Lecture 2 - Physical Layer

Computer Communication Networks
CS35201 - (001/ 002)
Fall 2022

Kent State University

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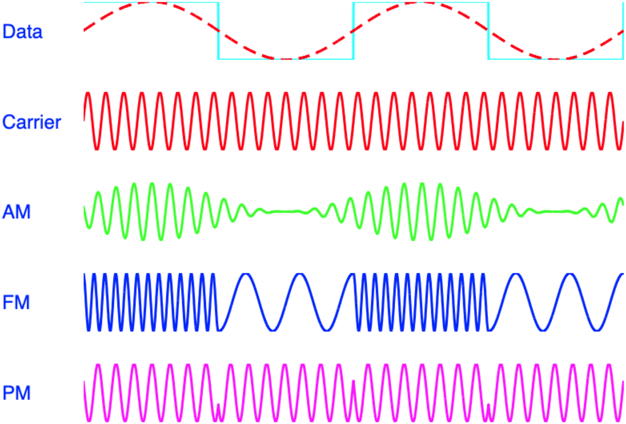
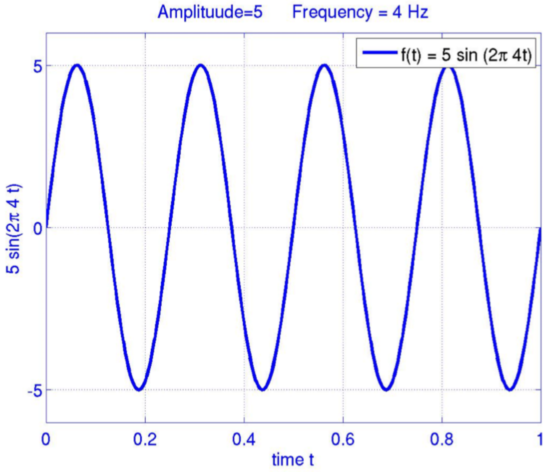
Outline I

Transmission Vehicle: Waves

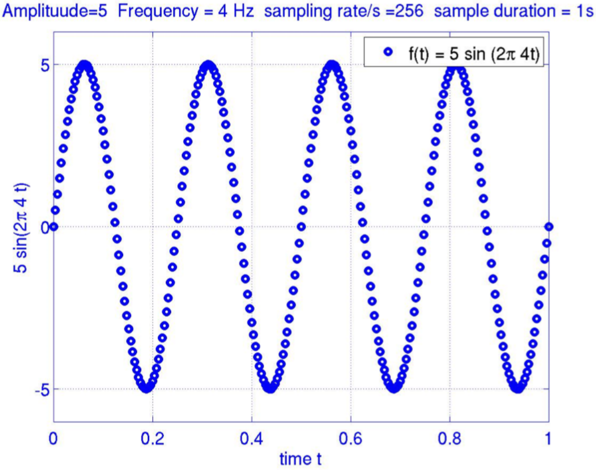
How to Transmit a Bit Point-to-Point?



Recall Waves

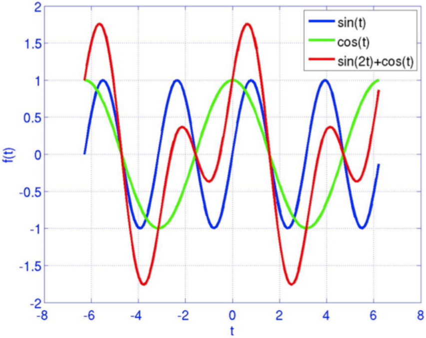


Recall Waves



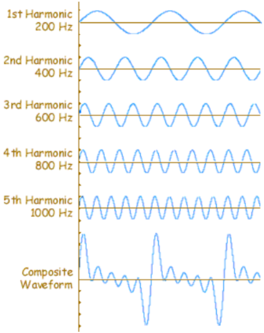
Frequency Domain Concepts

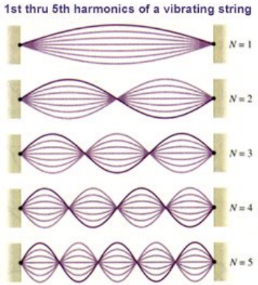
- Signals are often made up of many frequencies
- The Components of a signal are sine waves ⇒ Fourier analysis
- We can plot frequency domain functions



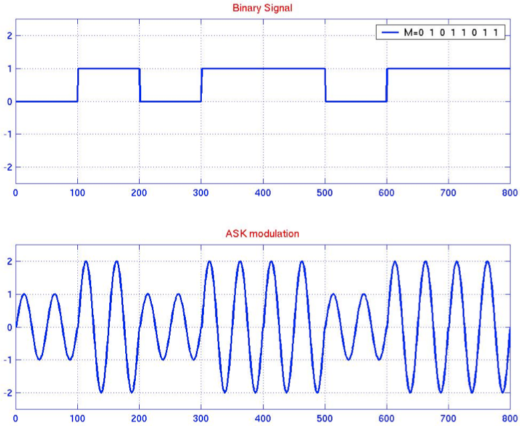
Harmonic Numbers

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





Harmonic Numbers



Definition "Signals"

- **Analog signal**: The signal varies in a smooth way over time.
- **Digital signal**: The signal maintains a constant level, then changes to another constant level.
- **Periodic signal**: The signal follows a repeated pattern over time.
- **Aperiodic signal**: The signal does not follow a pattern over time.

