The Physical Layer

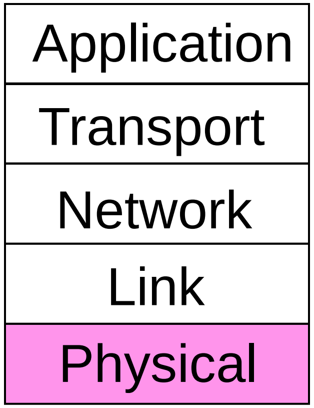
Outline

- Theoretical Basis for Data Communications
- Digital Modulation and Multiplexing
- Guided Transmission Media (copper and fiber)
- Public Switched Telephone Network and DSL-based Broadband
- Cable Television

The Physical Layer

Foundation on which other layers build

- Properties of wires, fiber, wireless limit what the network can do



Key problem is to send (digital) bits using only (analog) signals

- This is called modulation

Theoretical Basis for Data Communication

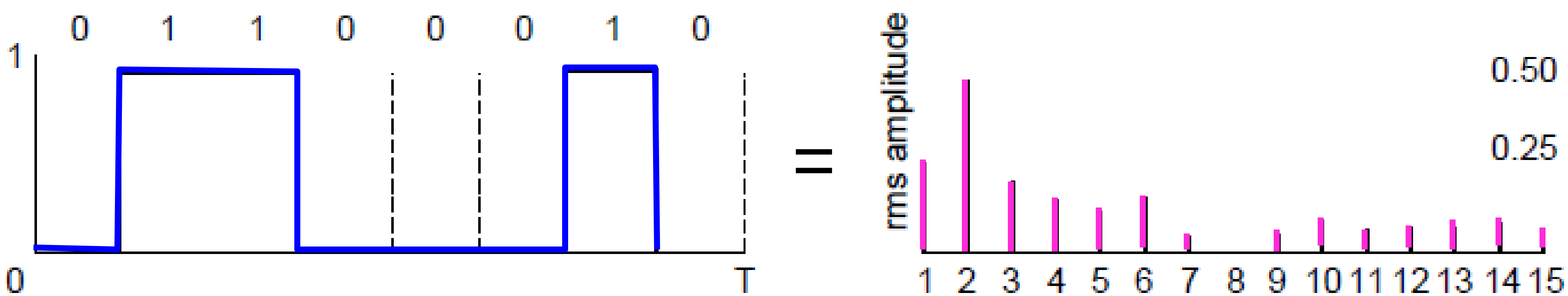
Communication rates have fundamental limits

- Fourier analysis »
- Bandwidth-limited signals »
- Maximum data rate of a channel »

Fourier Analysis

A time-varying signal can be equivalently represented as a series of frequency components (harmonics) aka **Fourier series**:

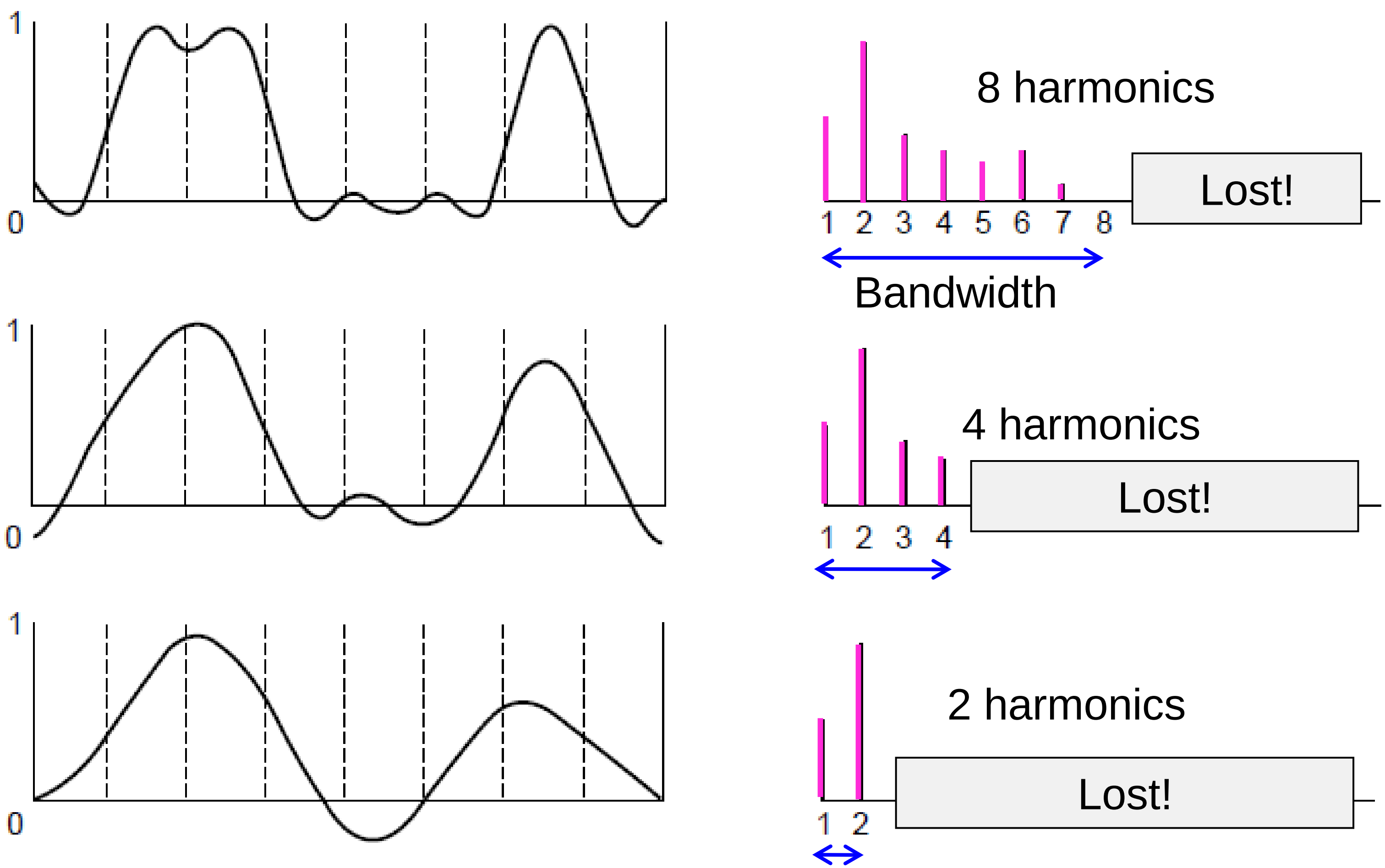
$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n f t) + \sum_{n=1}^{\infty} b_n \cos(2\pi n f t)$$



Signal over time ⟶   a, b weights of harmonics

Bandwidth-Limited Signals

Having less bandwidth (harmonics) degrades the signal



Maximum Data Rate *with a Finite Bandwidth Signal over a Noiseless Channel*

Nyquist's theorem relates the data rate to the bandwidth (B) and number of signal levels (V):

$$\text{Max. data rate} = 2B \log_2 V \text{ bits/sec}$$

Example: a noiseless 3KHz channel used for **voice-grade telephone line** cannot transmit binary signals faster than 6000 bps

