COMS3200

COMS3200 – Week 4
Physical Layer

School of Information Technology and Electrical Engineering
The University of Queensland

COMS3200

Outline

- Learning Objectives
  - Sample Exam Question
- Physical Layer
  - Fundamental Theory
    - Signals, Spectrum, Modulation
  - Transmission Media
  - Multiplexing, Switching
  - Example physical layer protocols

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Physical Layer

Application Layer
Transport Layer
Network Layer
Link Layer
Physical Layer

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Learning Objectives

- After this week, you should
  - understand characteristics of signals
    - e.g. frequency, amplitude, phase, spectrum, data-rate, bandwidth, signal-strength
  - understand and be able to apply Nyquist's theorem and Shannon's theorem
  - understand differences between analog and digital transmission
  - understand various types of modulation
  - understand differences between transmission media
  - understand channel multiplexing techniques

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Why and How?

- Why?
  - Need basic understanding of physical layer
- How?
  - Possibly difficult/confusing first-time through
  - Read textbook
  - Relate to previous knowledge
  - Ask questions!

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Exam Question…

- From previous exams:

If a two level (binary) amplitude modulation is assumed, the maximum throughput which can be achieved on a telephone line is 6 kbps (assuming 3 kHz is the highest allowed frequency). Current modems achieve much higher throughputs. Explain how it is achieved? Do you know any theorem to support your explanation?

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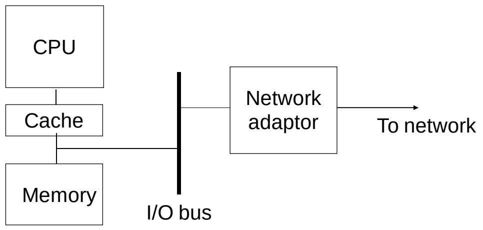
Network Nodes

- General purpose computers
- Specialised network devices



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Physical Layer

- Responsible for transmission of raw bit streams
  - Sender (transmitter): Convert bits to electromagnetic waves
  - Receiver: converts EM waves to bits
- Communication occurs over some *transmission medium (network link)*

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Terminology

- Guided
  - EM waves guided along physical path
    - Optical Fibre
    - UTP cable
- Unguided
  - Example: radio, infrared

- Channel sharing
  - Simplex
  - Half-duplex
  - Full-duplex

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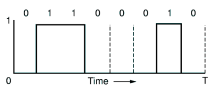
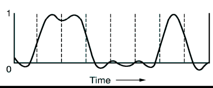
Time-varying signals

- Discrete (Digital)
  - Finite number of values (2,4,…)



- Continuous (Analog)
  - Infinite number of values



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Periodic Signals

- Repeat in time (with period T)

- example: sinusoid

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Signal Characteristics

- Amplitude
  - Intensity of signal
  - Instantaneous value
- Frequency
  - Inverse of the period
  - Repetitions of the period per second
- Phase
  - Position of signal

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Signal Analysis

Fourier Analysis:

- Fourier showed that (almost) any periodic waveform g(t) (period T, frequency f=1/T) can be constructed by summing sines and cosines of period T/n for n=1,2,… ∞
- Period T/n → frequency nf
- Summing harmonics
  - f=1/T is the frequency of the first harmonic

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Fourier Series

$$g(t) = \frac{c}{2} + \sum_{n=1}^{\infty}(a_n \sin(2\pi nft) + b_n \cos(2\pi nft))$$

Coefficients:

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

$$b_n = \frac{2}{T}\int_0^T g(t)\cos(2\pi nft)dt$$

$$c = \frac{2}{T}\int_0^T g(t)dt$$

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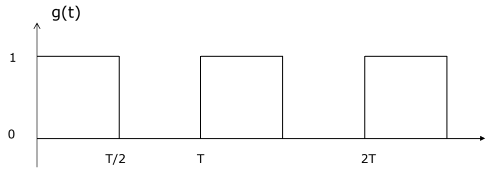
Example: Fourier Series of a Square Wave



$$c = \frac{2}{T}\int_0^T g(t)dt = \frac{2}{T}\int_0^{\frac{T}{2}} 1\cdot dt + \frac{2}{T}\int_{\frac{T}{2}}^T 0\cdot dt = 1$$

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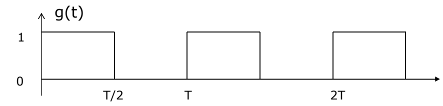
Example: Square Wave



$$a_n = \frac{2}{T}\int_0^T g(t)\sin(2\pi nft)dt = \frac{2}{T}\int_0^{\frac{T}{2}} 1\cdot\sin(2\pi nft)dt + \frac{2}{T}\int_{\frac{T}{2}}^T 0\cdot\sin(2\pi nft)dt$$

$$= \frac{2}{T}\int_0^{\frac{T}{2}}\sin(2\pi nft)dt = -\frac{2}{T}\frac{1}{2\pi nf}\cos(2\pi nft)\Big|_0^{\frac{T}{2}} = -\frac{1}{\pi n}[\cos(\pi nfT) - \cos(0)]$$

$$= -\frac{1}{\pi n}[\cos(n\pi) - 1] = \begin{cases}\frac{2}{n\pi} & \text{for n odd}\\ 0 & \text{for n even}\end{cases}$$