Definition

- **Peak Amplitude (a)** : The maximum strength of a signal $\Rightarrow$ in volts.
- **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.
- **Period (t)**: The time for one repetition of the signal $\Rightarrow t = \frac{1}{f}$.
- **Phase(ϕ)**: The relative position of the signal in time.
- **Wavelength(λ)**: The distance occupied by one cycle. Or Distance between two points of corresponding phase in two consecutive cycles.
- **Spectrum**: The range of frequencies contained in a signal.

Definition

- **Absolute Bandwidth**: The width of the spectrum.
- **Effective Bandwidth**: The narrow band of frequencies containing most of the energy.
- **Data**: Entities that convey meaning.
- **Signal**: Electric, electromagnetic or optical representations of data
- **Data Rate**: Ant transmission system has a limited band of frequencies. This limits the data rate that can be carried.
- **Transmission**: Communication of data by propagation and processing of signals.

Definition

- **Analog**: Continuous values of a signal within some interval $\Rightarrow$ e.g. sound, video
- **Digital**: Discrete values of a signal within some interval $\Rightarrow$ text, integers
- **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)

Outline I

Analog Signal vs. Digital Signal

- **Digital transmission**:
  - Uses two signaling levels $\Rightarrow$ representing 0 and 1
  - Data transmission using square waves
  - Digital transmission is concerned with content
  - The data could be analog (voice) or digital (data)
- **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 $\Uparrow$
  - Susceptible to noise $\Downarrow$
  - Greater attenuation $\Downarrow$
    - Reduction in signal strength
    - Pulses become rounded and smaller
    - Leads to loss of information

Means of Transmission

Data Signals vs. Carrier Signal

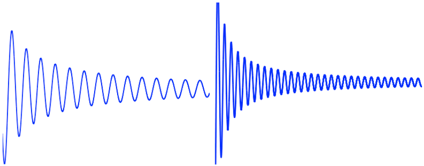
Carrier (digital, analog) $\times$ Signal (digital, analog)

- Analog data via Analog transmission, e.g. radio
- Analog data via Digital transmission (Sampling needed $\Rightarrow$ e.g. voice, audio, video)
- Digital data via Analog transmission $\Rightarrow$ Broadband & Wireless
- Digital data via Digital transmission (Baseband $\Rightarrow$ e.g. Ethernet)

Transmission Impairment
What could go wrong?

Common to both digital and analog transmission

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



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

Transmission Impairment
What could go wrong?

- 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

Transmission Impairment
How to Fix?

$\Rightarrow$ boost the signal

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

Voice/ Video/ Data Transmissions

- Voice
  - Frequency range
    - Hearing ⇒ 20Hz-20kHz
    - Speech ⇒ 100Hz- 7kHz
  - Voice can be easily be converted into electromagnetic signal
    - 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
- Video
  - Max frequency of 4.2 MHz
  - 525 lines scanned per frame at 30 frames per second ⇒ National Television Standards Committee (NTSC)
- Data
  - Bandwidth depends on data rate

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

Advantages of Digital Transmission

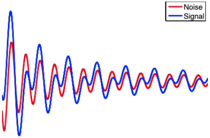
1. Digital technology
   - Low cost $\Rightarrow$ LSI/VLSI technology
2. Data integrity
   - Longer distances over lower quality lines
3. Capacity utilization
   - High bandwidth links economical
   - High degree of multiplexing easier with digital techniques
4. Security and Privacy
   - Encryption
5.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

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

Noise

- Additional signals inserted between transmitter and receiver
- Four types of noise:
  1. Thermal noise ⇒ Due to thermal agitation of electrons
     - Uniformly distributed
     - White noise
  2. Inter-modulation
     - Signals that are the sum and difference of original frequencies sharing a medium
  3. Crosstalk ⇒ A signal from one line is picked up by another
  4. Impulse
     - Irregular pulses or spikes ⇒ External electromagnetic interface
     - Short duration
     - High amplitude



Channel Capacity
Bandwidth vs. Data Rate

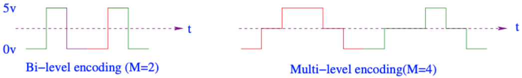
- Data Rate (in bits/s)
  - Rate at which data can be communicated
  - Depends on channel frequency and modulation technique
- Bandwidth (in cycle (Hz)) $\Rightarrow$ width of frequency band
  - Constrained by transmitter and medium

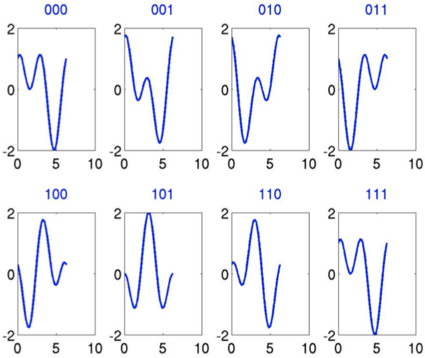
Channel Capacity

1. Noiseless Channel $\Rightarrow$ Nyquist Bit Rate
2. Noise Channel $\Rightarrow$ Shannon Capacity later

Encoding

Bi-level and Multilevel Encoding





Noiseless Channel Data Rate

Nyquist's Theorem

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

$$C = 2B \log_2 M \qquad (1)$$

- Doubling frequency **B** doubles the data rate
- The presence of noise can corrupt one or more bits
  - 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

