Physical Layer

- Responsibilities
  - defines how to transmit and receive bits on the physical medium
  - issues
    - analog or digital transmission
    - definition of 0 and 1 bits
    - bit rate
    - type of multiplexing, if any
    - circuit or packet switching
  - NOT the physical medium (e.g., wire, cable, fiber, air)

- Outline
  - theoretical limits on channels
  - analog and digital transmission
  - communications media including wireless and satellite
  - The PSTN and switching
  - The Mobile telephone system
  - Cable TV networks

- Assigned reading: Tanenbaum, Chapter 2

Data, Signaling, Transmission

- Data are entities that convey meaning.

- A signal is an electric or electromagnetic encoding of data.

- Signaling is the act of propagating a signal along a medium.
  - guided media: signals are sent along a physical path
    - ex. wire, cable, fiber
  - unguided media: signals are broadcast
    - ex. air, vacuum

- Transmission is the communication of data by the propagation and processing of signals. The transmission path is also known as a circuit or link.

- A guided transmission medium may be either
  - point-to-point: direct link (no intermediate devices) between two, and only two devices
  - multipoint: more than two devices share medium
### Analog and Digital Data

- **Analog data**
  - □ take on continuous values on some interval.
  - □ sensors are used to collect analog data
  - □ examples?

- **Digital data**
  - □ take on discrete values
  - □ examples?

### Analog and Digital Transmission

- **Analog transmission**
  - □ send signals without regard to their content
  - □ signals may represent either analog or digital data
  - □ use amplifiers to boost energy in signal due to *attenuation*, or weakening of the signal
  - □ amplification distorts analog signal because noise is also amplified

- **Digital transmission**
  - □ send signals that are known by all components in the network to represent 0's and 1's
  - □ original data may be either digital or analog
  - □ many ways to represent bits
  - □ repeaters used to restore signal periodically
  - □ unlike amplifiers, repeaters do not distort the signal (and data)
  - □ repeaters may also be used for analog signals, but it must be known that the signals represent digital data
Data and Transmission

What are examples of the following?

- Analog Data, Analog Transmission
- Digital Data, Analog Transmission
- Analog Data, Digital Transmission
- Digital Data, Digital Transmission

Digital Transmission

- Digital transmission is the future (the now)
- Due to VLSI technology, price of digital circuitry has continually dropped; not so for analog equipment
- Using repeaters, it is possible to transmit data over longer distances using lesser quality lines
- Multiplexing digital signals is cheaper than multiplexing analog signals
- Encryption techniques may easily be applied to digital data (or digitized analog data).
- Facilitates integration of multiple communication forms, including voice, video, and digital data.
**Analog and Digital Signaling**

- A *signal* is an electric or electromagnetic encoding of data.

- Analog signaling
  - Signal may be directly proportional to the data. Example?
  - Signal may be a carrier (sine wave) that is modulated according to the data (which may be analog or digital)

- Digital signaling
  - Series of voltage pulses that represent bits
  - May carry either (digitized) analog data or digital data

- Bit rate vs. baud (symbol) rate
  - Bit rate: number of bits transmitted per second
  - Baud or symbol rate: rate at which the signal is changed
  - Which is higher?

**Channels**

- A *channel* is that portion of a transmission path dedicated to a pair of transmitter/receivers
  - A channel is usually characterized by its bandwidth (measured in Hz)
  - The data rate is measured in bits per second (bps)
  - The greater the bandwidth of the channel, the higher the data rate that can be transmitted using the channel.

- A channel or transmission medium may be
  - Simplex: signals transmitted in only one direction
  - Half-duplex: signals transmitted in only both directions, but not simultaneously
  - Full-duplex: signals transmitted simultaneously in both directions

Signals

- A signal is a function of time.
- A signal is continuous if
  \[ \lim_{t \to a} s(t) = s(a) \]
- A signal is discrete if it takes on only a finite number of values.
- A signal is periodic if and only if
  \[ s(t + T) = s(t) \text{ for } -\infty < t < +\infty \]
  Otherwise, it is aperiodic.

