Chapter 2: The Physical Layer

Computer Networks

Maccabe

Computer Science Department
The University of New Mexico

August 2002

Topics

- Theoretical Foundations
- Guided Transmission
- Wireless Transmission
- Communication Satellites
- Public Switched Telephone Network
- Mobile Telephone System
- Cable Television

Theoretical Foundations

- Fourier Analysis
- Bandwidth-Limited Signals
- The Maximum Data Rate of a Channel

Fourier Analysis

- Any well behaved periodic function, $g(t)$, with period T can be expressed as:

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

- Fundamental frequency

$$f = \frac{1}{T}$$

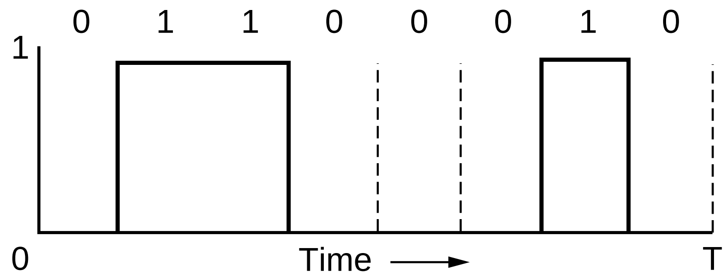
- each (collective) term is called a *harmonic*

Fourier Analysis (2)

Solving for a_n, b_n, and c

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

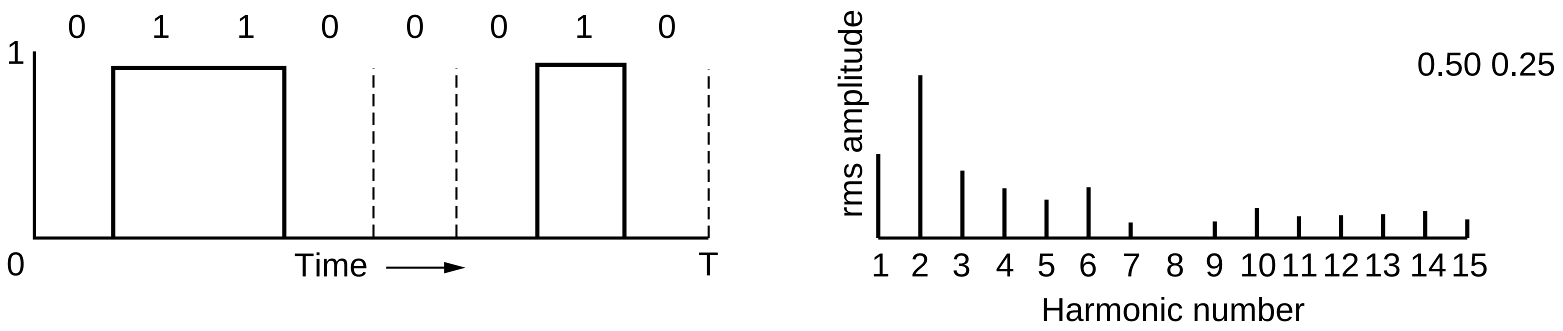
Example: Sending “b”



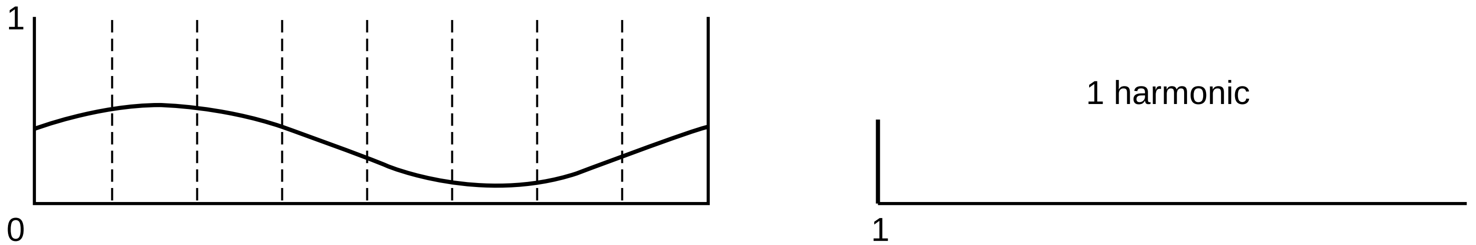
pretend that the pattern repeats:

$$
\begin{aligned}
a_n &= \frac{1}{\pi n}[\cos(\pi n/4) - \cos(3\pi n/4) + \cos(6\pi n/4) - \cos(7\pi n/4)] \\
b_n &= \frac{1}{\pi n}[\sin(3\pi n/4) - \sin(\pi n/4) + \sin(7\pi n/4) - \sin(6\pi n/4)] \\
c &= 3/4
\end{aligned}
$$

Sending “b” – One Harmonic

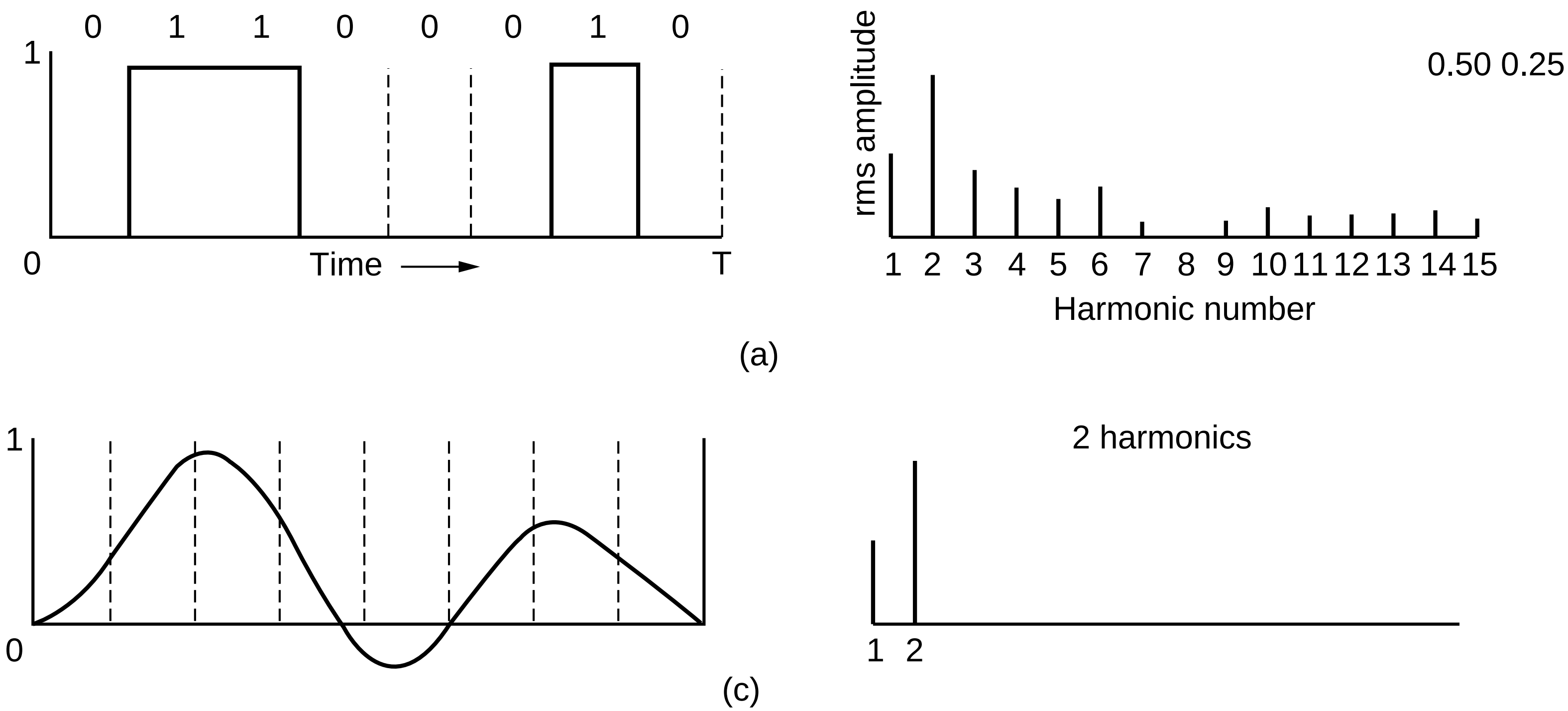


(a)

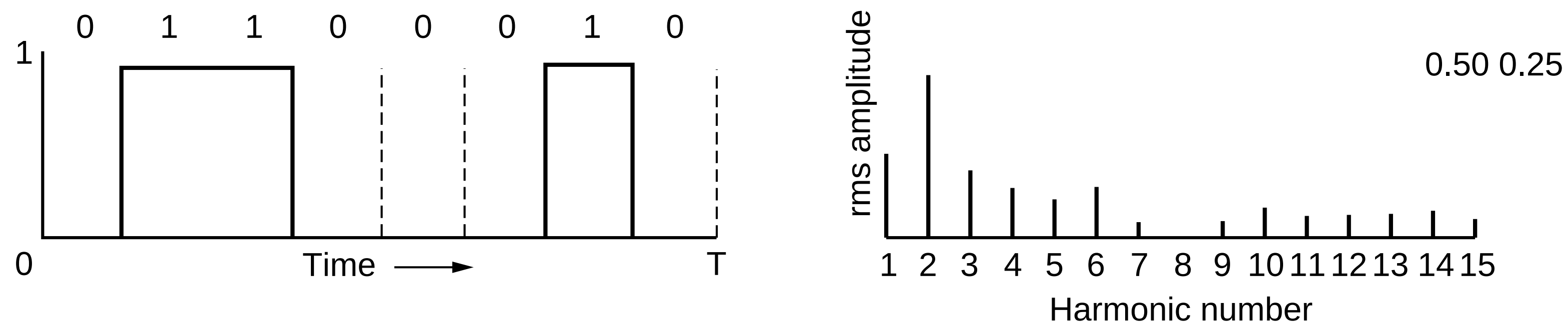


(b)

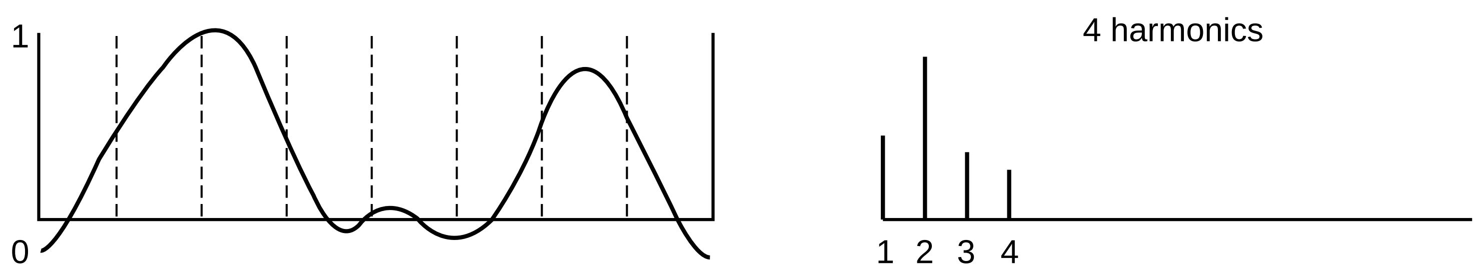
Sending “b” – Two Harmonics



Sending “b” – Four Harmonics

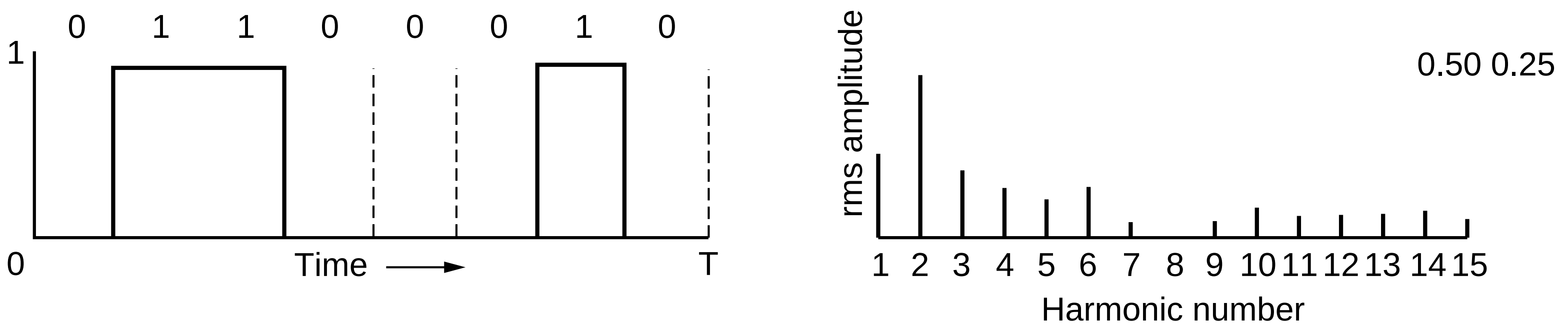


(a)

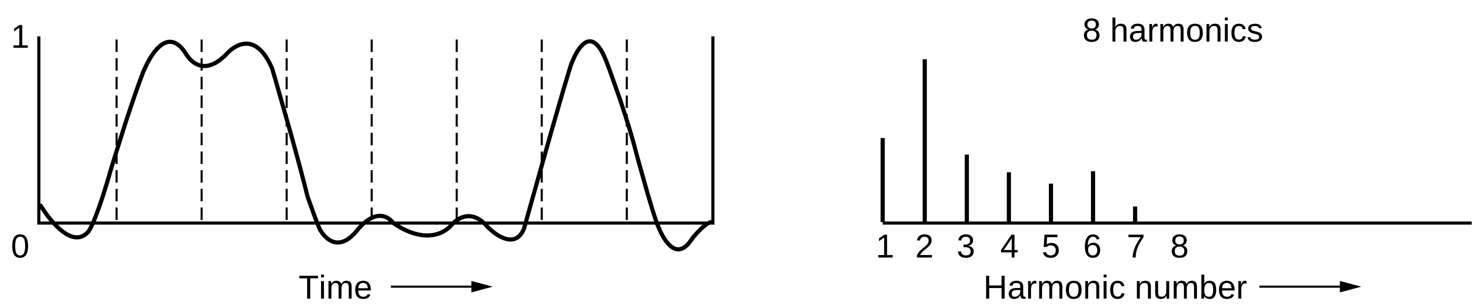


(d)