- Time to send a byte (8 bits) at a bit rate of *b* bits/sec = 8/b ➔ fundamental frequency (frequency of first harmonic) = b/8
- For a voice-grade line with cutoff frequency just above 3000 Hz, highest harmonic number is ~3000/(b/8) = 24000/b

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

Maximum Data Rate of a *Noisy* Channel

Shannon's theorem relates the data rate to the bandwidth (B) and signal strength (S) relative to the noise (N):

$$\text{Max. data rate} = B \log_2(1 + S/N) \text{ bits/sec}$$

Example: ADSL (Aysmmetric Digital Subscriber Line) based Internet access over a normal telephone line

- Bandwidth, B, is around 1MHz
- SNR depends strongly on distance of home from telephone exchange; for 1-2 Km short lines, a good SNR of 40dB is possible
- With 1MHz bandwidth and 40dB SNR, max. data rate is 13Mbps

Digital Modulation and Multiplexing

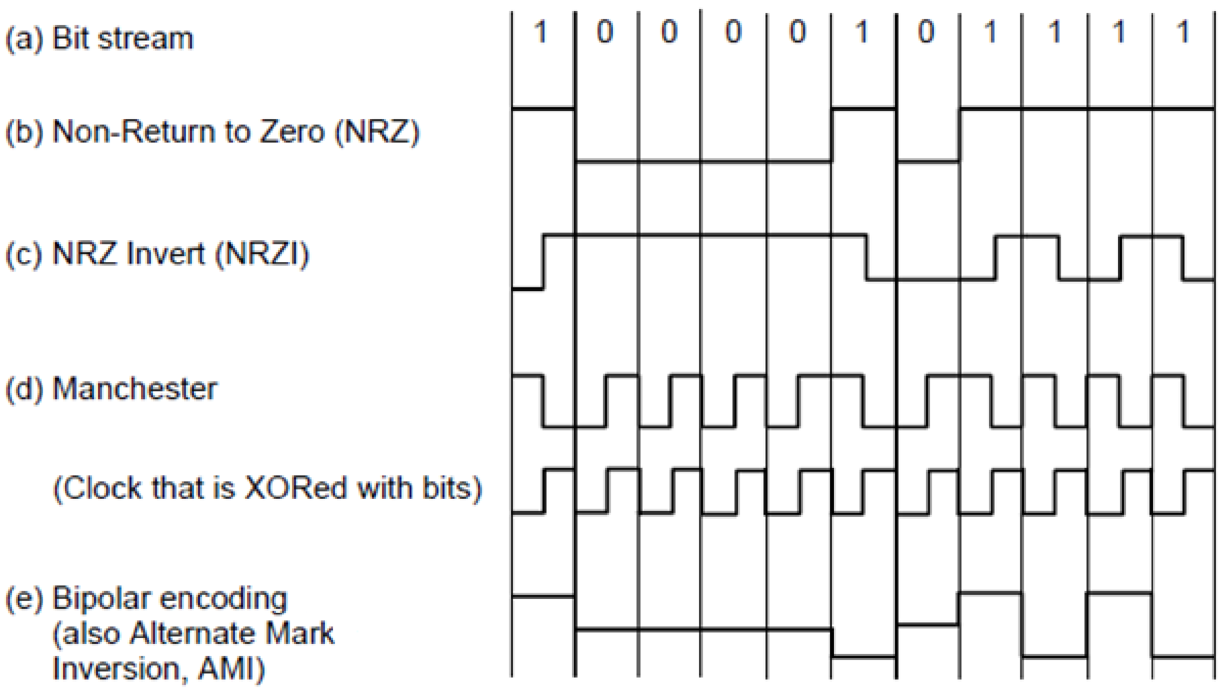
Modulation schemes send bits as signals; multiplexing schemes share a channel among users.

- Baseband Transmission »
- Passband Transmission »
- Frequency Division Multiplexing »
- Time Division Multiplexing »
- Code Division Multiple Access »

Baseband Transmission

Line codes send <u>symbols</u> that represent one or more bits

- NRZ is the simplest, literal line code (+1V="1", -1V="0")
- Other codes tradeoff bandwidth and signal transitions

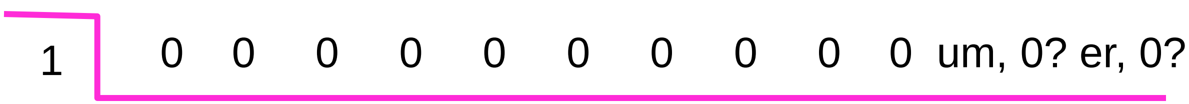


Four different line codes

Clock Recovery

To decode the symbols, signals need sufficient transitions

- Otherwise long runs of 0s (or 1s) are confusing, e.g.:



Strategies:

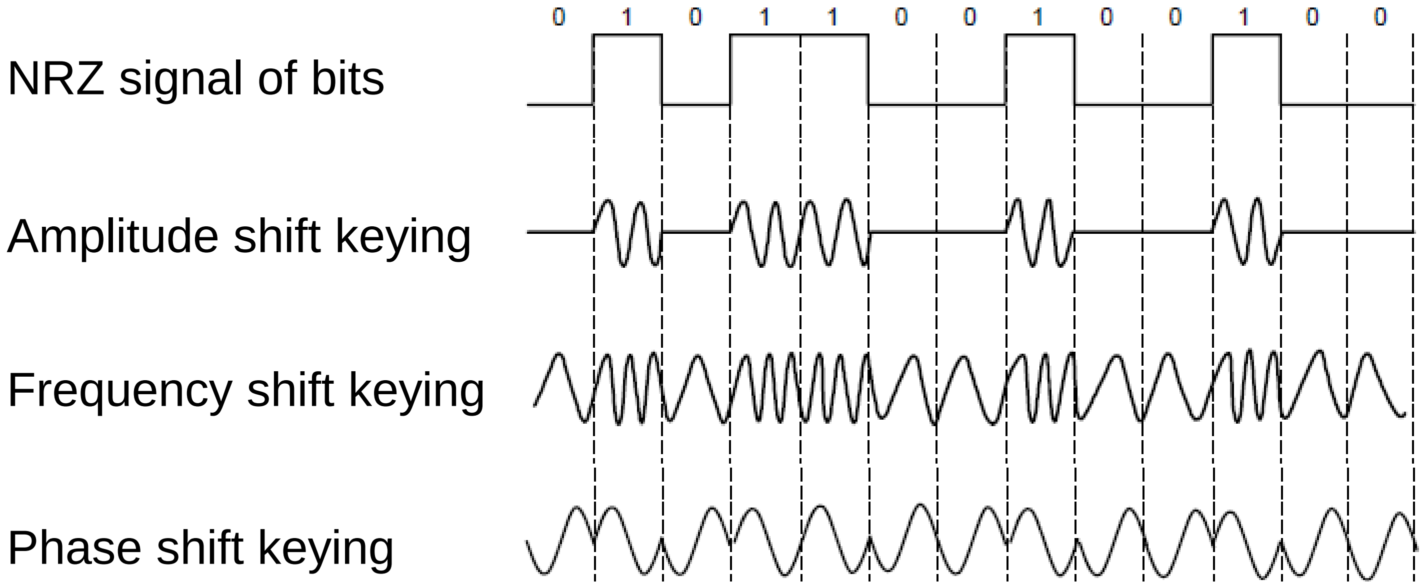
- Manchester coding, mixes clock signal in every symbol
- 4B/5B maps 4 data bits to 5 coded bits with 1s and 0s:

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

- Scrambler XORs tx/rx data with pseudorandom bits

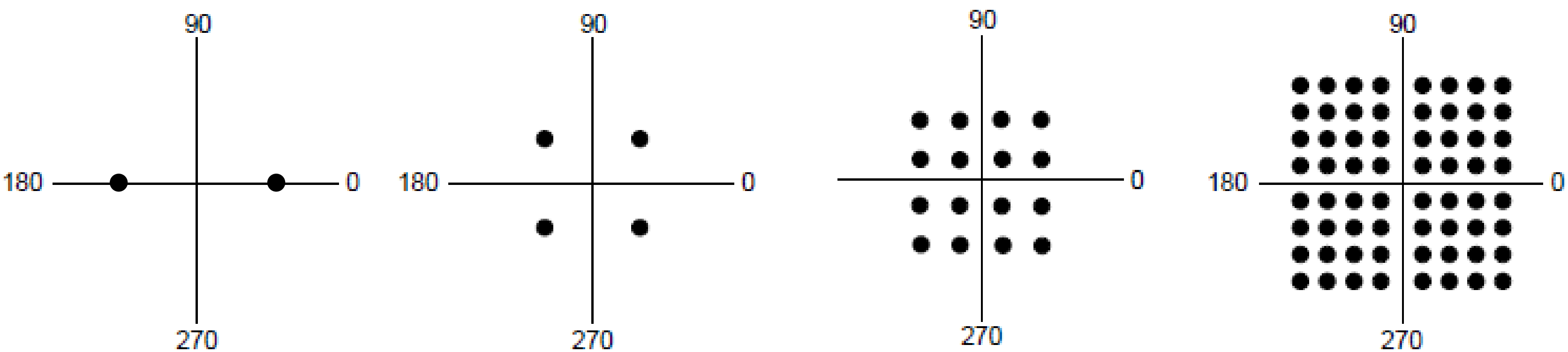
Passband Transmission (1)

Modulating the amplitude, frequency/phase of a carrier signal sends bits in a (non-zero) frequency range



Passband Transmission (2)

Constellation diagrams are a shorthand to capture the amplitude and phase modulations of symbols:



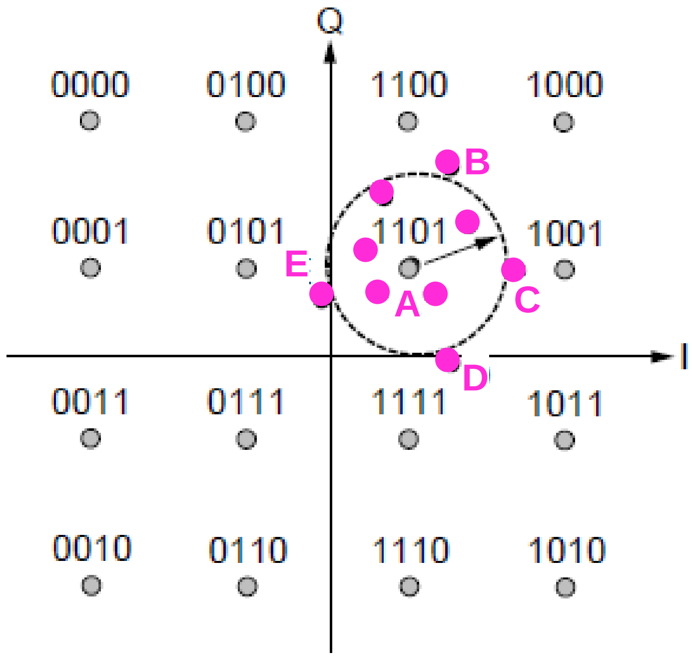
BPSK	QPSK	QAM-16	QAM-64
2 symbols	4 symbols	16 symbols	64 symbols
1 bit/symbol	2 bits/symbol	4 bits/symbol	6 bits/symbol

BPSK/QPSK varies only phase

QAM varies amplitude and phase

Passband Transmission (3)

Gray-coding assigns bits to symbols so that small symbol errors cause few bit errors:

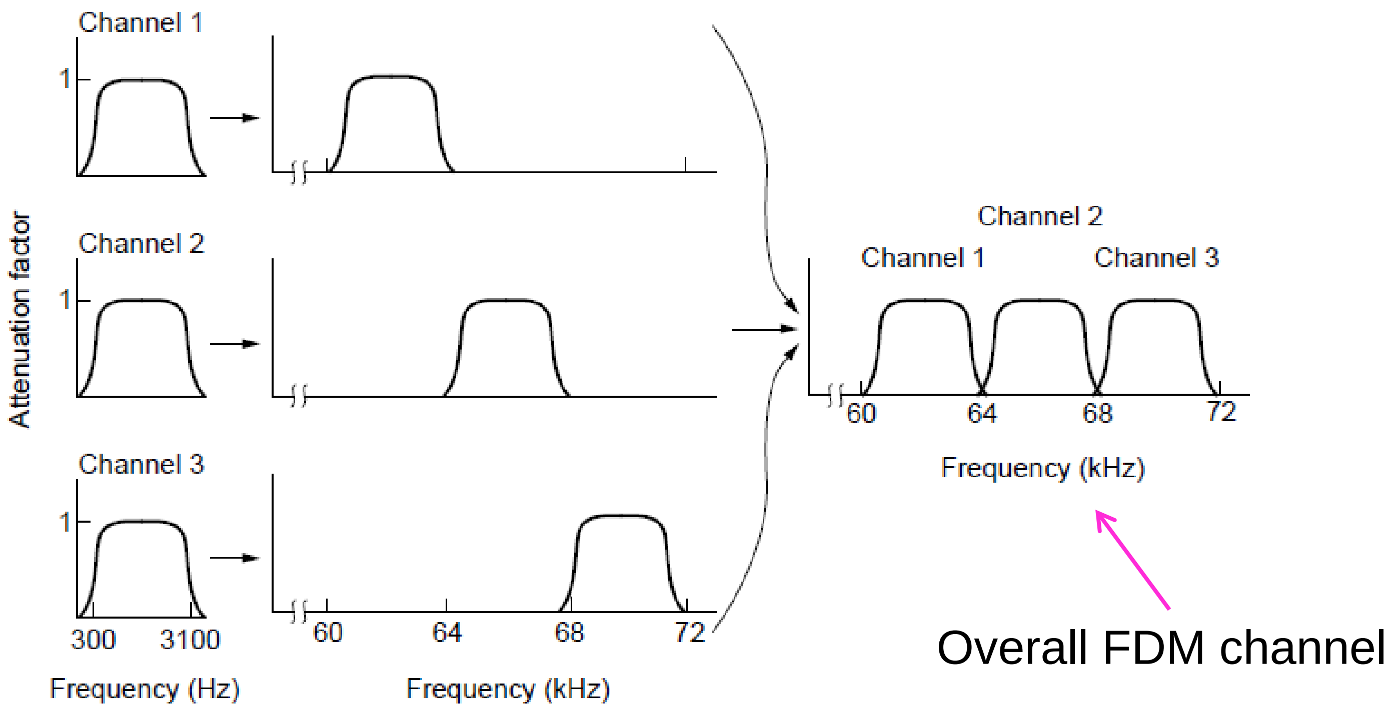


When 1101 is sent:

Point	Decodes as	Bit errors
A	1101	0
B	110<u>0</u>	1
C	1<u>0</u>01	1
D	11<u>1</u>1	1
E	<u>0</u>101	1

Frequency Division Multiplexing (1)

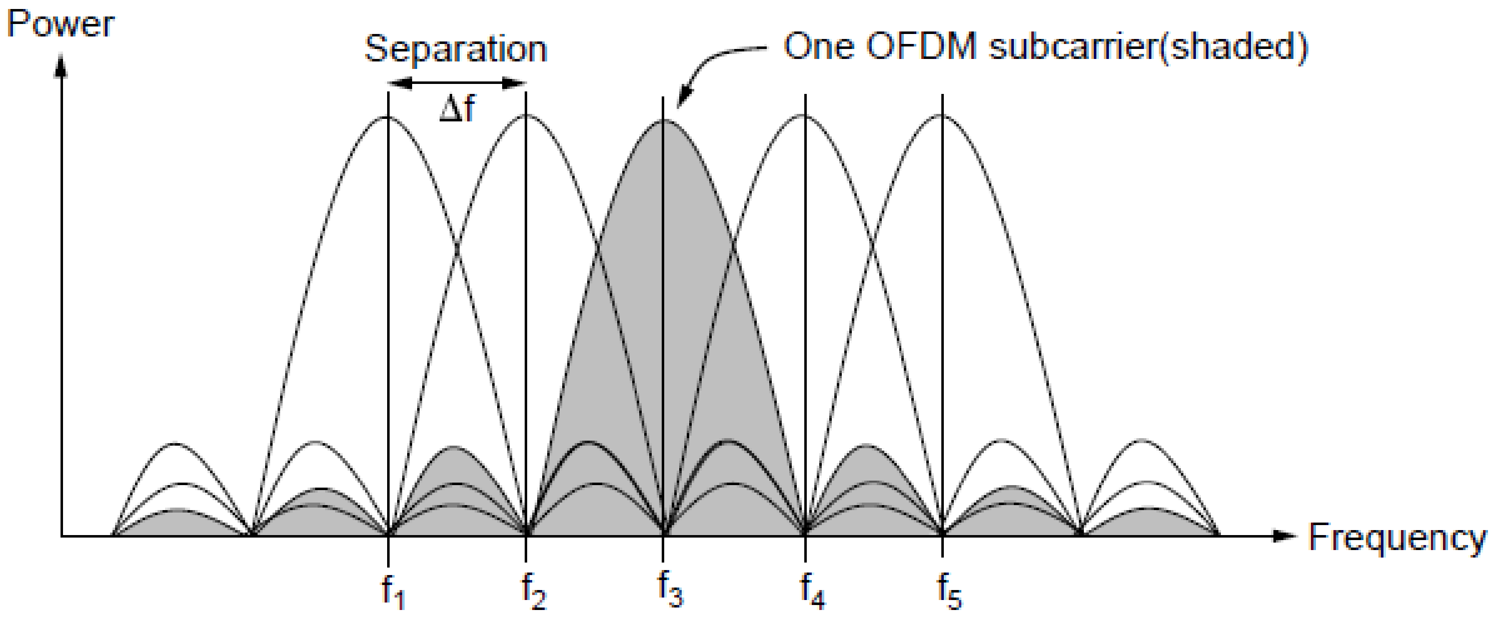
FDM (Frequency Division Multiplexing) shares the channel by placing users on different frequencies:



Frequency Division Multiplexing (2)

OFDM (Orthogonal FDM) is an efficient FDM technique used for 802.11, 4G cellular and other communications

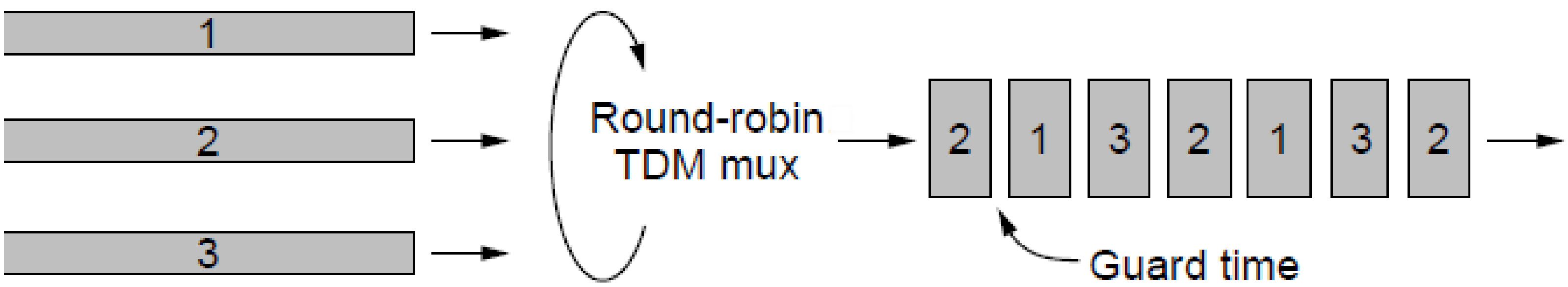
- Subcarriers are coordinated to be tightly packed



Time Division Multiplexing (TDM)

Time division multiplexing shares a channel over time:

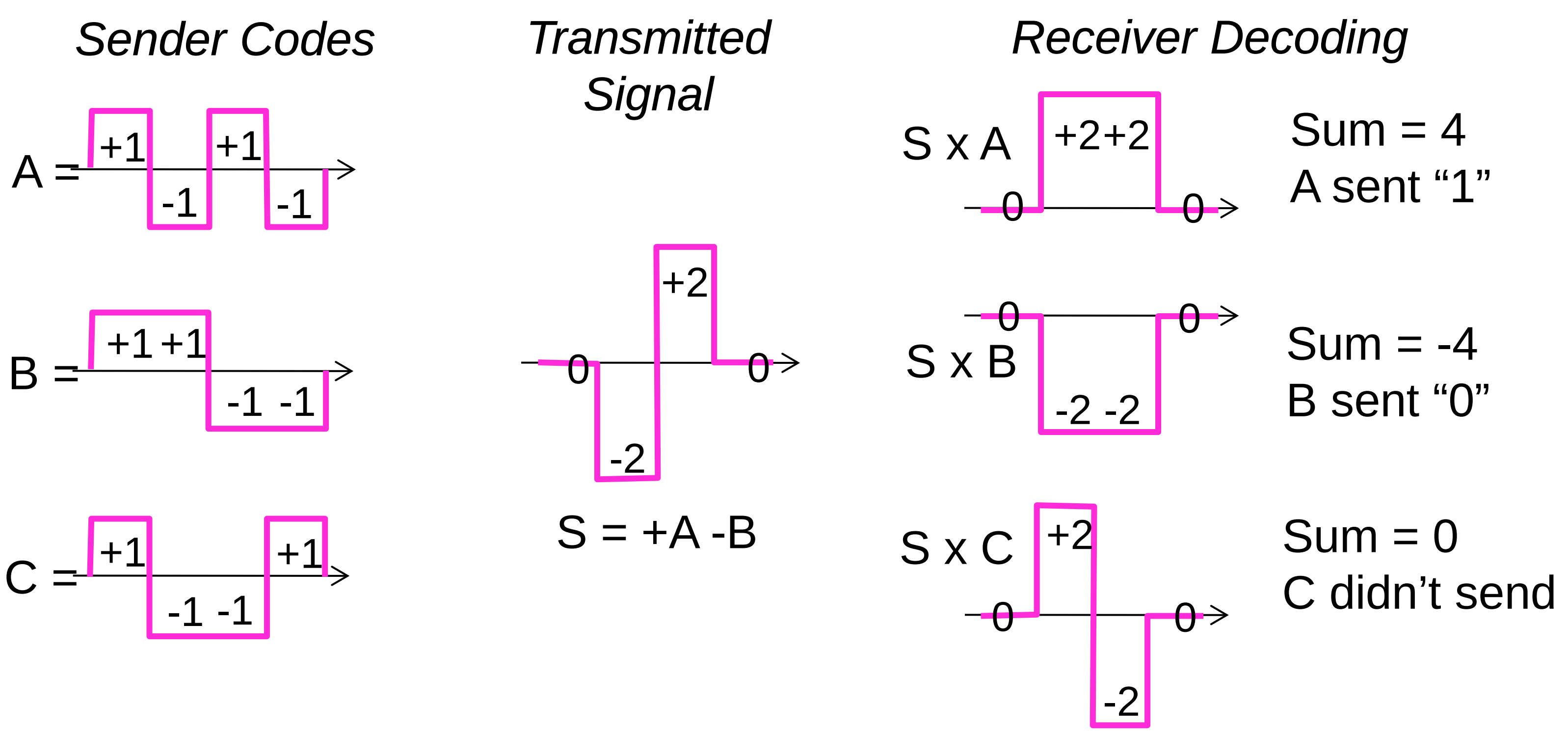
- Users take turns on a fixed schedule; this is not packet switching or STDM (Statistical TDM)
- Widely used in telephone / cellular systems



Code Division Multiple Access (CDMA)

CDMA shares the channel by giving users a code

- Codes are orthogonal; can be sent at the same time
- Widely used as part of 3G networks



Guided Transmission (Wires & Fiber)

Media have different properties, hence performance

- Reality check
  - Storage media »
- Wires:
  - Twisted pairs »
  - Coaxial cable »
  - Power lines »
- Fiber cables »

Reality Check: Storage media

Shipping data on tape / disk / DVD can be a sensible option, example:

- Mail one box with 1000 800GB tapes (6400 Tbit)
- Takes one day to send (86,400 secs)
- Data rate is 70 Gbps.

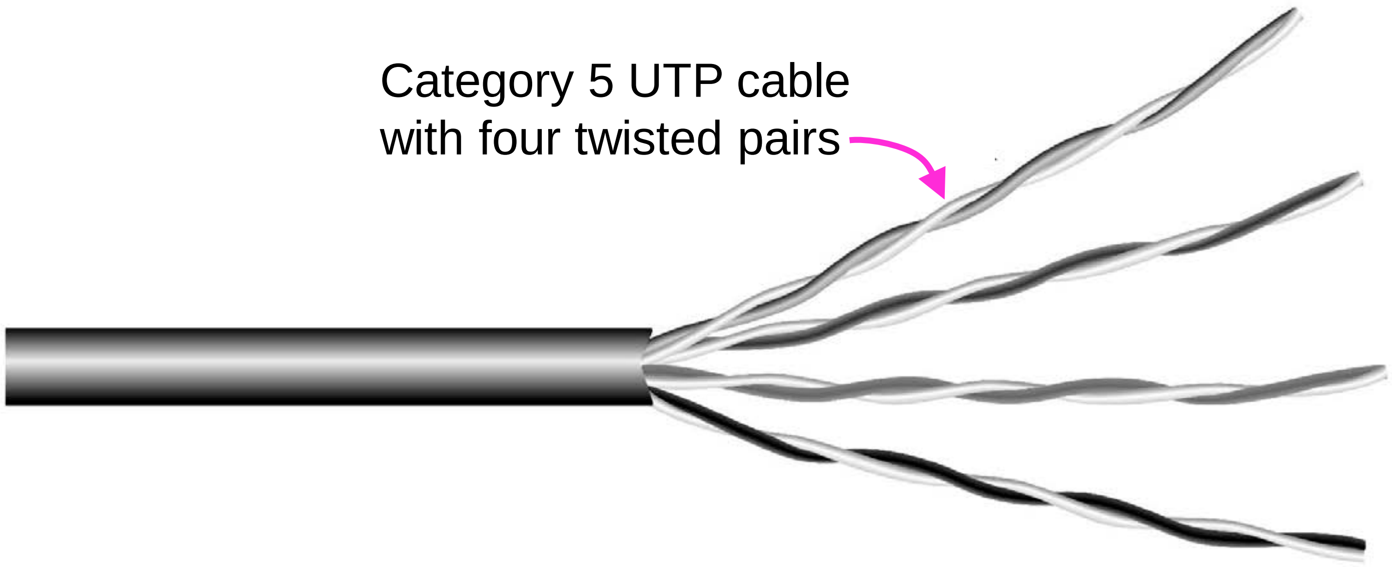
Data rate is faster than long-distance networks!

But, the message delay is very poor.