Periodic Signals

- Three characteristics of a periodic signal:
  - amplitude: instantaneous value at any time
  - frequency: inverse of the period, \( T \)
  - phase: measure of the relative position in time within a single period of a signal
- Using Fourier analysis, a signal can also be expressed as a function of frequency; the signal consists of components of different frequencies.
Fourier Analysis

- Any periodic signal can be represented as a sum of sinusoids, known as a Fourier series:

\[ x(t) = \sum_{n=0}^{\infty} a_n \cos(2\pi nf_0 t) + \sum_{n=0}^{\infty} b_n \sin(2\pi nf_0 t) \]

- \( f_0 \) is known as the fundamental frequency
  - \( f_0 = 1/T \), where \( T \) is the period of the signal
  - multiples of \( f_0 \) are referred to as harmonics

- The values of the coefficients:

\[
\begin{align*}
a_0 &= \frac{1}{T} \int_0^T x(t) dt \\
a_n &= \frac{2}{T} \int_0^T x(t) \cos(2\pi nf_0 t) dt \\
b_n &= \frac{2}{T} \int_0^T x(t) \sin(2\pi nf_0 t) dt
\end{align*}
\]

- The root-mean-square amplitudes, \( \sqrt{a_n^2 + b_n^2} \), are proportional to the energy of the corresponding frequency.

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How is Fourier analysis useful?

- The *spectrum* of a signal is the range of frequencies that it contains.

- The absolute bandwidth is the width of the spectrum.

- Most of the energy in a signal is contained in a relatively narrow band of frequencies. This band is referred to as the *effective bandwidth*, or just *bandwidth*.

- All transmission media have a finite bandwidth, which is determined by physical properties of the medium and the distance traversed.

- Thus, a given medium will filter out part of the signal, namely, the higher frequency components. In addition, an artificial filter may be applied to the channel.

- Fourier analysis helps us estimate how well a signal produced by a transmitter will be carried by a particular channel.

**Effects of Limited Bandwidth**

- (a) Time domain representation of a signal with limited bandwidth.
- (b) Spectrum with 1 harmonic.
- (c) Spectrum with 2 harmonics.
- (d) Spectrum with 4 harmonics.
- (e) Spectrum with 8 harmonics.

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Effects of Limited Bandwidth (cont.)

- Tanenbaum example, pp. 91–93.
  - 8 bits to be transmitted
  - for sake of analysis, imagine that these bits repeat forever, creating a periodic signal
  - channel: voice-grade line (3000 Hz)

<table>
<thead>
<tr>
<th>Bps</th>
<th>T (msec)</th>
<th>First Harmonic (Hz)</th>
<th># Harmonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>26.67</td>
<td>37.5</td>
<td>80</td>
</tr>
<tr>
<td>600</td>
<td>13.33</td>
<td>75</td>
<td>40</td>
</tr>
<tr>
<td>1200</td>
<td>6.67</td>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>2400</td>
<td>3.33</td>
<td>300</td>
<td>10</td>
</tr>
<tr>
<td>4800</td>
<td>1.67</td>
<td>600</td>
<td>5</td>
</tr>
<tr>
<td>9600</td>
<td>0.83</td>
<td>1200</td>
<td>2</td>
</tr>
<tr>
<td>19200</td>
<td>0.42</td>
<td>2400</td>
<td>1</td>
</tr>
<tr>
<td>38400</td>
<td>0.21</td>
<td>4800</td>
<td>0</td>
</tr>
</tbody>
</table>

Channel Capacity

- Nyquist theorem:
  - Given a bandwidth of $H$, the highest signal rate that can be carried is $2H$ bps.
  - In the general case, in which a signal element may represent more than one bit, we have:
    \[ \text{maximum data rate} = 2H \log_2 V \text{ bits/sec} \]
    where $V$ is the number of discrete signal levels.
  - Assumes the channel is free of noise.
Channel Capacity

- Example:
  - voice grade line: 3000 Hz
  - using binary encoding (each signal level represents 1 bit)
    
    \[
    \text{maximum data rate} = \frac{3000 \text{ Hz}}{2} = 1500 \text{ bits/sec}
    \]

  - using QAM encoding (studied later), we have 16 distinct signals, each representing 4 bits
    
    \[
    \text{maximum data rate} = \frac{3000 \text{ Hz} \times 4}{2} = 6000 \text{ bits/sec}
    \]

    though this number is not achievable in reality.