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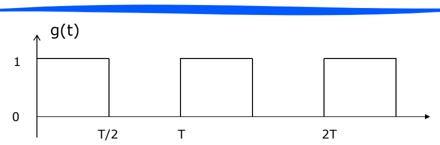
Example: Square Wave



$$b_n = \frac{2}{T}\int_0^T g(t)\cos(2\pi nft)dt = \frac{2}{T}\int_0^{\frac{T}{2}} 1\cdot\cos(2\pi nft)dt + \frac{2}{T}\int_{\frac{T}{2}}^T 0\cdot\cos(2\pi nft)dt$$

$$= \frac{2}{T}\int_0^{\frac{T}{2}}\cos(2\pi nft)dt = \frac{2}{T}\frac{1}{2\pi nf}\sin(2\pi nft)\Big|_0^{\frac{T}{2}} = \frac{1}{\pi n}[\sin(\pi nfT) - \sin(0)]$$

$$= \frac{1}{\pi n}[\sin(n\pi)] = 0$$

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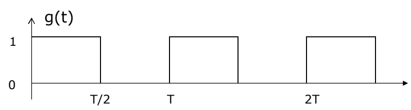
Example: Square Wave



a_1	0.6366
a_2	0
a_3	0.2122
a_4	0
a_5	0.1273
a_6	0
a_7	0.0909

Fourier Series of a Square Wave:

$$g(t) = \frac{1}{2} + \frac{2}{\pi}\sin(2\pi ft) + \frac{2}{3\pi}\sin(3\cdot 2\pi ft) + \frac{2}{5\pi}\sin(5\cdot 2\pi ft) + \frac{2}{7\pi}\sin(7\cdot 2\pi ft) + \ldots$$

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Fourier Applet

- http://www.phy.ntnu.edu.tw/java/sound/sound.html

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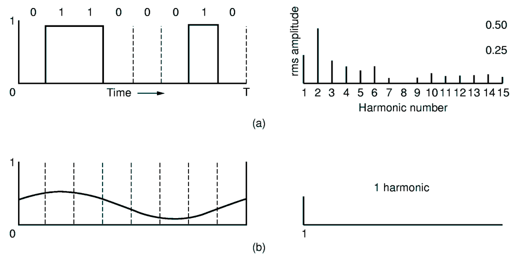
Another Example



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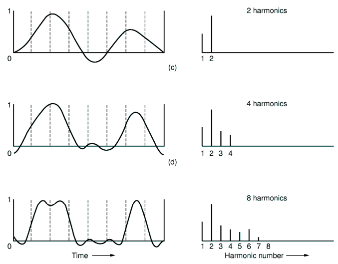
Fourier Analysis



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Signal analysis for binary Signaling

- Relation between data rate and harmonics for a telephone line with bandwidth of 3000Hz
- We are sending 8 bits per period T
  - bps = 8/T → T= 8/bps

Bps	T(msec)	First harmonic(Hz)	# Harmonics sent
300	26.67	37.5	80
600	13.33	75	40
1200	6.67	150	20
2400	3.33	300	10
4800	1.67	600	5
9600	0.83	1200	2
19200	0.42	2400	1
38400	0.21	4800	0

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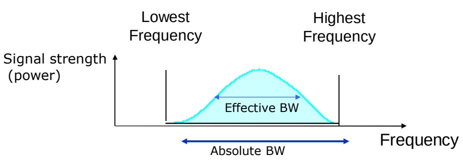
Spectrum

- Spectrum of a signal
  - Range of frequencies it contains
- Bandwidth
  - Absolute bandwidth
    - width of the spectrum
  - Effective bandwidth
    - where most of the energy is contained
    - (narrower than absolute bandwidth)



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Data rate vs Bandwidth

- Data rate
  - Usually measured in bits-per-second (bps)
    - or kbps, Mbps, Gbps, …
- Bandwidth
  - Measured in Hertz (Hz)
    - or kHz, MHz, GHz, …
- Not the same but are related
- Higher data rate implies higher bandwidth
- In the context of data networks, the term Bandwidth is often used "incorrectly", referring to Data Rate

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Signal Strength

- Signals propagating on transmission medium suffer *attenuation* of signal strength
- Decibel (dB) – measure losses (or gains) of signal strength
  - measures difference in power levels

    number of dB = $10\log_{10}(P_1/P_2)$
  - RELATIVE measure not absolute
    - 10dB means 10 times power
    - 3 dB means roughly ½ power, $\log_{10} 3 \approx 0.5$
  - dB is also used in other contexts, e.g. sound
    - Compare power with threshold of hearing ($10^{-12}W/m^2$)
    - 100dB -> $10^{-2}W/m^2$

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Voice Grade Telephone Channel

- Human hearing
  - Frequencies 20Hz to 20kHz
- Human speech
  - Most power concentrated < 4kHz
- Phone-line bandwidth
  - Restricted to 200Hz to 3200Hz approximately
    - Cutoff isn't sharp

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Frequency Band vs Bandwidth

- Frequency Band
  - Contiguous range of frequencies
    - Example: 200 to 3200 Hz
- Bandwidth
  - Difference between band limits
    - Example 3200Hz – 200Hz = 3kHz

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Maximum Data rate of a Channel

- Every transmission medium has frequency limitation
- Fundamental data rate limit (**Nyquist**)
  - Given, bandwidth = W
  - M = levels per signal (e.g. 2 for binary)
  - Maximum data rate = Max. channel capacity, $C = 2W\log_2 M$
    - For binary signals, C = 2W
  - This assumes noiseless channel

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Maximum Data Rate of a Channel (cont'd)

- $C = 2W\log_2 M$
- For a noiseless (perfect) channel with bandwidth 3kHz, what's the maximum data rate, if we use binary signalling?
- How come current modems can send up to 56kb/s over a 3kHz telephone line?

