ECE 333: Introduction to Communication Networks
Fall 2002

Lecture 4: Physical layer II

- Impairments - distortion, noise
- Fundamental limits
- Examples

1

Notes:

This lecture continues the discussion of the physical layer. Recall, the basic problem addressed at the physical layer is sending a sequence of bits over an analog communication channel. This is the topic of digital communication theory. Last time we considered a simple technique for mapping bits into an analog signal - namely mapping a 0 into a square pulse with a positive amplitude and mapping a 1 into a square pulse with a negative amplitude. When each pulse has duration of T sec., and one pulse is sent every T sec., this is sometimes called **Non Return to Zero** (NRZ) signaling. The receiver can then sample the received signal every T seconds to determine if 0 or 1 was sent. This analog signal could represent a voltage or current waveform. Recall, the **power** in such a signal is proportional to the square of its amplitude.

The above description is complicated by the fact that the analog signal arriving at the receiver will differ from the signal sent at the transmitter due to a variety of channel impairments. Last time we discussed one impairment - attenuation; attenuation is the loss in power a signal experiences as a function of the distance. For the above system, attenuation will cause the difference in amplitude between a 1 and a 0 to decrease. The hardware in the receiver will only be able to reliably distinguish between the signals that are separated by an adequate difference - the required difference is referred to as the **sensitivity** of the receiver. (The effect of attenuation is even more important, when considered in the context of noise, which we will discuss in the following.)
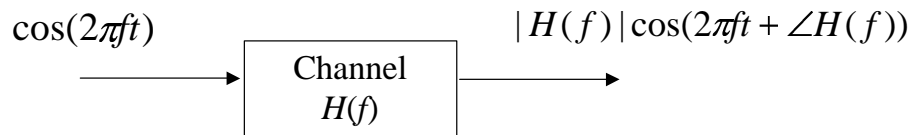
In this lecture, we will look at two other channel impairments - distortion and noise.
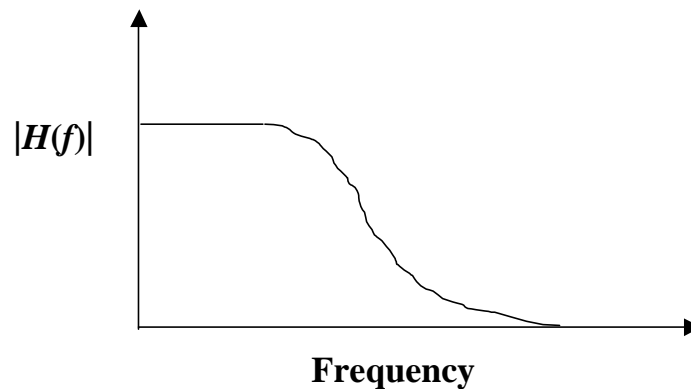
2

Distortion (Filtering)

Two properties:

1. Most analog channels are well modeled as a **_linear_** system.

2. Channel's attenuation and delay varies with frequency.

$$\cos(2\pi ft) \longrightarrow \boxed{\begin{array}{c}\text{Channel}\\ H(f)\end{array}} \longrightarrow |H(f)|\cos(2\pi ft + \angle H(f))$$

Ø $H(f)$ = **_frequency response_** of the channel.

Frequency response

$|H(f)|$

Frequency

- Depends on physics of medium and filters inserted by communication engineers.

- How does this impact transmitted signal?

Fourier Analysis

- ***Fourier analysis*** provides frequency content of signals:

- Suppose $s(t)$ is periodic with period T.

