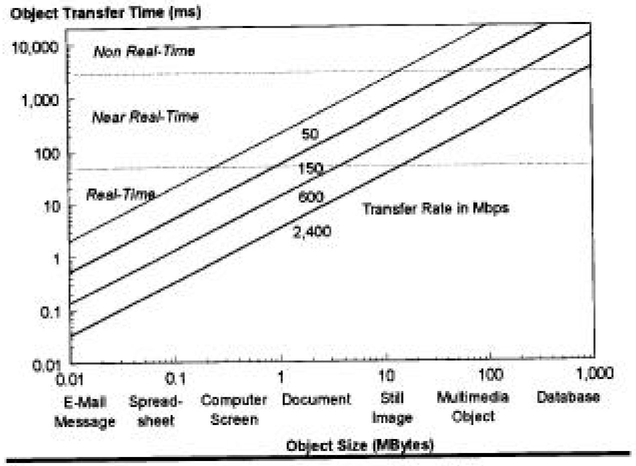


Figure 1.8 Object Transfer Time as a Function of Bandwidth

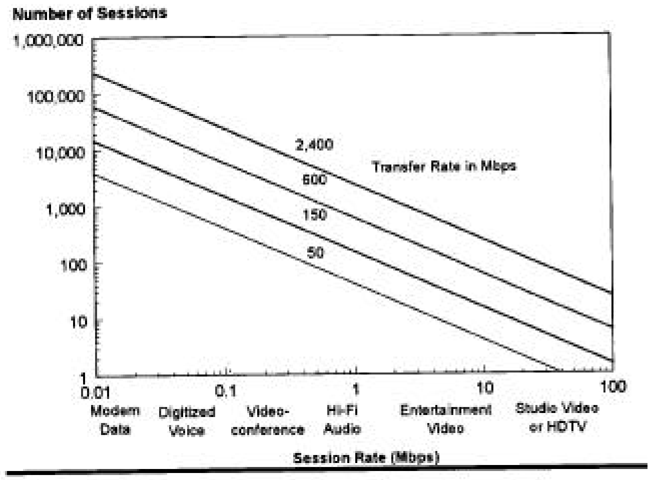


Figure 1.9 Number of Fixed Rate Application Sessions Supported

What is “broadband” ?

- Broadband: high bandwidths or data rates
- In its original meaning “broadband” referred to the technology used in cable television (CATV)
  - analog technology - multiple channels to be carried at different frequencies on the same coaxial cable (FDM)
- First LANs used CATV technology (broadband LANs)
  - broadband (e.g. IEEE 802.3 10BROAD36 & 802.4 broadband) vs. baseband LANs
- Today the term (mainly) refers to any network (or telecoms system) capable of conveying information in excess of voice bandwidths over a <u>single large chunk of undivided bandwidth (“unchannelized”)</u>

Transmission Modes

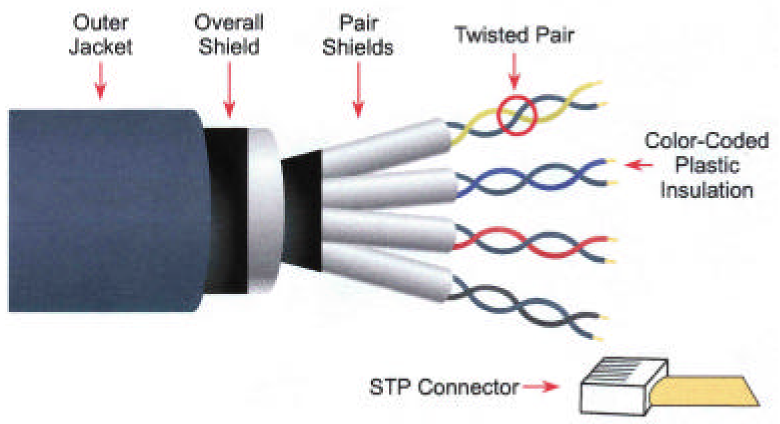
- Serial vs Parallel (SIPO register)
  - Parallel: faster, not suitable for long distances (cost, different transmission times on each wire)
  - Serial: slow, cheap and reliable
- Simplex vs duplex (and half duplex)
- Serial: Asynchronous vs Synchronous: Bit (clock), character (byte) and frame (Data link layer) synchronization
  - Asynchronous: Byte oriented, start & stop bits for byte synchronization, sampling frequency N*bit rate for bit synchronization
  - Synchronous: Data not transmitted in characters but in large streams of bits. Bit sync. either by embedding timing in signal (e.g. Manchester encoding) or by special hardware

Media

- Metal
  - Copper/Aluminium
  - UTP, STP, ScSTP, Coaxial
  - Bits as voltages using Manchester & NRZI Encoding
- Fiber
  - Bits as guided light; Manchester and 4B/5B encoding
- Wireless
  - Bits as radiated EM waves; typically modulated signals.

