Lecture 2
Physical Layer
(Computer Communication Networks)

CS 35201
Spring 2020

H. Peyravi
Department of Computer Science
Kent State University

§2.0.0 Contents

The contents of this lecture have been composed from various resources including those listed at the reference section.

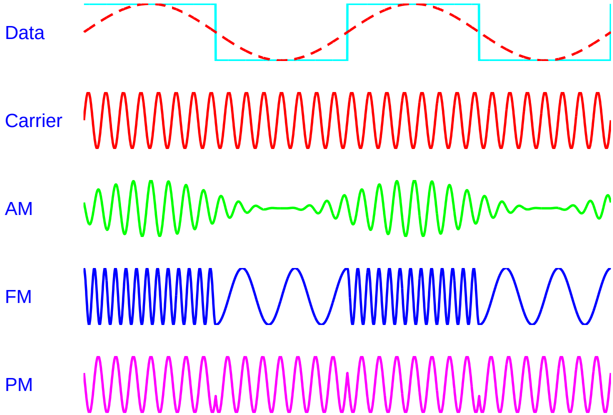
Reading List

- Chapter 2 (2.1-2.8) of [Tanenbaum and Wetherall, 2011]

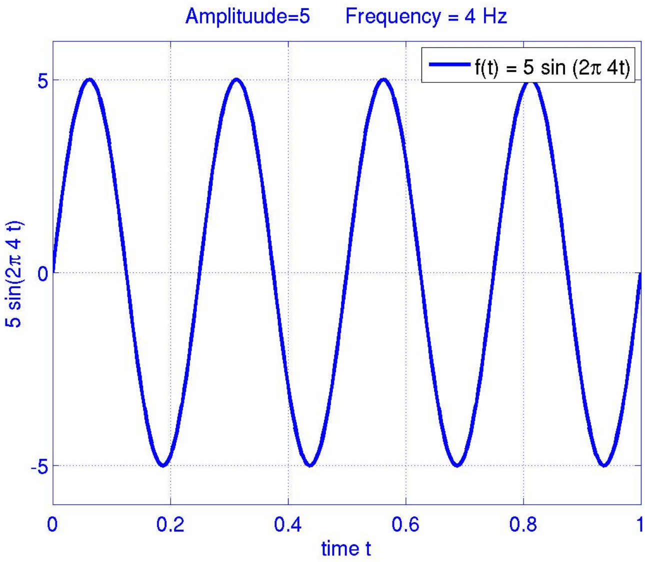
§2.0.0 Glossaries

ADSL	Asymmetric Digital Subscriber Line 88
ASK	Amplitude Shift Keying 51
CDM	Code Division Multiplexing 72
DMT	Discrete Multitone Modulation 88, 89
DSL	Digital Subscriber Line 88
DWDM	Dense Wave Division Multiplexing 83
FDDI	Fiber Distributed Digital Interface 54
FDM	Frequency Division Multiplexing 72, 83
FSK	Frequency Shift Keying 51
ITU	International Telecommunication Union 88
OOO	Optical-Optical-Optical 86
PCM	Pulse Code Modulation 52
PSK	Phase Shift Keying 51
SONET	Synchronous Optical Networking 54
TDM	Time-Division Multiplexing 72, 101
WC	Wavelength Converter 86
WDM	Wave Division Multiplexing 72, 83
WL	Wave Length 83, 85, 86

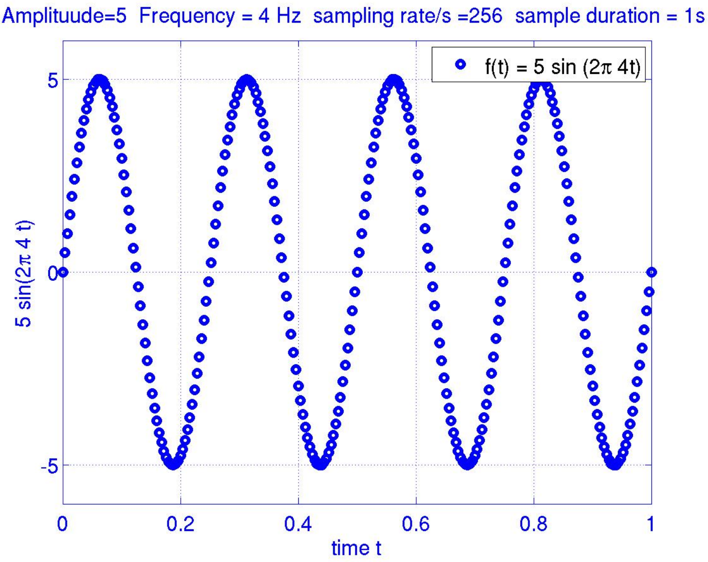
§2.1.0 How to Transmit a Bit Point-to-Point?



§2.2.0 Recall Waves I

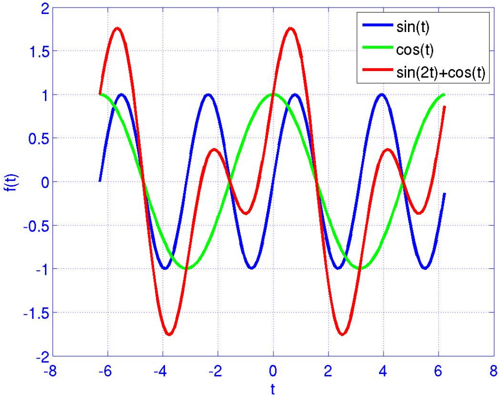


§2.2.0 Recall Waves II



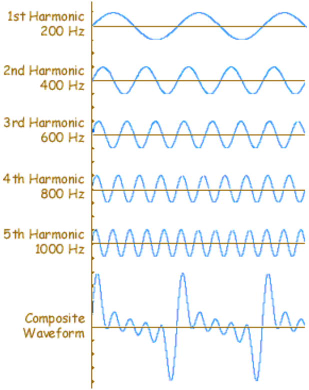
§2.2.1 Frequency Domain Concepts I

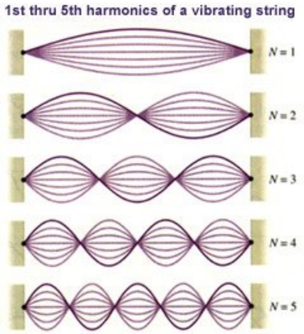
- Signals are often made up of many frequencies
- The Components of a signal are sine waves ⇒ Fourier analysis
- We can plot frequency domain functions



§2.2.2 Harmonic Numbers I

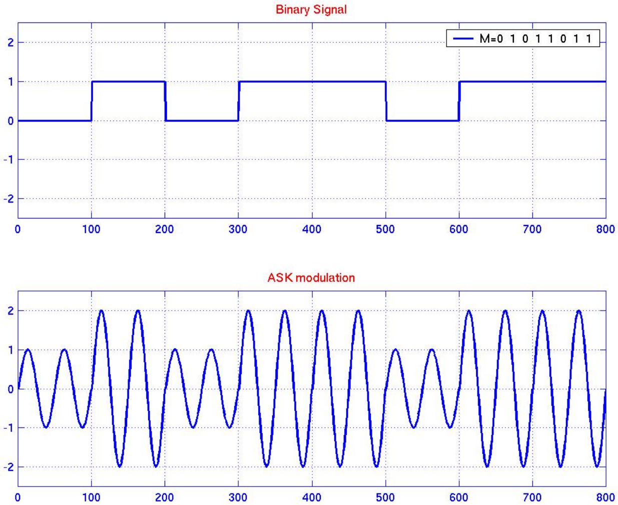
- Frequencies and their associated wave patterns are referred to as harmonics





- See other examples of wave patterns @
  http://www.physicsclassroom.com/class/waves/Lesson-4/Harmonics-and-Patterns

§2.2.2 Harmonic Numbers II



§2.3.0 Some Terminologies I

Definition 2.1 (Analog signal)

The signal varies in a smooth way over time.

Definition 2.2 (Digital Signal)

The signal maintains a constant level, then changes to another constant level.

Definition 2.3 (Periodic Signal)

The signal follows a repeated pattern over time.

Definition 2.4 (Aperiodic Signal)

The signal does not follow a pattern over time.

Definition 2.5 (Peak Amplitude (a))

The maximum strength of a signal $\Rightarrow$ in volts.

§2.3.0 Some Terminologies II

Definition 2.6 (Frequency(f))

The rate of change of a signal $\Rightarrow$ in Hz (or cycle per second)
The maximum strength of a signal $\Rightarrow$ in volts.

Definition 2.7 (Period (t))

The time for one repetition of the signal $\Rightarrow$ $t = 1/f$

Definition 2.8 (Phase (ϕ))

The relative position of the signal in time.

Definition 2.9 (Wavelength (λ))

The distance occupied by one cycle. Or Distance between two points of corresponding phase in two consecutive cycles.

§2.3.0 Some Terminologies III

Definition 2.10 (Spectrum)

The range of frequencies contained in a signal.

Definition 2.11 (Absolute Bandwidth)

The width of the spectrum.