  $\Rightarrow$ frequency content given by ***Fourier series***

$$s(t) = c_0 + \sum_{n=1}^{\infty} a_n \sin(2\pi f n t) + \sum_{n=1}^{\infty} b_n \cos(2\pi f n t)$$

Where $f = \dfrac{1}{T}$ is the fundamental frequency,

$$a_n = \frac{2}{T} \int_0^T s(t) \sin(2\pi f n t) dt \qquad b_n = \frac{2}{T} \int_0^T s(t) \cos(2\pi f n t) dt$$

$$c_0 = \frac{1}{T} \int_0^T s(t) dt$$

Fourier series can also be written as

$$s(t) = c_0 + \sum_{n=1}^{\infty} c_n \cos(2\pi n f t + \theta_n)$$

where

$$c_n = \sqrt{a_n^2 + b_n^2} \qquad \theta_n = \tan^{-1}(a_n / b_n)$$

Given Fourier series of transmitted signal and frequency response, $H(f)$, of the channel, what is the output?

Slide 3: A linear system is a system with the following property. If input $s_1(t)$ generates output $r_1(t)$ and input $s_2(t)$ generates output $r_2(t)$, then input $s_1(t) + \alpha s_2(t)$ generates the output $r_1(t) + \alpha r_2(t)$, where α is any real number.

Our emphasis is on linear distortion- non-linear channel effects are important in some applications, but will not be addressed here.

Slide 4: For example, in the telephone network, low pass filters are employed as part of analog to digital conversion of speech signals.

The **bandwidth** of a channel is the difference between the highest and lowest frequencies that the channel will pass. For real channels the cutoff is somewhat arbitrary.

Warning: The term bandwidth is also used to indicate the transmission rate of a link in bits/sec. This is not the same as the bandwidth of the channel defined above.

Slide 5: A function is periodic with period T if $s(t+T) = s(t)$ for all t.

There are some mathematical requirements needed for a periodic function to be represented by its Fourier series; a complete discussion of this requires some fairly advanced mathematics and will not be covered here.
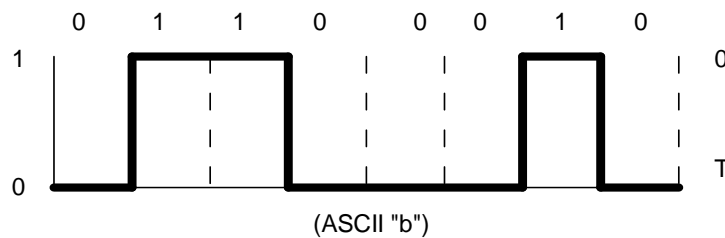
The frequency content of a large class of non-periodic functions is given by the **Fourier transform** of the function. This is covered in ECE 222.

Fourier Analysis Example

Consider sending ASCII "b" symbol (01100010) as a sequence of square pulses.

Assume it is sent over and over (so its periodic).

(ASCII "b")

$$g(t) = \begin{cases} 1 & \dfrac{T}{8} < t < \dfrac{3T}{8} \quad or \quad \dfrac{6T}{8} < t < \dfrac{7T}{8} \\ 0 & else \end{cases}$$
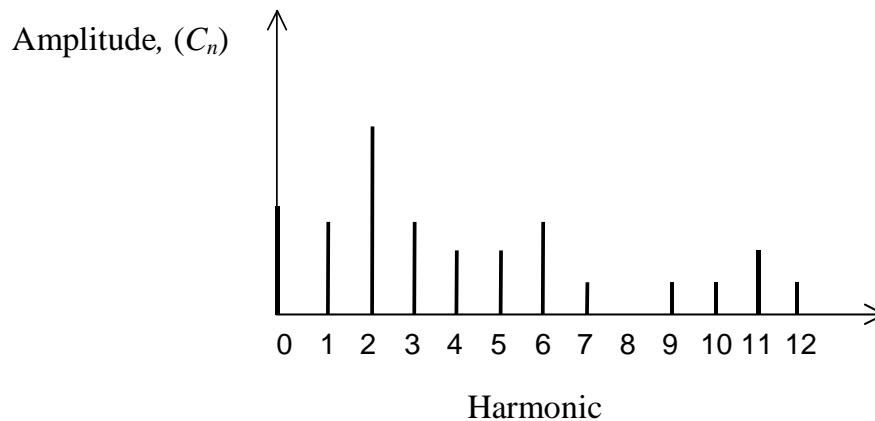
Calculation of Fourier Series:

$$C = \frac{1}{T} \int_O^T g(t)\, dt = \frac{1}{T} \int_{\frac{T}{8}}^{\frac{3T}{8}} 1\, dt + \frac{1}{T} \int_{\frac{6T}{8}}^{\frac{7T}{8}} 1\, dt = \frac{1}{T}\left[\frac{3T}{8} - \frac{T}{8} + \frac{7T}{8} - \frac{6T}{8}\right] = \frac{1}{T}\left[\frac{3T}{8}\right] = \frac{3}{8}$$

$$a_n = \frac{2}{T} \int_0^T g(t) \sin(2\pi n f t)\, dt$$

$$= \frac{2}{T} \int_{\frac{T}{8}}^{\frac{3T}{8}} \sin\left(\frac{2\pi n t}{T}\right) dt + \frac{2}{T} \int_{\frac{6T}{8}}^{\frac{7T}{8}} \sin\left(\frac{2\pi n t}{T}\right) dt$$

$$= \frac{1}{\pi n}\left[\cos\left(\frac{\pi n}{4}\right) - \cos\left(\frac{3\pi n}{4}\right) + \cos\left(\frac{6\pi n}{4}\right) - \cos\left(\frac{7\pi n}{4}\right)\right]$$

Similarly $b_n = \dfrac{1}{\pi n}\left[\sin\left(\dfrac{3\pi n}{4}\right) - \sin\left(\dfrac{\pi n}{4}\right) + \sin\left(\dfrac{7\pi n}{4}\right) - \sin\left(\dfrac{6\pi n}{4}\right)\right]$

9

Example

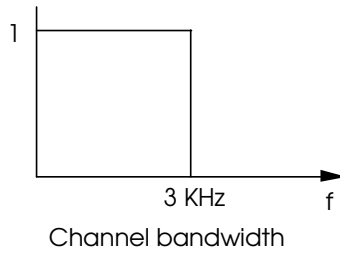Amplitude, (C_n)

0 1 2 3 4 5 6 7 8 9 10 11 12

Harmonic

- With 2400 bps modem, what is fundamental frequency?

- At 9600 bps?

10

Suppose channel is modeled as perfect low-pass filter with cutoff at 3000 Hz. (1st order model of voice grade telephone circuit.)
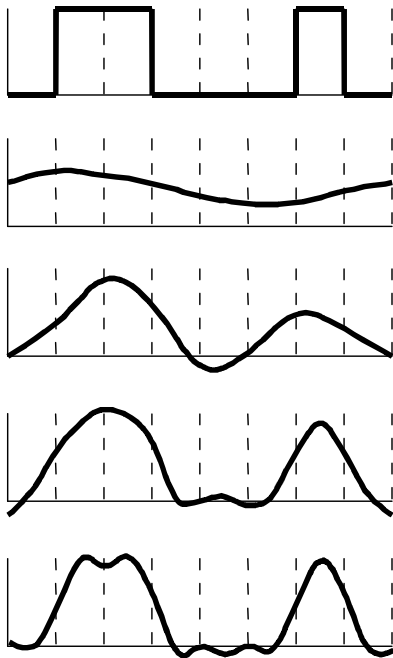
1

3 KHz   f

Channel bandwidth

What is the frequency content of the output signals?

- For 2400 bps modem?

- For 9600 bps?

Resulting Signals

TIME DOMAIN

FREQUENCY DOMAIN

1   2   3   4   5   6   7   8   9   10 11 12

1

1   2

1   2   3   4

1   2   3   4   5   6   7   8
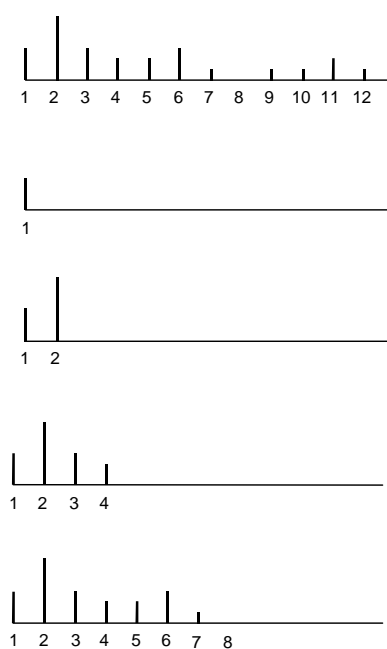
A similar example can be found in Sec. 3.3 of Leon-Garcia.