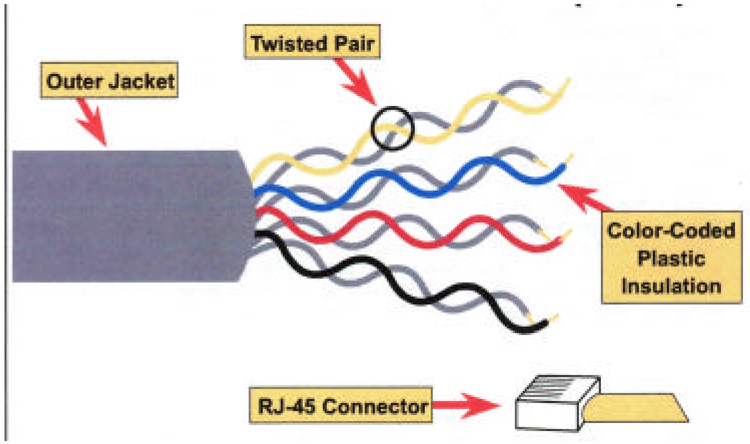
Shielded Twisted-Pair: STP

- Combines the techniques of shielding, cancellation, and twisting of wires . Analog & digital
- Each pair of wires is wrapped in metallic foil. Each 4 pairs of wires are wrapped in an overall metallic braid or foil.
- 10-100Mbps. Maximum length: 100m (need for repeaters). 150 Ohm.
- Shield acts like an antenna: susceptible to noise.
- Insulation and shielding increase the size, weight, and cost of the cable.



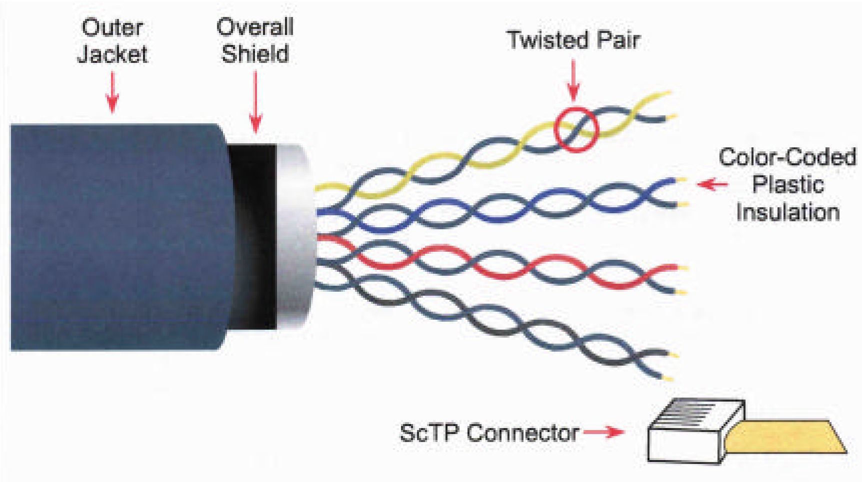
Unshielded Twisted-Pair UTP

- Composed of four pairs of wires.
- Each of the 8 individual copper wires is covered by insulating material.
- Each pair of wires are twisted around each other: relies solely on the cancellation effect to reduce EMI/RFI
- 10-100Mbps. Max length: 100m. Today, UTP is considered the fastest copper-based media. (CAT 5)



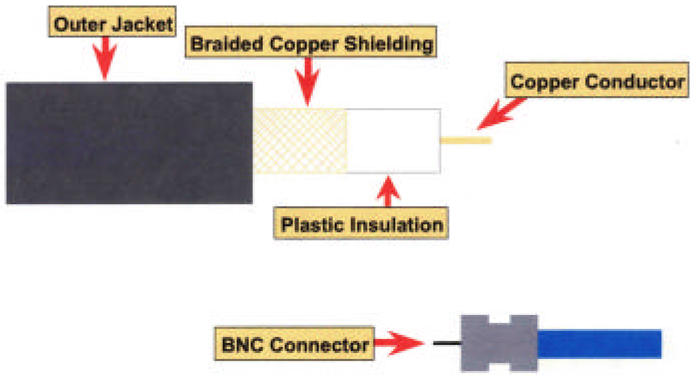
Screened UTP: ScTP

- A new hybrid UTP/STP cable. Also known as Foil Twisted Pair (FTP) .
- Essentially UTP wrapped in a metallic foil shield, or "screen".
- 100-120 Ohm.