Definition 2.12 (Effective Bandwidth)

The narrow band of frequencies containing most of the energy.

Definition 2.13 (Data)

Entities that convey meaning.

Definition 2.14 (Signal)

Electric, electromagnetic or optical representations of data

§2.3.0 Some Terminologies IV

Definition 2.15 (Data Rate)

Ant transmission system has a limited band of frequencies. This limits the data rate that can be carried.

Definition 2.16 (Transmission)

Communication of data by propagation and processing of signals.

Definition 2.17 (Analog)

Continuous values of a signal within some interval $\Rightarrow$ e.g. sound, video

Definition 2.18 (Digital)

Discrete values of a signal within some interval $\Rightarrow$ text, integers

§2.3.0 Some Terminologies V

Example 2.1 (Wavelength (λ))

Assume the signal velocity (speed) is c meters/s, then

$$\lambda = ct = \frac{c}{f} \qquad \lambda f = c$$

Where the speed of light $c = 3 \times 10^8$ meters/s (in free space)

§2.4.1 Two Forms of Transmissions

1. Digital transmission
   - Uses two signaling levels ⇒ representing 0 and 1
   - Data transmission using square waves
   - Digital transmission is concerned with content
   - The data could be analog (voice) or digital (data)
2. Analog transmission
   - Uses other waves
   - Analog signals are transmitted without regard to content
   - Continuously variable
   - The data could be analog (voice) or digital (data)
   - Cheap technology ⇑
   - Susceptible to noise⇓ *Why?*
   - Greater attenuation ⇓⇒ reduction in signal strength
     - Pulses become rounded and smaller
     - Leads to loss of information

§2.4.2 Means of Transmission

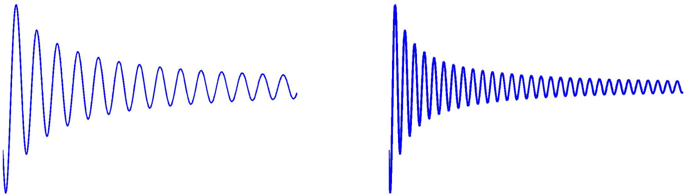
Carrier (digital, analog) $\times$ Signal (digital, analog)

1. Analog data via analog transmission
   - e.g., radio
2. Analog data via digital transmission
   - Sampling needed $\Rightarrow$ e.g., voice, audio, video
3. Digital data via analog transmission
   - Broadband & wireless
4. Digital data via digital transmission
   - Baseband $\Rightarrow$ e.g., Ethernet

§2.4.3 What Could Go Wrong? Transmission Impairment

Limitations ⇒ common to both digital and analog transmissions

1. Attenuation:
   - Decrease in signal strength (amplitude) as a function of distance
   - Increase in attenuation as a function of frequency *Why?*



2. Delay Distortion
   - Different frequency components travel at different speed *How?*
3. Noise ⇒ most problematic of all!
   - Thermal noise
   - Interference

§2.4.4 How to Fix?

$\Rightarrow$ boost the signal

1. Analog $\Rightarrow$ Amplification
   - Use amplifiers to boost the signal strength $\Rightarrow$ amplitude
   - This also amplifies noise $\Downarrow$
     - We can use filters
     - Filtering noise is a complex problem $\Downarrow$ *How?*
2. Digital $\Rightarrow$ Repeater
   - Just regenerates the square wave
     - Repeater receives signal
     - Extracts bit pattern
     - Retransmits
     - More resilient against ambiguity (error) *How?*
   - Noise is not amplified

Homework 2.1 (Amplifier vs. Repeater)

Discuss the difference between an amplifier and a repeater

§2.4.5 Voice/Video/Data Transmissions

1. Voice
   - Frequency range
     - Hearing ⇒ 20Hz-20kHz
     - Speech ⇒ 100Hz-7kHz
   - Voice can easily be converted into electromagnetic signal *How?*
     - Sound frequencies with varying volume is converted into electromagnetic frequencies with varying voltage ⇒ AM
   - Telephone Limits frequency range for voice ⇒ 300-3400Hz
   - Can be used on various media ⇒ wire, fiber optic, space
2. Video
   - Max frequency of 4.2 MHz
   - 525 lines scanned per frame at 30 frames per second ⇒ NTSC
3. Data
   - Bandwidth depends on data rate

§2.4.6 Advantages of Digital Transmission

1. Digital technology
   - Low cost ⇒ LSI/VLSI technology
2. Data integrity
   - Longer distances over lower quality lines
3. Capacity utilization
   - High bandwidth links economical
   - High degree of multiplexing easier with digital techniques
4. Security and Privacy
   - Encryption
5. Integration
   - Can treat analog and digital data similarly

§2.5.0 Transmission Impairment

- Signal received may differ from signal transmitted
  - Analog $\Rightarrow$ degradation of signal quality
  - Digital $\Rightarrow$ bit errors
- Transmission impairment caused by:
  - Attenuation and attenuation distortion
  - Delay distortion $\Rightarrow$ Only in guided media
    - Propagation velocity varies with frequency
  - Noise

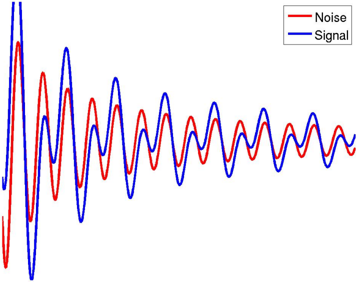
§2.5.1 Recall Attenuation

- Signal strength weakens with distance
- Attenuation depends on the medium
- Attenuation is an increasing function of frequency
- To receive a proper data
  - The received signal must be strong enough to be detected
  - The received signal must be sufficiently higher than noise to be received without error

§2.5.1 Noise

Additional signals inserted between transmitter and receiver

- Thermal noise ⇒ Due to thermal agitation of electrons
  - Uniformly distributed
  - White noise
- Inter-modulation
  - Signals that are the sum and difference of original frequencies sharing a medium
- Crosstalk ⇒ A signal from one line is picked up by another
- Impulse
  - Irregular pulses or spikes ⇒
    - External electromagnetic interference
  - Short duration
  - High amplitude



§2.6.0 Channel Capacity

- Data rate (in bits/s)
  - Rate at which data can be communicated
  - Depends on channel frequency and modulation technique
- Bandwidth (in cycles (Hz))
  - Constrained by transmitter and medium

Homework 2.2

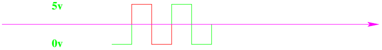
Explain the difference between bandwidth, data Rate, throughput, capacity. Give an example.

Channel Capacity

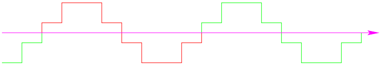
1. Noiseless Channel ⇒ Nyquist Bit Rate
2. Noisy Channel ⇒ Shannon Capacity

later

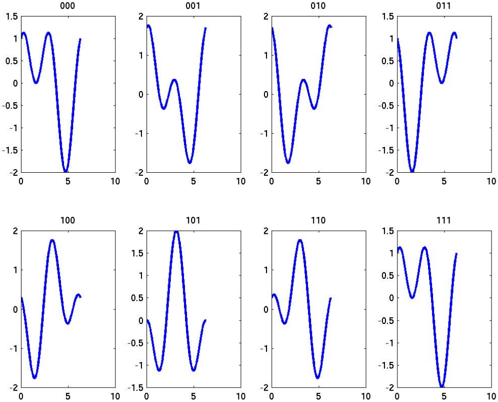
§2.6.1 Bi-level and Multilevel Encoding



Bilevel Encoding (M=2)



Multilevel Encoding (M=4)



§2.6.2 Channel Data Rate: Noiseless I

- Nyquist (1924) stated that for a noise-free channel frequency of B (Hz), and multilevel signaling M, the capacity (bps) can be computed as

$$\boxed{C = 2\,B\,\log_2 M} \tag{1}$$

- Doubling frequency B doubles the data rate
- The presence of noise can corrupt one or more bits *How?*
  - If data rate is increased, the bits become shorter, and more bits are affected by a given noise pattern
- At a given noise level, the higher the data rate, the higher the error rate

§2.6.2 Channel Data Rate: Noiseless II

Example 2.2 (Nyquist's Theorem: Noiseless Channel)

- What is the bandwidth of a noiseless 3 KHz channel with binary transmission?