At 2400 bits/sec (bps), we can send the "b" symbol 300 times per second. This results in a fundamental frequency of 300 Hz, the other harmonics will then be at 600 Hz, 900 Hz, etc.

At 9600 bits/sec (bps), the "b" symbol can be sent 1200 times per second, resulting in a fundamental frequency of 1200 Hz.

For the 300 bps modem, the first 10 harmonics will get through the ideal low pass filter, i.e., 300 Hz, 600 Hz, … ,3000 Hz. For the 1200 bps modem, only the first 2 harmonics get through - one at 1200 Hz, and one at 2400 Hz.

For this example, we clearly cannot send this waveform reliably through the channel at a rate higher than 24kbps, for at such a rate not even the first harmonic would get through.

As shown in this example, the effect of filtering is a smoothing and spreading out of the transmitted signals. The spreading in time causes the pulses associated with different bits to interfere with each other. This phenomenon is called ***intersymbol interference.***

Digital communication systems generally encode bits as a sequence of pulses, but not necessarily square pulses as in this example. Better pulse shapes can be chosen to reduce the effect of intersymbol interference.

Our discussion has focused on low-pass channels. Many realistic channels are band-pass - that is they have low attenuation only in a band of frequencies away from zero. In these cases some type of ***modulation*** is needed to shift the frequency content of the transmitted signal into the desired band (see Sect. 3.6 of Leon-Garcia)

13

Nyquist's Theorem

- Basic digital communication system:

    Map bits into sequence of pulses.

- How fast can pulses be sent and data be recovered?

- Number of pulses per second = baud rate.

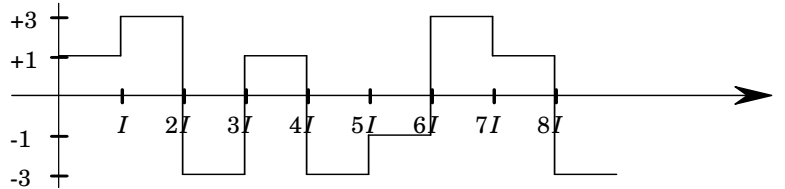| **Nyquist:** *Maximum baud rate = 2 x bandwidth of channel.* |
| --- |

    How many bits per second?

14

Symbol rate

- If each pulse corresponds to 1 bit then bit rate = baud rate.

In general, each pulse may is chosen from a set of V discrete values.

Ex: $V = 4$, set of representations = {-3 volts, -1 volt, +1 volt, +3 volts}, time interval = I seconds.

Bit rate = ?

Notes

More precisely Nyquist's Theorem gives a limit on the rate at which pulses can be sent without any intersymbol interference. The pulse shapes that achieve this limit are sometimes referred to as ***Nyquist pulses***.

Each allowable pulse is often called a ***symbol*** and the set of all symbols is called the (input) ***alphabet*** to the channel. Usually the alphabet will contain $V = 2^n$ symbols, in which case each symbol represents n bits. In this case the bit rate is equal to nB, where B denotes the baud rate. For example if $V=8$, then we are sending 3 bits per symbol and the bit rate is three times the baud rate.

Nyquist's theorem can be interpreted as saying with an alphabet of V symbols, the maximum bit rate over a channel with Bandwidth B is $2B\log_2(V)$.