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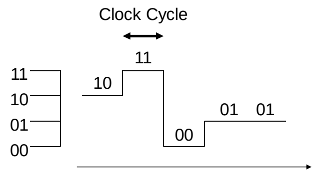
Multilevel Signalling

- More than two voltage levels per clock cycle
- With four levels, we can send 2 bits per clock cycle
- With M levels, we can send $\log_2(M)$ bits per clock cycle
- Nyquist: $C = 2W\log_2 M$
- Can we make M arbitrarily high?
  - Only for perfect (noiseless) channels
  - Noiseless channels do not exist



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Shannon's Theorem

- Included noise
  - SNR = signal to noise (power) ratio = S/N = signal power / noise power
    - Usually specified in decibels (dB)
- Channel capacity

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

- Defines theoretical upper bound
  - Is not necessarily achievable for practical systems, need perfect code
- Example, phone system with W = 3000Hz, SNR = 50dB
  - C = ?

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Example:

- W=3000Hz
- SNR=50dB=10^5
- C = $W\log_2(1 + S/N)$ = 3000Hz $\log_2(1+100000)$ = 49829 bps

Tip: $\log_2 x = \log_{10} x / \log_{10} 2$

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Signal Distortion

- Transmission media introduce distortions
  - Attenuation
    - Signal degradation
    - May vary by frequency
  - Phase (or delay) distortion
    - Different frequency components - different speeds
- Noise
  - Thermal – random motions of electrons
    - unavoidable
  - Crosstalk – coupling with other wires
  - Impulse noise – e.g. power spikes

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Analog and Digital Signals

- Analog
  - Arbitrary continuous function of time
  - Usually bounded
- Digital (square waves)
  - Fixed, discrete values
  - Fixed transition times
    - uniformly spaced

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Conversion

- Can convert analog to digital
  - digitise = sample + quantise + encode
- Can convert digital to analog for transmission
  - E.g. Audio signal on CD is digital, to play it via speakers it needs to be converted into an analog signal
- Important difference
  - Analog signals
    - Can amplify – but can't recover from effect of distortion or noise
  - Digital signals
    - Can regenerate original signal exactly, as long as SNR is high enough
  - High quality, long-distance transmission requires **digital**

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Modulation

- Direct transmission of digital signal is called baseband transmission
- Works for Ethernet via Cat 5-Cable
  - 10Base-T, 100Base-T
- Does not work or is not efficient for some media
  - Wireless
  - Signal needs to have a certain (radio) frequency to be able to propagate
  - Use Modulation to convert a digital signal into an Analog signal -> Broadband transmission

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Modulation

- To convert from digital to analog, a analog waveform (carrier) can be modulated (varied) by a digital signal
- Sine wave has 3 characteristics
  - Amplitude
  - Frequency
  - Phase
- Three types of modulation …

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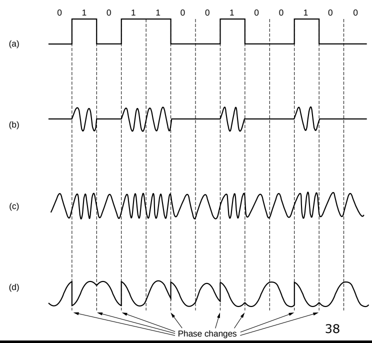
Modulation

- Binary signal
- Amplitude modulation
- Frequency modulation
- Phase modulation



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Modulation Combinations

- Can combine, e.g.
  - two amplitudes
  - two phases

gives four modulation combinations
  - called "symbols"
- Baud rate
  - symbol rate (symbols per second)
  - Clock rate of transmission

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Baud-rate vs Bit-rate

- Baud-rate ≠ bit-rate
- Bit-rate = baud-rate x bits per symbol
- Bits per symbol = $\log_2$(number of symbols)
- Example:
  - Baud rate = 10kBaud
  - 8 different symbols → 3 bits per symbol
  - Bit rate = 10kBaud * 3 bit = 30kbit/s
- Number of symbols = no. of distinct modulation combinations

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Higher Speeds

- For fixed bandwidth medium (e.g. phone line)
  - max. baud rate related to max. sampling rate
    - determined by bandwidth
    - Nyquist: Max Baud rate = 2* Bandwidth
- Can't increase baud rate
- Instead, increase bits per baud

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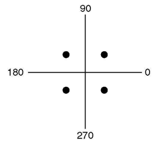
Modulation

- Modems (**Mo**dulator - **Dem**odulator) use a number of modulation techniques
- QPSK = Quadrature Phase Shift Keying
- Constellation pattern
  - Angle represents phase of signal
  - Distance from (0,0) represents amplitude
  - QPSK: only phase is varied
- 4 Symbols -> 2 bits per clock cycle