From Equation (1),

$$C = 2\,B\,\text{log}_2 M = 2 \times 3,000\,\text{log}_2\,2 = 6,000\ \text{bps}$$

Example 2.3 (Nyquist Bit Rate Limit)

Consider a noiseless channel with a frequency of 3000 Hz transmitting a signal with four signal levels (two bits). The maximum bit rate can be calculated as

$$\text{Bit Rate} = 2 \times \log_2 4 = 12,000 \text{ bps}$$

§2.6.2 Channel Data Rate: Noiseless III

Example 2.4 (Nyquist's Theorem: Noiseless Channel)

We need to transmit with the speed of 1 Mbps over a noiseless channel that has 64 kHz frequency. How many signal levels do we need?

$$C = 2\,B\,\log_2 M \quad \rightarrow \quad 2^{20} = 2 \times 64,000\ \log_2 M$$

$$\log_2 M = 2^{13}/1000 = 8.19 \quad \rightarrow \quad M = 256$$

Homework 2.3

Justify the use of $\log_{10}$ and $\log_2$ in Equations (2) and (3), respectively

§2.6.3 Shannon's Theorem I

Shannon (1948) developed a formula to identify the upper bound on the channel capacity

- The signal-to-noise ratio (S/N) is the ratio of power in a signal to the power contained in the noise that is present at a particular point in the transmission.

$$10 \log_{10} \frac{\text{signal power}}{\text{noise power}} = 10 \log_{10} \frac{S}{N} \text{ dB} \tag{2}$$

- With noise, the maximum channel capacity:

$$\boxed{C = B \log_2 (1 + \frac{S}{N}),} \tag{3}$$

where C is the capacity in bits per second and B is the channel frequency in Hz

Note: dB is logarithmic in equation (2)

§2.6.3 Shannon's Theorem II

Example 2.5 (Shannon's Theorem: Noisy Channel)

A noisy 3 KHz channel , and a signal to thermal noise of 30 dB can never transmit more than 30 Kbps *Why?*

$$10 \log_{10} \frac{S}{N} = 30 \text{ dB} \implies S/N = 10^3 = 1000$$

$$C = B \log_2 (1 + \frac{S}{N}) = 3,000 \log_2(1 + 1000)$$

$$C = 3,000 \times 9.9673 < 30 \text{ Kbps}$$

§2.6.3 Shannon's Theorem III

Example 2.6 (Shannon's Theorem: Noisy Channel)

Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero. I.e., the noise is so strong that the signal is faint.

$$C = B \log_2(1 + S/N) = B \log_2(1 + 0) = B \log_2 1 = 0$$

§2.7.0 Properties of Digital Transmission System

- We are interested in the bit rate (R) or transmission speed in bits/s
- How fast can bit be transmitted reliably over a given medium?
  $\Rightarrow$ This depends on:
  1. The amount of energy at the transmitter
  2. The distance the signal travels
  3. The amount of noise on the channel
  4. The bandwidth of the transmission channel
- As signaling speed increases
  - the pulses become narrower
  - the signal varies more quickly
- Higher signaling speed $\Rightarrow$ higher signal bandwidth
- Further, the bandwidth of a channel limits the bandwidth of the input

§2.8.0 Guided Transmission Media

1. Magnetic media
2. Twisted pairs
3. Coaxial cable
4. Power lines
5. Fiber optics

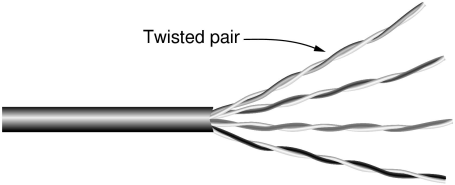
Note

- The medium and the signals determine the quality and characteristics of data being transmitted by the medium
- For guided, the medium itself is an important factor
- For Unguided, the bandwidth produced by the antenna is an important factor
- In both data rate and distance are main concerns

§2.8.1 Magnetic Media

- Write data onto magnetic media
  - Disks
  - Tapes
- Data transmission speed
  - Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway

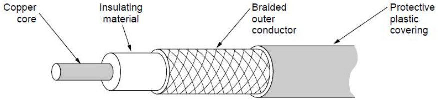
§2.8.2 Twisted Pair Media



Category 5 Unshielded Twisted Pair (UTP) cable

- Why twisting
  - Straight copper wires tend to act as antennas ⇒ pick up extraneous signals
  - Twisted cables help reducing interfering signals
- UTP consists of Conducting wires, non-conductive material, foil shield, braid shield, and jacket
- Transmission characteristics
  - For analog data amplifiers are required every 5km -6km
  - For digital data repeaters are required every 2km -3km
  - Limitation in distance, bandwidth, and data rate
  - susceptible to interference (noise, crosstalk)

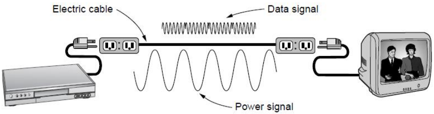
§2.8.3 Coaxial Cable



- Carries signals of higher frequency than Twisted-Pair
- A core (inner conductor) + insulator
- A shield (second conductor) + insulator
- A Plastic cover
- Comes with 50 and 75 Ohms

§2.8.4 Power Lines

- A network that uses household electrical wiring

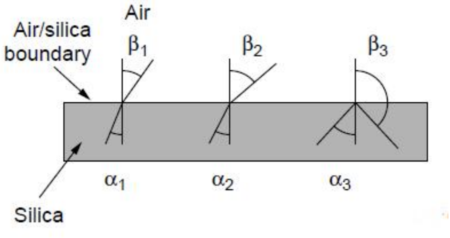


§2.8.5 Fiber Optics I

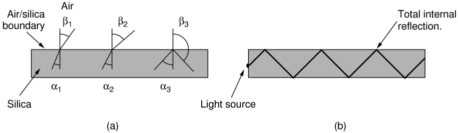
- Much greater capacity $\Rightarrow$ hundreds of Gbps
- Smaller size and weight
- Lower attenuation
- Electromagnetic isolation
- Much greater repeater spacing $\Rightarrow$ 10's of km
- Used for long haul, MAN, LAN, Loops
- 10^{14} to 10^{15} Hz
- Light Emitting Diode (LED)
  - Cheaper, wider operating temperature range
- Injection laser diode (ILD)
  - More efficient
  - Higher data rate
- Uses Wavelength Division Multiplexing
  - Transmitting multiple frequencies of light
- Transmission modes
  - Single mode
  - Multi mode

§2.8.5 Fiber Optics II

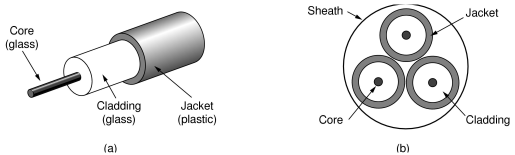
- Three examples of a light ray from inside a silica fiber impinging on the air/silica boundary at different angles



- Light trapped by total internal reflection



§2.8.6 Fiber Cables



- A comparison of semiconductor diodes and LEDs as light sources

Item	LED	Semiconductor laser
Data rate	Low	High
Fiber type	Multi-mode	Multi-mode or single-mode
Distance	Short	Long
Lifetime	Long life	Short life
Temperature sensitivity	Minor	Substantial
Cost	Low cost	Expensive

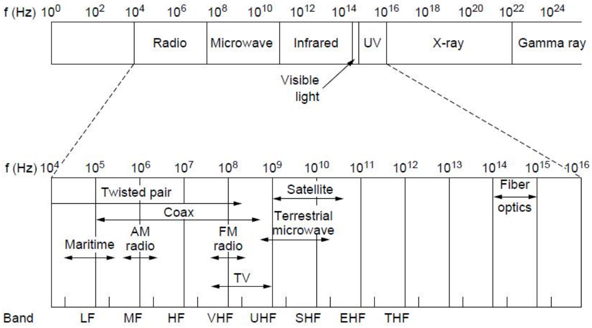
§2.9.0 Wireless Transmission: Unguided

Different Media

1. The Electromagnetic Spectrum
2. Radio Transmission
3. Microwave Transmission
4. Infrared Transmission
5. Light Transmission

§2.9.1 The Electromagnetic Spectrum I

- The electromagnetic spectrum and its uses for communication

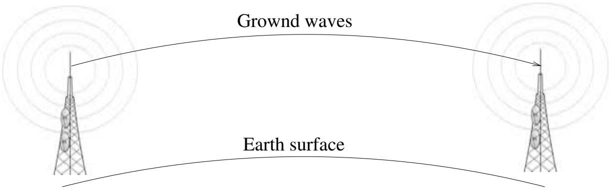


- Spread spectrum (SS) and ultra-wide-band (UWB) communication $\Rightarrow$ security
  1. Direct sequence $\Rightarrow$ adding extra chipping code
  2. Channel hopping $\Rightarrow$ randomly hop over several channels