Noiseless Channel Data Rate

Nyquist Examples

- Example 2.2: **Nyquist's Theorem: Noiseless Channel**
  What is the bandwidth of noiseless 3Khz channel with binary transmission?
  From Equation (1),

$$C = 2B \log_2 M = 2 \times 3000 \log_2 2 = 6000 bps$$

- 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

$$BitRate = 2 \times \log_2 4 = 12000 bps$$

Noiseless Channel Data Rate

Nyquist Examples

- 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?
  From Equation (1),

$$C = 2B\log_2 M \rightarrow 2^{20} = 2 \times 64000 \log_2 M$$

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

Noisy Channel Data Rate
Shannon's Theorem

- 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.

$$10 \log_{10} \frac{signal\ power}{noise\ power} = 10 \log_{10} \frac{S}{N} dB \qquad (2)$$

- With noise, the maximum channel capacity:

Noisy Channel Data Rate
Shannon's Theorem

- Shannon's Theorem

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

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

$$10\log_{10}\frac{S}{N} = 30dB \Rightarrow \frac{S}{N} = 10^3 = 1000$$

$$C = B\log_2(1+\frac{S}{N}) = 3000 log_2(1+1000)$$

$$C = 3000 \times 9.9673 < 30Kbps$$

Noisy Channel Data Rate

Shannon's Theorem

- Shannon's Theorem
- 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.

$$C = B \log_2(1 + \tfrac{S}{N}) = B \log_2(1 + 0) = B \log_2 1 = 0$$

Outline I

Guided Transmission Media

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

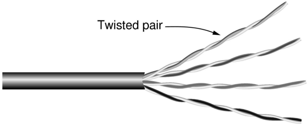
Note

- 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

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

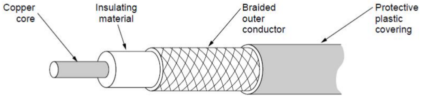
Twisted Pairs



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)

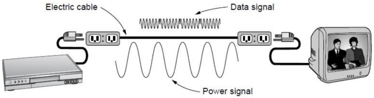
Coaxial Cable



- 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

Power Lines

- A network that uses household electrical wiring

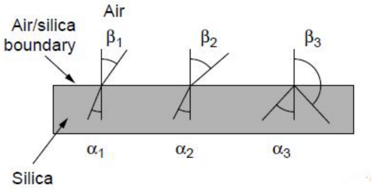


Fiber Optics

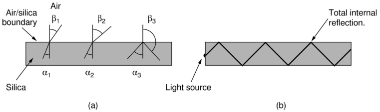
- Much greater capacity $\Rightarrow$ hundreds of Gbps
- Smaller size and weight
- Lower attenuation
- Electromagnetic isolation
- Much greater repeater spacing $\Rightarrow$ 10's of km
- Used for long haul, MAN, LAN, Loops
- 10^{14} to 10^{15} Hz
- Light Emitting Diode (LED)
  - Cheaper, wider operating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

Fiber Optics

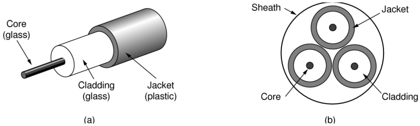
- Three examples of a light ray inside a silica fiber impinging on the air/silica boundary at different angles



- Light trapped by total internal reflection



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

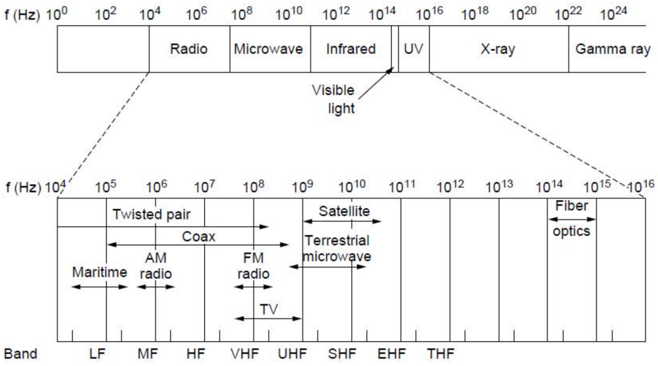
Wireless Transmission Media

Different Media

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

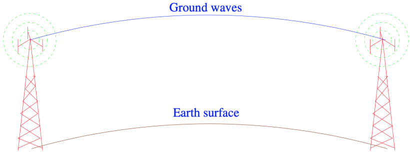
Electromagnetic Spectrum

- The electromagnetic spectrum and its uses for communication

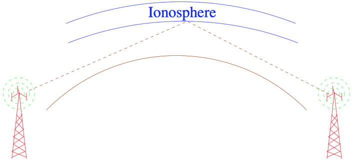


Radio Transmission

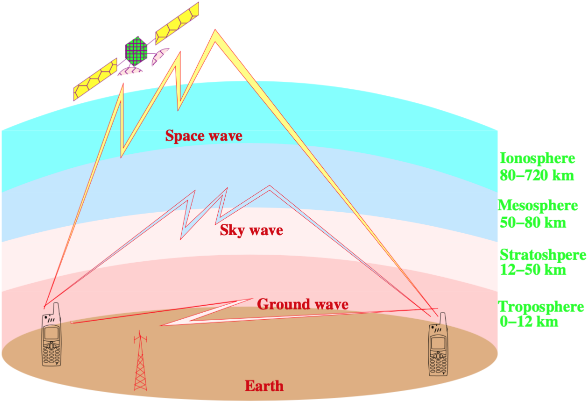
- In the Very Low Frequency (VLF), Low Frequency (LF), and Medium Frequency (MF) bands, radio waves follow the curvature of the earth