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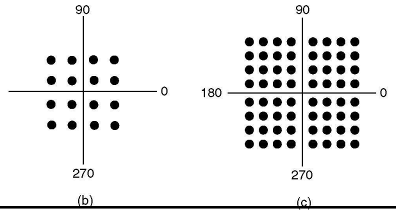
Modulation

- QAM-16
  - Quadrature Amplitude Modulation-16 (16 Symbols → 4 bits per symbol)
  - Amplitude and Phase is varied
- QAM-64
  - 64 symbols → 6 bits per symbol



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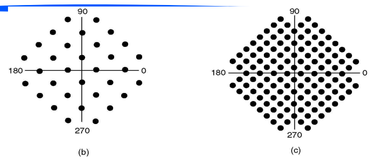
Modem Standards



- (a) V.32 for 9600 bps
  - 2400 baud
  - 32 symbols → 5 bits/symbol (4bits data, 1 bit parity)
  - 2400 baud * 4 bps = 9600 bps
- (b) V32 bis for 14,400 bps
  - 2400 baud, 6 data bits per symbol, 1 parity bit
- Remember: Channel capacity is limited by Shannon's theorem

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Modem standards…

- V.32
  - 32 constellation points (4 data bits +1 parity bit)
  - 9600bps at 2400 baud
- V.32bis
  - 14400bps at 2400 baud
  - 128 point constellation pattern (6 bits +1 parity)
- V.34
  - 28800bps at 2400 baud
  - 12bits/baud
- V.34bis
  - 33600bps at 2400 baud
  - 14bits/baud
- V.90
  - 56000bps max downstream
  - 33600bps max upstream

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Analog to Digital Conversion

- Sampling theorem (Nyquist)
  - "A bandlimited signal can be recovered from a periodic sampled sequence of the signal if the sampling frequency is at least twice the highest frequency in the signal spectrum"
  - I.e. need to sample at twice the highest frequency component
- Sampling faster – waste
- Sampling slower – aliasing possible

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A-D Conversion

- Sampling
  - Measure signal Amplitude at regular time intervals
  - Pulse Amplitude Modulation (PAM)
- Quantization
  - Convert measure amplitude into discrete levels, for example 64
- Encoding
  - Pulse Code Modulation (PCM)
  - Encode the 64 levels as a 6-bit signal using binary signalling
- Telephone system uses PCM
  - 8000 samples per second
    - According to Nyquist, this allows to represent signals up to 4kHz
  - 7- or 8-bit quantization

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Transmission Media

- Magnetic Media
- Twisted Pair
- Coaxial Cable
- Fibre Optic
- Wireless

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Transmission Media 1

- Magnetic/Optical Media
  - High bit-rates possible
    - e.g. carrying 1000 CD-ROMs for an hour = 1.5 Gbps (1000 x 650 x 1024 x 1024 x 8 / 3600)
  - Delay characteristics are poor
    - e.g. no data received for an hour
- Never underestimate the bandwidth (bit-rate) of a station wagon full of tapes hurtling down the highway

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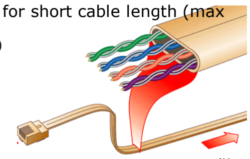
Transmission Media 2

- Twisted pair wire
  - Two insulated copper wires twisted around each other in a helical form (like DNA)
  - Can run several km without amplification (depending on bit rate)
  - Copper wires act like antenna, radiate and receive signals
    - Twisting reduces electrical interference
  - Can be used for analog (e.g. telephone) or digital transmission (LAN)
  - Bit rates to 1000 Mbps possible for short cable length (max 100m)
    - e.g. UTP (Unshielded twisted pair)
  - Most common applications
    - telephone wire
    - UTP LAN cabling



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Telephone Wire Can Do Many Things….

- POTS (Plain Old Telephone Service)
  - Analog transmission
  - Voice grade lines – bit rates to 56kbps
    - Requires modem
- ISDN (Integrated Services Digital Network)
  - Digital transmission
  - Bit rates to 144kbps (2x 64kbps data channels + 16kbps control channel)
    - Requires ISDN terminal adaptor

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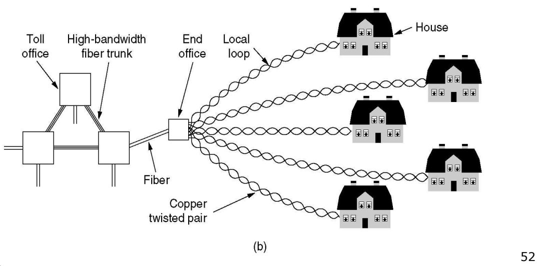
Fixed Telephone System

- Dedicated copper wire pair from end office to each House



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ADSL

- ADSL (Asymmetric Digital Subscriber Line)
  - Provides high-speed Internet access
  - Downstream rate (to home/office) up to 8Mbps
  - Upstream rate (to exchange) up to 1Mbps
  - Other DSL variants are available xDSL (HDSL High bit-rate, VDSL Very high bit-rate, …)
  - ADSL uses same telephone copper wire as dial-up modems with same SNR. What about Shannon's limit?
    - $C = W\log_2(1 + S/N)$