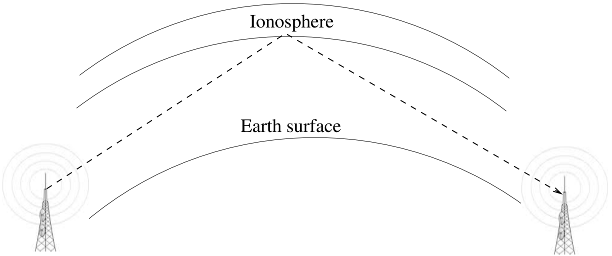
later

§2.9.2 Radio Transmission I

- In the VLF, LF, and MF bands, radio waves follow the curvature of the earth

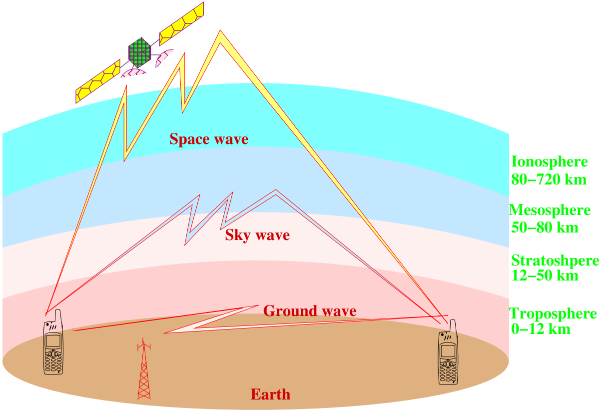


- In the HF band, they bounce off the ionosphere



§2.9.2 Radio Transmission II

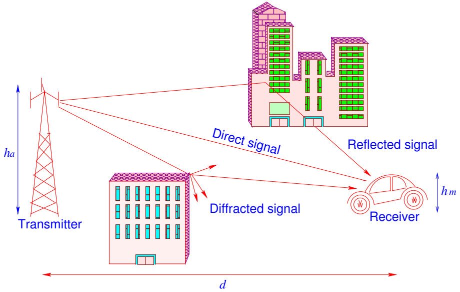
Signal Propagation



§2.9.2 Radio Transmission III

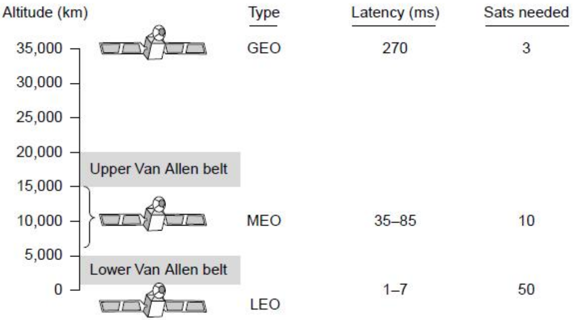
Propagation Mechanisms

- Reflection
- Diffraction
- Scattering



§2.9.3 Communication Satellites I

- Geostationary Satellites
- Medium-Earth Orbit Satellites
- Low-Earth Orbit Satellites



- Factors
  - Altitude, round-trip delay, number of satellites for global coverage

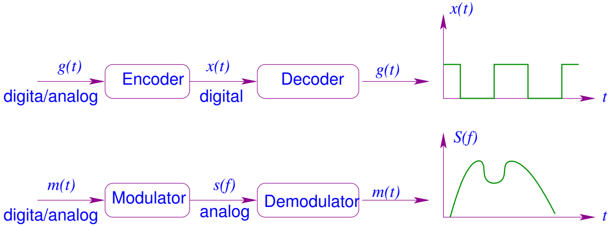
§2.9.3 Communication Satellites II

- Advantages/Disadvantages
  - Larger coverage area ⇑
  - Transmission cost is independent of distance ⇑
  - Satellite to Satellite communication is very precise ⇑
  - Higher bandwidth are available ⇑
  - Launching satellites into orbit is costly ⇓
  - Satellite bandwidth is gradually becoming used up⇓
  - Large propagation delay⇓

Band	Downlink	Uplink	Bandwidth	Problems
L	1.5 GHz	1.6 GHz	15 MHz	Low bandwidth; crowded
S	1.9 GHz	2.2 GHz	70 MHz	Low bandwidth; crowded
C	4.0 GHz	6.0 GHz	500 MHz	Terrestrial interference
Ku	11 GHz	14 GHz	500 MHz	Rain
Ka	20 GHz	30 GHz	3500 MHz	Rain, equipment cost

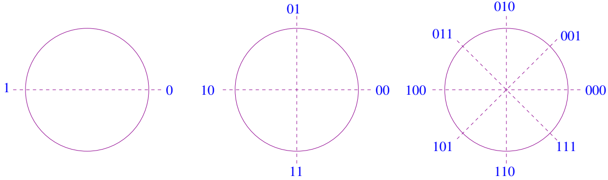
§2.10.0 Modulation (Encoding) Techniques I

- Modulation is the process of encoding source data onto a carrier signal with frequency f
- Modulation can be performed by varying , or modulating, some attributes of the sinusoidal signal.
- All modulation techniques involve one or more of the three fundamental frequency domain parameters:
  - Amplitude $\Rightarrow$ Amplitude modulation $\Rightarrow$ AM
  - Frequency $\Rightarrow$ Frequency modulation $\Rightarrow$ FM
  - Phase $\Rightarrow$ Phase modulation $\Rightarrow$ PM



§2.10.0 Modulation (Encoding) Techniques II

- In amplitude modulation
  - Two different amplitudes are used to represent 0 and 1
- In Frequency modulation (frequency shift keying)
  - Two or more different tones are used
- In phase modulation (simplest form)
  - The carrier wave is systematically shifted 0 or 180 degrees at uniform spaced intervals to represent 0 and 1
  - Shifts of 45, 135, 225, or 315 degrees are used to transmit 2 bits of information



⇒ The goal is to optimize some characteristics of the transmission

Recall Modulation Techniques from Section 2.4.2.0

§2.10.1 Encoding Digital Data ⇒ Digital Signal

- Discrete, discontinuous voltage pulses
- One voltage level to binary 1 and another to binary 0
- Each pulse is a signal element
- Binary data encoded into signal elements
- In Unipolar All signal elements have same sign
  - 0: +.5v, 1: +1.5v
- In Polar One logic state represented by positive voltage the other by negative voltage
  - 0: +.5v, 1: -.5v

Definition 2.10.1.1 (Modulation rate)

The Rate at which the signal level changes. It is Measured in baud
⇒ signal elements per second
⇒ sample per second

§2.10.2 Encoding Digital Data ⇒ Analog Signal

- A modem converts digital data to analog signal
- The basic techniques are
  - Amplitude Shift Keying (ASK)
  - Frequency Shift Keying (FSK)
  - Phase Shift Keying (PSK)

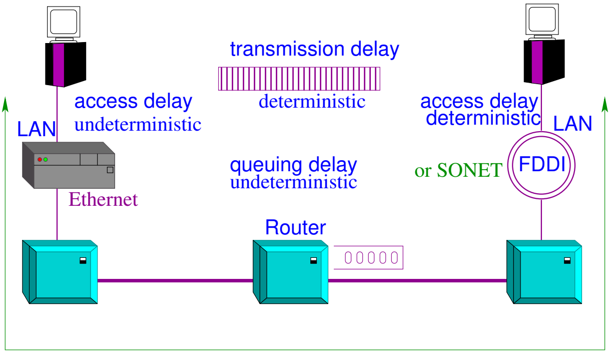
§2.10.3 Encoding Analog Data ⇒ Digital Signals

- Analog data (Voice and video) are digitized ⇒ sampled
- The simplest technique is Pulse Code Modulation (PCM) ⇒ later
  - Sampling the analog data periodically and quantizing the samples
  - Slicing continious waves to digitized waves

§2.10.4 Encoding Analog Data ⇒ Analog Signals

- Analog data are modulated by a carrier frequency to produce an analog signal in a different frequency band
- The basic technique are
  1. Amplitude modulation (AM)
  2. Frequency modulation (FM)
  3. Phase modulation (PM)

§2.11.0 E2E Delay



Propagation delay (deterministic)
Pysical delay (speed of light)
flight time

- Message delay between two points ⇒ e.g., 24 ms

[0] Fiber Distributed Digital Interface (FDDI)
[1] Synchronous Optical Networking (SONET)

§2.11.1 Delay Components

- Propagation delay
- Transmission delay
- Queuing delay
- Access delay

E2E Delay

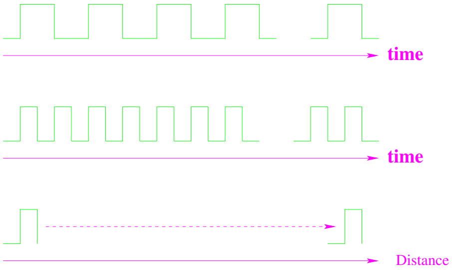
- Sometimes we are interested RTT
- No queuing delays in direct link
- Bandwidth not relevant if Size = 1 bit *Why?*
- Software overhead is included in RTT
  - Could be dominant is short distance

Homework 2.4 (Delay Components)

Identify four different delay components associated with the first class US postal service when you drop an envelop in a mail box.

§2.11.2 How Fast a Bit Can Travel?

- Bandwidth
  - Bandwidth related to "bit width" ⇒ width of frequency band *How?*



- Two Factors
  1. The length of a bit in time *How?*
  2. The speed it travles *How?*

Speed of light

- 3.0×10^8 meters/second in a vacuum
- 2.3×10^8 meters/second in a cable
- 2.0×10^8 meters/second in a fiber

§2.11.3 Bit Width in Time and Space

- What is the length of a bit in time?
  - Depends on the speed of communication channel
    - in bits/sec or in MHz
- What is the length of a bit in meters?
  - Depends on the speed of light/electricity in the medium

Example 2.7 (Bit Width in Time and Space)

Consider a 100 Mbps optical communication channel that carries bits of data between two nodes that are 50 km apart. Assume the speed of light in the optical fiber is 200,000 km/s (2×10^8 m/s).