- In the High Frequency (HF) band, they bounce off the ionosphere

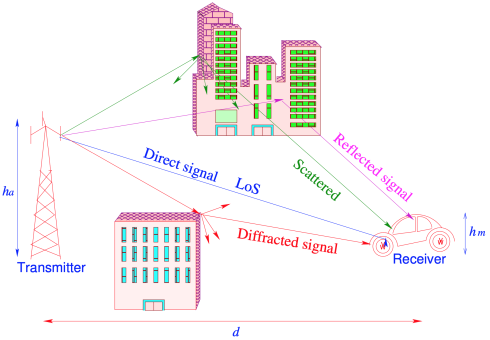


Propagation Mechanisms



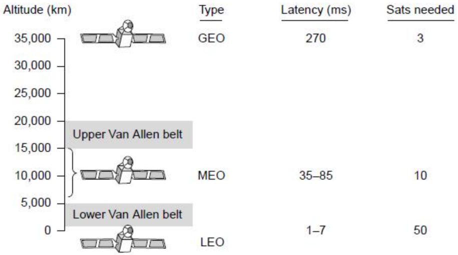
Propagation Phenomenon

1. Reflection
2. Refraction
3. Diffraction
4. Scattering



Satellite Communications

1. Geosynchronous Equatorial Orbit (GEO)
2. Medium Earth Orbit (MEO)
3. Low Earth Orbit (LEO)



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

Satellite Communications
Advantages/Disadvantages

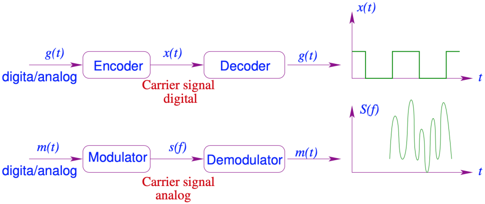
- Larger coverage area ⇑
- Transmission cost is independent of distance ⇑
- Satellite to Satellite communication is very precise ⇑
- Higher bandwidth are available ⇑
- Launching satellite into orbit is costly ⇓
- Satellite bandwidth is gradually becoming used up ⇓
- Large propagation delay ⇓

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

Outline I

Encoding

- The process of encoding the carrier signal
  - Modulation
    - if the carrier signal is analog ⇒ (DSL, Cable, phone lines)
  - Encoder
    - if the carrier signal is analog ⇒ (DSL, Cable, phone lines)
    - if the carrier signal is digital ⇒ (Ethernet, fiber optics)
- Sometimes the terms are used interchangeably



What is Modulation?

- 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 signals
- All modulation techniques involve one or more of the three fundamental frequency domain parameters:

1. Change amplitude .... ⇒ Amplitude Modulation (AM)

$$\color{red}{a}\,sin(ft + \theta)$$

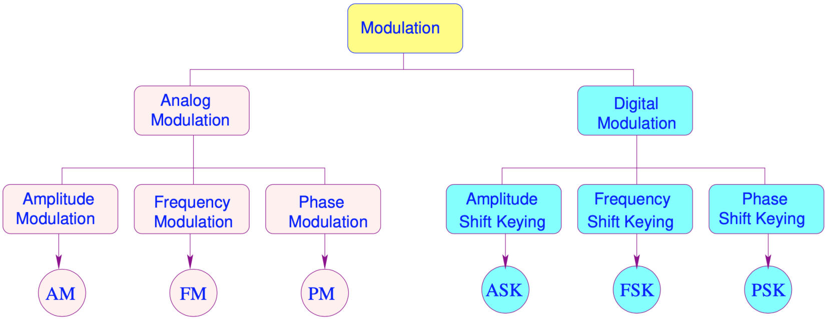
2. Change Frequency .... ⇒ Frequency Modulation (FM)

$$a\,sin(\color{red}{f}\,t + \theta)$$

3. Change phase .... ⇒ Phase Modulation (PM)

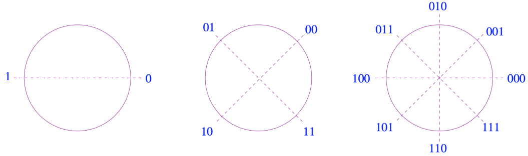
$$a\,sin(ft + \color{red}{\theta})$$

Modulation Techniques



Modulation Techniques

1. In Amplitude Modulation (AM) ⇒ amplitude shift keying
   - Two different amplitudes are used to represent 0 and 1
2. In Frequency Modulation (FM) ⇒ frequency shift keying
   - Two or more different tones are used
3. In Phase Modulation (PM) ⇒ phase shift keying (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° , 315° are used to transmit 2 bits of information
   - Shifts of 22.5°, 45°, 67.5°, 90°, $\cdots$ are used to transmit 3 bits