Sending “b” – Eight Harmonics



(a)



(e)

Bandwidth-Limited Signals

- Bandwidth – range of frequencies transmitted without significant power loss
- Distortion – different Fourier components may be diminished at different rates
- Frequency of the highest harmonic
  - Desired bit rate of b bits/sec (e.g., 2400 bps)
  - $T = 8/b$ sec (e.g., 3.33 milliseconds)
  - highest harmonic = 1/T or 1/(8/b) Hz (e.g., 1/(8/2400) = 300Hz)
- Voice-grade line – filter at about 3100Hz limits bps to 24,800

Data Rates and Harmonics

Bps	T(msec)	First Harmonic (Hz)	# Harmonics Sent
300	26.67	37	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

Maximum Data Rate of a Channel

- Nyquist, 1924: noiseless channel
  - low-pass filter of bandwidth H
  - signal can be reconstructed using $2H$ samples per second
  - Nyquist's theorem: maximum data rate $= 2H \log_2 V$ bps (V is the number of discrete levels)
- Shannon, 1948: random (thermodynamic) noise
  - signal-to-noise ratio S/N
  - decibel: $10 \log_{10} S/N$
  - Shannon's theorem: maximum data rate $= H \log_2(1 + S/N)$bps
  - 3000-Hz, 30 dB implies 30,000 bps

Topics

- Theoretical Foundations
- Guided Transmission
- Wireless Transmission
- Communication Satellites
- Public Switched Telephone Network
- Mobile Telephone System
- Cable Television

Magnetic Media

- Sneaker Net
- Great bandwidth, poor latency

UTP (Unshielded Twisted Pair)

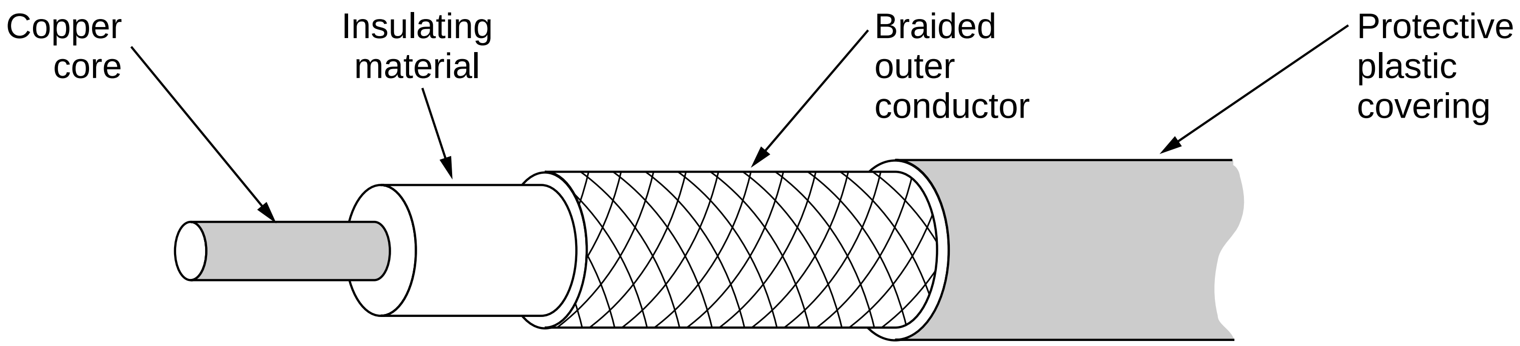
- waves from different twists cancel
- more twists per centimeter
  - less crosstalk
  - better quality over longer distance
- Categories

Category	Bandwidth
3	16 MHz
5	100 MHz
6	250 MHz
7	600 MHz

(a) Category 3, (b) Category 5

Coax (Coaxial Cable)

1 GHz Bandwidth for modern cables



Fiber Optics

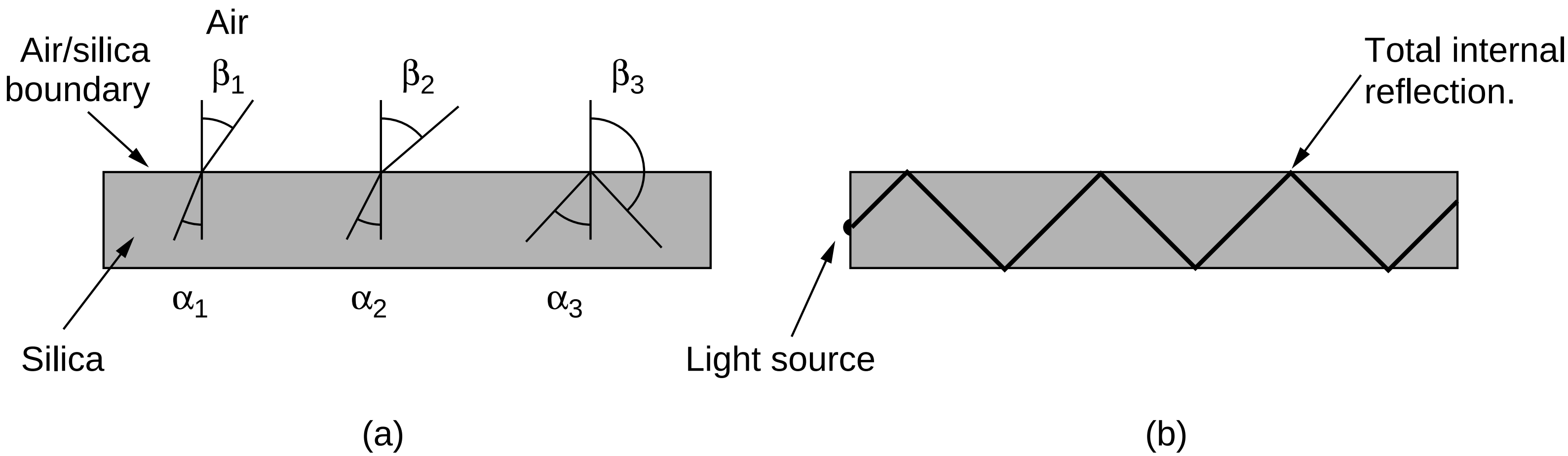
- Rant about growth rates
- Basics
- Transmission of light
- Fiber Cables
- Fiber Optic Networks
- Fiber and Copper

Growth Rates, an aside
Or, you think you have it good

- Computing
  - 1981: 4.77 MHz (original IBM PC)
  - 2001: 2 GHz
  - 20x / decade!
- Communication
  - 1981: 56 kbps (ARPANET)
  - 2001: 1 Gbps
  - 125x / decade!!!
- Lies, damn lies, and statistics . . .
  - Communication has just become commodity
  - Parallel computing is the answer to the limit

Basics

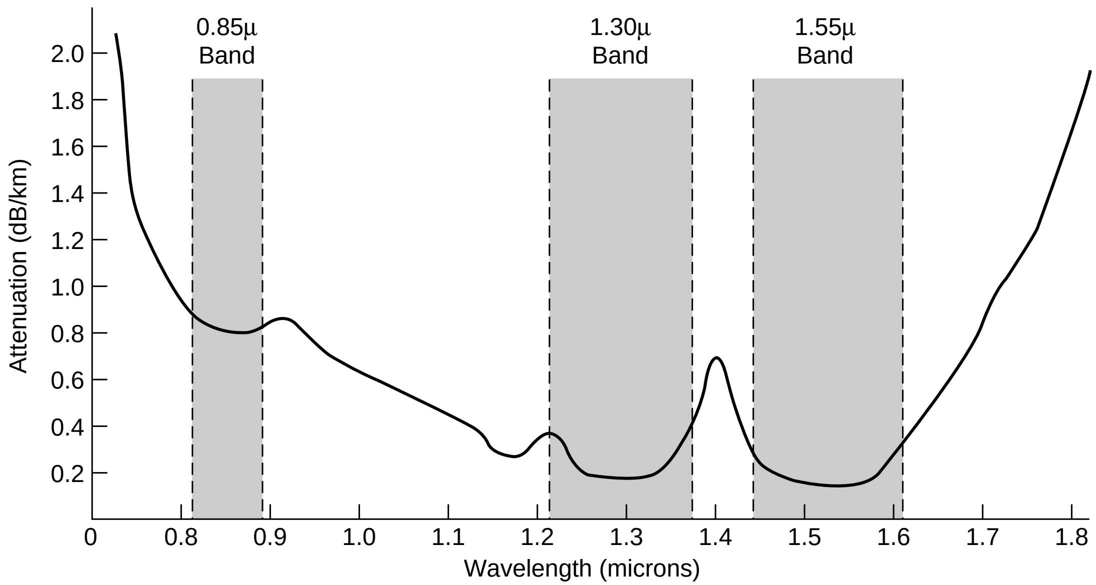
- light source, transmission medium, detector
- refraction and reflection



- single-mode (wave guide): one wavelength of light
- multi-mode: multiple wavelengths

Transmission of Light

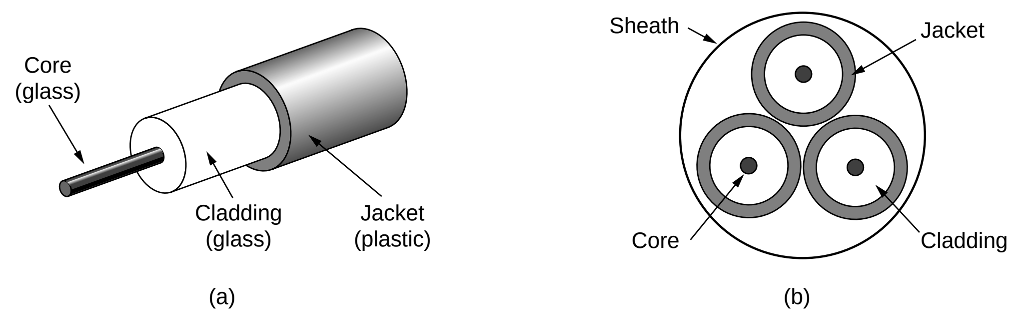
$$\text{Attenuation in decibels} = 10 \log_{10} \frac{\text{transmitted power}}{\text{received power}}$$



chromatic dispersion

- lower the signalling rate
- shaped pulses (solitons)

Fiber Cables



Structure

- core: 8–10 microns
- cladding: keep light in the core
- jacket: protects cladding

Connecting cables

- Fiber sockets (10-20% loss)
- Mechanical splices (10% loss)
- Fused splices (minimal loss)

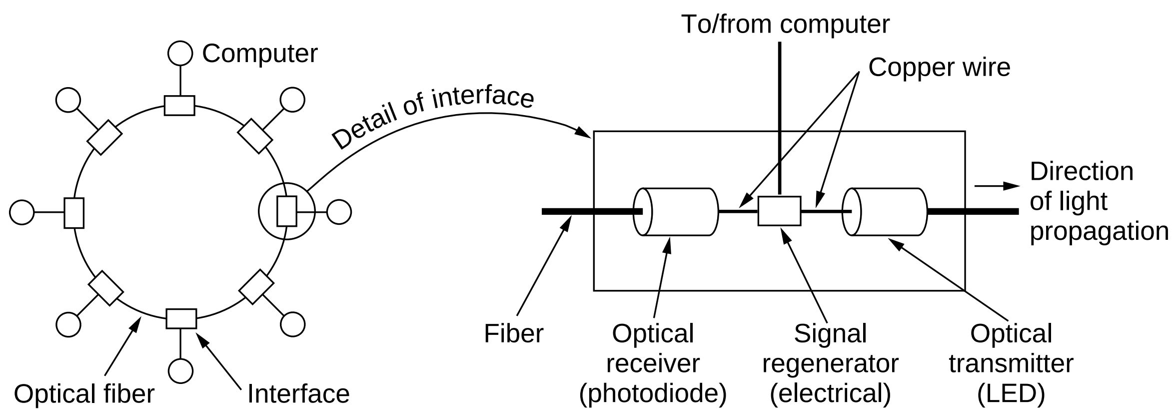
Fiber Cables – LEDs and Semiconductor Lasers

Item	LED	Laser
Data rate	Low	High
Fiber type	Multimode	Multimode or single mode
Distance	Short	Long
Lifetime	Long	Short
Temp sensitivity	Minor	Substantial
Cost	Low	High