Transmission Impairments

- Attenuation
  - Signal strength of signal falls off with distance.
  - Amplifiers or repeaters used to strengthen signal
  - Attenuation increases with frequency
    - distorts analog signals
    - equalization circuits can “spread” attenuation over frequencies (used in phone network).

- Delay distortion
  - Different frequency components propagate at different speeds over guided media.
  - Causes *intersymbol interference* in digital transmission.

- Noise. Examples:
  - crosstalk: unwanted coupling between signal paths (e.g., nearby twisted pair)
  - impulse noise: due to variety of causes (lightning, system flaws), causes spikes in signal; little effect for analog data, but severe impact on digital data
Effect of Noise on Channel Capacity

- Signal-to-Noise ratio
  - measured in decibels
    \[(S/N)_{dB} = 10 \log_{10} \frac{\text{signal power}}{\text{noise power}}\]

- Shannon's Theorem
  - another upper bound on channel capacity
    
    \[
    \text{maximum data rate} = H \log_2(1 + S/N) \text{bps}
    \]

- Example: channel of 3000 Hz and \(S/N\) of 30 dB
    
    \[
    \text{maximum data rate} \approx \text{bps}
    \]

How does this result comply with the result from Nyquist's Theorem for the same parameter values without noise?

---

Transmission Media

There are many options for sending data from point A to point B.

- Magnetic
- Twisted pair
- Coaxial cable
- Power lines
- Fiber optics
- Wireless
**Twisted Pair**

Consists of pair of twisted, insulated copper wires, about 1mm thick. To gain bandwidth, sets of pairs are grouped into a single cable.

- twisting the wires reduces electrical interference
- used for both analog and digital transmission
- various grades of cable are used
- data rate up to 10Gbps
- used for many decades in the phone system, still dominate local loops
- Very commonly used in LANs today

---

**Coaxial Cable**

Two types are widely used

- 50-ohm, also called baseband
  - up to 1-2 Gbps over 1 km
  - previously widely used in long-haul telephone lines (now largely replaced by fiber)
  - May still be used in some LANs

- 75-ohm cable, also called broadband
  - Originally, analog transmission and cable TV
  - about 450 MHz for 100 km
  - usually, the cable is divided into 6 MHz channels
  - amplifiers are required to boost signals
Power Lines

- Used at low data rates by electricity companies for years
- Use in the home: data signal is superimposed on a low-frequency power signal.

- Difficulties with household wiring:
  - It doesn’t carry high-frequency signals well
  - Its electrical properties vary
  - It can act as an antenna

Optical Fibers

- Composition
  - ultra-thin (2 to 125 µm) fiber of glass that can transmit light pulses in one direction
  - three concentric sections
    - core: innermost; one or more very thin strands of glass or plastic
    - cladding: surrounds each fiber, glass or plastic coating with optical properties much different from core (specifically, lower index of refraction)
    - jacket: plastic surrounding one or more cladded fibers, to protect against moisture, abrasion, crushing, etc.
Optical Transmission and Reception

- Internal reflection occurs with indices of refraction of core and cladding

![Diagram of optical fiber and light source](image)

- Light in 3 wavelength windows propagate best
  - 850 nm, 1300 nm, 1550 nm

- Multiple angles (modes) may propagate
  - multimode fiber - multiple modes propagate
  - single-mode fiber - only one mode propagates
  - which is more expensive?

- Light sources
  - Light Emitting Diode (LED)
  - Injection Laser Diode (ILD)

- Reception - photodiode

Advantages of Optical Fibers

- Higher bandwidth
  - data rates of multiple Gbps over 10s of kilometers demonstrated

- Small size and light weight compared to copper

- Much lower attenuation, implying greater spacing of repeaters

- Immunity to electromagnetic interference

- do not radiate energy
  - cause no interference
  - very difficult to tap

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Uses of Optical Fibers

- For many years have been used in Long-line telephone networks, increasingly installed in the local loop
- Cable television networks are increasingly converting to fiber
- Optical LANs
  - must accommodate unidirectional property of light
  - examples: ring (FDDI), dual-bus systems (DQDB), switch-based systems (ATM LAN), passive stars

Electromagnetic Waves

Moving electrons create electromagnetic waves that can propagate through free space.