- The goal is to optimize some characteristics of the transmission
  - Code efficiency, code density, error detection/correction

Phase Shift Keying (PSK)

- Phase Shift Keying (PSK) variations are used in most wireless devices
- The two-level PSK is called Binary Phase Shift Keying (BPSK)
- Uses two phases to represent binary digits
- Phase shift with reference to previous bit
  - Binary 0: signal burst of same phase as previous signal burst
  - Binary 1: signal burst of opposite phase to previous signal burst
- 4-level Quadrature Phase Shift Keying (QPSK)
  $\Rightarrow$ Each element represents more than one bit

$$
\begin{array}{cc}
acos(2\pi ft + \frac{\pi}{4}) & acos(2\pi ft + \frac{3\pi}{4}) \\
acos(2\pi ft - \frac{3\pi}{4)} & acos(2\pi ft - \frac{\pi}{4})
\end{array}
$$

Encoding Digital Data to 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 2.17.1.1 (Modulation rate)

The rate at which the signal level changes. It is measured in baud

$\Rightarrow$ signal elements per second

$\Rightarrow$ sample per second

Encoding Digital Data to Analog Signal

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

Encoding Analog Data to Digital Signals

- Analog data (Voice and Video) are digitized $\Rightarrow$ sampled
- The simplest technique is Pulse Code Modulation (PCM) $\Rightarrow$ later
  - Sampling the analog data periodically and quantizing the samples
  - Slicing continuous waves to digitized waves

Encoding Analog Data to 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)

Pulse Code Modulation (PCM)

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

Theorem 2.17.5.3 (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.

$$\textbf{Sampling rate (Hz)} \geq \textbf{2W}$$

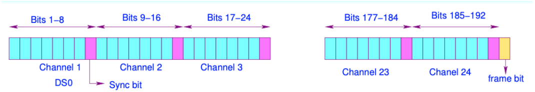
Pulse Code Modulation (PCM)

Example 2.7 (PCM for voice phone)

- Signal bandwidth $= 4$ kHz
- Minimum sample rate $R = 2 \times W = 8,000$ samples/second
- Period $T = 1/R = 0.000125$ sec. $= 125\mu s$
- 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

T1 Network

Example 2.8 (T1 Network)



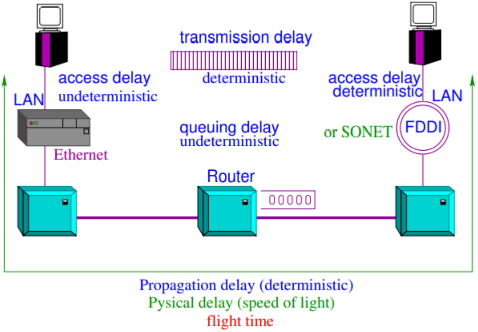
- Maximum Bandwidth

$$\left(8\frac{bits}{channel} \times 24\frac{channel}{frame} + 1\frac{frame\ bit}{frame}\right) \times 8000\frac{frames}{second}$$
$$= 1,544,000\frac{bits}{second} = 1.544\ Mbps = DS1 \quad (4)$$

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

Outline I

End-To-End Delay



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

Fiber Distributed Digital Interface (FDDI)
Synchronous Optical Networking (SONET)

Delay Components

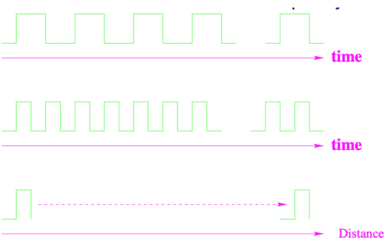
- How to calculate E2E Delay?
  1. Access Delay
     - Depends on channel availability
     - Depends on contention/scheduling
  2. Propagation delay
     - Depends on the distance
     - e.g., speed of light
     - Delay = Distance / Speed of light
  3. Transmission delay
     - Depends of the Speed/Frequency/Bandwidth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

E2E Delay

- Sometimes we are interested about Round Trip Time (RTT)
- There is no queuing delays in direct link
- Bandwidth not relevant if size $= 1$ bit
    - It takes one cycle time $(\frac{1}{f})$ to process
    - Very small compared to the propagation delay
- Software overhead is included in RTT
    - Could be dominant is short distance

Hown Fast a Bit can Travel?

- Bandwidth
  - Bandwidth related to "bit width" $\Rightarrow$ width of a frequency band



  - Two Factors
    - The length of a bit in time
    - The speed it travels

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

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 2.9 (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 optical fiber is 200,000 km/s ($2 \times 10^8 m/s$).

- What is the length of a bit (in time) in the fiber?
  $\frac{1 bit}{100 Mbps} = \frac{1}{100 \times 2^{20}} sec. = 0.009 \mu s$
- What is the length of a bit (in meters) in the fiber?
  $2 \times 10^8 \frac{m}{s} \times \frac{1}{100 \times 20^{20}} s = \frac{2 \times 10^8}{100 \times 2^{20}} m = 1.9$ meters

Bit Width in Time and Space

Relative importance of bandwidth and latency, which One?