- What is the length of a bit (in time) in the fiber?

$$\frac{1 \text{ bit}}{100\ Mbps} = \frac{1}{100 \times 2^{20}} \text{ sec.} = 0.009\ \mu s$$

- What is the length of a bit (in meters) in the fiber?

$$2 \times 10^8 \frac{m}{s} \times \frac{1}{100 \times 2^{20}}\ s = \frac{2 \times 10^8}{100 \times 2^{20}}\ m = 1.9\ \boxed{\text{meters}}$$

§2.11.4 Delay Components

- How to calculate E2E delay?
  - Access delay
    - Depends on channel availability
    - Depends on contention/scheduling
  - Propagation delay
    - Depends on distance
    - e.g., speed of light
    - Delay = Distance / Speed of Light
  - Transmission delay
    - Depends of the Speed/Frequency/Bandwidth of the channel
    - e.g., 100 MHz
    - Delay = Frame-Size / Bandwidth
  - Queuing delay
    - Depends of the buffer size

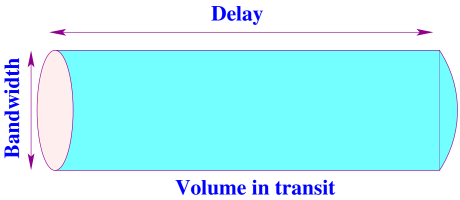
§2.11.5 Bandwidth vs. Delay

- Relative importance of bandwidth and latency
  - Propagation delay dominates for small messages
    - Assume 100 Mbps channel
    - 1 bit from LA to NY takes 100 ms + 0.00001 ms
  - Transmission delay dominates for large messages
    - 100 Mb from LA to NY takes 100 ms + 1000 ms

Homework 2.5 (dominant factors)

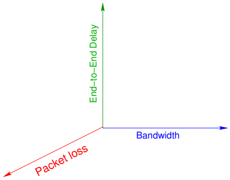
1. Name a network in which propagation delay is dominant
2. Name a network in which bandwidth is dominant
3. Name a network in which software/queuing delay is dominant

§2.11.5 Delay × Bandwidth Product



- Example: 100ms RTT and 45Mbps Bandwidth = 560 KB of data
- Bandwidth (throughput)
  - Amount of data that can be transmitted per time unit
  - Example: 10Mbps
  - link versus end-to-end
  - Notation
    - KB = 2^{10} bytes
    - Mbps = 2^{20} bits per second

§2.12.0 Quality of Service (QoS) Metrics



- We can optimize for delay, bandwidth or loss, but not all ! *Why?*
- Other metrics are
  - Jitter $\Rightarrow$ delay variation
  - Traffic burstiness $\Rightarrow$ different definitions

§2.13.0 Pulse Code Modulation (PCM) I

- Sampling is the first step in digitizing an analog signal
- How often one should take a sample?
  - period, cycle, frequency?
- How fast the signal varies with time? $\Rightarrow$ bandwidth

➥ *Recall Nyquist and Shannon Theorems, 2 and 3*

Definition 2.13.0.1 (Bandwidth)

The bandwidth of a signal is a measure of how fast the signal varies.
Bandwidth is measured in cycles/sec or Hertz

Theorem 2.13.0.2 (Bandwidth Limitation)

A basic result from signal processing theory is that if a signal has bandwidth W (Hz), then the minimum sampling rate is $2W$ samples/second.

Sampling rate (Hz) $\geq 2W$

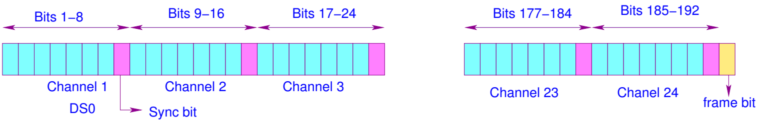
§2.13.0 Pulse Code Modulation (PCM) II

Example 2.8 (PCM for voice phone)

- Signal bandwidth = 4 kHz
- Minimum sample rate $R = 2 \times W = 8,000$ samples/second
- Period T = 1/R = 0.000 125 sec. = 125 μs
- In telephone systems voice samples are represented by 8 bits
- Phone bit rate for PCM of 8,000 samples/sec = $8,000 \times 8$ = 64 Kbps

§2.13.0 Pulse Code Modulation (PCM) III

Example 2.9 (T1 Network)



- **Maximum Bandwidth**

$$\left(8\frac{bits}{channel} \times 24\frac{channel}{frame} + 1\frac{frame\ bit}{frame}\right) \times 8000\frac{frames}{second}$$

$$= 1,544,000\frac{bits}{second} = 1.544\ Mbps = DS1 \qquad (4)$$

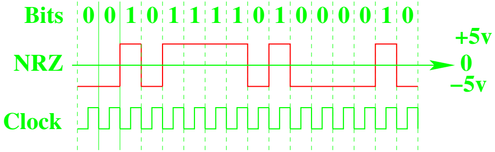
- 24 time slots $\Rightarrow$ 24 DS0's
  - Each 8 bits wide $\Rightarrow$ 8000×8 = 64 Kbps
  - Frame rate 8000 times per second, $\Rightarrow$ each 125 μ sec.
    - 8K is the magic number
- **Maximum Throughput**
  - No Sync bit, no frame bit $\Rightarrow$ overhead
  - 7×8000 = 56 Kpbs $\Rightarrow$ each channel
  - $56 \times 24 = 1.344$ Mbps

§2.14.0 Encoding Schemes

1. Non-return to Zero-Level (NRZ-L)
2. Non-return to Zero Inverted (NRZI)
3. Bipolar -AMI
4. Pseudoternary
5. Manchester
6. Differential Manchester
7. B8ZS
8. HDB3

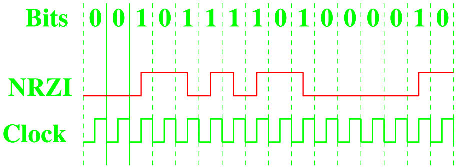
§2.14.1 Non-return to Zero-Level (NRZ-L)

- Two different voltages used: 1 (high) and 0 (low)
  - Constant voltage during the bit interval
  - No transition ⇒ no return to zero voltage
- Often, negative voltage (1), positive voltage (0) ⇒ NRZ-L
- Absence of voltage for zero, constant positive voltage for one
- Easy to engineer ⇑
- Makes good use of bandwidth ⇑
- Uniform distribution of 1s and 0s ⇒ tune the clock ⇑
- Used for magnetic recording, not often used for signal transmission
- Consecutive 1s or 0s ⇒ unable to recover the clock ⇓



§2.14.2 Non-Return to Zero Inverted (NRZI)

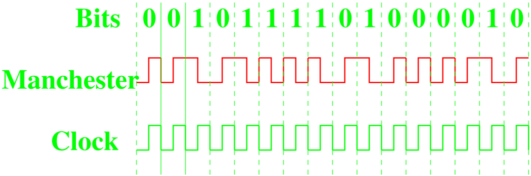
- Data encoded as presence or absence of signal transition at beginning of bit time
- Makes a transition from the current signal to encode a 1
  - Transition (low to high or high to low) denotes a binary 1
  - No transition denotes binary 0
  - An example of differential encoding
- Stays at the current signal to encode a 0
- Solves the problem of consecutive 1's ⇑
  - How about consecutive 0's



➥ *Transition in middle of interval ⇒ easy to synchronize*

§2.14.3 Manchester Coding

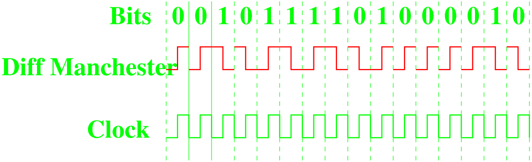
- 0 = low to high
- 1 = high to low



- Solves the problem of both consecutive 0's and consecutive 1's ⇑

§2.14.4 Differential Manchester Coding

- Signal change (low-to-high or high-to-low) represts 1
  - 1 = absence of transition
  - 0 = presence of transition
- Data represented by changes rather than levels
- More reliable detection of transition rather than level
- In complex transmission layouts it is easy to lose sense of polarity



- Provide better synchronization ⇑
- Solves both consective 0's and consective 1's
- Technology choice

§2.14.5 Coding Schemes: 4B/5B

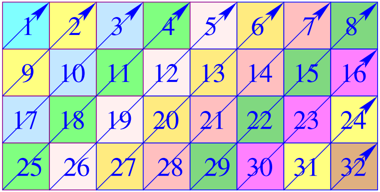
- Breaks a consecutive 0s and 1s by inserting extra bits into bit stream
- Every 4 bits of the actual data are encoded in a 5-bit code
- Each 1 has no more than one leading 0
- Each 1 has no more than two trailing 0s
- It uses NRZI

Data (4B)	Codeword (5B)	Data (4B)	Codeword (5B)
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