Ex: A standard 300 bps modem uses an alphabet with 2 symbols, $V = 2$, so it is also a 300 baud modem. A standard 9600 modem uses an alphabet with 16 symbols, each symbol represents 4 bits, so it is a 2400 baud modem.
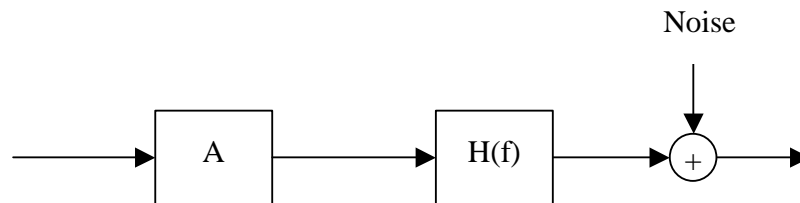
Noise

Noise

- Noise is due to thermal agitation of electrons & interference from other electromagnetic waves.

- Amount of noise present is measured by ***Signal-to-Noise Ratio (SNR)***

SNR typically measured in **dB**'s

Shannon's Result

Noise limits maximum data rate:

Shannon: *Maximum number of bits/second* $= W \log_2 (1 + S/N)$

W = channels Bandwidth.

S/N = signal-to-noise ratio (linear)

Ex: $W = 3000$ Hz, SNR $= 30$ dB $\Rightarrow$ S/N $= 1000$

Max $= 3000 \log_2 (1 + 1000) \simeq 30,000$ bps

Notes:

The signal-to-noise ratio in dB's is 10 $\log_{10}$ of the linear value.

Shannon's result as stated here applies to an ideal band-pass (or low-pass) channel with a certain type of noise called ***additive white Gaussian noise***. However this result can be generalized to many other types of channels. More precisely it refers to the maximum rate that can be attained with arbitrary small bit error rates.

Shannon's result is very deep; we have not developed the background here to even state it precisely or justify it. The point you should take away from this is that there is a provable upper bound on the bit rate for a communication channel. (If you want to learn more about this take ECE 428 - Information Theory) Approaching this bound requires the use of very sophisticated error correcting codes (more about this in a couple of lectures.)

Note on voice grade telephone channels V.34 modems have a rate of 28.8 kbps, which is not far off from the 30kbps approximated in the above example. The higher rates on

Note for a given alphabet size an upper bound on the maximum data rate (assuming Nyquist pulses are used) is the *minimum* of the Nyquist and Shannon limits.

Examples of common Transmission media

Transmission media:

     Guided:
         Copper - Twisted Pair, Coax
         Fiber (glass)

     Unguided (wireless)
         Fixed, Line-of-sight (microwave, satellite)
         Mobile (cellular)

Notes:

Two types of copper wiring are commonly used in networks - unshielded twisted pair (UTP) and coxial cable (Coax).

UTP:
- Two insulated copper wires twisted to reduce antenna effects.
- Very common in current telephone system between home and local office.
- Legacy phone networks limited useful bandwidth of UTP to 3 KHz.
- Actual copper wire has usable bandwidth of 1-MHz
- Data rates decrease with distance: (using entire bandwidth)
  - 50 Mbps over ~ 100 m
  - 5 Mbps over ~ 1 km
- ADSL systems use UTP to provide 1.5-6 Mbps to the home.