Example 2.10 (Propagation delay dominates)

Assume a 100 Mbps channel in which you send a bit from NY to LA

Delay = Propagation delay + Transmission delay = 100 ms + 0.00001 ms

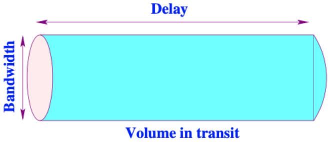
Example 2.11 (Transmission delay dominates)

Assume a 100 Mbps channel in which you send 100 Mb from NY to LA

Delay = Propagation delay + Transmission delay = 100 ms + 1000 ms

Bit Width in Time and Space

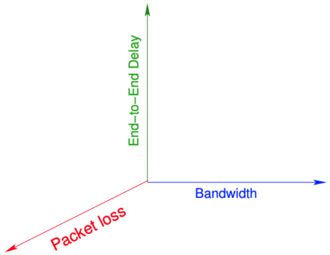
Which One?



Example 2.12 (Amount of data in transit) Assume 100 ms RTT and 45 Mbps Bandwidth = 560 KB of data

- Amount of data in transit $= 100ms \times 45 \times 2^{20} b/s = 560KB$
- Bandwidth (throughput)
  - Sometimes "Bandwidth" is misused for data rate
  - Example: 10Mbps
  - Link versus end-to-end $\Rightarrow$ often we are interested in E2E delay
  - Correct notations
    - KB $= 2^{10}$ bytes
    - Mbps $= 2^{20}$ bits per second

Quality of Service (QoS)



- We can optimize for delay, bandwidth or loss, but not all!
- Other metrics are
  - Jitter ⇒ delay variation
  - Traffic burstiness ⇒ different definitions

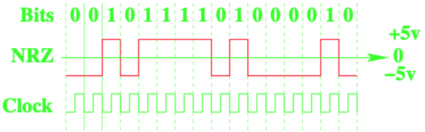
Outline I

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

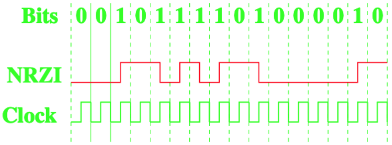
Non-return to Zero-Level

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



Non-return to Zero-Level Inverted

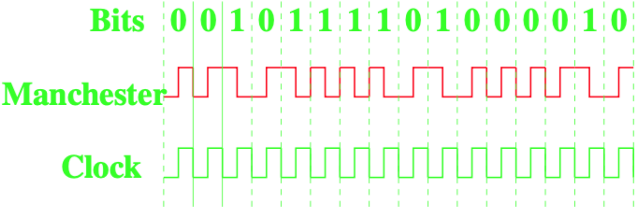
- Data encoded as presence or absence of signal transition at beginning of bit time
- Makes a transition from the current signal to encode a 1
  - Transition (low to high or high to low) denotes a binary 1
  - No transition denotes binary 0
  - An example of differential encoding
- Stays at the current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

Manchester Coding

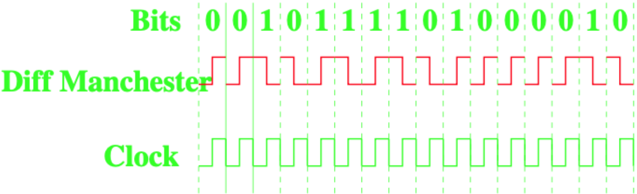
- 0 = low to high
- 1 = high to low



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

Differential Manchester Coding

- Signal change (low-to-high or high-to-low) represent 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 consecutive 0's and consecutive 1's
- Technology choice

Coding Schemes: 4B/5B

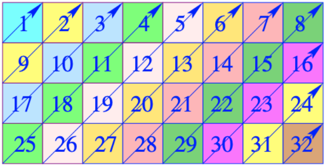
- Breaks a consecutive 0s and 1s by inserting extra bits into bit stream
- Every 4 bits of the actual data are encoded in a 5-bit code
- Each 1 has no more than one leading 0
- Each 1 has no more than two trailing 0s
- It uses NRZI

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 $\Uparrow$
- 20% overhead $\Downarrow$

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

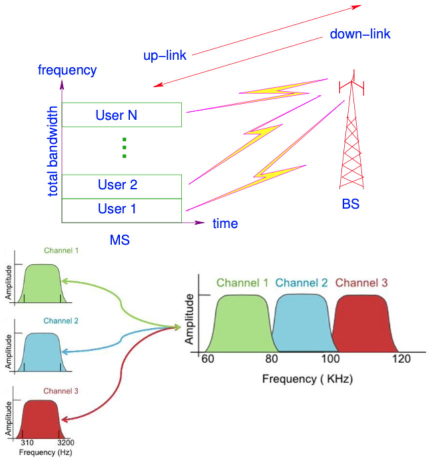


Outline I

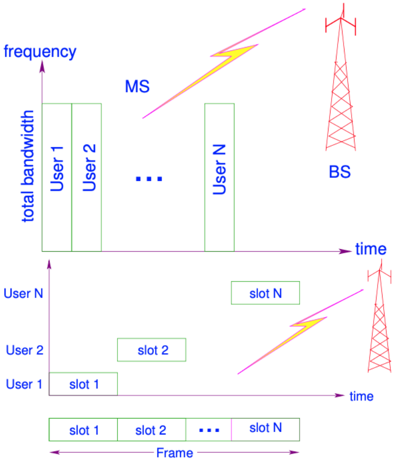
Common Multiplexing Techniques

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

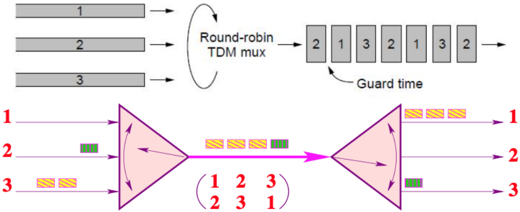
Frequency Division Multiplexing (FDM)