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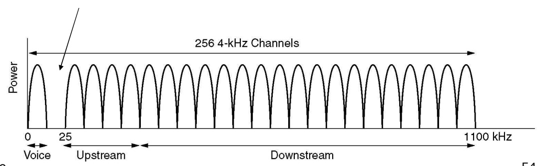
ADSL

- Not limited to 3kHz bandwidth like dial-up modems
  - Telco needs to install special equipment at the telephone exchange to suppot ADSL
- Use 1.1 MHz BW (256 4kHz channels)
  - Can be allocated for upstream or downstream -> Asymmetric
  - Does not interfere with voice traffic (separate channel)
  - "Guard band": gap between channels, reduces interference



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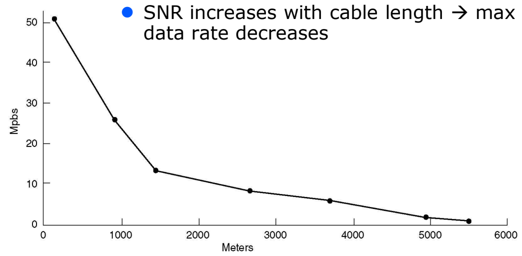
Digital Subscriber Lines

- Bandwidth vs. distance over category 3 UTP for DSL (upper limit)
- SNR increases with cable length → max data rate decreases



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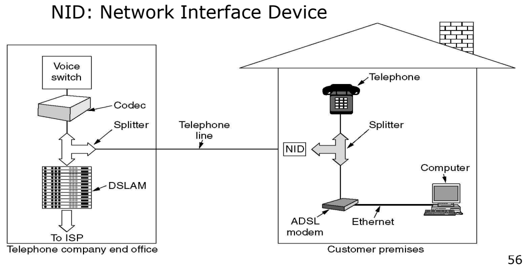
Digital Subscriber Lines

A typical ADSL equipment configuration

DSLAM: Digital Subscriber Line Access Multiplexer (ADSL Modem at Exchange)

NID: Network Interface Device



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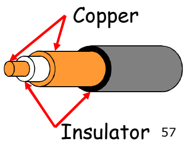
Transmission Media 3

- Coaxial Cable (coax)
- Two types
  - 50 ohm (digital transmission)
  - 75 ohm (cable TV, analog transmission)
- Better shielding than twisted pair
  - Higher speeds
  - Longer distances
- Used for cable TV, and cable Internet Access
- Used to be main transmission media for telephone trunk lines, now replaced with optical fibre



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Internet over cable modem

- Uses same cables as used for cable TV (75 ohm)
- up to 40 Mbps downstream
- up to 20 Mbps upstream
- Higher bandwidth than ADSL, but is a **shared medium** (i.e. 40 Mbps shared by neighbours (500-2000))

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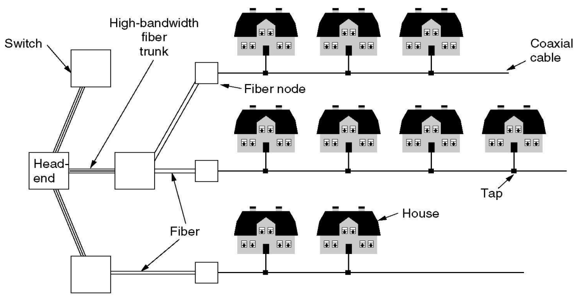
Internet over Cable, Hybrid Fibre Coax (HFC)



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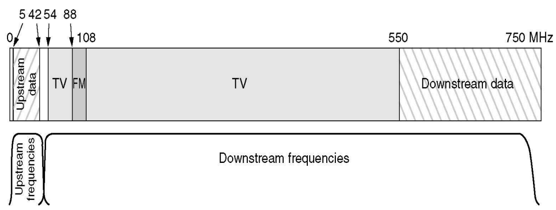
Cable modem - spectrum allocation (FDM)

- Frequency allocation in a typical cable TV system used for Internet access



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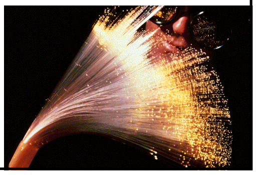
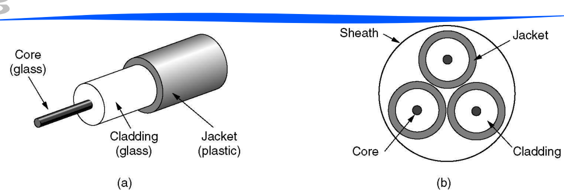
Transmission Media 4

- Fibre Optic Cable
  - Data carried as laser-generated light pulses (not electrical signals, but still electromagnetic waves)
  - Much lower attenuation than copper wires
    - Higher data rates, Tbps is possible
    - Greater cable length
  - Resistant to EMI, noise
  - More secure than copper wire (harder to tap)



Fiber Cables



(a) Side view of a single fiber.
(b) End view of a sheath with three fibers.