- Wave characteristics
  - Frequency
  - Wavelength
- Wireless communication is based on broadcast/receipt of waves using electronic circuits attached to antennas.
- In a vacuum, all waves propagate at the same speed
- Fundamental relation among frequency, wavelength, and speed:
The Electromagnetic Spectrum

- Radio, microwave, infrared, and visible light are good for transmission
- UV, X-rays, gamma rays would be good due to their higher frequencies, but:
  - hard to produce and modulate
  - do not propagate well through buildings
  - interfere with our ability to live

Frequency Bands and Bandwidth

- Carrying capacity is proportional to the bandwidth of the media
- Computing a frequency band:
  \[
  \frac{df}{d\lambda} = -\frac{c}{\lambda^2}
  \]
  
  Then \[\Delta f = \frac{c \Delta \lambda}{\lambda^2}\]
- Given the width of a wavelength band \(\Delta \lambda\), you can compute corresponding frequency band \(\Delta f\).
- Example:
  \[
  \lambda = 1.55 \times 10^{-6}
  \]
  \[
  \Delta \lambda = 0.17 \times 10^{-6}
  \]
  \[
  \Delta f =
  \]

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Radio Transmission

- **Description**
  - frequencies in 30 MHz to 1 GHz
  - radio is omnidirectional, whereas microwaves are focused
  - line of sight is not required
  - Tight licensing needed due to interference

- **Uses**
  - packet radio (often a defense application)
  - ALOHA-type networks
  - cellular telephone
  - personal communication network (PCN)
  - wireless LANs (growing rapidly)

---

Use of Frequencies

- Most transmissions use a narrow frequency band: $\Delta f/f << 1$

- Wide band variations:
  - Frequency hopping spread spectrum (Lamarr & Antheil)
  - Direct sequenced spread spectrum
  - Ultra-WideBand (UWB)
Radio Transmission Characteristics

- VLF, LF, and MF bands follow the ground
- HF and VHF bands bounce off ionosphere

Terrestrial Microwave

- Description
  - parabolic dishes mounted on towers
  - “line of sight” distance from one another
  - Ex: 100 ft towers can be 80 km apart
  - for long distance transmission, use relay towers in a point-to-point fashion

- Uses
  - long-haul telecommunications service, as alternative to coax cable for television and voice
  - communication between buildings (closed-circuit TV)
  - digital data in small regions (radius < 10 km)
Terrestrial Microwave

- Advantages
  - No right of way
  - Relatively inexpensive

- Disadvantages
  - Susceptible to interference
  - Multipath fading
  - Water absorption
  - Crowded spectrum

Electromagnetic Politics

Since everyone wants a higher data rate, everyone wants more spectrum.

- Governing agencies:
  - Worldwide: ITU-R
  - USA: FCC
  - FCC and ITU do not always agree...

- If we use a frequency band for some use, there are three ways to decide on who gets to use it:
  - Beauty contest
  - Lottery
  - Auctions
Electromagnetic Politics (cont.)

A different approach: allow everyone to transmit at will in certain bands.

- Unlicensed bands: ISM and U-NII
- Characteristics:
  - Transmit at will
  - Power is regulated
  - Band locations vary from country to country

Infrared and Millimeter Waves

- Widely used for short-range communication
- Description
  - Relatively directional
  - Used for remote controls
- Advantages/disadvantages
  - Easy to build and cheap
  - Do not pass through solid objects
  - Cannot be used outdoors

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**Lightwave Transmission**

- In use for centuries before modern networks

- Description
  - Highly focused laser
  - Photodetector used as receiver
  - Unidirectional requires matched pairs

- Advantages/disadvantages
  - Very high bandwidth, low cost
  - No radio licensing
  - Susceptible to rain, fog, atmospheric seeing:

**Communications Satellites**

- History
  - Weather balloons
  - The moon

- Attractive properties make them useful

- Three types related to their period
  - Geostationary
  - Medium-Earth Orbit
  - Low-Earth Orbit

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Type</th>
<th>Latency (ms)</th>
<th>Sats needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>35,000</td>
<td>GEO</td>
<td>270</td>
<td>3</td>
</tr>
<tr>
<td>25,000</td>
<td>MEO</td>
<td>35–85</td>
<td>10</td>
</tr>
<tr>
<td>15,000</td>
<td>LEO</td>
<td>1–7</td>
<td>50</td>
</tr>
</tbody>
</table>