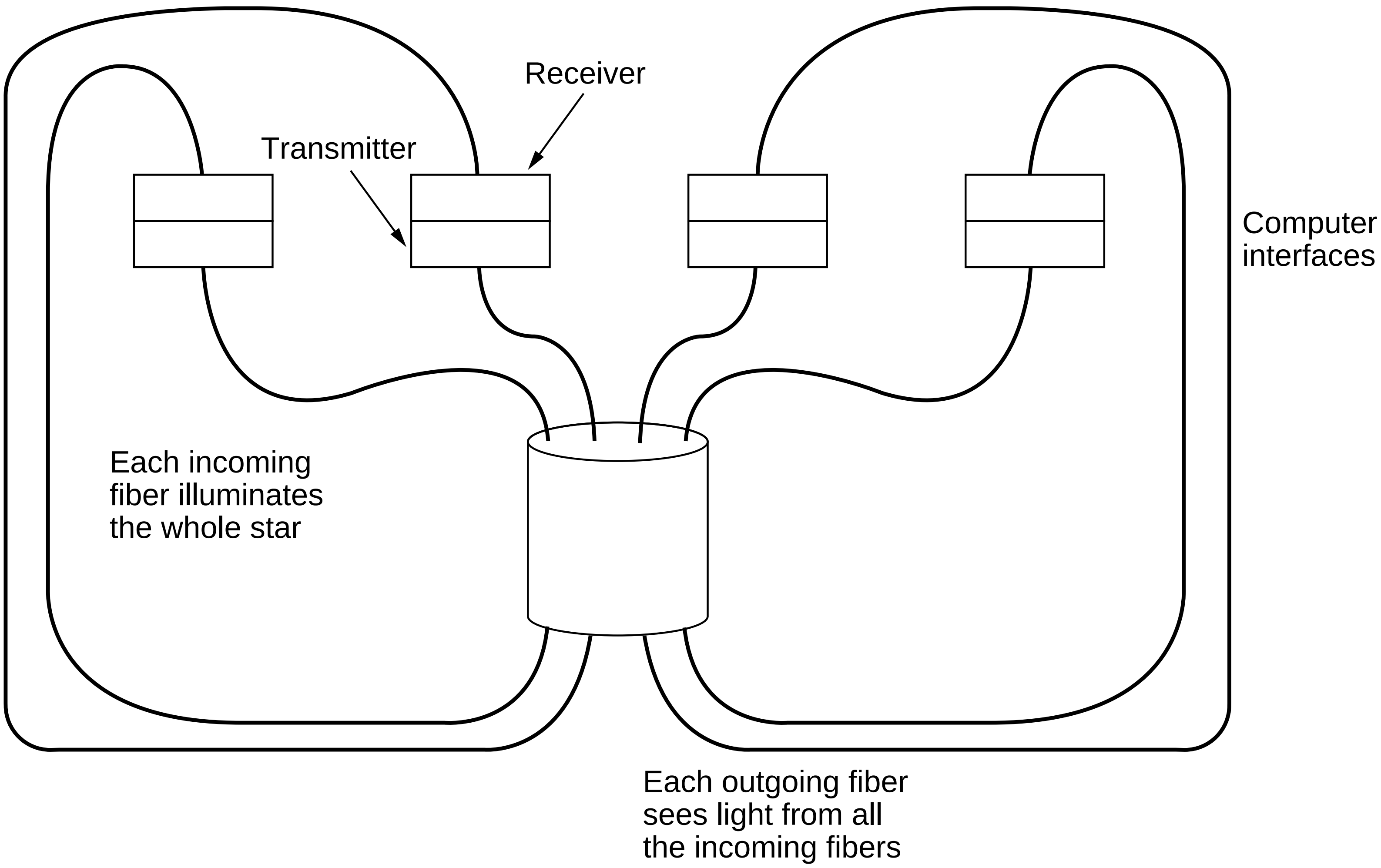
Fiber Optic Networks

Fiber taps are not so easy

passive and active taps



Fiber Optic Networks–Star Network



Fiber and Copper

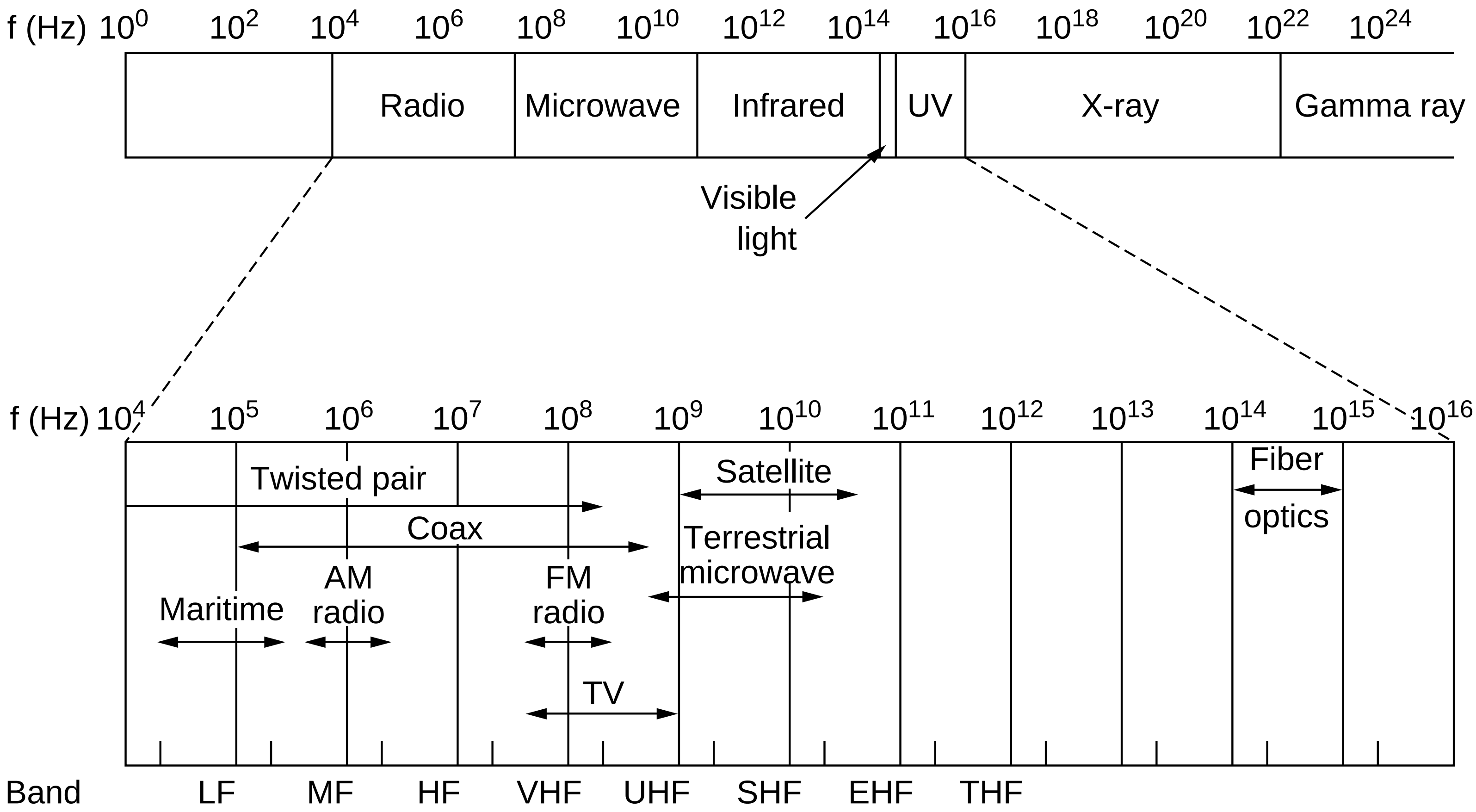
- Advantages of fiber
  - higher bandwidth
  - fewer repeaters
  - lighter
  - thiner
  - more secure (doesn’t leak and is harder to tap)
- Disadvantages
  - new technology
  - one-way communication
  - interfaces are more expensive

Topics

- Theoretical Foundations
- Guided Transmission
- Wireless Transmission
- Communication Satellites
- Public Switched Telephone Network
- Mobile Telephone System
- Cable Television

Electromagnetic Spectrum

$$\lambda f = c$$



Wide band

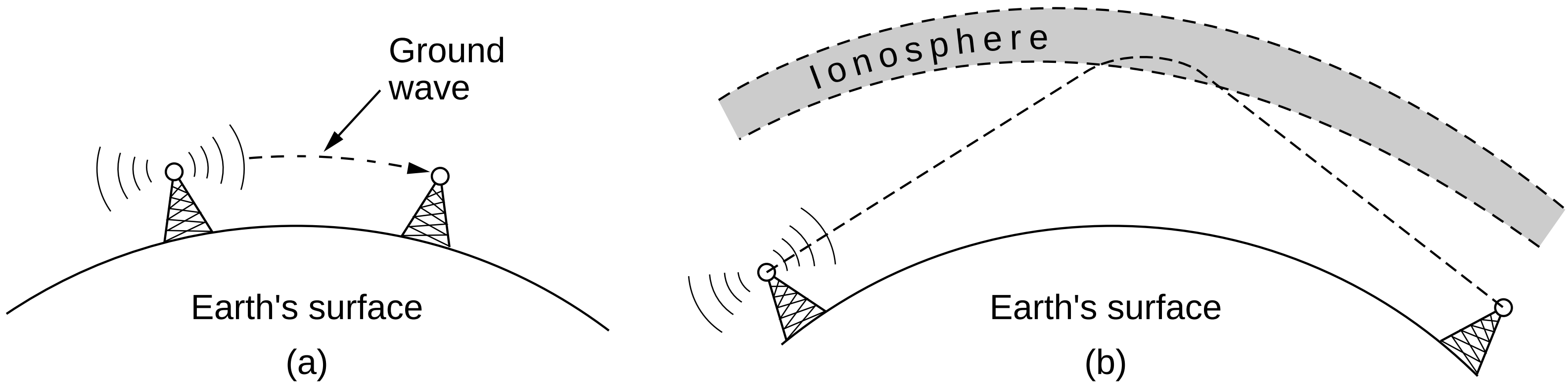
Most transmission use a narrow frequency band to optimize reception

- Frequency hopping spread spectrum
  - change frequencies hundreds of times per second
  - security
  - avoids multipath fading
- Direct sequence spread spectrum
  - spread the signal over a wide frequency band
  - used in cell phones

Radio Waves

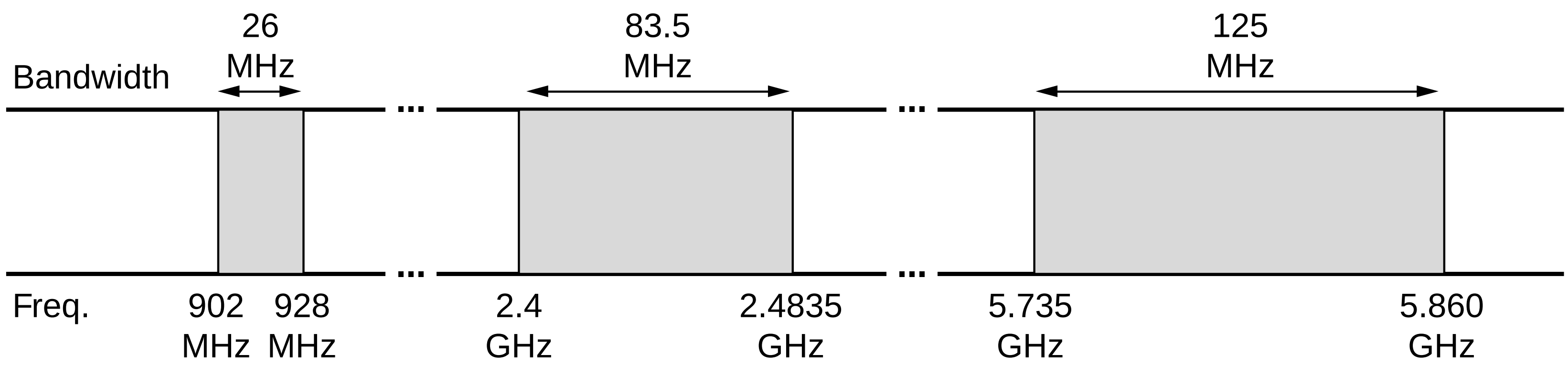
- Low frequency
  - low bandwidth
  - penetrate buildings
  - follow curvature of earth
  - omnidirectional
- Higher frequencies
  - bad for life forms
  - straight line
  - bounce off of obstacles
  - absorbed by rain

Radio Transmission



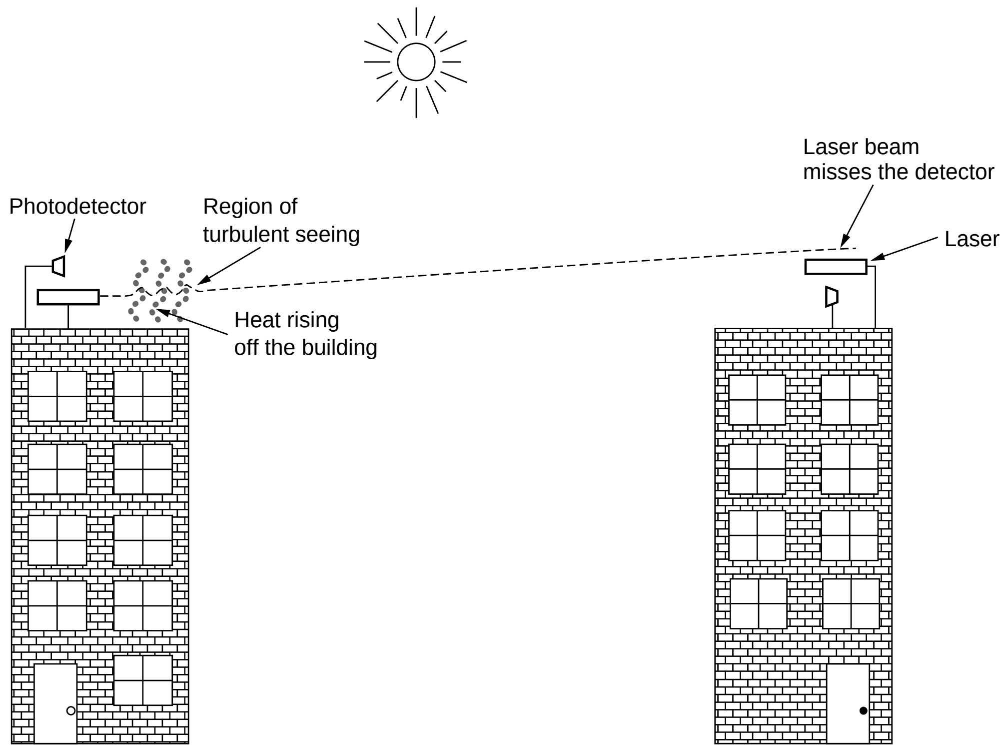
Politics

- beauty contest
- ISM: Industrial, Scientific, Medical



Others

- Infared – doesn't penetrate walls
- Lightwave
  - old light signals
  - lasers



Topics

- Theoretical Foundations
- Guided Transmission
- Wireless Transmission
- Communication Satellites
- Public Switched Telephone Network
- Mobile Telephone System
- Cable Television

