Information Technology
Inside and Outside
- David Cyganski & John A. Orr

VI. Transmission and Storage Technology

14. What Is Bandwidth and How Is It Used?

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14. What Is Bandwidth and How Is It Used?

- Objectives:
  - the fundamental limits imposed by the speed of light, and the fact that in modern-day communications and computation, ``light speed" is not all that fast;
  - the implications of the speed of light on long-distance (satellite)communications and on short-distance data transmission, such as within a computer;
  - the distinction between data transmission rate and data latency (delay);
  - the fact that everything in the world has a limited bandwidth, and the reasons for this fact;
  - similarities and differences of the three fundamental communications media: free space (radio), wires, and optical fiber;
  - the principles by which optical fiber transmits signals, and its advantages over wires; and
  - methods of transmission of information over a given bandwidth, through the use of modulation and pulses separated in time.

- The concepts of ***latency*** and ***information rate***
  - **Latency** is another word for **delay**; specifically, it is the time delay involved in the movement of a message from one location to another. ➔ the time that it takes to move 1 bit from source (origin) to sink (destination).
  - **Information rate** is the number of bits that can be sent at the source or received at the sink per second.

14.2 Real-Time Data Transmission

- What do we mean by real-time transmission of data?
- **The data is available soon enough** after its creation to be of as much use as it would be if no processing or transmission delays had been involved.
  - **if a human voice is delayed by 0.5 second**
  - **the slave flash must light within less than 1/200th of a second,or within 5 milliseconds.**
  - **traffic engineers require real-time data regarding the occupancy of streets and the flow of traffic**

- An ultimate limit as to how **small a delay** can be achieved in the movement of data.➔ **the finite speed of light** and the now well-verified **theory by Albert Einstein** that no information can be relayed at speeds that exceed the speed of light.

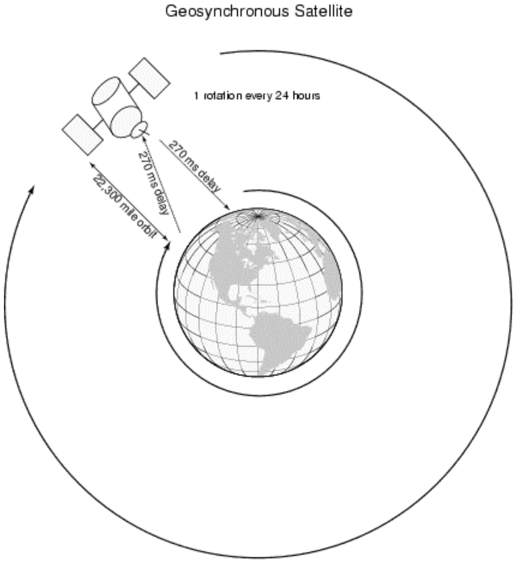
14.3.1 Geosynchronous Satellites(停止軌道衛星)

- A geosynchronous satellite orbits the Earth at a height of **22,300 miles**. (22300x1.6=**35,000km**)
- If the satellite is rotating in the same direction as the Earth, the satellite appears to stay still over the same spot on Earth
  (one orbit of the Earth is 24 hours).
- A geosynchronous satellite is always in the same place with respect to antennas on the ground, a very useful attribute for simple, low-cost and continuous communications coverage.
- The travel time of a radio signal moving at the speed of light, a **delay from one side** of the connection to the other of ➔ **270 ms**.
- **Total delay** between when you say something and when you hear the other person's response is **540 ms**.

14.3 Delay Time and the Speed of Light(2)

14.3.1 Geosynchronous Satellites(停止軌道衛星)

Figure 14.1: A communication satellite in geosynchronous orbit above the Earth.