Wires – Twisted Pair

Very common; used in LANs, telephone lines

- Twists reduce radiated signal (interference)



Link Terminology

Full-duplex link

- Used for transmission in both directions at once
- e.g., use different twisted pairs for each direction

Half-duplex link

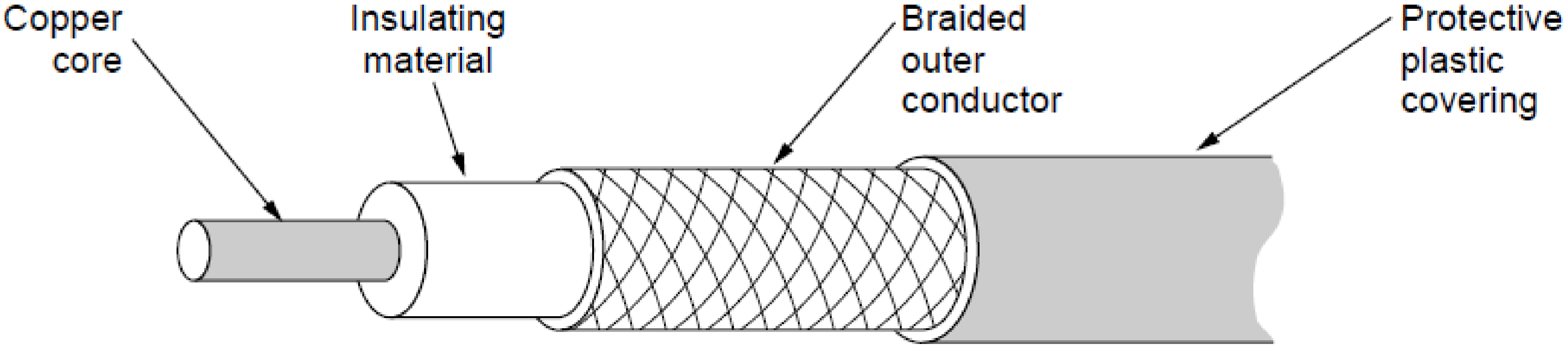
- Both directions, but not at the same time
- e.g., senders take turns on a wireless channel

Simplex link

- Only one fixed direction at all times; not common

Wires – Coaxial Cable (“Co-ax”)

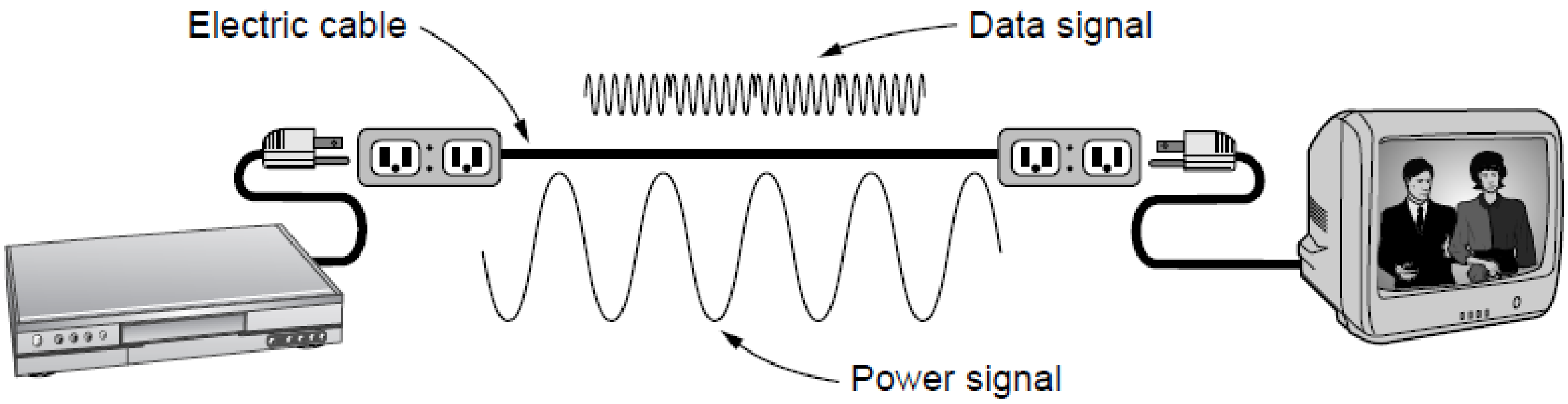
Also common. Better shielding and more bandwidth for longer distances and higher rates than twisted pair.



Wires – Power Lines

Household electrical wiring is another example of wires

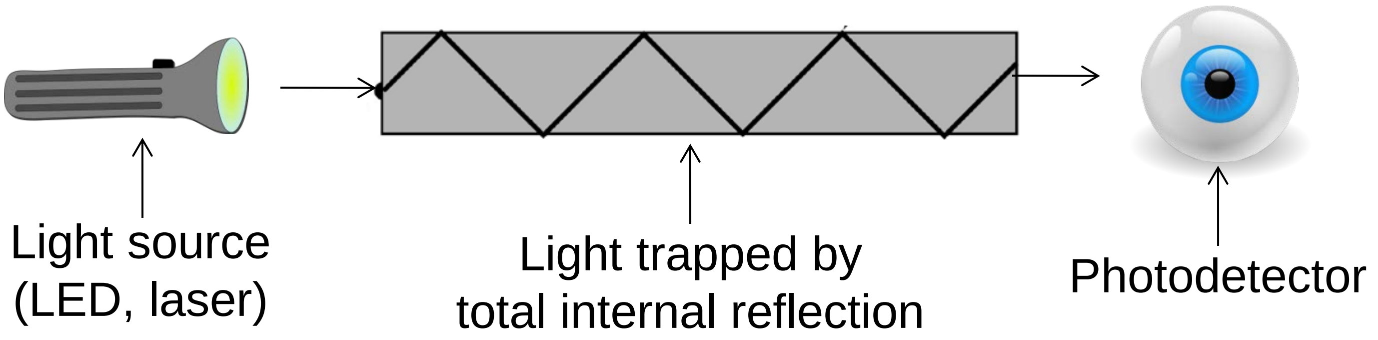
- Convenient to use, but horrible for sending data



Fiber Cables (1)

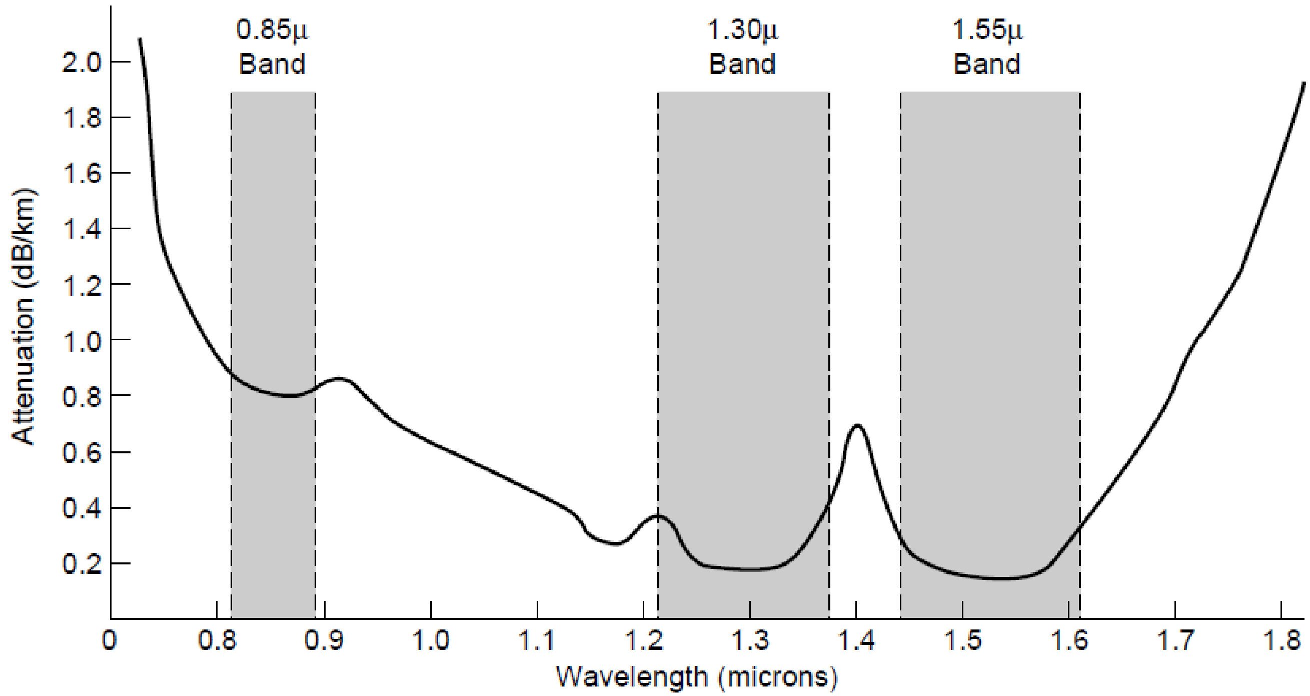
Common for high rates and long distances