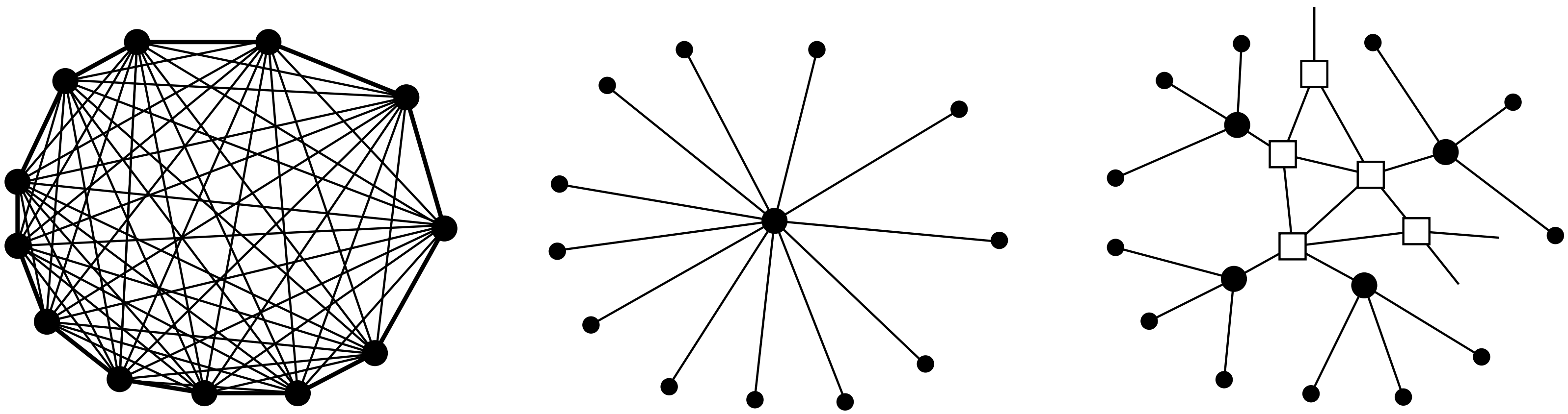
Topics

- Theoretical Foundations
- Guided Transmission
- Wireless Transmission
- Communication Satellites
- Public Switched Telephone Network
- Mobile Telephone System
- Cable Television

Public Switched Telephone Network

- Structure
- Politics (skip)
- The Local Loop
- Trunks and Multiplexing
- Switching

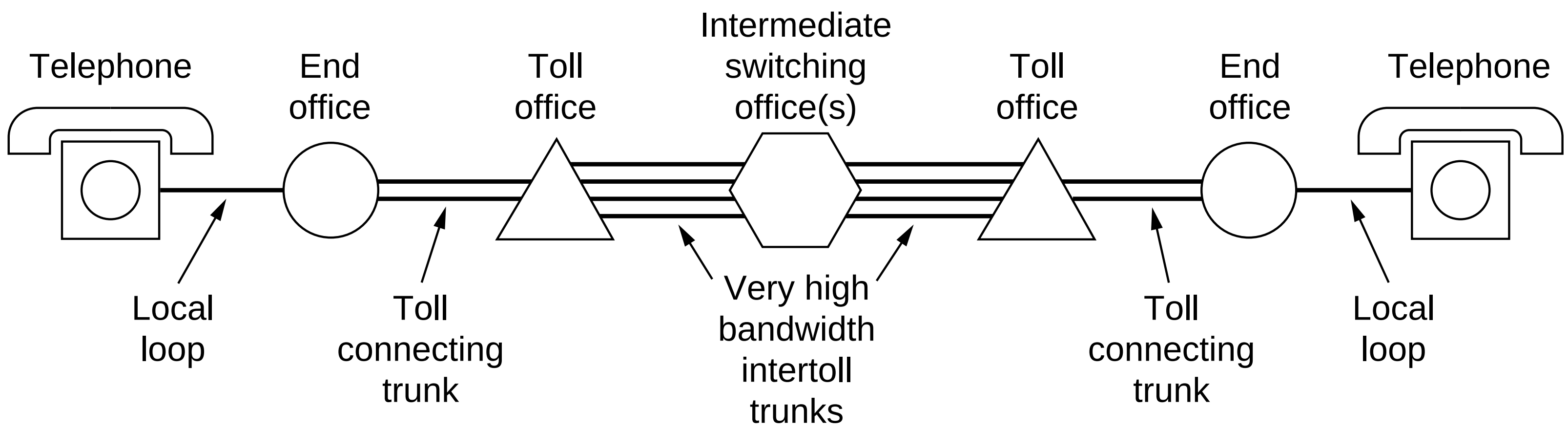
Network Structure



(a) (b) (c)

- minimize number of wires
- add multiple levels

Typical Circuit



- local loops
- trunks
- switching offices

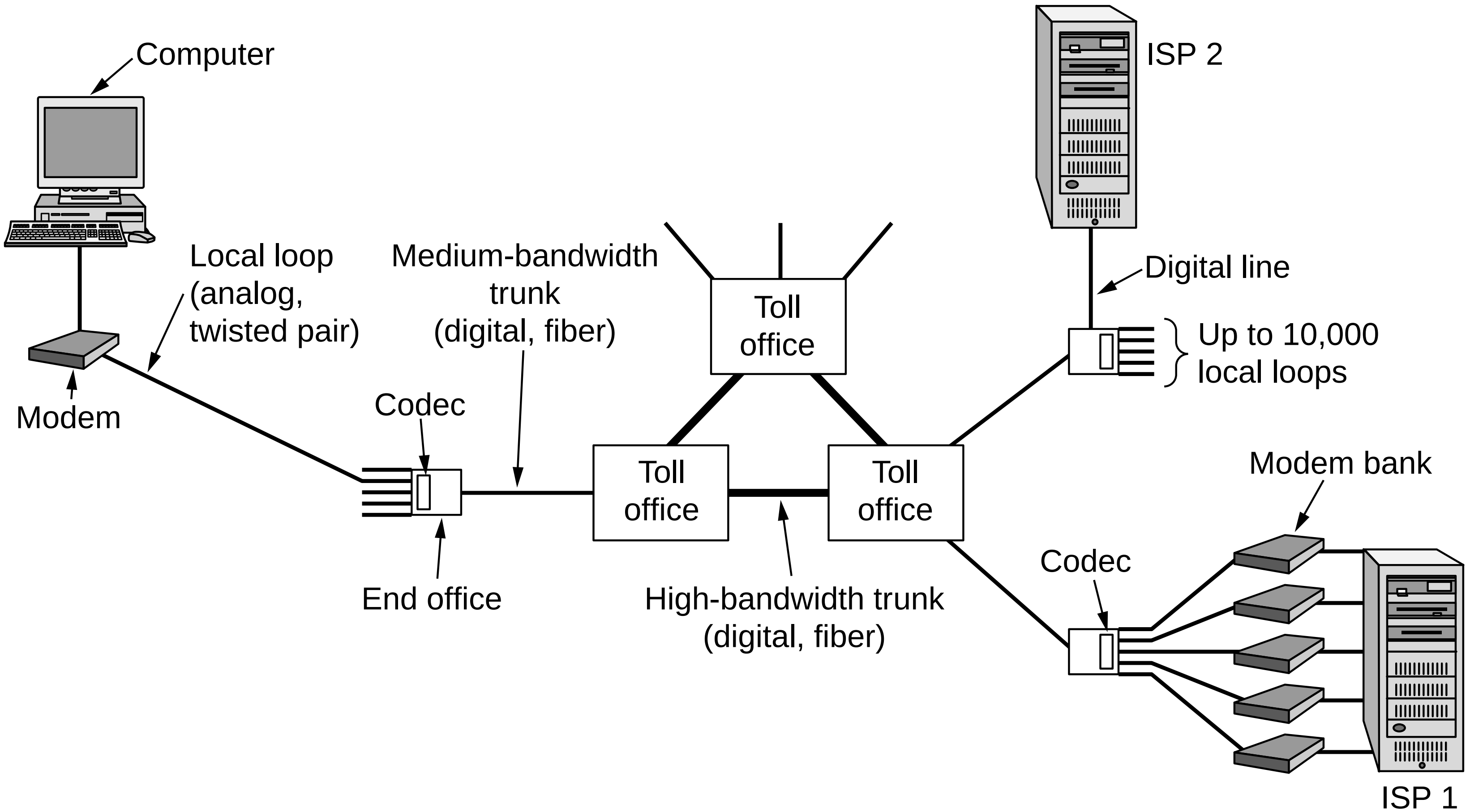
The Local Loop

- Modems
- (A)DSL
- Wireless

Modems

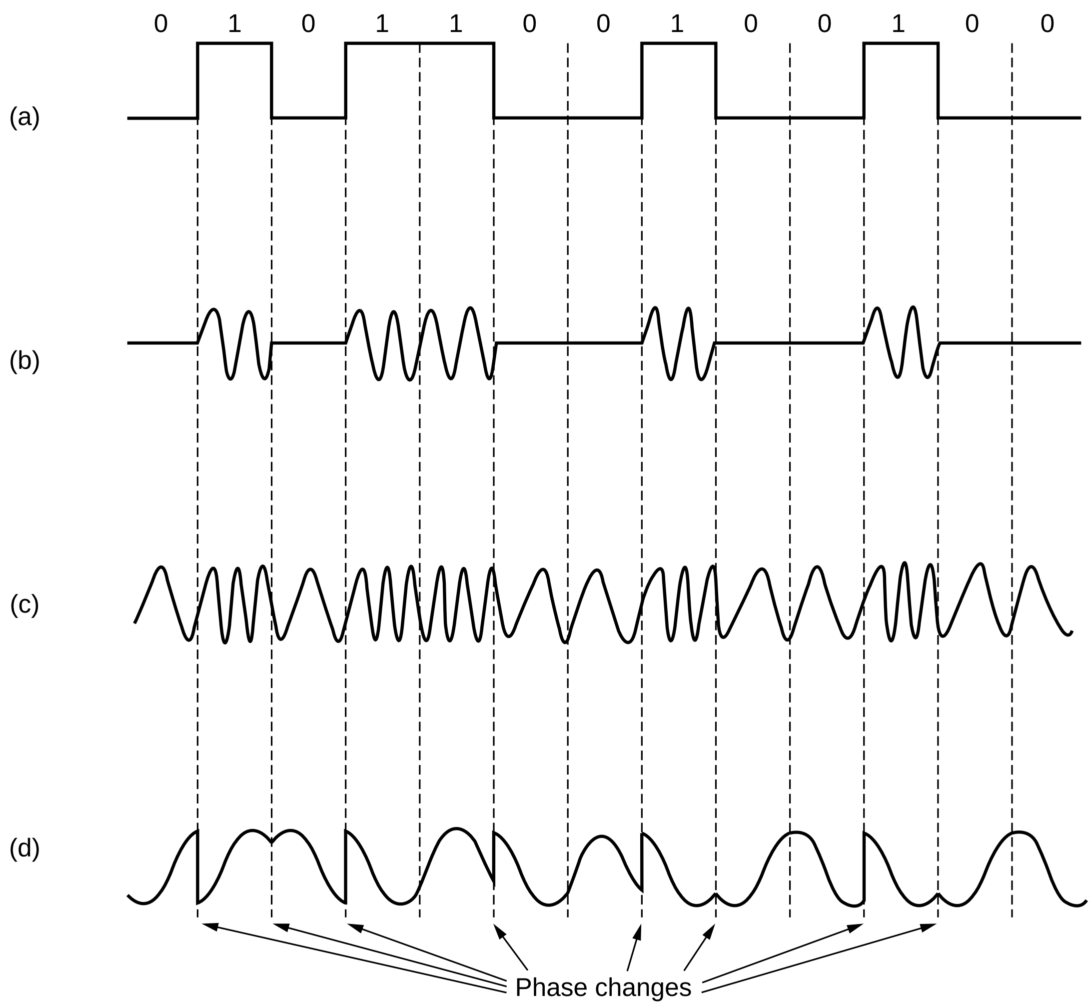
- Analog and digital transmission
- Sine wave carrier
- Baud
- Phase shift keying
- Limits