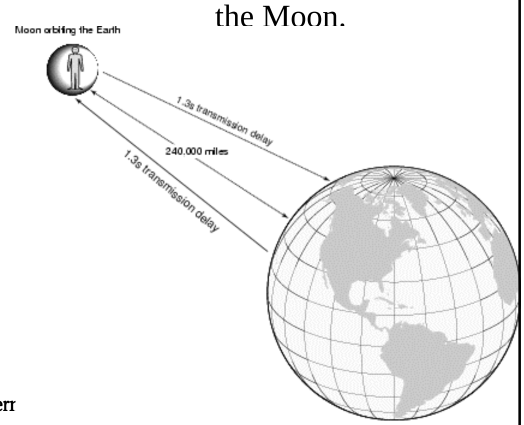


14.3 Delay Time and the Speed of Light(3)

14.3.2 Inter planetary Communications(行星間 通信)

- The moon is **240,000 miles** from Earth.(**380,000 km**)
- The finite speed of light introduces a round-trip **delay time of 2.6 seconds** in any conversation with an astronaut
- The average (over many orbits) of the distance between **Mars and Earth** at the point in any year when they are closest to each other in their orbits is **50 million miles**. The round-trip time between them at the speed of light is, in this case, **9 minutes**. → The controller on Earth needs to **wait at least 9 minutes** before the result of a command is evident.

Figure 14.2: Time delay of communications between Earth and the Moon.



14.3 Delay Time and the Speed of Light(4)

14.3.3 Internet Distributed Computing

- It is not uncommon to hear on the nightly news about some new success by certain groups in **cracking** ever more complicated, ever more supposedly **secure encryption systems**. Quite often, we hear that the key was **the use of thousands of computers scattered throughout the country, cooperating in a massive brute-force effort**. It makes sense that if a lock has a huge number of combinations, then huge numbers of people can cooperate in finding the right key by simultaneously trying different keys on many identical copies of the lock.
- ***Parallelizable solution :*** means that we can solve the problem ***N*** times faster by having ***N*** people(or computers as the case may be) working in parallel to solve it.
- ***Piecewise parallelizable***: a step in the solution process can be parallelized
- Unfortunately,**the limitations introduced by the speed of light** may again intervene to **make the parallel solution slower than the one-computer solution.**

14.3 Delay Time and the Speed of Light(5)

14.3.3 Internet Distributed Computing (2)

- **Single machine (serially)** : step takes 1 millisecond x 5 steps = **5 ms**
- **Parallel processing : at least 20 milliseconds (very long!!!)**

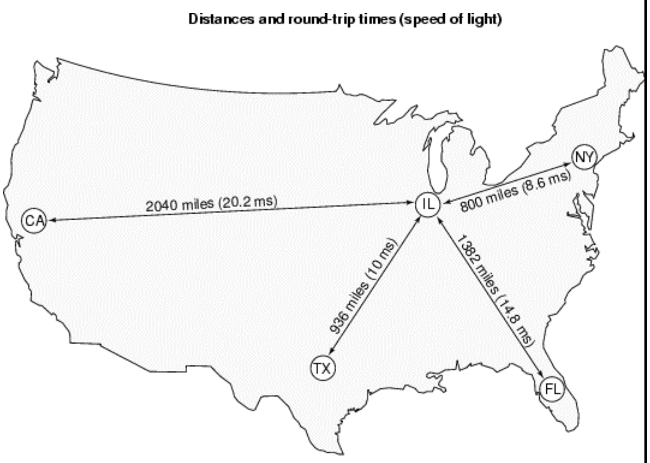


Figure 14.3: The speed of light greatly impacts the ability of computers distributed across the Internet to cooperate in the solution of large-scale problems. It takes at least 20 thousandths of a second (20 ms) to move data from Illinois to California.