- Clock Recovery ⇑
- 20% overhead ⇓

§2.14.6 Scrambling

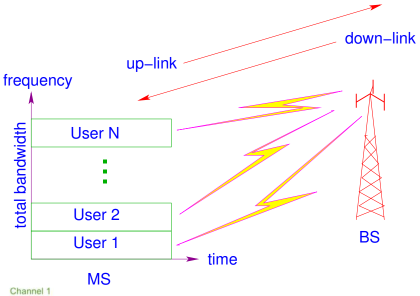
- Use scrambling to replace sequences that would produce constant voltage
- Filling sequence
  - Must produce enough transitions to achieve synchronization
  - Must be recognized by receiver and replace with original
  - Same length as original
- Write the sequence into a 2D array and read the diagonals

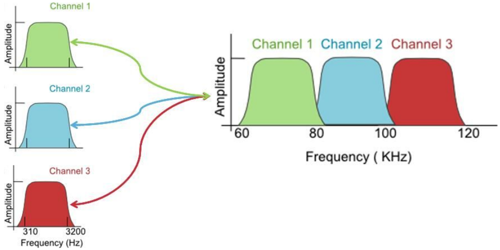


§2.15.0 Common Multiplexing Techniques

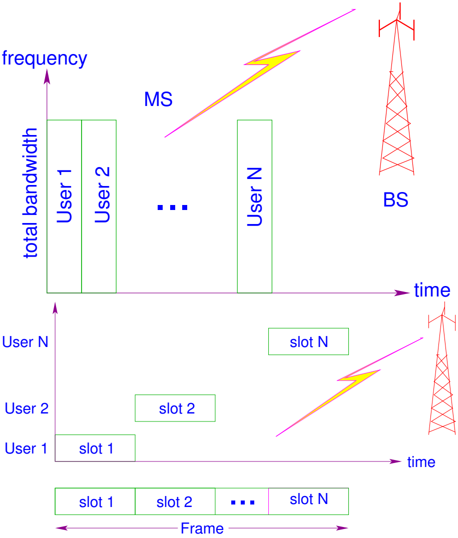
1. Frequency Division Multiplexing (FDM)
   - Radio, TV, HDTV approach
2. Time-Division Multiplexing (TDM)
   - Ethernet approach
3. Code Division Multiplexing (CDM)
   - WiFi, Cell Phone approach
4. Wave Division Multiplexing (WDM)
   - Fiber Optics approach

§2.15.1 Frequency Division Multiplexing (FDM)

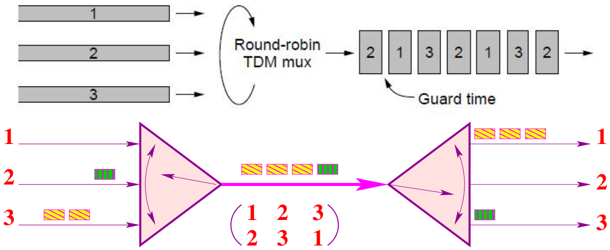




§2.15.2 Time Division Multiplexing (TDM) I

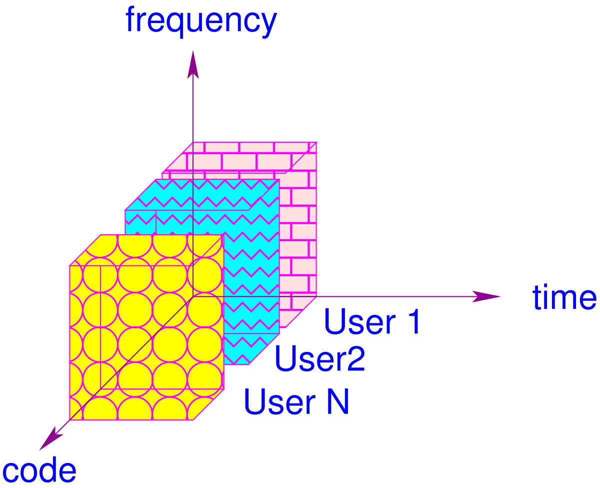


§2.15.2 Time Division Multiplexing (TDM) II



- Schedule link on a per-packet basis ⇒ Statistical multiplexing
- Interleaving packets
- Buffer contending packets
- FIFO may be used for buffering
- Buffer overflow is called congestion

§2.15.3 Code Division Multiplexing (CDM) I



- Also Called Spread Spectrum

§2.15.3 Code Division Multiplexing (CDM) II

- It is a tradeoff between bandwidth efficiency (reliability integrity) and security
  - More bandwidth is consumed than in narrow-band $\Downarrow$
  - Produces louder signal $\Rightarrow$ easier to detect $\Uparrow$
  - The receiver knows the parameters of the spread spectrum signal
- Frequency spectrum of data signal is spread using a code uncorrelated with the data
- Advantages/Disadvantages
  - Low power spectral density
    - Spreading the signal over a large frequency-band makes the power spectral density very small
  - Interference limits the operation $\Rightarrow$ SS
  - Privacy $\Rightarrow$ chipping-code/hopping-code
  - Random access $\Rightarrow$ better than FDM and TDM

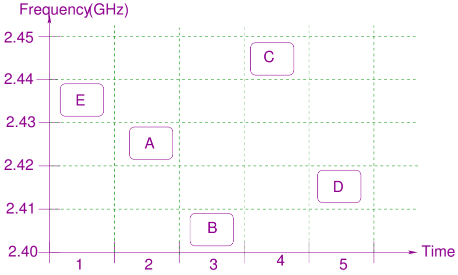
SS Types

1. Frequency Hopping
2. Direct Sequence

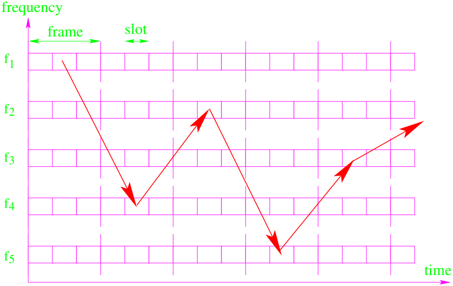
§2.15.3 Code Division Multiplexing (CDM) III

FHSS

Hopping code: E A B C D



§2.15.3 Code Division Multiplexing (CDM) IV



§2.15.3 Code Division Multiplexing (CDM) V

DSSS

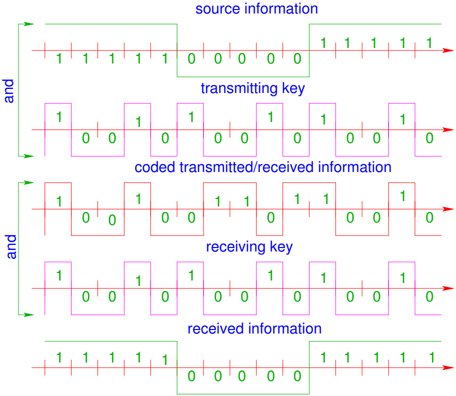
- Most widely recognized form of spread spectrum
- Data stream 101
- Chipping code
  - 0 = 1110 1100 011, and
  - 1 = 0001 0011 100
- Transmitted sequence ⇒ redundant bit pattern

0001 0011 100	1110 1100 011	0001 0011 100
1	0	1

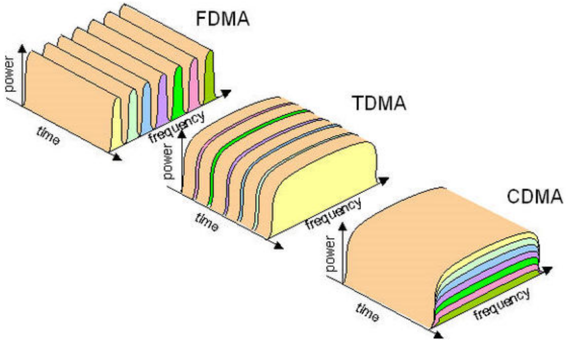
How Does it Work?

Code Division Multiplexing (CDM)

§2.15.3 Code Division Multiplexing (CDM) VI



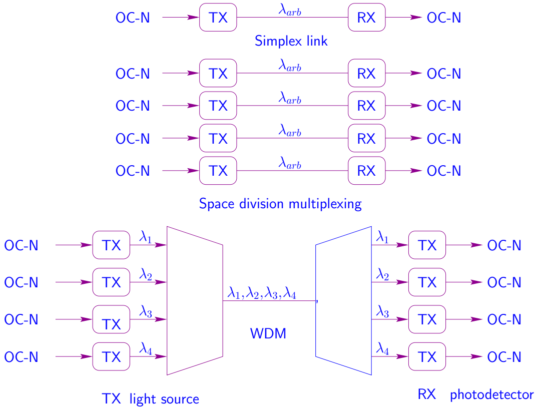
§2.15.3 Code Division Multiplexing (CDM) VII



§2.15.4 Wave Division Multiplexing (CDM) I

- The technology that combines a number of wavelengths onto the same fiber is known as WDM
  - Conceptually WDM is the same as FDM
  - Various channels (wavelengths or frequencies) must be properly spaced to avoid inter-channel interference
  - The term Dense Wave Division Multiplexing (DWDM) refers to the upgrade of the original WDM where wave lengths are separated by several 10s or 100s of nano-meters
  - Transmits multiple signals using different Wave Lengths (WLs) of light simultaneously
  - Each WL represents a different transmission channel