Core is between 8 Microns and 63 Microns
- 1 Micron = 1/1'000 of a Millimeter
- Thickness of a human hair: 100 microns

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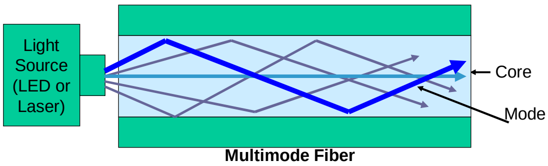
Optical Fiber



- Light entering at a an angle > than a certain value is trapped inside the fiber and is completely reflected at the fibre boundary
- Light rays entering at different (discrete) angles are called *modes*
- Fibre that allows multiple modes to propagate are called Multimode Fibres

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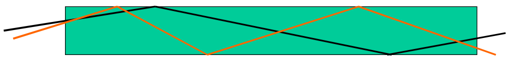
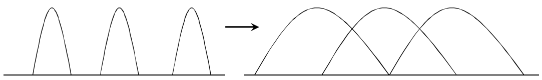
Modal Dispersion

- Modal Dispersion
  - Different modes in the same light pulse travel different distances
  - Over a long enough distance, the modes from sequential clock cycles tend to overlap, causing problems



Effect of Modal Dispersion on light pulses:



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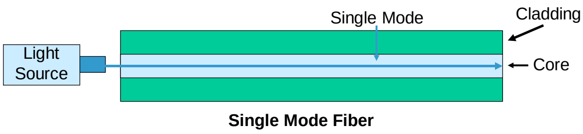
Single-Mode Fiber



- Core is so thin that only one mode can propagate. No modal dispersion, so can span long distances without distortion
- Only limiting factor for single mode fibres is attenuation

Panko-3.17 65

Optical Fibres

- **Attenuation**
  - Decreases with wavelength
  - (increases with frequency c=f*λ → f=c/ λ)
    - 850 nm: ~ 0.35 dB/km
      - Can use inexpensive LEDs as light source
    - 1300 nm: ~ 0.15 dB/km
      - Requires more expensive Laser as light source
    - 1550 nm: ~ 0.05 dB/km
      - Requires more expensive Laser as light source
  - Current optical fibers can be more than 100km long (without repeaters) and transport more than 50 Gbps

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Multimode vs Single-Mode Fibres

- Multimode Fiber
  - Cheap
  - Limiting factor is Modal Dispersion
  - Mostly used for LANs
- Single Mode Fiber
  - More expensive
  - No Modal Dispersion
  - Only limiting factor is attenuation (which is very low)
  - Higher data rate, longer cables
  - Used as trunk lines

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Copper vs Fiber

- Advantages of Fiber
  - Higher bandwidths
  - Low attenuation (fewer repeaters)
  - Not affected by
    - power surges, interference
    - corrosive chemicals
  - Thin & lightweight (installation cost)
- Disadvantages
  - Unidirectional
    - Need two fibres for full duplex transmission
  - Cost

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Last Lecture - Recap

- Physical Layer
  - Bandwidth <-> data rate
    - Fourier, Shannon, Nyquist
  - Digital/Analog
  - Signalling
    - Modulation
    - Baud-rate, Bit-rate
  - Transmission Media
  - This lecture:
    - Multiplexing
    - Switching (circuit-switching, packet switching)
    - Mobile Phone Networks

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Transmission Media 6

- Wireless transmission
  - Microwave/Radio signals
    - Often line of sight
      - signal travels in straight line (for high frequency) from source to destination (about 50km max. due to earth's curvature)
      - repeater stations needed (e.g. at Mt Cootha for Ipswich-St. Lucia link)
  - Signal strength decreases with $1/r^2$ (inverse square law) → limiting factor
    - In guided media (copper, fibre) signal strength decreases linearly with 1/r
  - IEEE 802.11 (WaveLAN)
  - Infrared signals
    - Within a room or just between two devices

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Spectrum Allocation

- In Australia, frequency bands are allocated by the Australian Communications and Media Authority (ACMA).
  - http://www.acma.gov.au
- In the US, it is the Federal Communications Commission (FCC)
- E.g. Telstra needs a license for its frequency band used for mobile telephony
  - License for spectrum is typically sold by auction
    - E.g. Auction of 3G spectrum in Germany raised US$ 48 Billion!
- There are unlicensed bands, called ISM bands (Industrial, Scientific and Medical)
  - Can be used by for free (some limitations, power etc.)
  - Wireless LANs operate in such ISM bands (2.4 GHz, 5 GHz)

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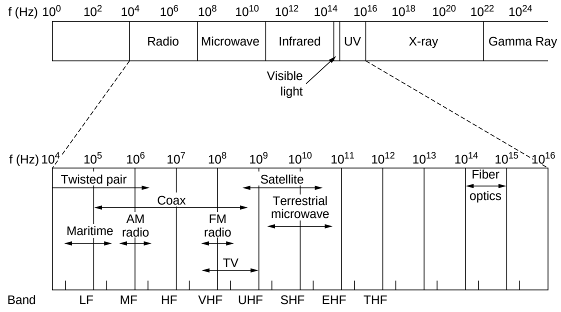
Electromagnetic Spectrum



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Multiplexing

- Sharing a physical channel
  - e.g. many conversations over telephone trunk-line, wireless channel etc.
- TDM = Time Division Multiplexing
- FDM = Frequency Division Multiplexing
- WDM = Wavelength Division Multiplexing
  - Different name for FDM in the context of optical transmission (c=λ*f)
- CDMA = Code Division Multiple Access