Coaxial Cable (Coax)
- Construction and shielding gives coax higher bandwidth and noise immunity than twisted pair. (Also higher cost)
- Two common types:
  - 50 Ω (Baseband) Coax (For 1 km length, data rate ~ 1-2 Gbps).
    - Used to be common in phone network (replaced by fiber).
    - Common in LANs (e.g. some versions of Ethernet)
  - 75 Ω (Broadband) Coax:
    - Most commonly found in cable TV network.
    - Data rates up to 1 Gbps possible depending on distance.
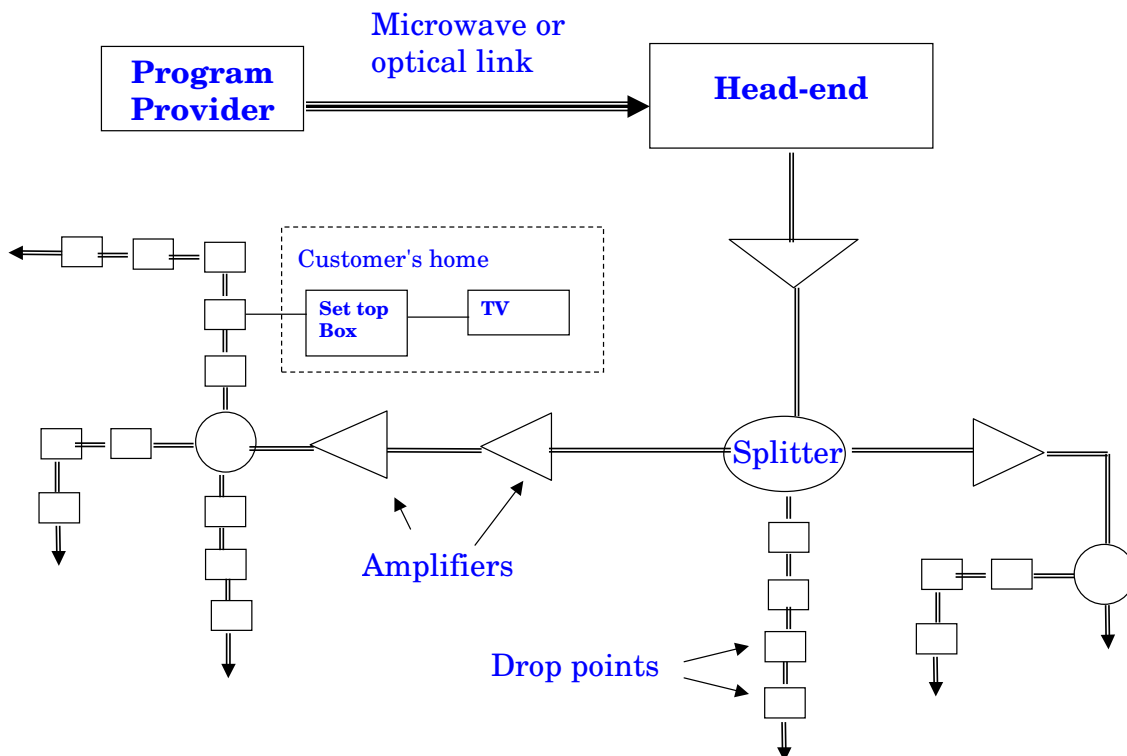
Cable TV Networks

Notes:

Traditional CATV networks:
- Used analog signaling and analog amplifiers.
- Tree topology made up of coaxial cable links from the head end to the customer's.
- Uses 500 MHz Bandwidth divided into 6 MHz channels.
- One way transmission (used analog amplifiers which only amplified signal in downstream direction)

In 1999, CATV network reached over 50% of US households and could reach over 90% with relatively minor additional infrastructure.

The CATV Network has evolved to be able to support a mix of application including internet connectivity.

Significant changes include:
- Digital transmission with advanced video compression techniques.
- Replacing either the coax between the head-end and the drop points with fiber, (this is called fiber to the curb (FTTC) alternatively some systems only a portion of this coax is replaced resulting in a Hybrid Fiber Coax (HFC) system.
- Upgrading hardware to allow bi-directional communication -this is done either by laying a second cable for upstream communication or by using a "split system" which divides the available bandwidth into two portions - one for upstream and one for down stream

Optical Fiber

Fiber has a much higher bandwidth and better noise immunity than Coax.

- Current systems at ~10-100 Gbps

- Feasible limit in excess of 50 Tbps

- Used in telephone network backbone and most WANs

- Used in some high-speed LANs and MANs.

Notes:

An optical fiber is a very thin, flexible medium capable of guiding an optical signal. This signal is generated by either a semiconductor laser or a Light Emitting Diode (LED) at the transmitter. At the receiver, an optical detector, such as a photo diode is used. Optical fibers are typically made from very pure glass (fused silica). Plastic fibers are also used for short links (such as in office buildings); plastic fiber supports a lower data rate but is cheaper.