Time Division Multiplexing (TDM)

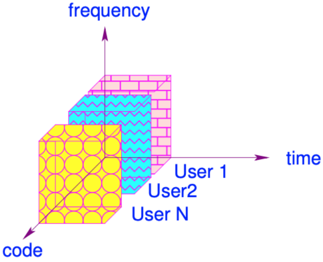


Time Division Multiplexing (TDM)



- 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

Code Division Multiplexing (CDM)



- Also Called Spread Spectrum
- 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 (key) uncorrelated with the data

Code Division Multiplexing (CDM)

Advantages/Disadvantages

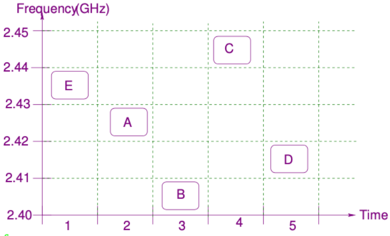
- Low power spectral density $\Downarrow$
  - Spreading the signal over a large frequency-band makes the power spectral density very small
- Interference limits the operation $\Rightarrow$ Subscriber Station (SS) $\Downarrow$
- Privacy $\Rightarrow$ chipping-code/hopping-code $\Uparrow$

SS Types

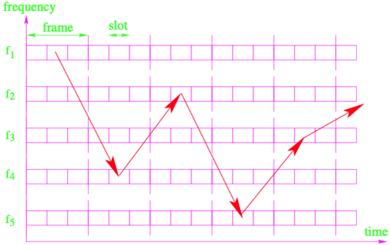
1. Frequency Hopping
2. Direct Sequence

Frequency Hopping Spread Spectrum (FHSS)

- Hopping code: E A B C D
- 5 channels

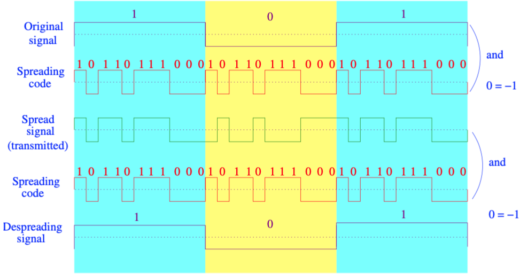


- 3 users can use a channel but at different times (TDM)
- They use the same key



Direct Sequence Spread Spectrum (DSSS)

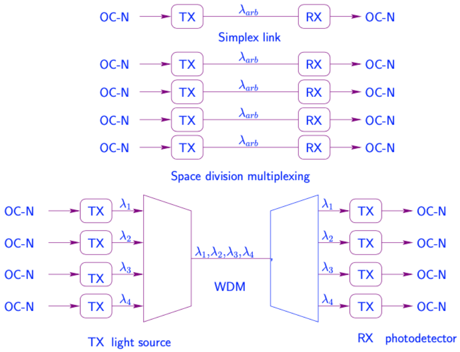
- Most widely recognized form of spread spectrum
- Data stream 101
- Chipping code: 10110111000



Wave Division Multiplexing (WDM)

- 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

Wave Division Multiplexing (WDM)

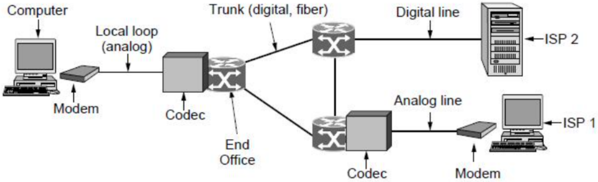


- OC-N (Optical Carrier) $\Rightarrow$ N = 1, 3, 12, 24, 48, 192
- TX $\Rightarrow$ transmitter
- RX $\Rightarrow$ Receiver

Outline I

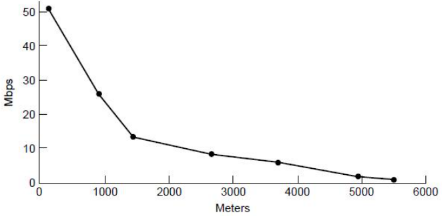
Applications of Multiplexing Techniques

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



Asynchronous Digital Subscriber Lines

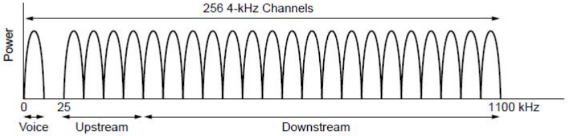
- Another name is Broadband as oppose to DS0=56 kbps telephone line
- Bandwidth versus distance over Category 3 UTP for DSL