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Geostationary Satellites

- Description
  - satellite acts as microwave relay station
  - uplink on one frequency band divided into sub-bands
  - downlink (broadcast) on another frequency band also divided into sub-bands
  - transponder relays between uplink and downlink
  - geosynchronous orbit of about 36,000 km
  - 2 degree separation between satellites

- Comparison to terrestrial links
  - longer propagation delay
  - cost not a function of distance between source and destination
  - high bandwidth

- Uses
  - telephone
  - data
  - television

Geostationary Satellites (cont.)

- Frequency Usage

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

- Satellite spacing is an issue with current technology
- Typical life is around 10 years
- Frequency use is getting crowded in certain bands
Geostationary Satellites (cont.)

- Makeup
  - Modern satellites have about 40 transponders using 80MHz each
  - Transponder beams may be time-slotted
  - Footprints have been made smaller...
  - Very Small Aperture Terminals (VSATs) used for rural network communication

Medium-Earth Orbit Satellites

- Exist between the two Van Allen belts
- Characteristics/use:
  - Orbit is about 6 hours
  - Use less power
  - GPS, orbiting at 18,000 km
Low-Earth Orbit Satellites

- Iridium Project (etc.):
  - Goal: Provide worldwide telecom service with mobile phones
  - Low, short orbit (750 km) satellite network
  - Short orbital period requires many satellites
  - Phones as well as cells (the satellites) move
  - Each cell contains 174 full duplex channels, 283,272 total.

Low-Earth Orbit Satellites (cont)

- In Iridium, communication takes place mostly in space
- Globalstar:
  - Uses 48 LEO satellites
  - Satellites are traditional bent-pipe design
  - Some switching goes through ground communication
**Satellite vs Fiber**

- Fiber is the long-term winner due to cost and bandwidth
- Satellites fill many niche markets:
  - Bypassing the local loop
  - Ubiquitous availability
  - Mobile communication
  - Broadcasting
  - Terrain problems
  - Right of way problems

**Digital Modulation and Multiplexing**

Digital modulation is the process of converting between bits and the signals that represent them.

- Baseband transmission: signal occupies frequencies based on the signaling rate
- Passband transmission: regulating amplitude, phase, or frequency to convey bits
- Multiplexing: sharing of multiple signals on a channel
Digital Data, Digital Signals

This is baseband transmission.

- Example situations?

- Encoding scheme: mapping from data bits to signal elements

- Properties of Good Encoding Schemes
  □ Lack of high frequency components in signal. Why? How?
  □ Signal synchronization capability. Why? How?
  □ Lack of dc component in signal. Why? How?

Encoding Schemes

- Nonreturn to Zero (NRZ-L)
  □ Simplest codes to implement
  □ Rules?
  □ Features?

- Manchester Biphase (Manchester-L)
  □ Rules?
  □ Features?

- Delay modulation
  □ Rules?
  □ Features?

- Bipolar
  □ more than two signal levels
  □ used in T1-PCM carriers
  □ Rules?
  □ Features?
Modems

An example that uses passband transmission.

- Use of analog signaling to transmit digital data over the public telephone network
- Requires use of modem to convert digital data to analog signals, and vice versa
- Amplitude modulation (amplitude shift keying)
  - vary amplitude of carrier
  - commonly, one of the amplitudes is zero
- Frequency modulation (frequency shift keying)
  - vary frequency of carrier
  - allows full duplex on voice grade line by using different frequencies for different directions
- Phase modulation (phase shift keying)
  - vary phase of carrier
  - may use more than simply a 180° shift (binary)
  - this allows higher bit rate than baud rate
  - ex. eight angles results in bits per signal element

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Modulation Schemes

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Some Uses for Modulation

- Signal may be directly proportional to data. Example?