Analog and Digital Transmission



- modem – modulator, demodulator
- codec – coder, decoder

Modems – Sine Wave Carrier

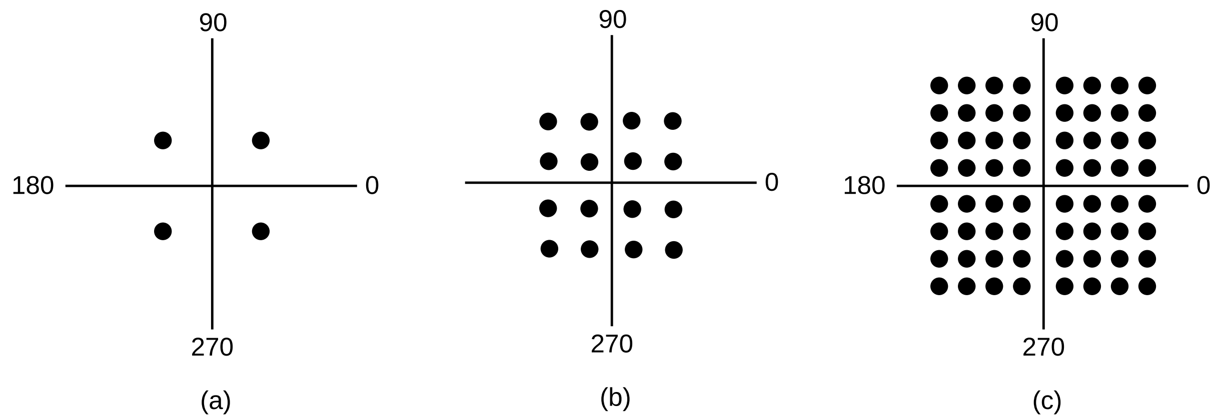


(a) binary, (b) AM, (c) FM, (d) phase modulation

Baud and Symbols

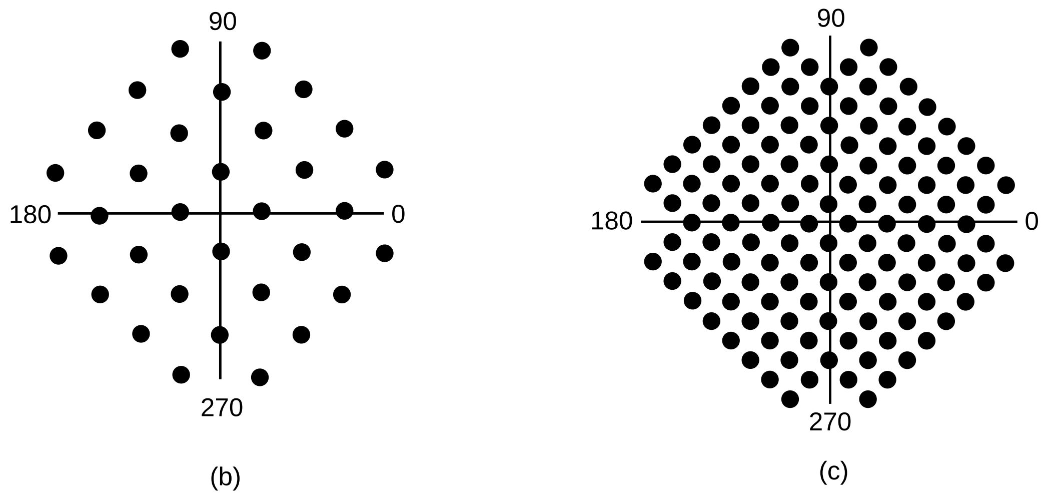
- Baud rate is the sampling rate
- Baud is the time to read one symbol
- When the number of symbols is 2, the baud rate is the bit rate
- Modern modems use large sets of symbols

Quadrature Phase Shift Keying



- Constellation diagrams
- Amplitude (distance from origin)
- Phase
- QAM: Quadrature Amplitude Modulation

Trellis Coded Modulation



- add bits for error correction
- V.32: 32 constellation points, 4 data bits, 1 parity bit
- V.32bis: 6 data bits, 1 parity bit

Limits

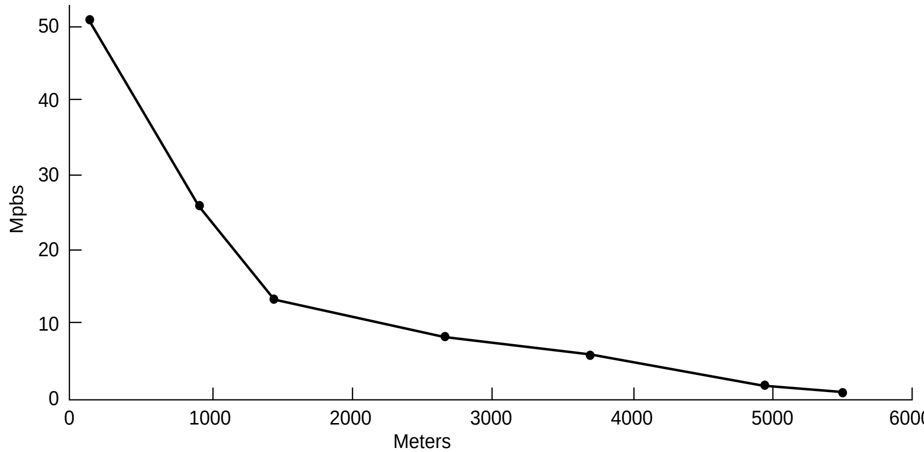
- Base sampling rate – 2400 baud

Standard	Data bits	bps
V.32	4	9600
V.32bis	6	14,400
V.34	12	28,800
V.34bis	14	33,600

- Variations
  - handshake to determine line quality
  - compression
- 35 kbps is the Shannon limit, 56 kbps?
  - eliminate one local loop
  - V.90 56-kbps down stream, 33-kbps upstream
  - V.92 48-kbps down stream, 48-kbps upstream

DSL: Digital Subscriber Line

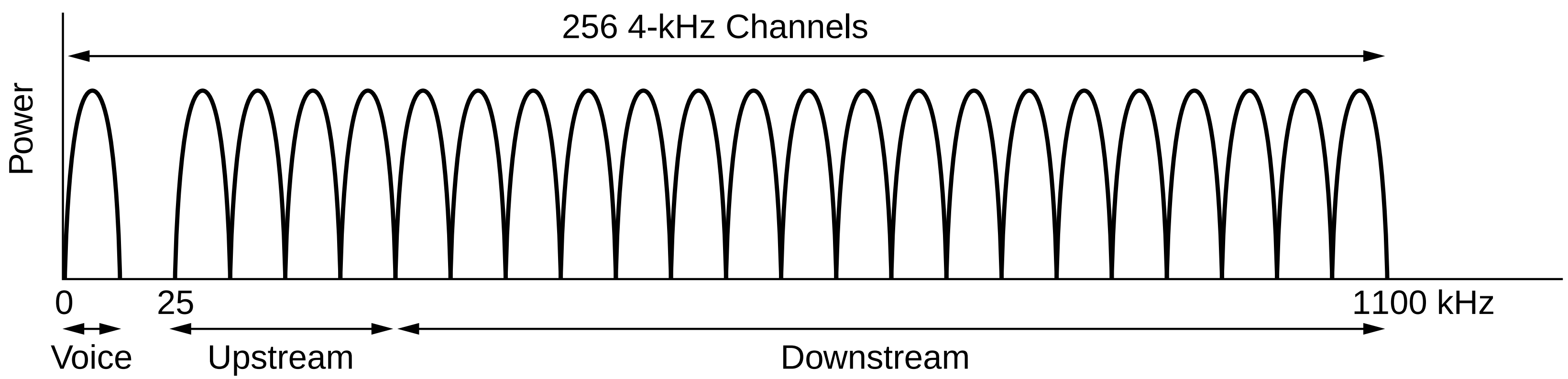
- Remove the filters
- Bandwidth



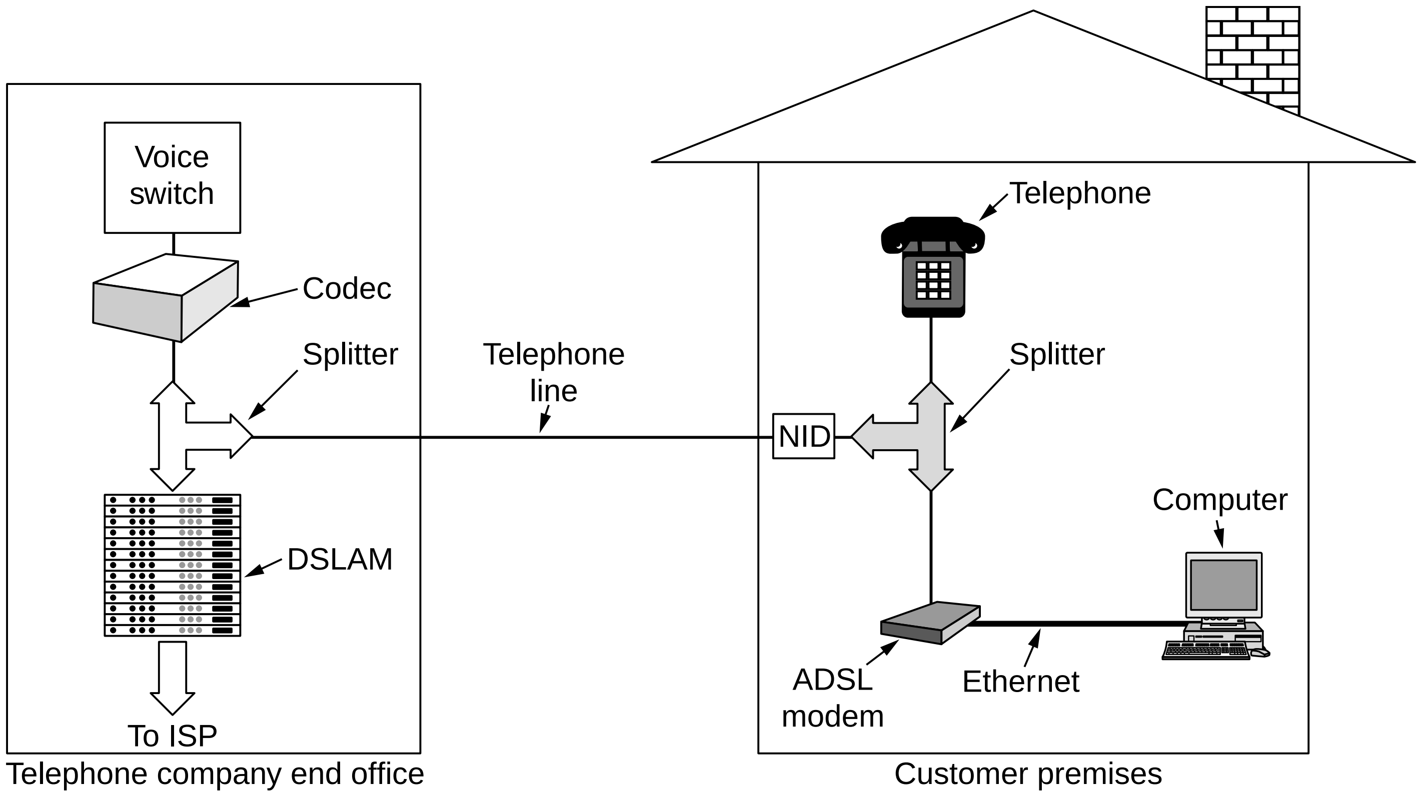
- Goals
  - use existing Cat-3 lines
  - not interfere with current phone uses
  - always on
  - much better than 56kbps

Techniques

- POTS (Plain Old Telephone Service) – Frequency Multiplexing
- DMT (Discrete MultiTone)

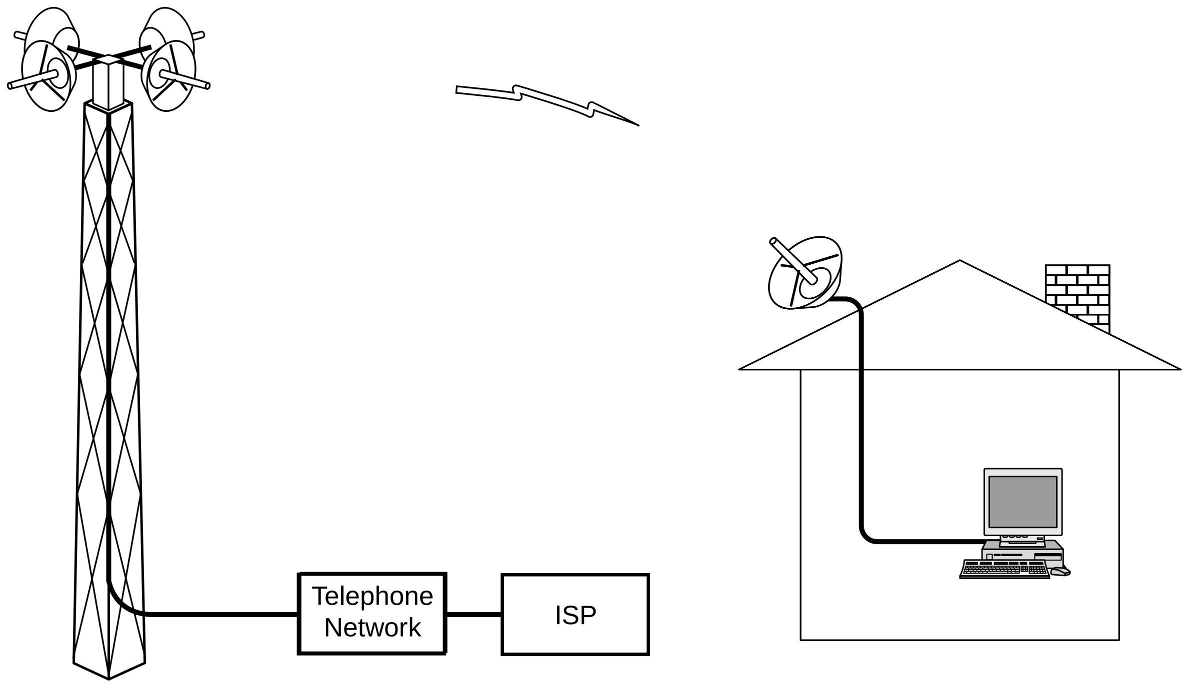


DSL Equipment



- NID: Network Interface Device
- ADSL Modem: 250 QAM modems
- DSLAM: Digital Subscriber Line Access Multiplexer