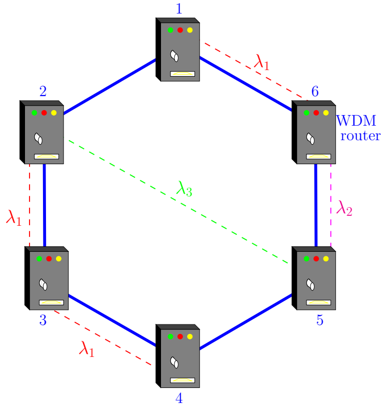
§2.15.4 Wave Division Multiplexing (CDM) II



- OC-N (Optical Carrier) $\Rightarrow$ N = 1, 3, 12, 24, 48, 192
- TX $\Rightarrow$ tranmitted
- RX $\Rightarrow$ Receiver

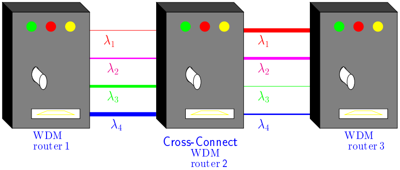
§2.15.5 Optical Routing

- Wavelength-routing networks employ spatial reuse of WLs
  - Allow the same WL to be used by multiple light-paths in the same network provided that they don't share a common link
  - Allow scalability
    - May be limited in non-reconfigurable networks *Why?*



§2.15.6 Wavelength Conversion

- Simple wavelength-routing:
  - A light-path between two nodes along a particular route use a single WL
  - Hunting for the same WL is required along a path
    - 2-to-4 uses $\lambda_1 \Rightarrow$ previous slide
- This constraint can be avoided by the use of Wavelength Converters (WCs)

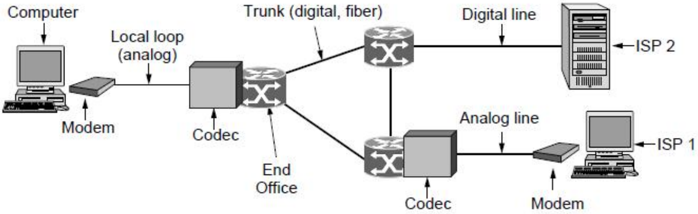


Connection 1: λ_1 - λ_3
Connection 2: λ_2 - λ_4
Connection 3: λ_3 - λ_2
Connection 4: λ_4 - λ_1

- WCs result in improvement in network performance
- WCs must be all optical converters
- The extent to which Optical-Optical-Optical (OOO) will be used remains to be determined.

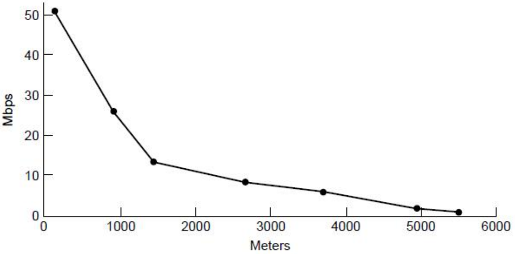
§2.16.0 Applications of Multiplexing Techniques

- Use of both analog and digital transmission for computer -to-computer call
- Conversion done by modems and codecs



§2.16.1 Asynchronous Digital Subscriber Lines I

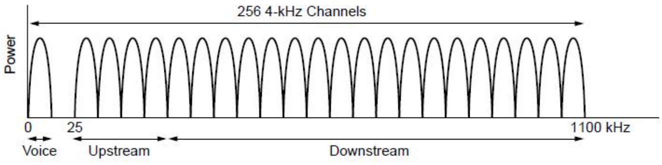
- Another name is Broadband as oppose to DS0=56 kbps telephone line
- Bandwidth versus distance over Category 3 UTP for DSL



- Digital Subscriber Line (DSL) is an International Telecommunication Union (ITU) standard for Asymmetric Digital Subscriber Line (ADSL) using Discrete Multitone Modulation (DMT)
  - Upto 12Mbps

§2.16.1 Asynchronous Digital Subscriber Lines II

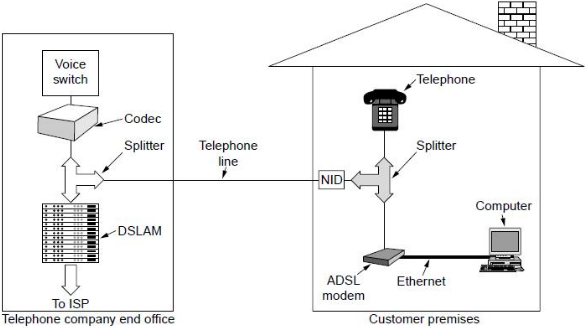
- DMT separates the ADSL signal into 255 carriers (bins) centered on multiples of 4.3125 kHz
  - DMT has 224 downstream and upto 31 upstream frequency channels



  - It uses Coded Orthogonal Frequency Division Multiplexing (COFDM)
  - Fast Fourier Transform (and the inverse iFFT) is used to convert the signal on the line into the individual channels
  - Quadrature amplitude modulation (QAM) or phase-shift keying (PSK) is used to encode the bits within each channel (bin)

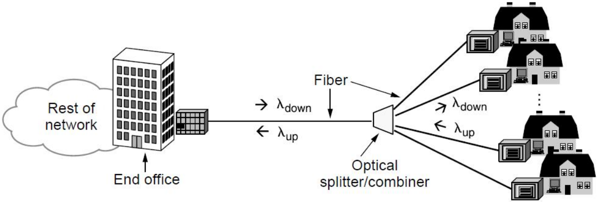
§2.16.1 Asynchronous Digital Subscriber Lines III

A typical DSL configuration



NID: Network Interface Device
DSLAM: DSL Access Multiplexer

§2.16.2 Fiber to the Home (FttH) I



- Passive optical network (PON) for Fiber To The Home
  - PON is a point-to-multipoint, fiber to the premises
- A single optical fiber serves multiple premises
  - Typically 32-128

§2.16.2 Fiber to the Home (FttH) II

- Downstream signals are broadcast to all premises sharing a single fiber
  - Encryption is used to prevent eavesdropping
- Several standards:
  - IEEE 802.3 $\Rightarrow$ EPON (Ethernet PON)
  - APON (ATM PON) G983 of ITU
  - BPON (Broadband PON) G983 of ITU
  - GPON (Gigabit PON) G984 of ITU
  - 10GPON as 10 Gbit/s downstream and 2.5 Gbit/s upstream
- Uses Time Division Multiplexing

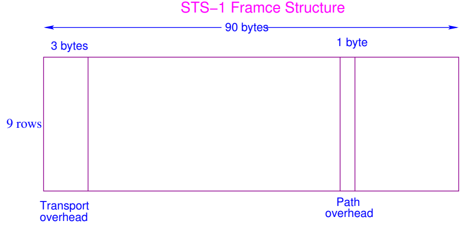
§2.16.3 SONET/SDH I

Standard Transmission Links

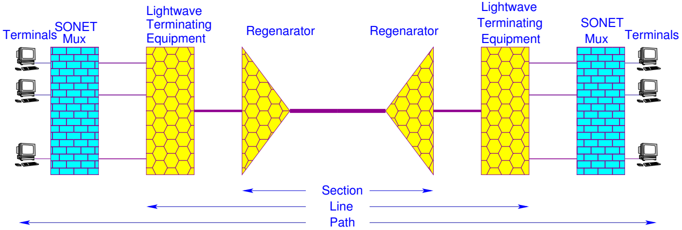
Type	Bandwidth	Applications
ISDN	64 Kbps	for digital voice/data
T1	1.544 Mbps	24 64Kbps, old technology
T3	44.736 Mbps	30 T1
STS-1	51.840 Mbps	sync. transfer signal optical
STS-3	155.250 Mbps	for optical fiber
STS-12	622.080 Mbps	for optical fiber
STS-24	1.244160 Gbps	for optical fiber
STS-48	2.488320 Gbps	for optical fiber

- SONET: Synchronous Optical Network
  - Clock-ed based framing 8000/s
- ITU standard for transmission over fiber
- STS-1 (51.84 Mbps)
- Byte-interleaved multiplexing
- Each frame is 125μs long.