- Data may be modulated onto a carrier. Why?
  - specifically for unguided media
  -

- Example of amplitude modulation (AM):

Refinements of Modulation Schemes

- Using binary signaling, maximum bit rate over voice grade line (3000 Hz) is:

- Many modems use combinations of modulation techniques to send multiple bits per baud

- Quadrature Amplitude Modulation (QAM)
  - uses 12 phase shifts, 2 amplitudes
  - supports bits per signal element

- Example modem standards
  - V.32: uses QAM at 2400 baud, bps
  - V.32 bis: 64 elements, 2400 baud, bps
  - higher rates require other techniques

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Dealing With Noise

It is desirable that small bursts of noise do not cause many bit errors.

- Solution: use of Gray code:

```
 0000 0100 1100 1000
 0001 0101 1101 1001
 0011 0111 1111 1011
 0010 0110 1110 1010
```

When 1101 is sent:

<table>
<thead>
<tr>
<th>Point</th>
<th>Decodes as</th>
<th>Bit errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1101</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>1100</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1001</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>1111</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>1010</td>
<td>1</td>
</tr>
</tbody>
</table>

Multiplexing

- Definition
  - A “high capacity” link carries $n$ separate channels of data.
  - At the transmitting end of the link, a multiplexer combines inputs from $n$ inputs and transmits them on the single link.
  - At the receiving end of the link, a demultiplexer accepts the single data stream, separates the data according to channel, and delivers them to the appropriate output lines.

- Motivation?
Frequency Division Multiplexing

- Different signals are carried simultaneously by modulating each onto a different carrier frequency.
- The carrier frequencies are sufficiently separated that the bandwidths do not overlap.
- The bandwidth of each modulated signal is centered around its carrier frequency, and is called a *channel*.
- The unused portions of the spectrum between channels are called *guard bands*.
- Examples?

Orthogonal Frequency Division Multiplexing (OFDM)

- Variation of FDM that doesn’t use guard bands
- Channel is divided into many subcarriers independently sending data
- Designed so that subcarriers don’t interfere with each other:

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**Time Division Multiplexing**

- Different channels given full bandwidth at different times.

- Dynamic allocation
  - Channel allocated on demand basis
  - Examples?

- Static allocation
  - Channel is divided into frames.
  - Frames are divided into timeslots.
  - Each slot is dedicated to a particular “conversation.”
  - A source with a higher data rate may be assigned more slots than a source with a lower rate.

**Code Division Multiplexing**

Commonly called Code Division Multiple Access (CDMA).

- A narrowband signal is spread out over a wider frequency band

- Allows multiple users to share a frequency band

- The separation is based on coding theory:
  - Bit time is subdivided into $m$ chips
  - Each station is assigned an $m$-bit chip sequence
  - All chip sequences are pairwise orthogonal

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The Public Switched Telephone Network

- Designed decades ago with the goal of voice transmission
- Performance not originally compatible with computer networking
- Structure evolved from fully-interconnected to hierarchical:

![Diagram of telephone switch hierarchy]

Most common switch is AT&T 5ESS
- dual processor, fault tolerant
- front-end computer for all setup and admin
- complex switching fabric that must switch channels in both space and time.

How to change control software in real time?

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Original Telephone Switch Hierarchy

- 10 Regional offices (fully interconnected)
- 67 Sectional offices
- 230 Primary offices
- 1300 Toll offices
- 19,000 End offices
- 200 Million telephones

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Hierarchy, Post AT&T Breakup

- LATA: Local Access and Transport Area (roughly, an area code)
- IXC: Interexchange carrier (long-distance company)
- LEC: Local exchange carrier (one of the RBOCs)

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Connection Using the Local Loop

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Digital Subscriber Lines

- High-bandwidth over the local loop
  - With modems, filters artificially limit bandwidth
  - With DSL, the filter is removed; physics becomes the limit:

![Graph showing attenuation over distance]

- xDSL varieties:
  - ADSL: Asymmetric DSL
  - IDSL: ISDN-like DSL
  - HDSL: High-bit-rate DSL
  - CDSL: Consumer DSL
  - RADSL: Rate-adaptive DSL
  - VDSL: Very high-speed DSL
  - SDSL: Symmetric or single DSL
  - SHDSL: Single-pair high-speed DSL

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DSL Technologies

- Available Spectrum: 1.1 MHz
- Uses FDM to partition available bandwidth:
  - Upstream, downstream, and POTS each receive bandwidth
  - Ex: Discrete MultiTone (DMT):

![Diagram showing DMT with 256 4-kHz Channels]

- Typical Configuration:

![Diagram showing typical DSL configuration]

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Fiber to the Home (FttH)

- Uses Passive Optical Network (PON) architecture:
  - Two types: GPONs and EPONs
  - Capable of very high data rates
  - Technical issues are mainly about sharing the bandwidth

Use of TDM in the Phone System

- Transmission of digitized voice
  - typically uses more bandwidth than original signal
  - solution?