Wireless Local Loop

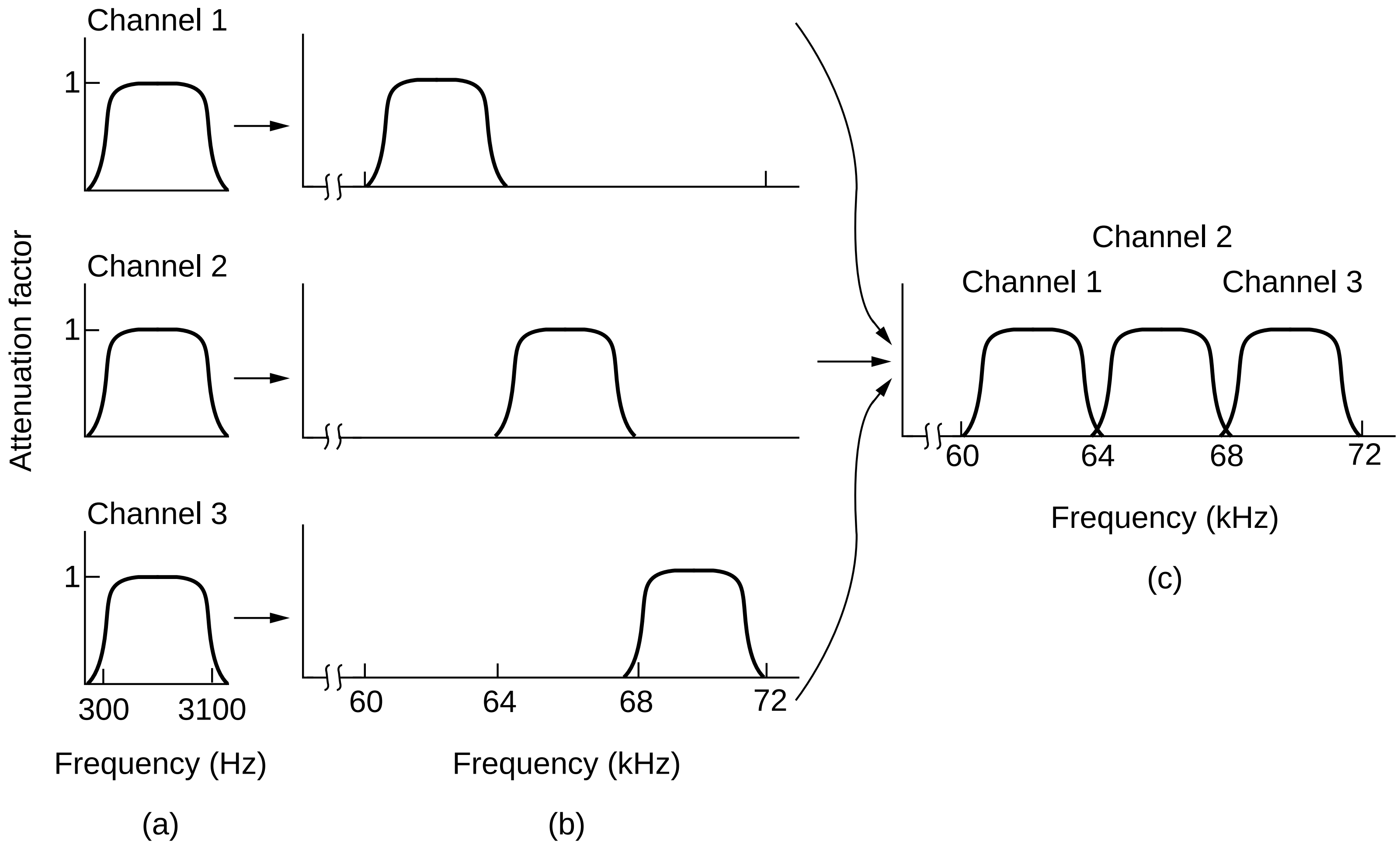


- IEEE 802.16 (Broadband wireless)
- 36Gbps down 1 Gbs up
- Put the ISP on Sandia crest
  - good line of sight
  - no rain or tree leaves!

Trunks and Multiplexing

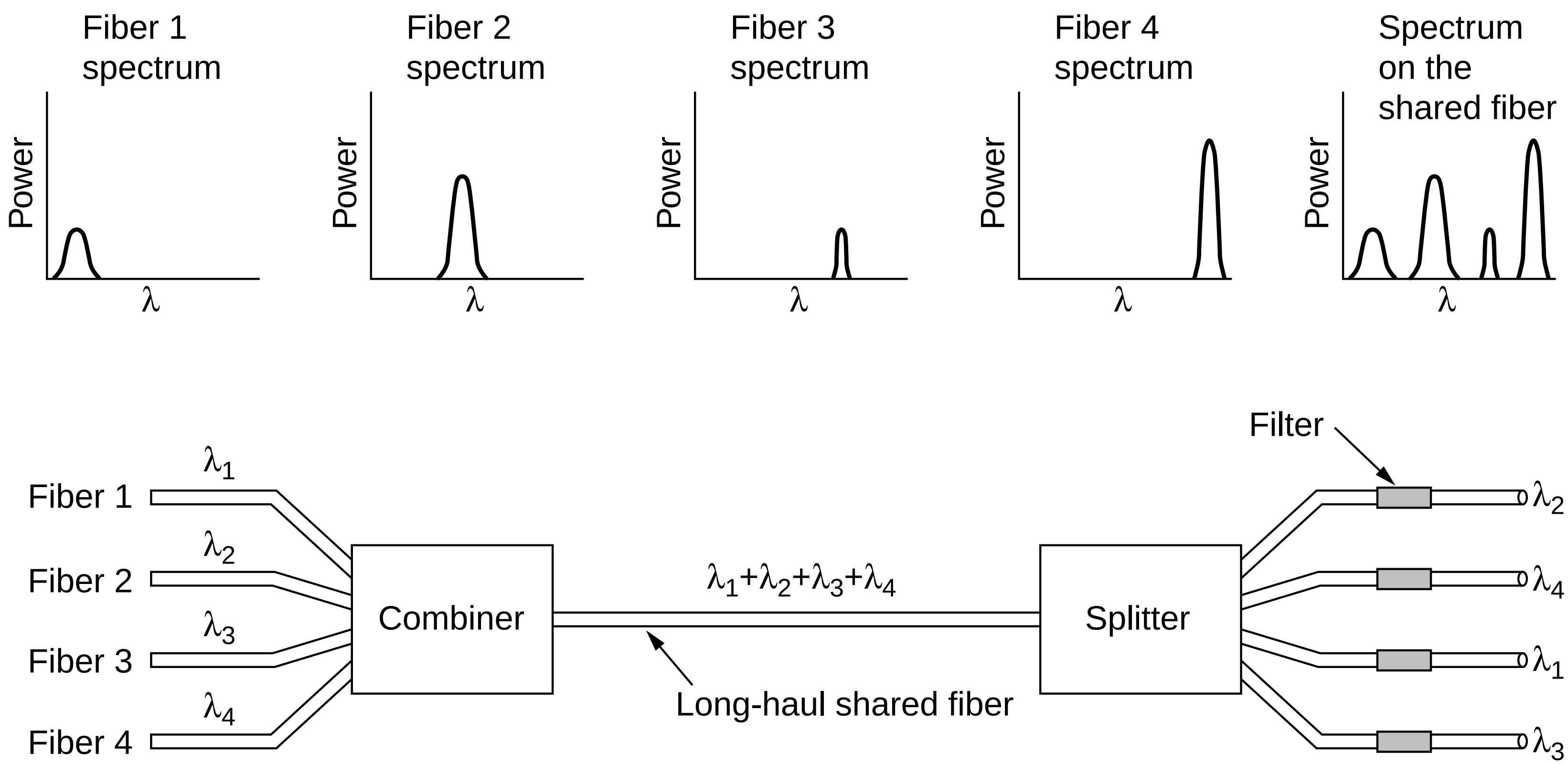
- Frequency division multiplexing
- Wavelength division multiplexing
- Time division multiplexing
  - aside on compression
- SONET

Frequency Division Multiplexing



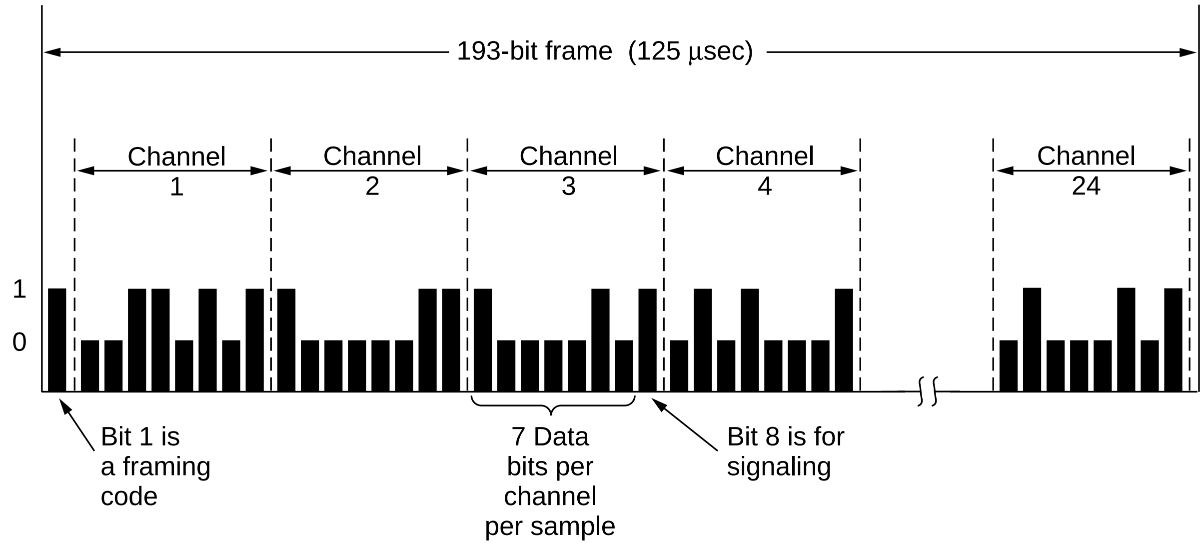
(a) 3 signals, (b) 3 frequency shifted signals, (c) combined signal

Wavelength Division Multiplexing



- FDM for optical

Time Division Multiplexing (T1)

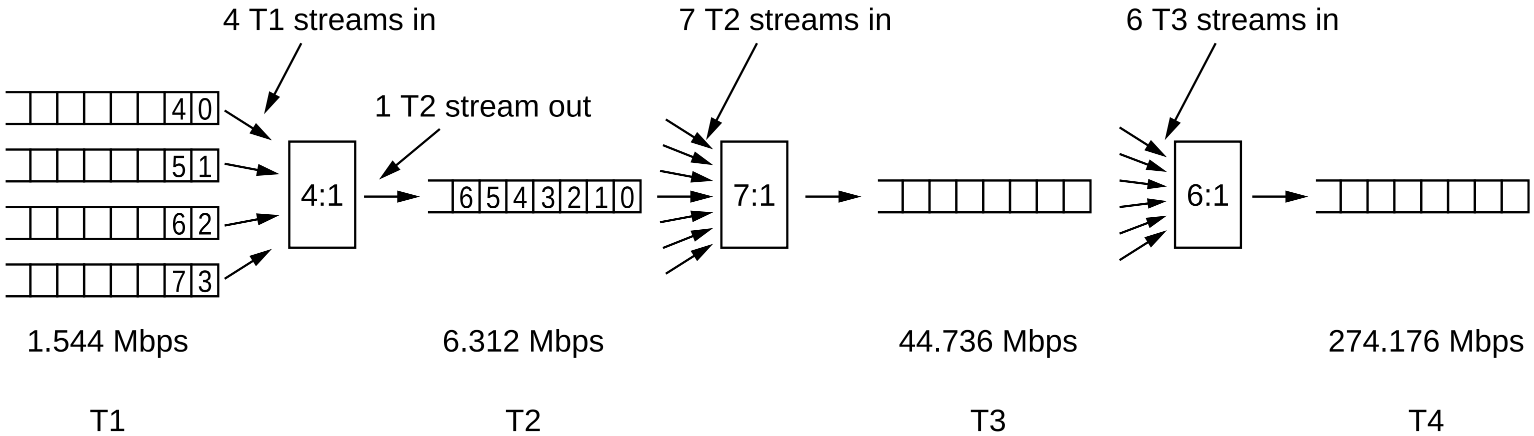


- codec 8000 samples / second (4000 Hz signals)
- 125 μsec / sample
- PCM (Pulse Coded Modulation)
- codec is multiplexed between 24 analog lines
- each analog line inserts 8 bits every 125 μsec
- $7 \times 8000 = 56,000$ bps / channel
- 1.544 Mbps aggregate

Framing

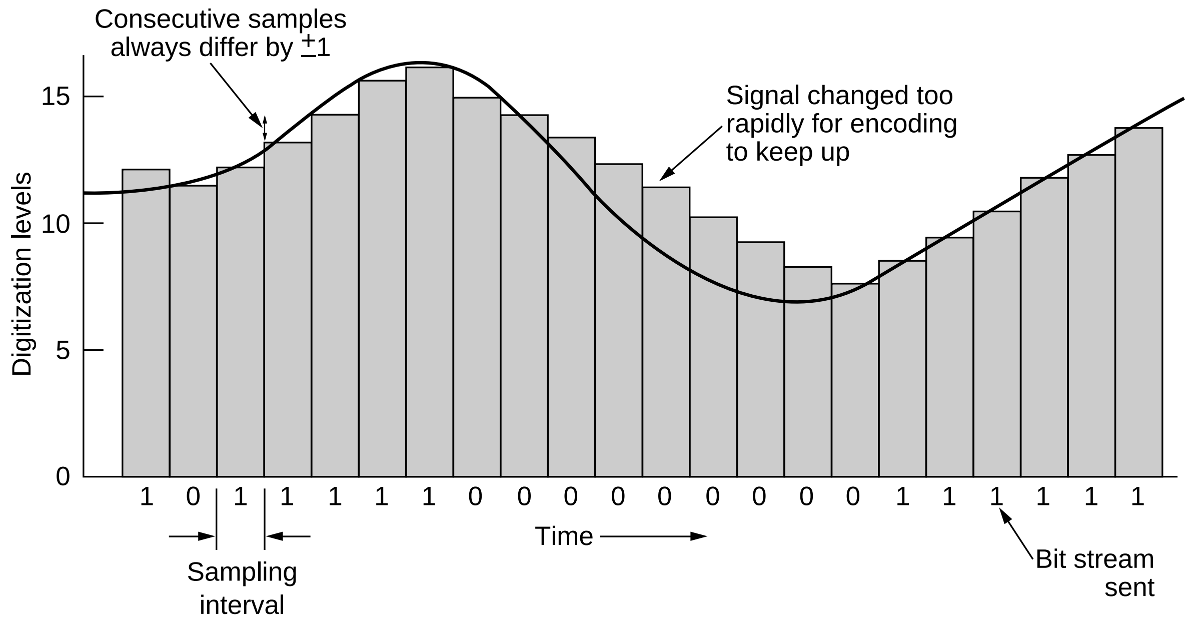
- Framing bit is used to recover the sender's clock
- The framing bit is 010101010101010....
- I.e., 4000 Hz
- Filtered for analog customer (3100 Hz filter)
- Not likely for digital customers