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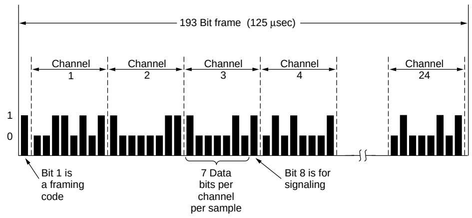
Time Division Multiplexing

- Users allocated entire bandwidth
- Channels are allocated via time slots
- Used in telephony
  - POTS (8000 1/s*8bit= 64kbit/s)
  - T1 carrier: 24x8x8000 + 8000*1 = 1.544Mbit/s
  - GSM (uses TDM and FDM)



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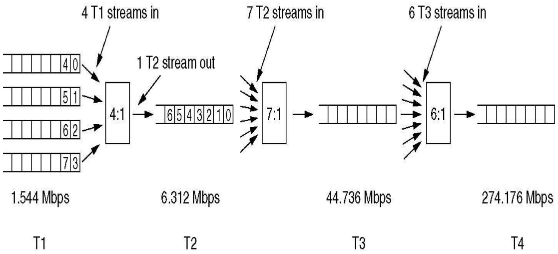
Time Division Multiplexing

- Multiplexing T1 streams into higher carriers (faster clock rate)



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Frequency Division Multiplexing

- Each channel gets separate frequency band
  - non-overlapping
  - one band per channel
  - E.g radio, TV, Trunk lines in Telephony (replaced by TDM today)
- Signals are
  - frequency shifted, then
  - combined

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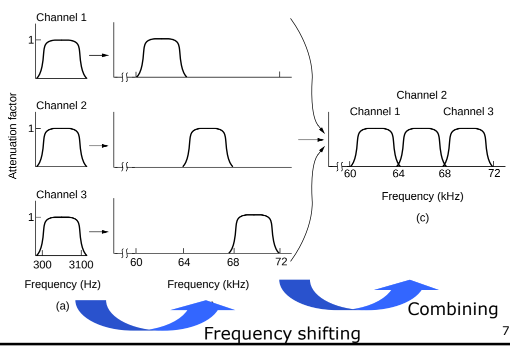
Frequency Division Multiplexing (cont.)



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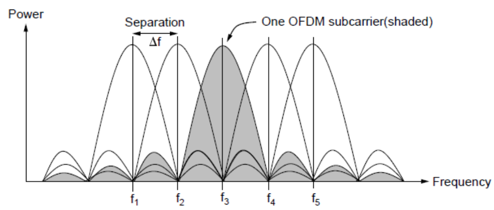
Orthogonal Frequency Division Multiplexing (OFDM)



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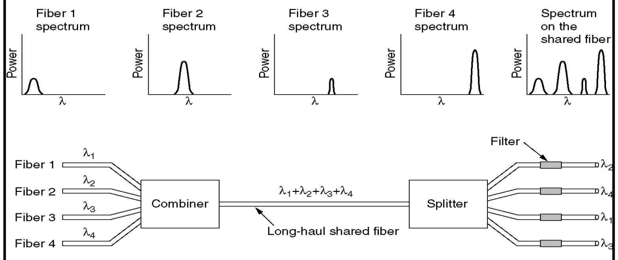
Wavelength Division Multiplexing

- WDM – variant of FDM for fiber optic channels



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Code Division Multiplexing (CDMA)

- Used in 3G mobile phone networks, WLAN, Bluetooth…
- Instead of different timeslots or frequency bands, "Codes" are used to separate the signals
- Two types of CDMA (both defined in 802.11)
  - Frequency Hopping
  - Direct Sequence Spread Spectrum

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CDMA

- Frequency hopping
  - Spectrum is divided into FDM channels
  - Sender uses a FDM channel only for a short time ("dwell time"≈400µs) and then jumps to other channels
  - Hopping is done according to pseudo random sequence → code
  - Sender and receiver must use same code and must be synchronised
  - If there are propagation problems at specific frequencies, impact is minimal due to short dwell time

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CDMA

- Direct Sequence Spread Spectrum (DSSS)
  - At the sender, the signal is multiplied (modulated) with special signal -> chip sequence or Code, which is specific to the sender
  - The receiver applies the same code to extract the wanted signal from the superimposition of all signals
  - Each sender uses the entire channel (time and frequency)
  - Very resistant to interference

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Switching

Circuit switching
Packet switching

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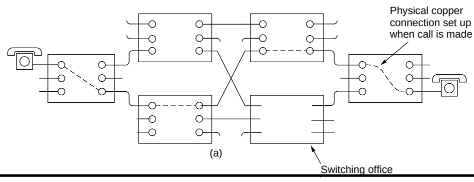
Switching

- Telephone system uses *circuit-switching*
  - Connection established between source and destination *before* "data" transferred
  - Connection set-up implies reservation of resources
  - In the early days of telephony, a physical circuit was established end-to-end
  - Today we have virtual circuits



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Message Switching

- No physical connection (circuit)
- Blocks of data *stored and forwarded by network nodes*
  - Blocks passed in entirety
  - Possible unlimited size