14.3 Delay Time and the Speed of Light(6)

14.3.4 Personal Computers

- The actual speed at which information travels **along the wires** on circuit cards in a computer is actually less, equal to about **one half the speed of light**.
- The act of obtaining a piece of **information from memory by the CPU**
    - **1) The CPU must first send a message to the memory that indicates the numerical address of the information to be read--the postal clerk extends a hand to the pigeonhole that has the address of the information that is needed.**
  - **2) The memory device responds by sending the information contained in the addressed memory slot--the postal clerk withdraws his hand from the slot with the card that was in it.**
- The distance is **the distance between the CPU and memory** components inside the computer = **1 foot** ➔ four billionths of a second(**$4/10^9$ sec=4ns**).
  - 250 million instructions (that is,operations) per second, also referred to as **250 MIPs**. (max)
  - A ***cache* memory** located within **an inch** or two of the CPU
  - ➔ **PCs with 400 MIPs**, work stations boast speeds of **600 MIPs**

14.3 Delay Time and the Speed of Light(7)

14.3.4 Personal Computers (2)

Figure 14.4: Main computer circuit board of a mid-9 zeroes generation workstation that employed cache memory to improve information access speeds.

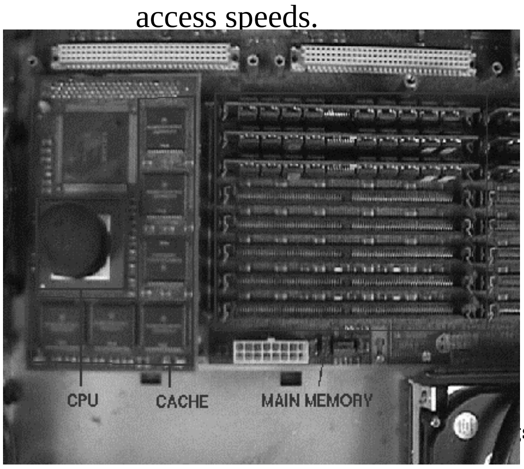
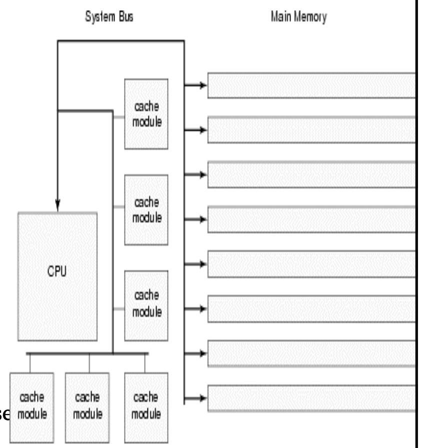


Figure 14.5: Diagram of the main computer circuit board shown in Figure 14.4.



14.4 Finite Data Rate and Real-Time Transmission

- **A conveyor belt**, 20 feet apart ➔ the data rate is **1 bps**
  (where, "0"=empty state of ping-pong ball, "1"=placing a ball)
- A **CD-like encoding scheme** in which a stereo pair of signals is sampled at **44 kHz** each and encoded as **16 bits per sample**, then our outgoing bit rate is approximately **1.4 Mbps**. Thus, immediately after sending the first bit, we would begin generating a backlog and have about 1.4 million bits ready to send by the time the second slot was available, a backlog of 2.8 million bits by the third slot time, and so on.

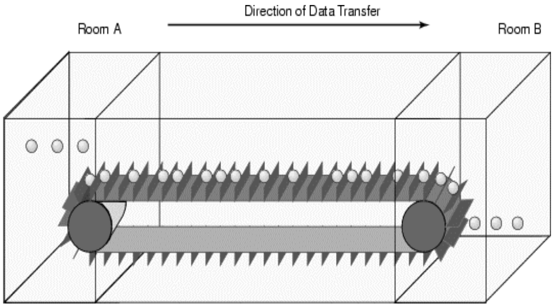


Figure 14.6: A binary communication system based upon a conveyor belt that moves ping pong balls (representing ones) or not (representing zeroes) from one room to another.

14.4 Finite Data Rate and Real-Time Transmission(2)

- **A song with a 3-minute duration**
  ➔ accumulate **2.5344×10^8 bits**
  ➔ **a total of 8 years**
  *** 1 Year = 365 x 24 x 3600 sec = 3.15×10^7 sec**
- ***Transmission latency***, sometimes called ***transmission propagation delay***, determines message delay only if the ***source rate*** of data is below the ***information rate capacity*** of the communications channel.