Multiple T1s



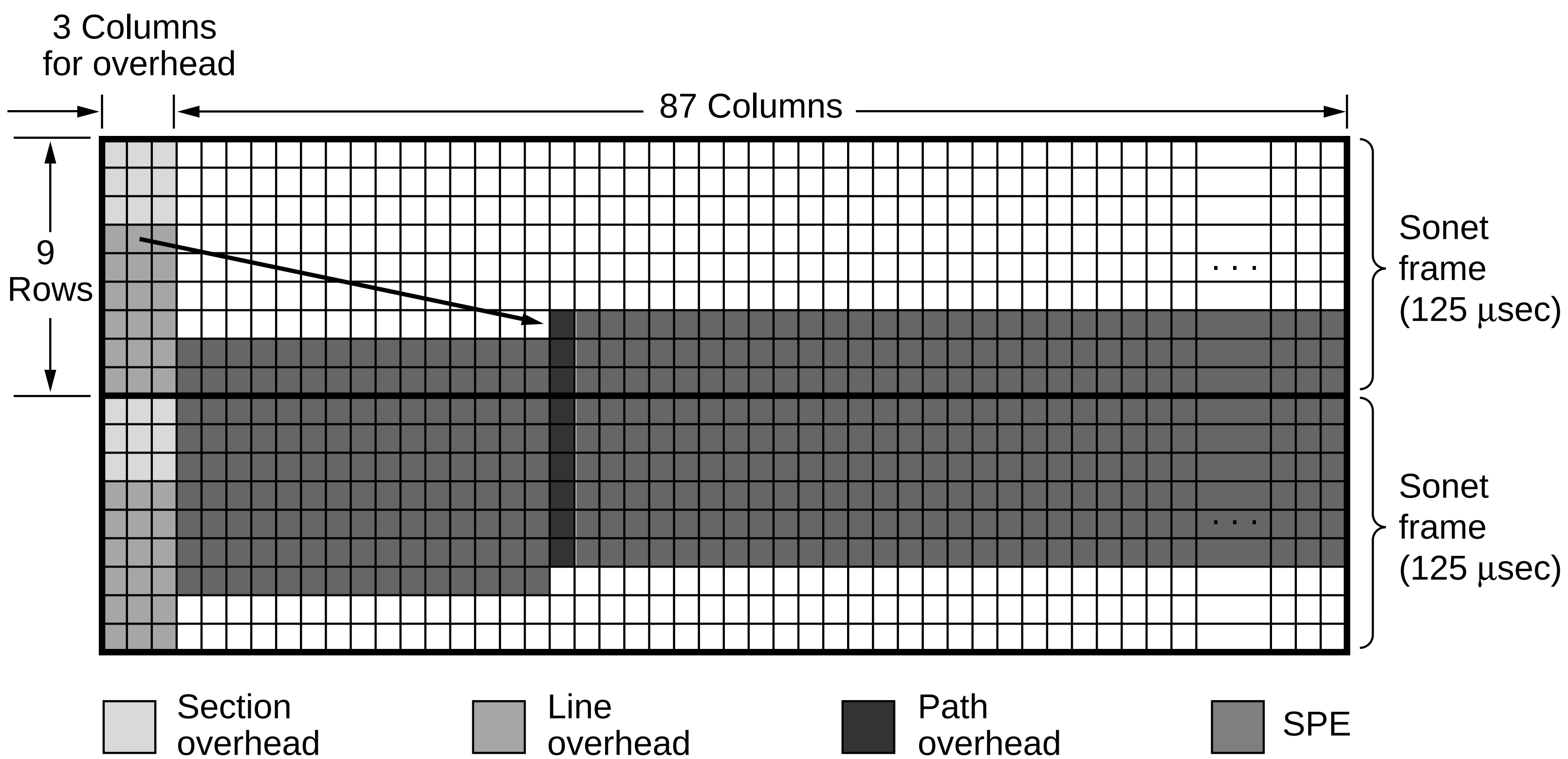
- Bitwise multiplexing
- 4 to 1; 7 to 1; and 6 to 1
- Overhead added at each step for framing and recovery
- T2 and T4 are only used inside the phone company

Compression



- differential modulation (send change to value, rather than value)
- delta modulation (shown) $+1$ or -1
- predictive encoding: extrapolate from earlier values and then send the change to this extrapolation

SONET (Synchronous Optical NETwork)



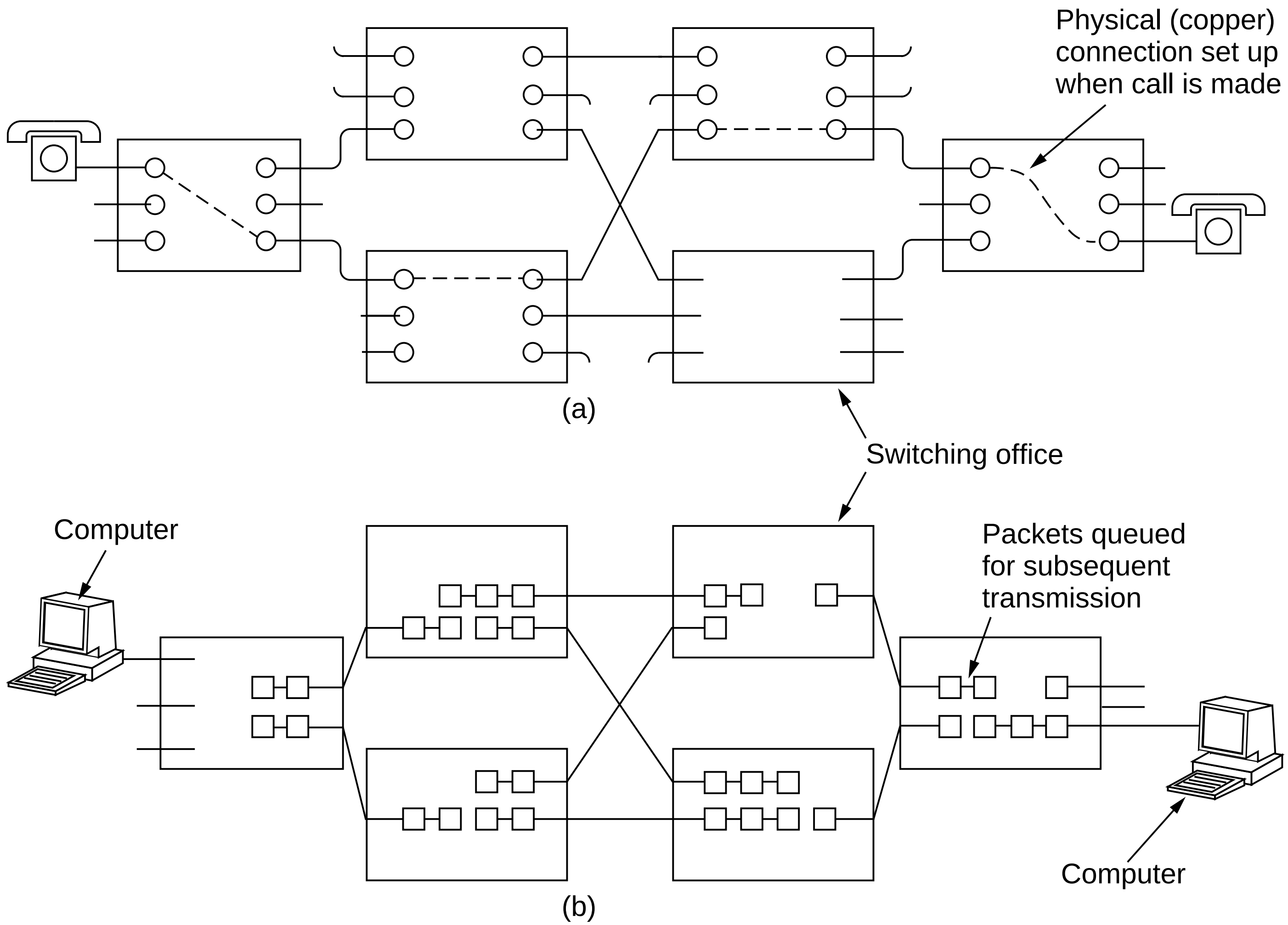
- STS-1 Synchronous Transport Signal-1
- SPE – Synchronous Payload Envelope

SONET Rates

SONET		SDH	Data rate (Mbps)		
Electrical	Optical	Optical	Gross	SPE	User
STS-1	OC-1		51.84	50.112	49.536
STS-3	OC-3	STM-1	155.52	150.336	148.608
STS-9	OC-9	STM-3	466.56	451.008	445.824
STS-12	OC-12	STM-4	622.08	601.344	594.432
STS-18	OC-18	STM-6	933.12	902.016	891.648
STS-24	OC-24	STM-8	1244.16	1202.688	1188.864
STS-36	OC-36	STM-12	1866.24	1804.032	1783.296
STS-48	OC-48	STM-16	2488.32	2405.376	2377.728
STS-192	OC-192	STM-64	9953.28	9621.504	9510.912

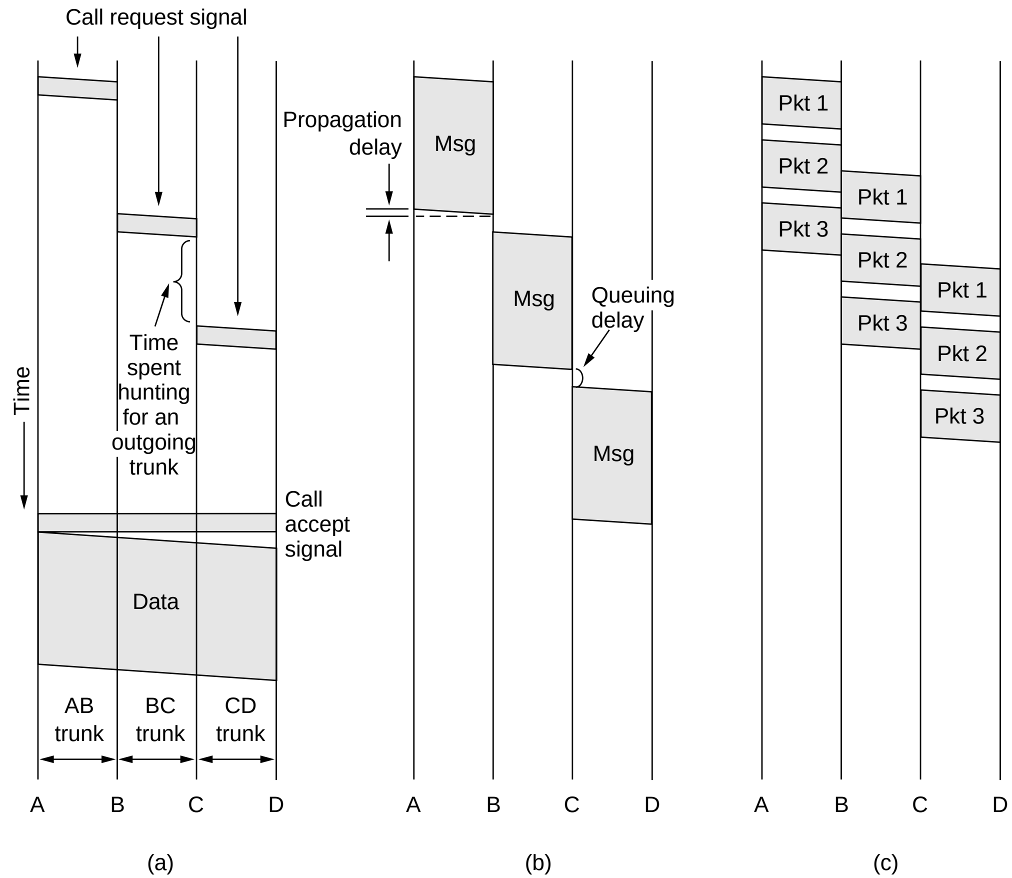
- Gross – signalling rate
- SPE – excludes line and selection overhead
- User – excludes path overhead

Switching



(a) circuit switched, (b) packet switched

Message Switching



(a) circuit, (b) message, and (c) packet switching store-and-forward

Packet v Circuit Switching

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
Transparency	Yes	No
Charging	Per minute	Per packet

Topics

- Theoretical Foundations
- Guided Transmission
- Wireless Transmission
- Communication Satellites
- Public Switched Telephone Network
- Mobile Telephone System
- Cable Television