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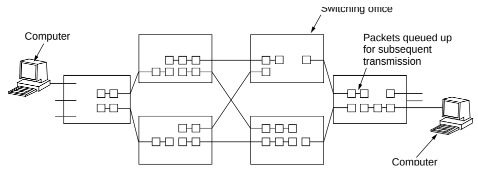
Packet Switching

- Used in Internet
- Like message switching but *upper limit* on block size
- More effective use of channels, statistical multiplexing
- Prevents channel monopolisation
- Suitable for interactive traffic
- Can reduce delay, no setup required



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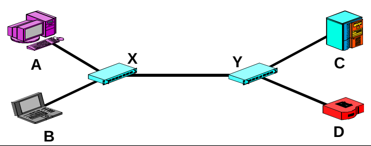
Statistical Multiplexing

- Assume traffic between A-C and B-D
  - Traffic is "bursty", periods of silence and periods of traffic at maximum bit rate (We assume the maximum bit rate is 64kbit/s and the average bit rate is 16kbit/s)
  - In circuit switching, we need to reserve 128kbit/s between X and Y.
  - In packet switching, we can use the fact that the traffic between X and Y is only 32kbit/s on average.
  - The problem is when there is a burst of traffic between A-C and B-D at the same time
    - Buffering
    - Allocate more resources than required on average



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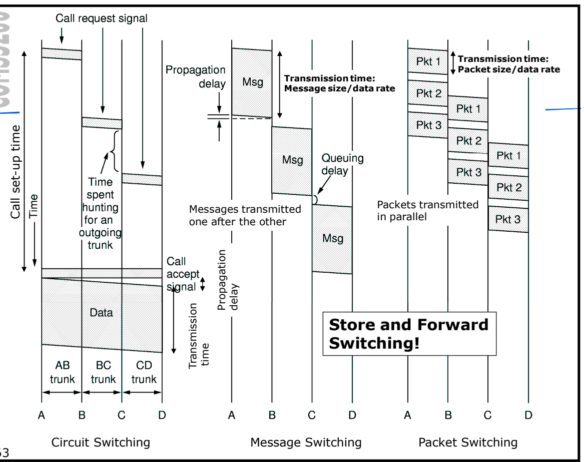

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End-to-End Delay

- E2e delay in Circuit Switching:
  - T=Call setup time + propagation delay + transmission time
- E2e delay in Message Switching (*k* hops):
  - T= k*(propagation delay per hop + transmission delay per hop)
- E2e delay in packet Switching
  - T=? (Tutorial)

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Key Differences: Circuit vs Packet Switching

- Setup time
- Bandwidth
  - Circuit switching reserves and possibly wastes bandwidth
  - Packet Switching makes more efficient use of resources through statistical multiplexing
- Transparency
  - Circuit switching supports transfer of *anything*
  - Packet switching must adhere to certain framing, packet structure etc.
- Charging
  - Circuit switching – by time
  - Packet switching – by packets (& time)

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Mobile phone networks

- Second generation (2G)
  - Four different standards: one of them - GSM used in Europe and Australia
  - GSM (Global System for Mobile Communication)
    - Has 124 simplex channels (FDM)
    - Channel uses 200 kHz band
    - Channel supports 8 connections (TDM)
  - Some second generation mobile phones use CDMA

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Mobile phone networks

- Third generation mobile phones (3G)
  - 2 Mbps for stationary users
  - 384 kbps for walking users
  - 144 kbps for car connections
- Versions of W-CDMA are used in Australia (W-CDMA 2100/900/850)
- 2.5G networks:
  - GPRS (IP packet network over GSM)
  - EDGE (Enhanced Data Rates for GSM)

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Recap

- Fourier
  - Signals can be represented as sum of sine and cosine waves (harmonics)
  - The higher the bandwidth of a channel (more harmonics), the better we can reconstruct the signal at the receiver
  - Higher bandwidth -> higher data rate

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Recap

- Nyquist
  - Maximum data rate of a noiseless (ideal) channel with M-ary signalling (M different symbols)

$C = 2\,W\log_2 M$

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Recap

- Shannon:
  - Theoretical upper-limit for channel capacity (bps) for any kind of signaling, given the channel bandwidth W and Signal-to-Noise Ratio (SNR)

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

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Exam Question Again

- From previous exams:

  If a two level amplitude modulation is assumed, the maximum throughput which can be achieved on a telephone line is 6 kbps (assuming 3 kHz is the highest allowed frequency). Current modems achieve much higher throughputs. Explain how it is achieved. Do you know any theorem to support your explanation?
- What if we drop the assumption of binary signaling from the question?

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Summary

- Transmitted bits have to be converted into signals for transmission
- Signals can be digital or analog
- Mapping of bits to bauds can be 1:1, 1:N, or N:1
- There are limitations for channel data rate
- Channel can be shared (TDM, FDM, WDM)
- Most networks are packet switched

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Readings

- Tanenbaum: Chapter 2, Sections: 2.1, 2.2, 2.3.1, (2.4), 2.5.2, 2.5.3, 2.5.4, 2.5.5, 2.6.3, 2.6.4, 2.6.5, 2.7.2, 2.7.3, 2.8.1, 2.8.2, 2.8.3, 2.8.4, 2.8.5
- Next week
  - Data Link Layer
  - Tanenbaum Ch. 3 (4^{th} or 5^{th} edition)

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