14.5 Physical Origin of Bandwidth Limitations

- The **human ear** = the **band-pass** response
- The idea of **Fourier decomposition** and the frequency response curve
- The **human ear** as a **communications channel** provides a good model for understanding any other communications channel; there are similar limitations due to physical phenomena, and these limitations can also be described by frequency response curves.

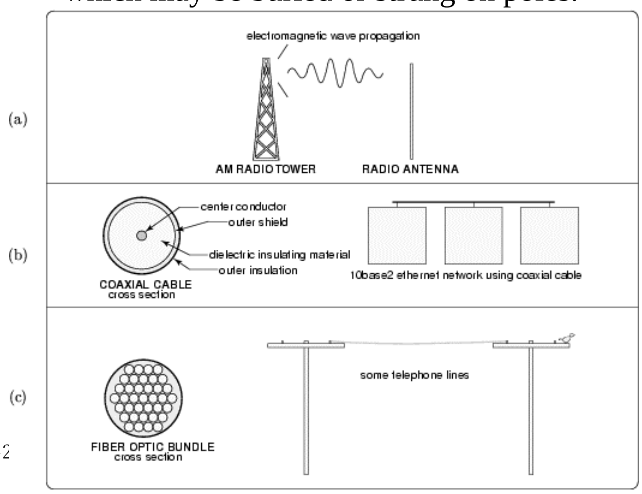
14.5 Physical Origin of Bandwidth Limitations

- **Three ways of information transmission**

  1) A **free-space electro magnetic wave**:
  radio, television, cellular telephones, wireless modems, and microwave telephone and data links.
  2) **A variation of a current or voltage on a pair of wires (a cable)**:
  cable television, the telephone local loop (the part of the telephone system that enters your home and links it to nearby central offices), and cable-based local area computer networks such as Ether net and Apple talk.
  3) **A variation of light intensity in a fiber-optic cable**:
  the telephone *long lines* system (the part of the telephone system that links distant central telephone offices and provides overseas connections

14.5 Physical Origin of Bandwidth Limitations(2)

Figure 14.7: (a) Antennas are used to launch and receive free space radio transmissions. (b) Examples of coaxial cable used for cable television and data networking. (c) A bundle of fiber-optic cables, which may be buried or strung on poles.

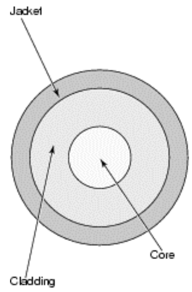


14.6 Fiber -Optic Transmission

❑ A **fiber-optic cable** is a **coaxial arrangement of glass or plastic material** of immense clarity.

❑ The typical construction of a fiber-optic cable
- ➢ The ***core***: a clear cylinder of optical material
- ➢ The ***cladding***: another clear wrapper of optical material
- ➢ ***Jacket***: a plastic or Teflon jacket to protect and stiffen the fiber

Figure 14.8: Cross section of optical fiber cable showing the coaxial arrangement of optical conductors of different indices of refraction, and a protective jacket.



14.6 Fiber -Optic Transmission(2)

❑ **A ray of light striking the surface of water** in a tank from its origin in air above the tank. The indices of refraction for air and water are such that the light ray is bent, as shown, towards more vertical path.
- ➢ **n1 x d1 = n2 x d2**

  (n: the index of refraction of a material 1, d: density)
- ➢ **the index of refraction of a material(n) proportions to (1/d)**

❑ Regardless of the angle at which the light hits the surface of the water, it will be bent closer to the vertical, with vertical rays passing through unbent. The situation is quite a bit different for light rays that originate below the surface of the water.