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

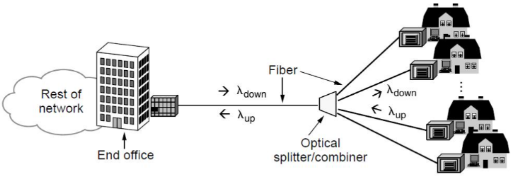
Asynchronous Digital Subscriber Lines

- 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



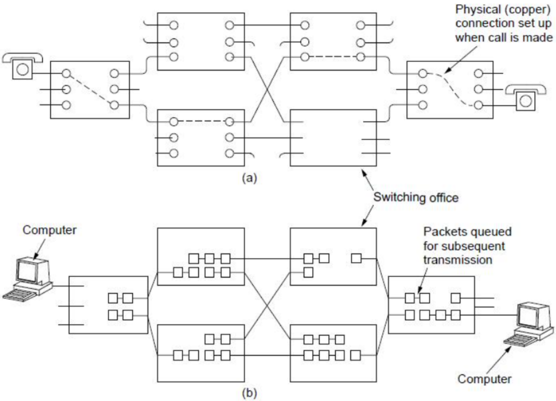
  - It uses Coded Orthogonal Frequency Division Multiplexing (COFDM)
  - Fast Fourier Transform (and the inverse iFFT) is used to convert the signal on the line into the individual channels
  - Quadrature amplitude modulation (QAM) or phase-shift keying (PSK) is used to encode the bits within each channel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

Fiber to the Home (FttH) I



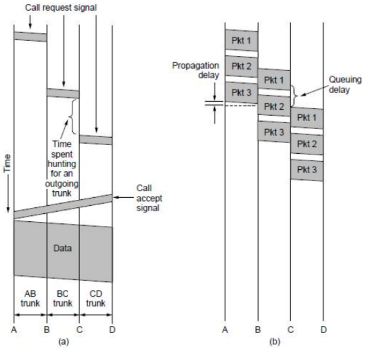
- Passive optical network (PON) for Fiber To The Home
  - PON is a point-to-multipoint, fiber to the premises
- A single optical fiber serves multiple premises
  - Typically 32-128

Circuit Switching/Packet Switching



(a) Circuit switching. (b) Packet switching

Circuit Switching/Packet Switching
Timing of events



(a) Circuit switching. (b) Packet switching

Circuit Switching/Packet Switching

comparison of circuit Switching vs. packet Switching

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

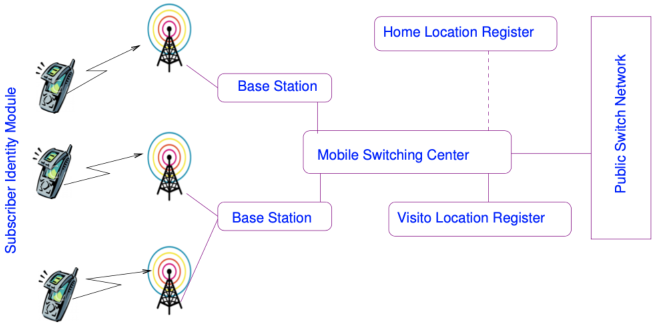
A comparison of circuit-switched and packet-switched networks

Mobile Telephone System

Cell phone Generations Compared

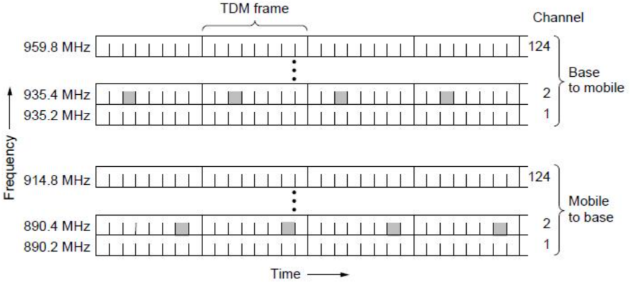
	Standard	Technology	SMS	Voice Switching	Data Switching	Data Rate
1G	AMPS, TACS	Analog	No	Circuit	Circuit	N/A
2G	GMS, CDMA, EDGE, GPRS	Digital	Yes	Circuit	Circuit	236.8 kbps
3G	UTMS, CDMA2000, HSPDA, EVD0	Digital	Yes	Circuit	Packet	384 kbps
4G	LTE Advanced, IEEE 802.16 (WiMax)	Digital	Yes	Packet	Packet	upto 1 Gbps
5G	IMT-2020, ITU	Digital	Yes	Packet	Packet	$>$ 1 Gbps
6G	?	Digital	Yes	Packet	Packet	upto 100 Gbps

GSM
Global System for Mobile Communications



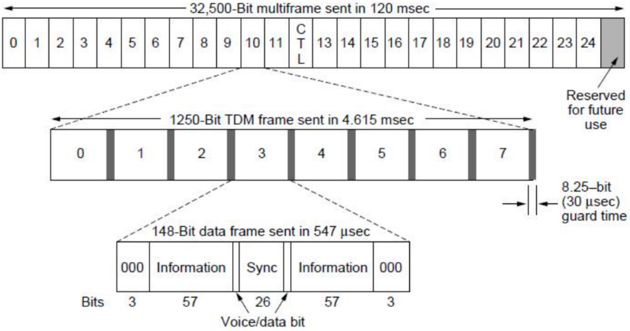
GSM

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



GSM

- A portion of the GSM framing structure



Outline I

References

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