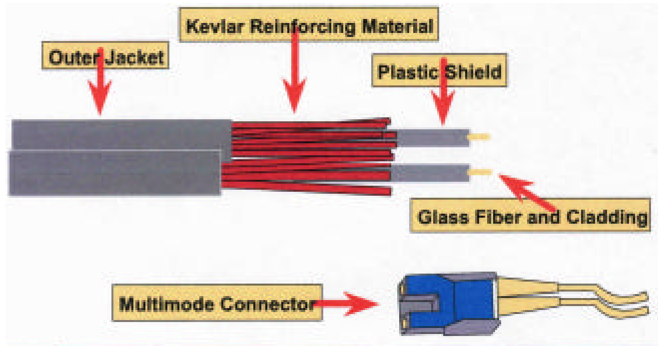
Coaxial

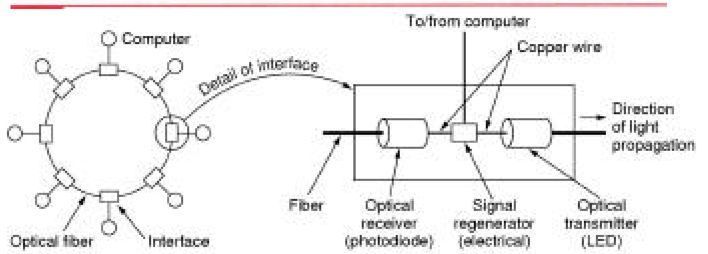
- Copper/aluminium core surrounded by a stack of insulating material, a cylindrical conductor (braid) and a protective plastic sheath. Copper braid or metallic foil acts as the second wire in the circuit, and as a shield for the inner conductor.
  - Baseband Coaxial Cable: 50/75ohm 500MHz, 10-500Mbps, Max length: 500m
  - Broadband: analog TV cabling, multiple 6MHz channels sharing 300-450MHz.



Optical Fiber

- Signals that represent bits are converted into beams of light.
- Not susceptible to electromagnetic interference and is capable of higher data rates 100+Mbps. BUT more expensive
- Single Mode:One stream of laser generated guide. Max length 3000 m
- Multimode: Multiple streams of LED generated light. Max length 2000 m



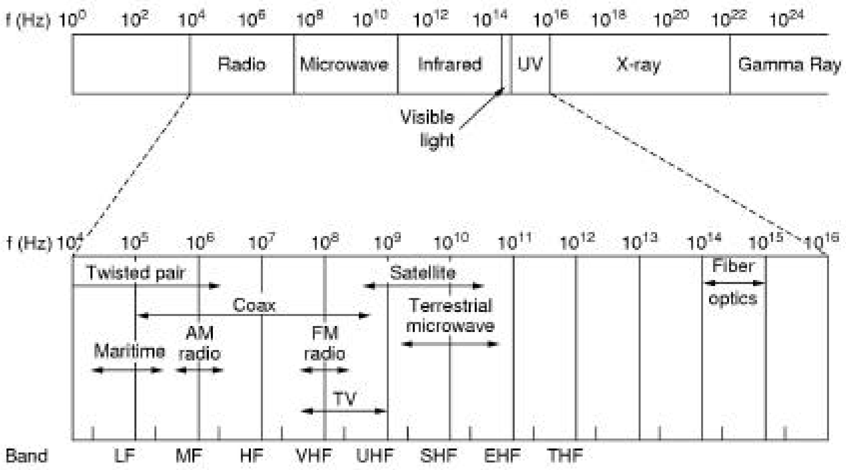


Wireless Communication

- Wireless signals are electromagnetic waves which can travel through the vacuum of outer space or through media such as air. No "physical" medium is necessary.
- The Electromagnetic Wave Equation:

$$f * l = c,$$

where *f=cycles/sec, l=wavelength, c=speed of light*



Media Standards

- Standards Organisations:
  - *IEEE* - Institute of Electrical and Electronics Engineers: Ethernet & Token Ring
  - *UL* - Underwriters Laboratories: primarily concerned with safety standards. They also rate twisted-pair media for performance.
  - *EIA* - Electronic Industries Alliance
  - *TIA* - Telecommunications Industry Association
- TIA/EIA Standards
  - TIA/EIA-568-A & TIA/EIA-569-A: the most widely used standards
    - horizontal cabling
    - telecommunications closets
    - backbone cabling
    - equipment rooms
    - work areas
    - entrance facilities
- http://www.siemon.com/