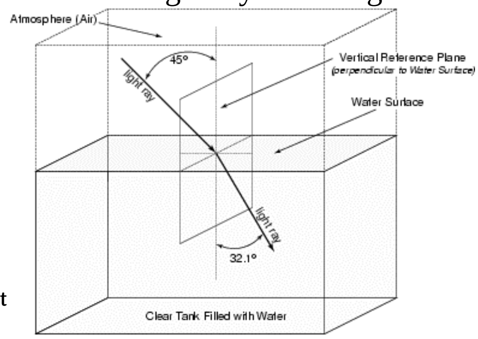


Figure: A ray of light is shown passing through a material interface as it moves from the air into the tank of water. The bending or refraction of the ray of light is determined by the velocity of light in each material.

14.6 Fiber -Optic Transmission(3)

❑ Light striking the under side of the water surface at an angle sufficiently close to the vertical will be bent further away from the vertical on exiting into the air. More interesting is the fact that when light strikes this boundary at a sufficiently shallow angle, it is totally reflected as if it had struck a mirror

❑ This ***total internal reflection*** phenomenon occurs only if the light is in the ***denser*** medium (that is, the one with the higher index of refraction and hence slower speed of light) and strikes an interface with the less dense medium. ➔ The maximum grazing angle : the ***critical angle*** of the interface.

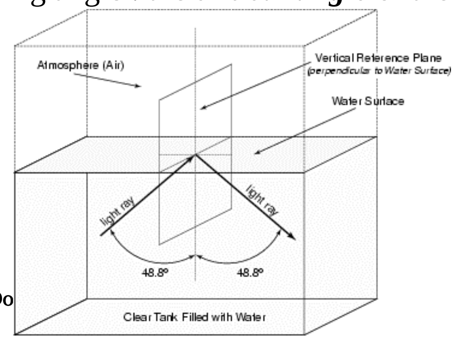


Figure 14.10:A light ray that strikes the air-water interface from the water at an angle larger than the ***critical angle*** is totally reflected.

14.6 Fiber -Optic Transmission(4)

❑ Any rays entering the fiber-optic cable at an **angle shallower than the critical angle** will bounce off the core-cladding interface and go on to strike another side of the cable at the same angle, repeating until it comes out the far end.

❑ The clarity of fiber-optic cable is about **0.1 dB/km (currently)**
➔ only **1/10 of the light at the far end** of a cable, a length of **100 km**

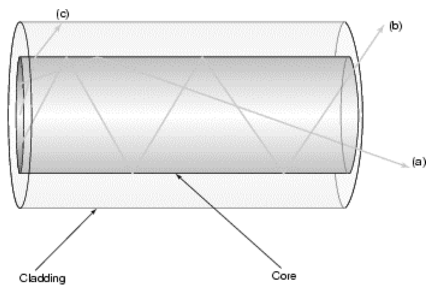


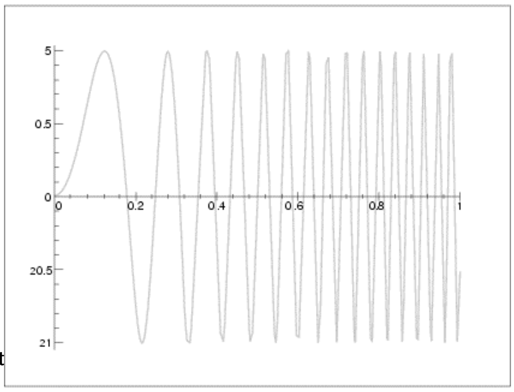
Figure 14.11: Side view of an optical fiber cable showing the paths of light rays that enter the face at different angles. Note how different the path lengths are of the two rays that are shown. The rays labeled (a) and (b) propagate through the fiber, but with different path lengths. Ray (c) is lost in the cladding.

14.6 Fiber -Optic Transmission(5)

14.6.1 Talking Through Your Pipe

Figure 14.12: When you speak into a long tube, your voice exits with most of the higher audio frequencies attenuated. As a result your voice sounds muffled and baritone.

Figure 14.13: Chirp waveform that will be used in our experiment with summing waveforms delayed as if by various path lengths in a tube.