§2.16.3 SONET/SDH II

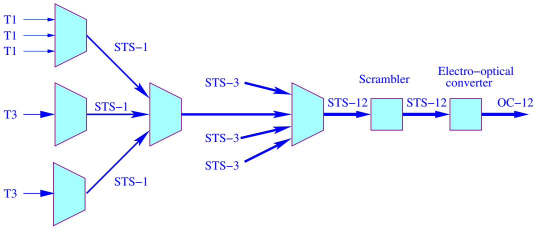


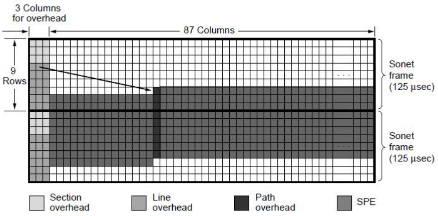
- Each frame is 125 μs long $\Rightarrow$ 8000/s
- Frame length= $90 \times 9 \times 8 = 6,400$ bits long



§2.16.3 SONET/SDH III

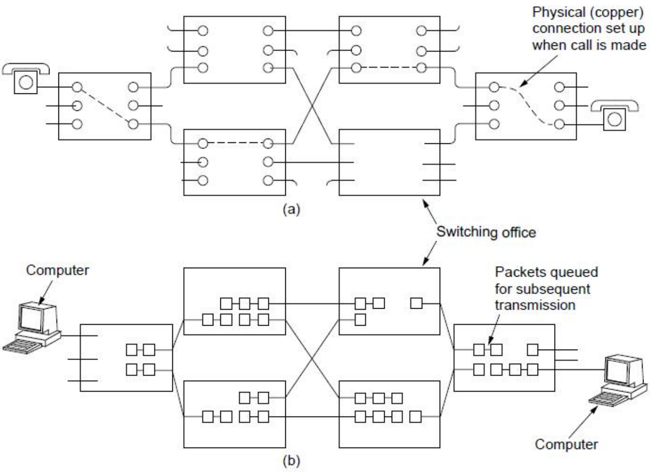
- How do we encapsulate small packets
  - Use a pointer in the transport header





Two back-to-back SONET frames

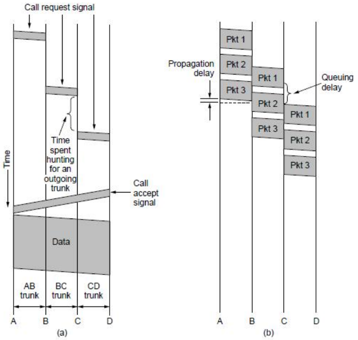
§2.17.0 Circuit Switching/Packet Switching I



(a) Circuit switching. (b) Packet switching

§2.17.0 Circuit Switching/Packet Switching II

Timing of events



(a) Circuit switching. (b) Packet switching

§2.17.0 Circuit Switching/Packet Switching III

Other Characteristics

Item	Circuit switched	Packet switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
Is a switch crash fatal	Yes	No
Bandwidth available	Fixed	Dynamic
Time of possible congestion	At setup time	On every packet
Potentially wasted bandwidth	Yes	No
Store-and-forward transmission	No	Yes
Charging	Per minute	Per packet

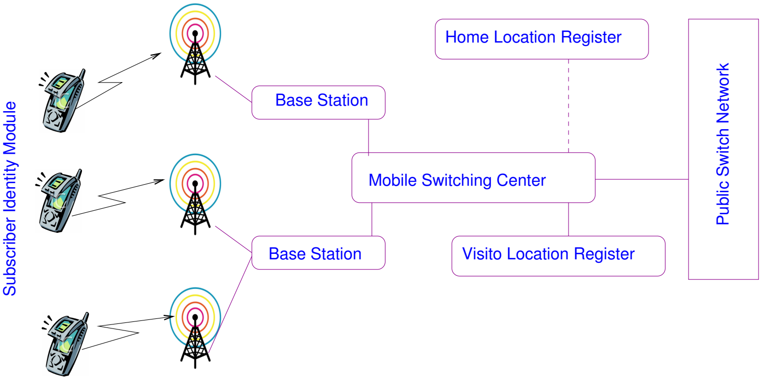
A comparison of circuit-switched and packet-switched networks

§2.18.0 Mobile Telephone System

- First-Generation (1G) Mobile Phones Analog Voice
- Second-Generation (2G) Mobile Phones Digital Voice
- Third-Generation (3G) Mobile Phones Digital Voice + D
- Fourth Generation (4G)
  - Download at 100 Mbit/s for high mobility, e.g., trains
    - 1 Gbit/s for low mobility communication, e.g., pedestrians

§2.18.1 GSM I

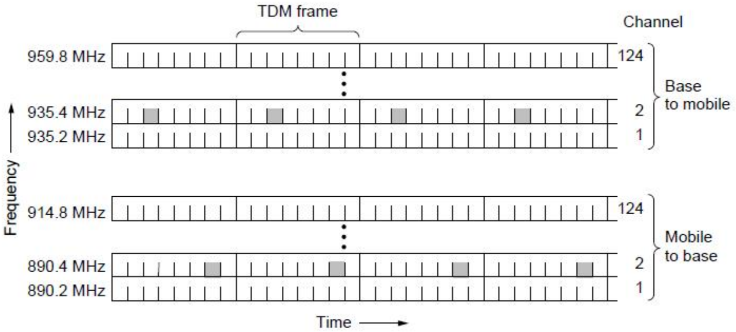
Global System for Mobile Communications



§2.18.1 GSM II

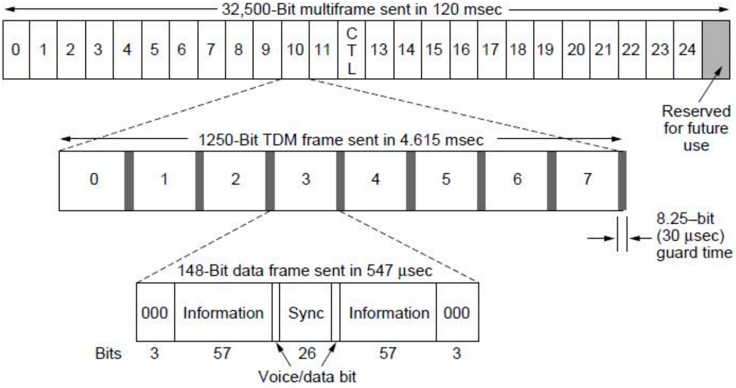
Global System for Mobile Communications

- GSM uses 124 frequency channels,
  - Each of which uses an eight-slot TDM system

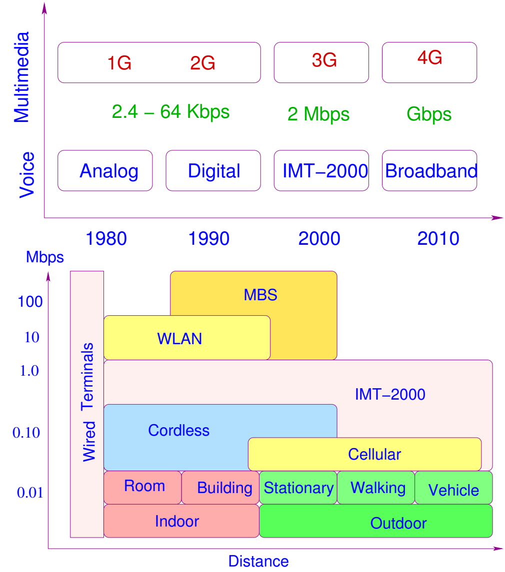


§2.18.1 GSM III

- A portion of the GSM framing structure



§2.19.0 Summary



§2.20.0 Suggested Exercises From the Text

2 A noiseless 4-kHz channel is sampled every 1 msec. What is the maximum data rate? How does the maximum data rate change if the channel is noisy, with a signal-to-noise ratio of 30 dB?

3 Television channels are 6 MHz wide. How many bits/sec can be sent if four-level digital signals are used? Assume a noiseless channel.

4 If a binary signal is sent over a 3-kHz channel whose signal-to-noise ratio is 20 dB, what is the maximum achievable data rate?

8 It is desired to send a sequence of computer screen images over an optical fiber. The screen is 2560 1600 pixels, each pixel being 24 bits. There are 60 screen images per second. How much bandwidth is needed, and how many microns of wavelength are needed for this band at 1.30 microns?

13 Calculate the end-to-end transit time for a packet for both GEO (altitude: 35,800 km), MEO (altitude: 18,000 km) and LEO (altitude: 750 km) satellites.

25 Ten signals, each requiring 4000 Hz, are multiplexed onto a single channel using FDM. What is the minimum bandwidth required for the multiplexed channel? Assume that the guard bands are 400 Hz wide.

26 Why has the PCM sampling time been set at 125 μsec?

27 What is the percent overhead on a T1 carrier? That is, what percent of the 1.544 Mbps are not delivered to the end user? How does it relate to the percent overhead in OC-1 or OC-768 lines?

37 Three packet-switching networks each contain n nodes. The first network has a star topology with a central switch, the second is a (bidirectional) ring, and the third is fully interconnected, with a wire from every node to every other node. What are the best-, average-, and worst-case transmission paths in hops?

38 Compare the delay in sending an x-bit message over a k-hop path in a circuit-switched network and in a (lightly loaded) packet-switched network. The circuit setup time is s sec, the propagation delay is d sec per hop, the packet size is p bits, and the data rate is b bps. Under what conditions does the packet network have a lower delay? Also, explain the conditions under which a packet-switched network is preferable to a circuitswitched network.

40 In a typical mobile phone system with hexagonal cells, it is forbidden to reuse a frequency band in an adjacent cell. If 840 frequencies are available, how many can be used in a given cell?

§2.21.0 References

[Tanenbaum and Wetherall, 2011] Tanenbaum, A. S. and Wetherall, D. J. (2011).
Computer Networks: 5th Edition.
Prentice Hall PTR.