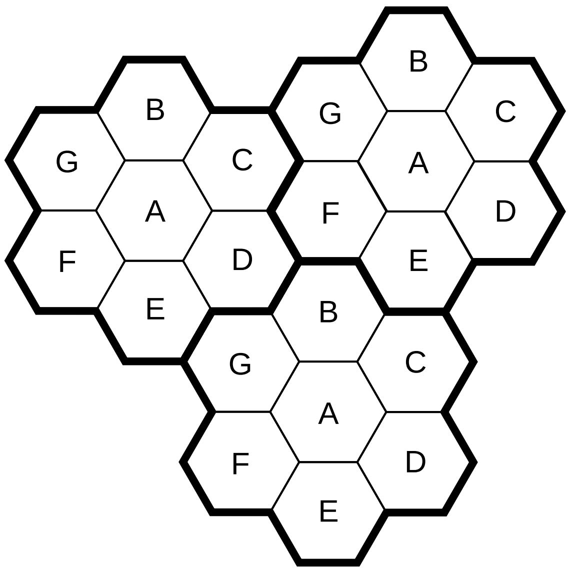
Mobile Telephone System

- First-Generation: Analog Voice
- Second-Generation: Digital Voice (skip)
- Third-Generation: Digital Voice and Data (skip)

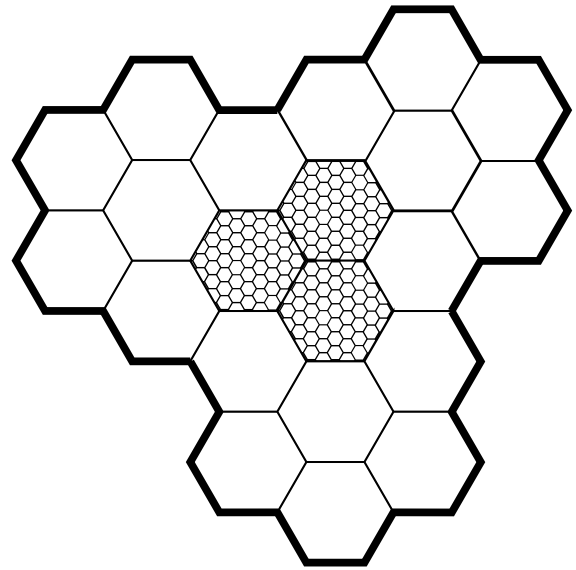
History

- Push-to-talk – 1946
- Improved Mobile Telephone System (IMTS) – 1960
  - still hilltop transmission
  - 23 channels – individual conversations
  - 2 frequencies – send and receive
- Advanced Mobile Phone System (AMPS) – 1982
  - cells
  - typically 10-20 km across

Cells



(a)



(b)

- Frequency sets have a buffer of two cells
- Micro-cells are added to respond to more users
- Temporary micro-cells for events

Mobility

- MTSO – Mobile Telephone Switching Office
- AKA, MSC – Mobile Switching Center
- At any time each phone is in one cell
- Switching center controls **handoff**
- Handof takes about 300msec
- Hard handoff – connection gets dropped

More Details: Channels

- 832 full duplex channels
- Each channel is 30 kHz wide (frequency division multiplexing)
- Transmission channels 824–849 MHz
- Receive channels 869–894 MHz
- Signal properties:
  - straight (requires line of sight)
  - bounce off buildings and ground (multipath fading)
  - absorbed by plants
- 21 channels reserved for control
- 45 voice channels (to avoid re-using channels used in nearby cells)

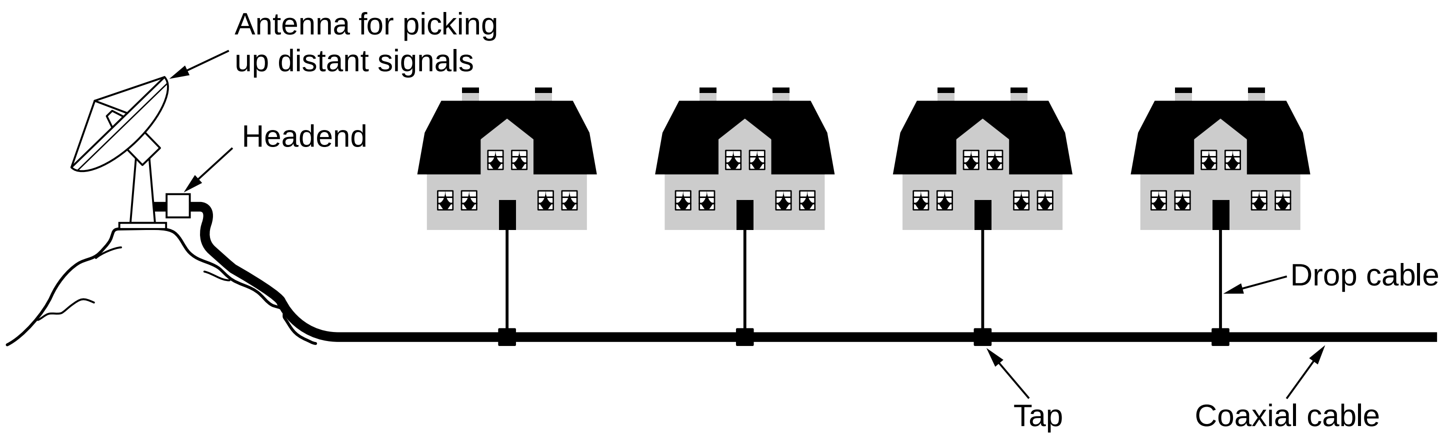
More Details: Call Management

- 32-bit serial number
- 10-digit phone number (encoded in 34 bits)
- Startup sequence
  - Scan 21 channels to find strongest base station
  - Broadcast serial number and phone number
  - Base station reports to MTSO
  - Phone re-registers about every 15 minutes
- On “send” phone send number and identifier (retransmit on collision)
- Idle phones listen for pages, when an incoming call is accepted, the phone switches to the appropriate channel

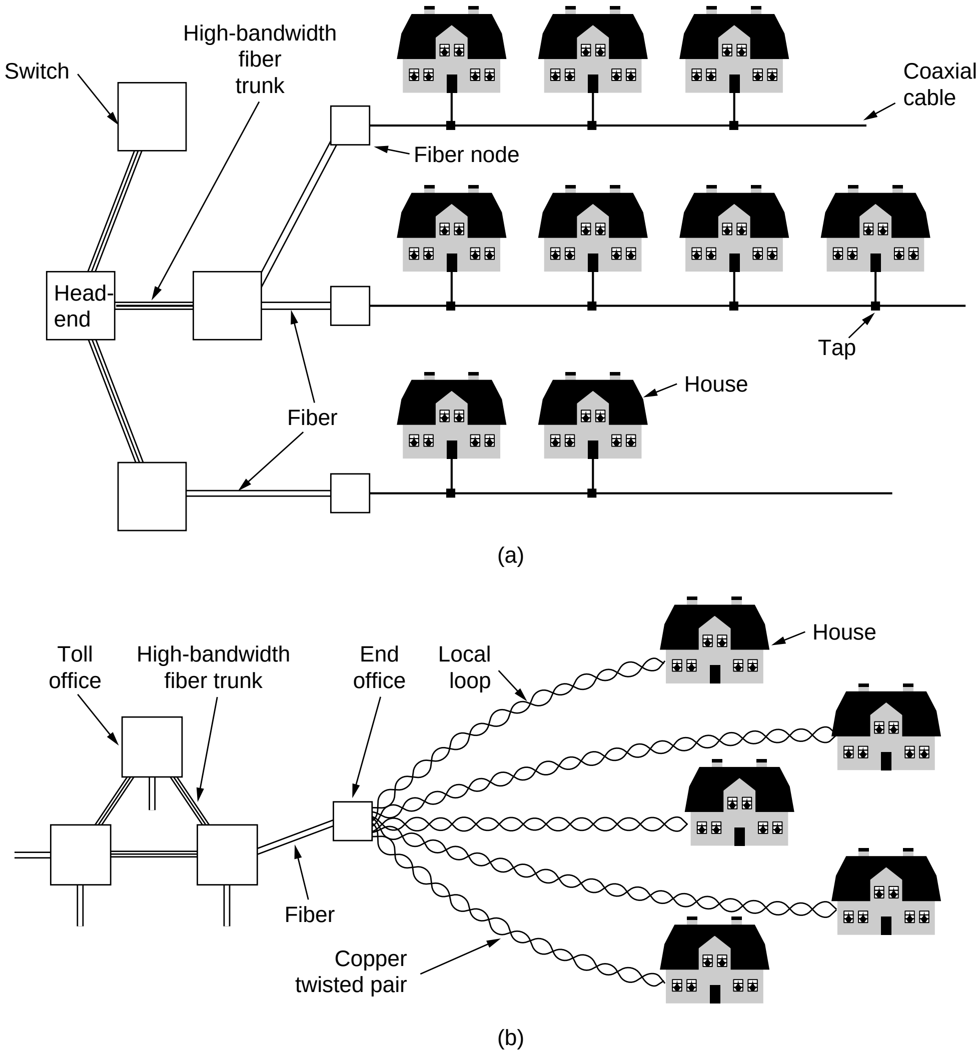
Topics

- Theoretical Foundations
- Guided Transmission
- Wireless Transmission
- Communication Satellites
- Public Switched Telephone Network
- Mobile Telephone System
- Cable Television

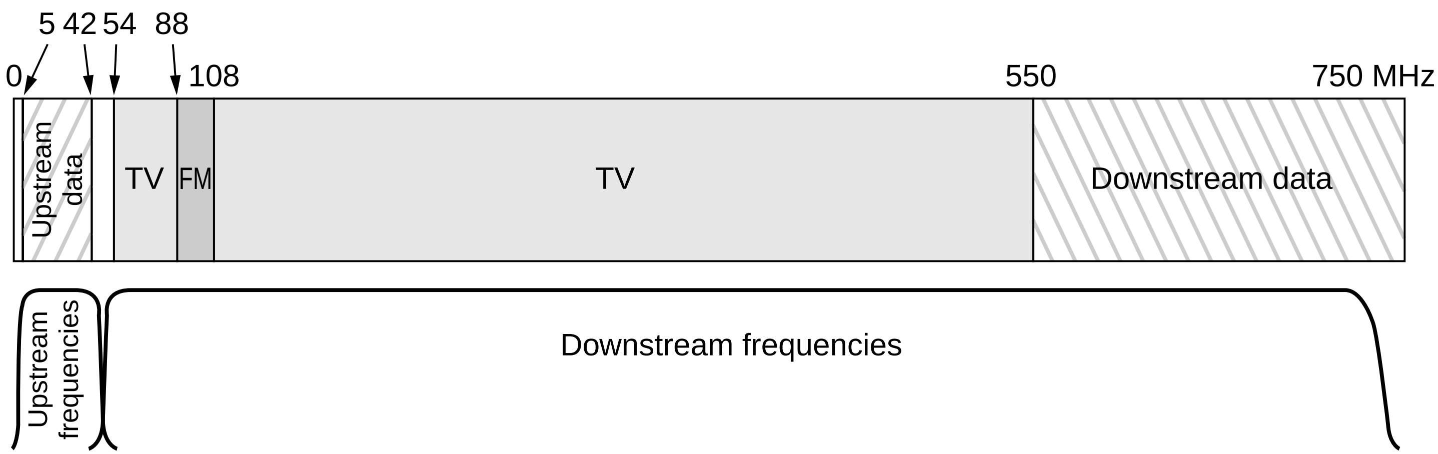
Community Antenna



Internet over Cable

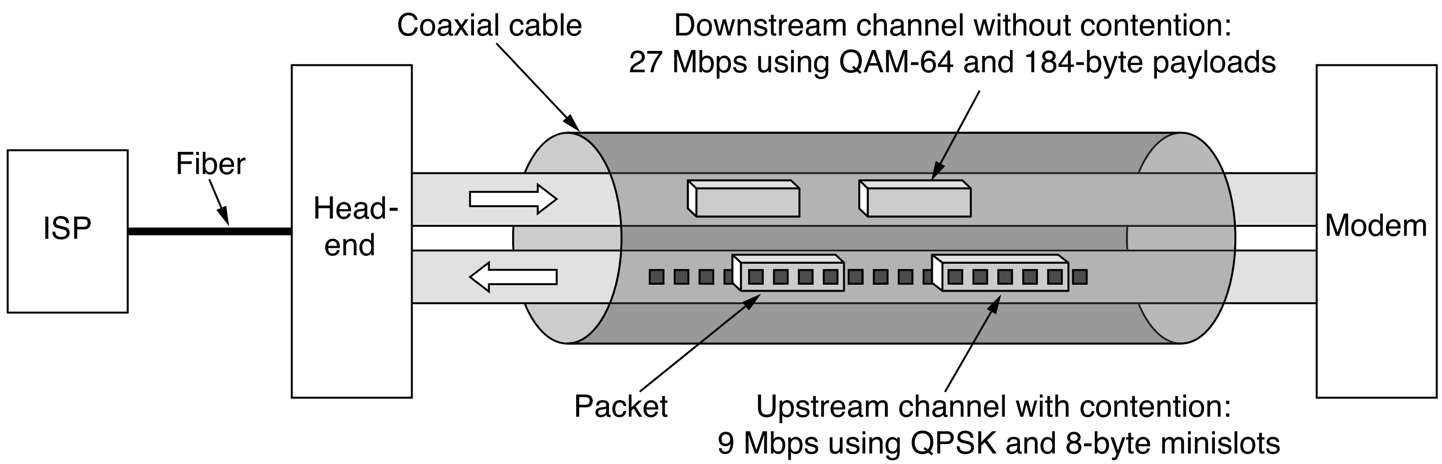


Spectrum Allocation



- Downstream analog
  - Each channel is 6 MHz
  - With QAM-64 we get 6×6 Mbps (or 27 Mbps without overhead)
- Upstream uses QSPK, only 2 bits per baud

Cable Modems



- Initialization
  - upstream and downstream channels
  - minislot (about 8 bytes) for requesting bandwidth
  - *ringing* to determine distance from head-end
- Contention for upstream
- All data packets are encrypted