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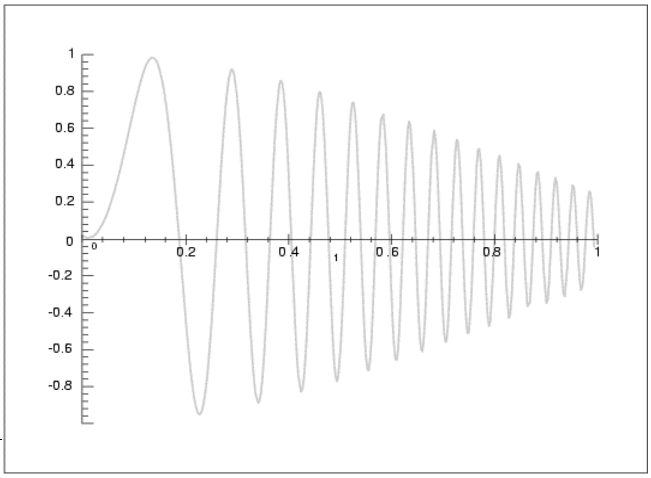
14.6 Fiber -Optic Transmission(6)

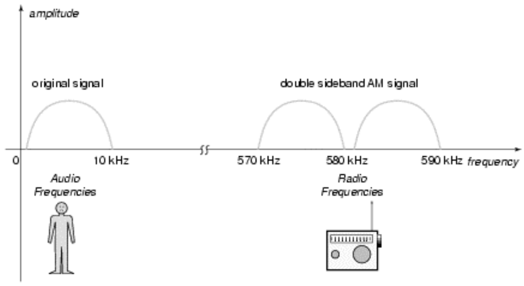
14.6.1 Talking Through Your Pipe (2)

Figure 14.14: Result of summing 50 copies of the waveform in the previous figure. Note that the frequency components of this waveform are suppressed progressively with increasing frequency.



14.7 Human Laws Set Limits Too!

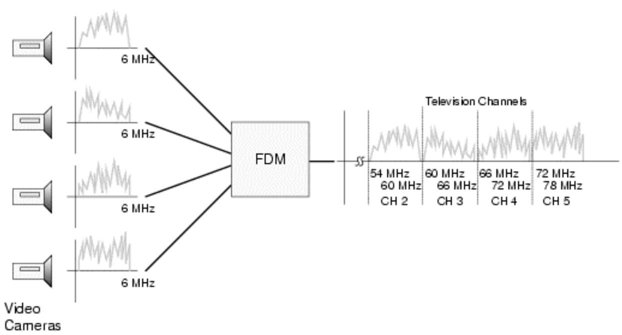
❑ **DSBSC-AM** (Double sideband Suppressed Carrier Amplitude Modulation)
❑ If the original signal (we call this the ***baseband*** signal) occupies a certain finite bandwidth, then the new signal is also finite in bandwidth but,as can be seen, centered at a new frequency.
❑ ***Frequency division multiplexing* (*FDM*) & *Demodulation***
❑ **Figure 14.15:** Audio signals undergo the modulation process described in the text to obtain AM radio signals, which are arranged into evenly spaced channels that we can tune to with our AM radios.



14.7 Human Laws Set Limits Too!(2)

❑ Commercial **AM radio** stations must filter out any content in **voice and music above 10 kHz** so that the FDM processed signals will fit within **20 kHz assigned slots in the AM band**
❑ **FM transmission** requirements are much less stringent, allowing an **18 kHz original content bandwidth** that makes FM music sound so much better even when not played on a stereo receiver, which uses the fact that two channels are effectively used for each FM stereo source.

Figure 14.16: FDM is used to transmit many channels of television information to users simultaneously over the same cable or radio spectrum.



14.8 Pulse Transmission Limits and Bandlimits

- A **maximum data rate** (a maximum number of bits per second) : proportional to the **available bandwidth**, but is also a **function of the amount of noise** to be found on that channel.