- Pulse Code Modulation
  - sample analog data according to Nyquist theorem. rate?
  - basis for T1 carrier
**Multiplexing of T1 Carriers**

TDM allows multiple T1 carriers to be multiplexed onto higher-order carriers.

- T1 multiplexed onto T2 onto T3 onto T4:

  4 T1 streams in → 1 T2 stream out
  6.312 Mbps

  7 T2 streams in
  1.544 Mbps

  6 T3 streams in
  44.736 Mbps

  7 T3 streams in
  274.176 Mbps

  6 T4 streams in
  44.736 Mbps

**Wavelength Division Multiplexing**

- Variation of FDM used in optical fibers
- Often used with on/off keying
- Simple, passive technology

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Switching

- Definition: transfer data (signals) from one channel to another channel

- Switching Implementations. Examples?
  - human
  - electro-mechanical relays
  - software
  - electronics

- Circuit Switching (CS)
  - dedicated communication path from source to destination during entire “call”
  - three phases
    - connection setup
    - data transfer
    - connection release
  - example?

- Message Switching (MS)
  - send entire message in store and forward manner
  - advantages over circuit switching
    - higher line efficiency
    - synchronous operation of source and destination not required
    - no “calls” blocked, just increased delay
    - multicast possible
    - message priorities can be established
    - error control on a per message basis

- Packet Switching (PS)
  - like MS, only limit one length of data sent
  - break message up into packets
  - advantage?
  - two main flavors:
    - datagrams, in which packets are sent independently
    - virtual circuits, in which a logical connection is established for packets to traverse
Switching Comparison

- Physical Layout

(a)(b)

Switching office

Physical (copper) connection set up when call is made

Packets queued for subsequent transmission

(b)

Switching office

Computer

Computer

RT

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Switching Comparison

- Behavior over time and space

(a) (b) (c)

Time

Call request signal

Propagation delay

Time spent hunting for an outgoing trunk

Call accept signal

Msg

Data

AB trunk

BC trunk

CD trunk

A B C D

A B C D

A B C D

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Switching Comparison (cont.)

- Advantages and disadvantages:

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

Cellular Radio

- Variants include AMPs and D-AMPS, GSM, CDMA, 3G, etc.

- Description
  - Geographic region divided into 10-20 km cells
  - In crowded regions, microcells can be used
  - Each cell contains a base station
  - All base stations connected to MTSO/MSC
  - Key feature: frequency reuse
  - May use FDMA, TDMA, or CDMA

(a) (b)
Analog Cellular

The AMPS system is originally based on analog transmission of analog data.

- Description
  - 832 full-duplex channels (pairs of simplex channels) using FDMA
  - Two carriers were originally given half of the channels each
  - Channel categories: control, paging, access, data
  - Control information is sent 'digitally' using Frequency Shift Keying
  - Voice data is analog

- Call management
  - On power-up, 66-bit registration info sent digitally
  - Base station receives information, informs MTSO, which logs it
  - Phone re-registers approximately every 15 minutes
  - Placing/receiving calls work differently...
  - Highly insecure

Digital Cellular

- Multiple standards have existed across the world:
  - US had AMPS-based (D-AMPS and D-AMPS 1900), GSM, and CDMA-based
  - Japan used a variant of D-AMPS
  - About everyone else used GSM
  - GSM is now used virtually everywhere

- Description:
  - Digital signaling and encoding of everything
  - Signaling techniques may be TDMA or CDMA (see next slide)
  - All well-known advantages of digital over analog

- PCS/PCN: single (worldwide-use) phone concept
  - Uses microcell technology
  - Requires large infrastructure investments
Cellular Multiple Access Methods

- Frequency Division Multiple Access (FDMA)
  - Used in original AMPS
  - Same as Frequency Division Multiplexing
  - Easy to implement but inefficient