The transmitted signal optical signal is usually an on/off pulse at some wavelength, e.g. the light source will be turned on for a length of time to correspond to a 1 and turned off for the same length of time to correspond to a 0. (For obvious reasons, this is sometimes called *On/Off Keying*).

A technique called *Wavelength Division Multiplexing (WDM)* allows the sending of independent signals on different wavelengths of the same fiber. (e.g. 80 signals at 2.4 Gbps each).

Typically when discussing optical systems, the wavelength of the signals is referred to instead of the frequency. Of course the frequency is simply the speed of light divided by the wavelength.

Attenuation of light through fiber in the infrared region.
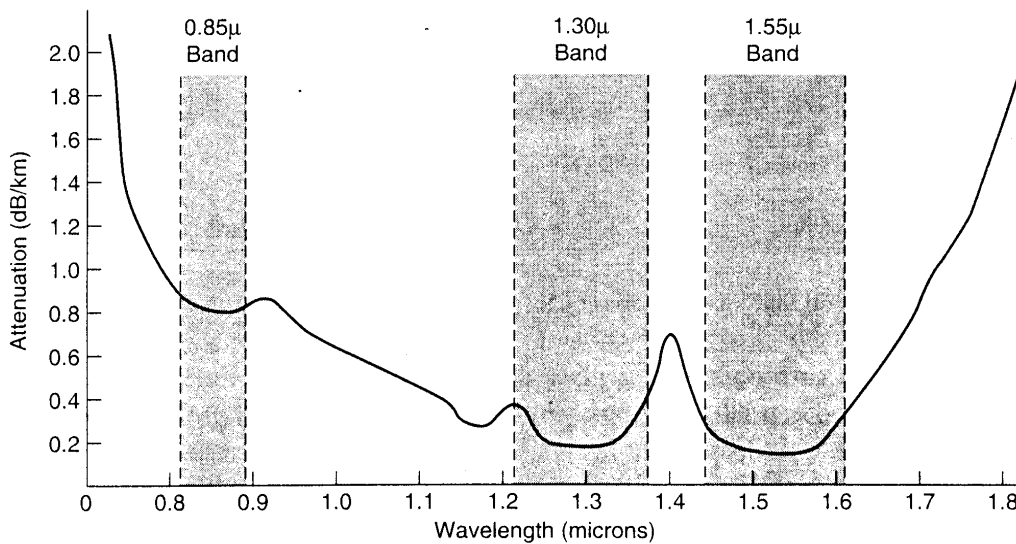
Shaded areas are commonly used bands.

Some newer "all-wave" fiber has no notch at 1.4 microns.

Comparison of Fiber and Copper

Fiber Advantages:

- Much higher bandwidth

- Low attenuation (fewer repeaters)

- Immune to power surges, e-mag interference

- Thin and lightweight

- Cheap core material (sand)

- Inherently secure

Copper

- Huge installed base

- Cheaper interfaces

For new installations over MAN or WAN distance, fiber is clear winner.

27

Wireless Transmission

Electromagnetic waves in radio, microwave, infrared or visible bands are used for wireless communications.

Fixed:

Usually requires line-of sight path.
Often cheaper to deploy than fiber. (but lower rates)

Ex.'s

1. **Microwave** - commonly used in telephone and TV. Can suffer interference due to atmospheric conditions.

2. **Infrared –** Used for indoor network applications, e.g., wireless LANs, PC to Palm Pilot.

3. **Geosynchronous Satellite –** basically a microwave repeater. Delays up to 300 msec. Typical satellites can support 500 MHz of bandwidth, divided into multiple transponders each with 36 MHz bandwidth. Each can handle 50 Mbps.

Note: A single fiber has greater bandwidth than all the communications satellites ever launched.

28

Mobile wireless (e.g. cellular systems)

"anywhere, anytime" connectivity.

Time-varying channel

Much higher error rates than wired links.

Power limitations

Limited frequency spectrum must be shared

Mobility also has impact on higher layer functions (e.g. routing)

29