$C=2B \log_2(M)$: Nyquist Channel Capacity (in noiseless channel)

$C=B \log_2(1+S/N)$: Shannon Channel Capacity (in noisy channel)

- **Bell Laboratories electrical engineer Harry Nyquist**
- **It is impossible to transmit more than 2*B* pulses per second through a *B* Hz bandwidth channel and to unravel those pulses at the other end into 2*B* pieces of information again.**
- **This best possible pulse** is also **impossible** to use in reality because it literally lasts forever.
- Telephone system supports **4 kHz bandwidth** ➔ **never** transmit more than **8 kbps** with a **modem**.

14.8 Pulse Transmission Limits and Bandlimits(2)

Figure 14.17: The **pulse shape** that allows the greatest number of separable pulses to be sent over a finite bandwidth channel is shown.This pulse is **zero periodically** except at one distinguished point in the otherwise unbroken pattern.

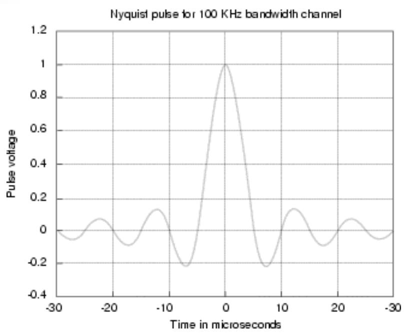
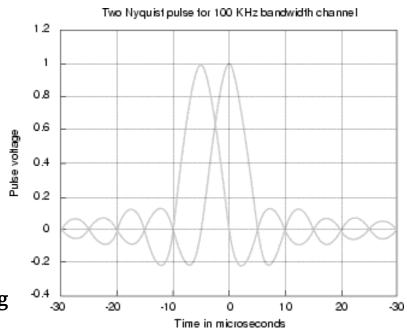


Figure 14.18: Two bits represented by two sinc pulses, one **at Time -10** and one **at Time 0**. Note that the peaks are distinct, and that at the time when one pulse is at its peak, the other pulse amplitude is zero.



14.8 Pulse Transmission Limits and Bandlimits(3)

14.8.1 Information Rates above the Pulse Rate

- The simplest such scheme merely involves sending a given **``basic shape'' with different heights.**
- **Four transparencies in front of the light:**
  - one is opaque (**no light flash**),
  - one is completely clear (**full brightness flash**),
  - and the other two are semi transparent to different degrees (**low and medium brightness flashes**).
- Each pulse is transmitted with one of **16 heights**. These pulses are still perfectly separable but now each one carries **4 bits of information**,corresponding to the **16 possible levels** with which it was **transmitted**.
- So, could we transmit each one with **256 levels** and get **8 bits per pulse?**
- How about **65,536 pulse levels** for **16 bits per pulse**?
  ➔ **YES, but impractical.**

14.8 Pulse Transmission Limits and Bandlimits(4)

14.8.1 Information Rates above the Pulse Rate

- If we apply the **channel capacity theorem** to a typical telephone line, we discover that about **40 kbps is the maximum** we will ever be able to squeeze out of the existing phone system. Thus, modern modem technology, as of the mid 1990s, finally hit the ceiling imposed by the nature of noise, power, and information. In fact, to obtain **a slightly higher rate of 56 kbps**, it was necessary to change the ground rules in use and to modify the telephone equipment so as to lower the amount of noise that corrupted the typical phone connection.

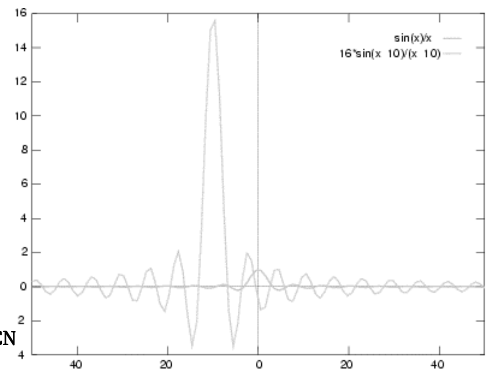


Figure: Two **sinc(x)=sin(x)/x** pulses of different heights.