- Time Division Multiple Access (TDMA)
  - Uses time division multiplexing of FDM channels
  - Access technique of D-AMPS variants and GSM
  - Advantages over FDMA: reduced interference, extended battery life, digital services possible

- Code Division Multiple Access (CDMA)
  - Standard for 3G wireless
  - Uses Direct Sequence Spread Spectrum to transmit signals
  - Uses (relatively) a very wide spectrum but supports many more users
  - Users on same frequency bands coexist in same area
  - Frequency reuse in adjacent cells

The Global System for Mobile Communications (GSM)

Originating as a single European 2G standard, it has since evolved to 3G and 4G versions and has come to dominate.

- Architecture:

- Components:
  - Handset with SIM
  - Air interface
  - Base stations
  - Switching network connected to PSTN

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GSM Air Interface

- Runs on several frequency ranges worldwide
- Allocates much more spectrum than AMPS
- Uses pairs of frequencies multiplexed with TDM:

  Frequency
  959.8 MHz 935.4 MHz 935.2 MHz 914.8 MHz 890.4 MHz 890.2 MHz

  Base to mobile
  124
  2
  1

Third-Generation (3G) Digital Cellular

The original goal was to integrate digital voice and data at high data rates.

- Other goals:
  □ Deployment by year 2000
  □ World-wide standard
  □ High-quality voice
  □ Messaging, Multimedia, Internet
  □ Data rates: 2Mbps stationary and 384 kbps moving vehicle

- Realities:
  □ Deployments began in 2001, by major carriers in 2003 and 2005 and beyond
  □ US and Euro versions were ultimately made compatible in ’99
  □ Voice and data integration works fairly well
  □ Data rate specs are not clearly specified; various rates are sold

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Fourth-Generation (4G) Digital Cellular

The primary goal here is to improve on 3G.

- Other goals:
  - Peak download speed 100 Mbps in trains, cars
  - 1Gbps stationary and walking
  - Highly secure
  - IP-based
  - All-in-one solution for phones, laptops, etc.

- Realities:
  - Existing "4G" deployments aren't really 4G

Cable Television Networks

- History:
  - Community antenna television:
    - Large antenna
    - Head end amplifier
    - Coaxial cable delivering signals

  - 1974: Time, Inc. starts HBO
    - Other channels follow suit
    - Large corporations purchase existing systems
    - Inter-city infrastructure built
Cable Internet

- Construction:
  - □ Originally, head-end with 1-way amp
  - □ Amps replaced with 2-way amps to implement internet access
  - □ Hybrid Fiber Coax (HFC) construction
  - □ Similar to phone system with one significant difference:
    - Switch
    - Toll office
    - Head-end
    - Local loop
    - High-bandwidth fiber trunk
    - House
    - Tap
    - Fiber node
    - Fiber

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Spectrum Allocation

- TV channels on cable:
  - □ 6 MHz each
  - □ Occupy 54-550 MHz region (except for FM radio bands)
  - □ Low end of band not used

- Data on cable:
  - □ Low end used for upstream data
  - □ High end (above 550 MHz) for downstream

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Cable Modems

Early proprietary schemes have largely given way to DOCSIS

- Data Over Cable Service Interface Specification (DOCSIS):
  - External modem
  - 10 Mbps modem to Ethernet or USB
  - Always on with bidirectional encryption
- Modem initialization:
  - Receive “parameter packet”
  - Perform ranging
  - Receive minislot for bandwidth requests
  - Login with unique ID
- Upstream data:
  - TDM using minislots
  - Access: slotted ALOHA protocol, binary exponential backoff
  - DHCP to request IP address
- Downstream data:
  - Fixed packet size
  - Built-in error correcting and other overhead

ADSL Versus Cable

The comparison depends on whom you ask

- Significant differences:
  - ADSL:
    - Twisted pair to the house
    - Dedicated connections
    - Specific bandwidth guarantees
    - Unavailable if distance from headend is too great
    - More secure and reliable
    - Choice of ISP
  - Cable:
    - Coaxial cable to the house
    - Shared connection
    - Unspecific bandwidth
    - Less secure, less reliable
    - Available if you have cable
    - Often no ISP choice