- Long distance ISP links, Fiber-to-the-Home
- Light carried in very long, thin strand of glass



Fiber Cables (2)

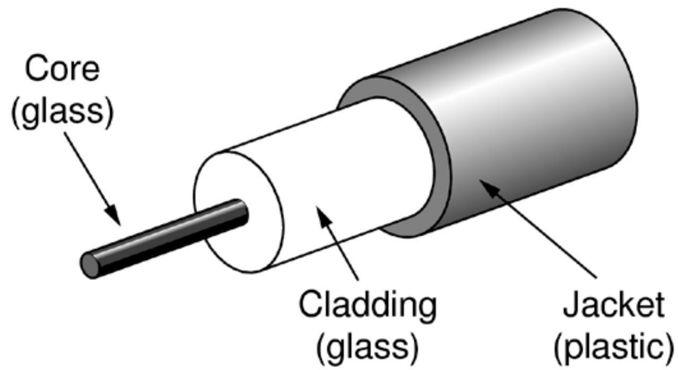
Fiber has enormous bandwidth (THz) and tiny signal loss – hence high rates over long distances



Fiber Cables (3)

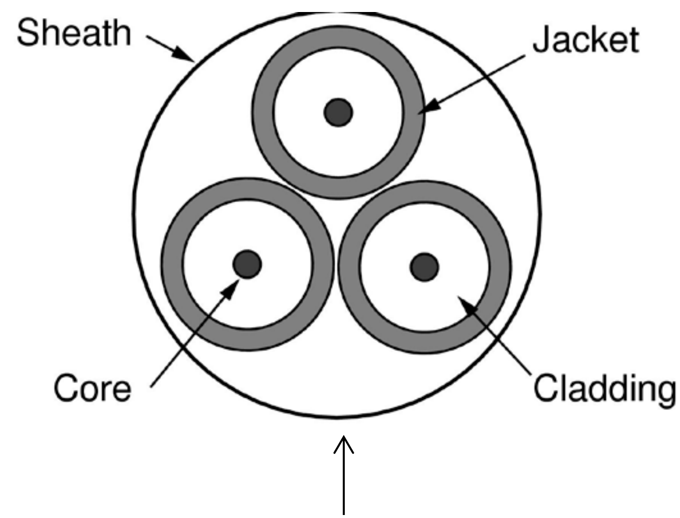
<u>Single-mode</u>

- Core so narrow (10um) light can't even bounce around
- Used with lasers for long distances, e.g., 100km



<u>Multi-mode</u>

- Other main type of fiber
- Light can bounce (50um core)
- Used with LEDs for cheaper, shorter distance links



Fibers in a cable

Fiber Cables (4)

Comparison of the properties of wires and fiber:

Property	**Wires**	**Fiber**
Distance	Short (100s of m)	Long (tens of km)
Bandwidth	Moderate	Very High
Cost	Inexpensive	Less cheap
Convenience	Easy to use	Less easy
Security	Easy to tap	Hard to tap

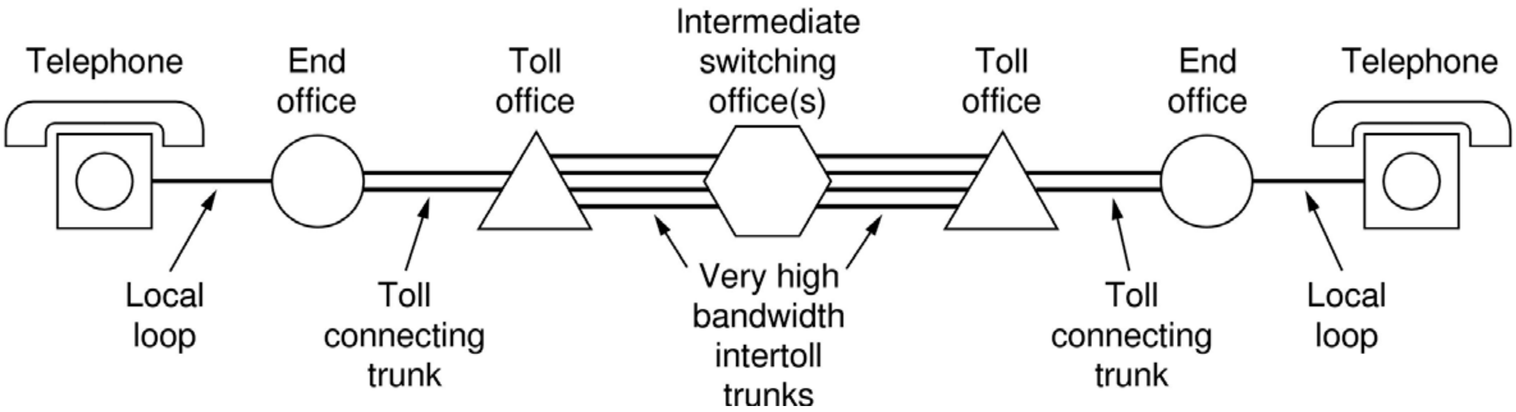
The Public Switched Telephone Network

- Structure of the telephone system »
- Politics of telephones »
- Local loop: modems, ADSL, and FTTH »
- Trunks and multiplexing »
- Switching »

Structure of the Telephone System

A hierarchical system for carrying voice calls made of:

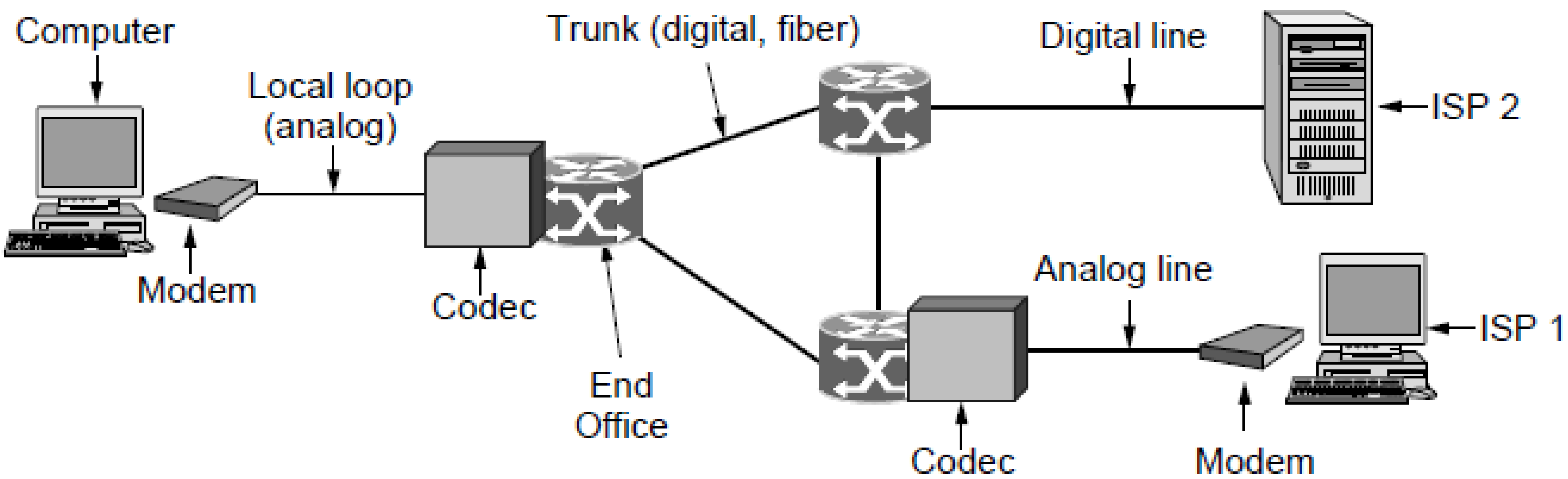
- Local loops, mostly analog twisted pairs to houses
- Trunks, digital fiber optic links that carry calls
- Switching offices, that move calls among trunks



Local loop (1): modems

Telephone modems send digital data over an 3.3 KHz analog voice channel interface to the POTS

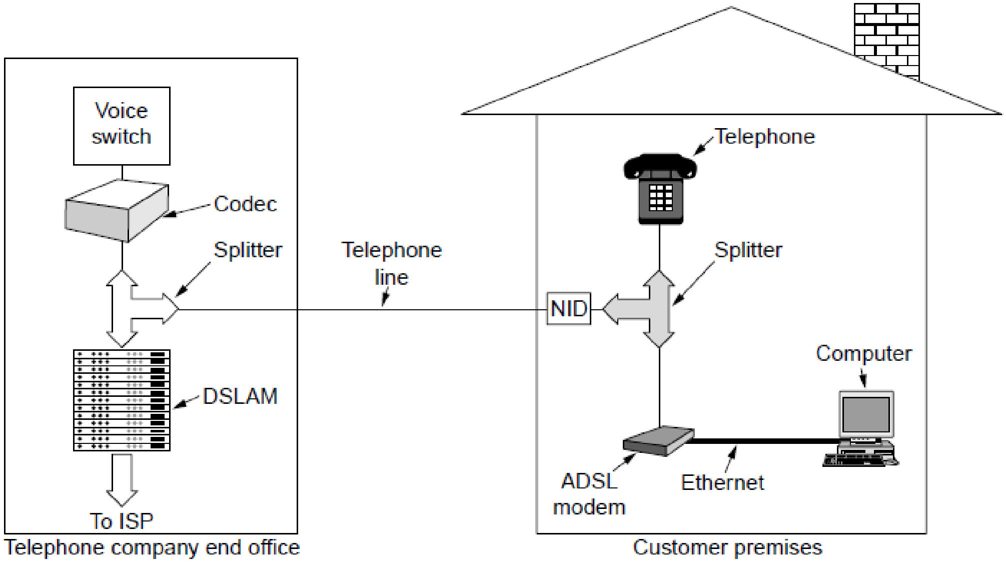
- Rates <56 kbps; early way to connect to the Internet

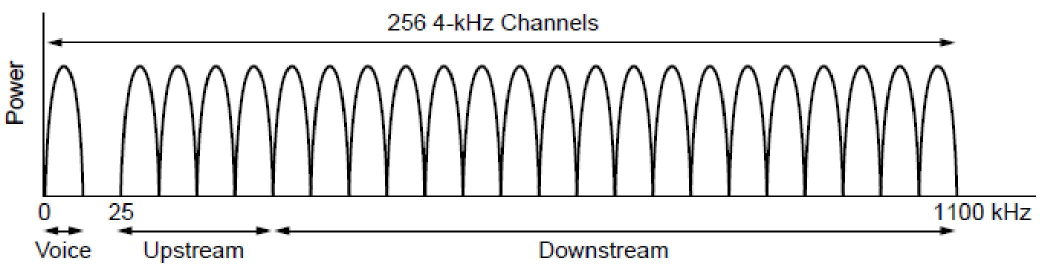


Local loop (2): Digital Subscriber Lines

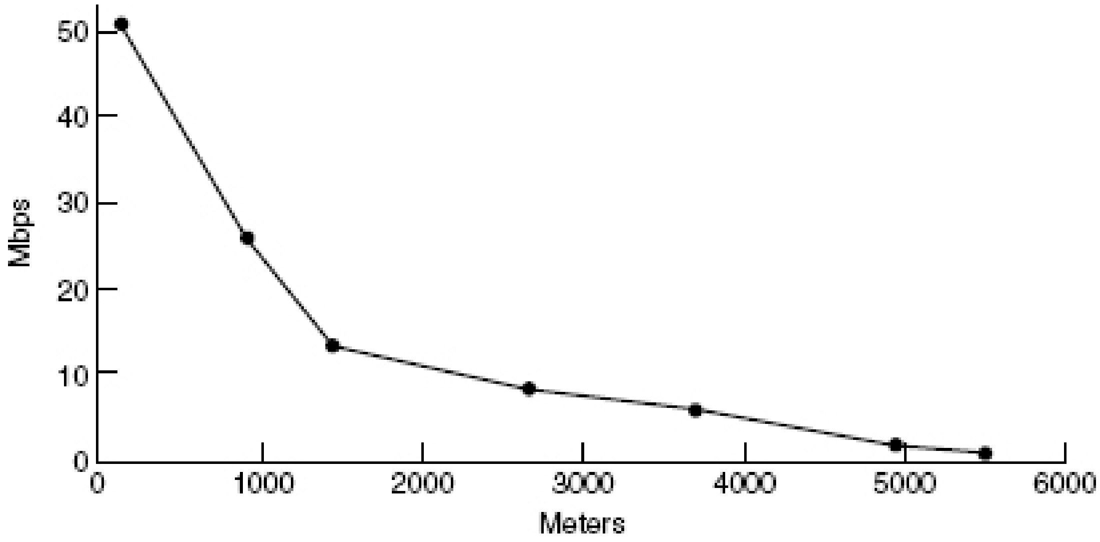
DSL broadband sends data over the local loop to the local office using frequencies that are not used for POTS

- Telephone/computers attach to the same old phone line
- Rates vary with line
  - ADSL2 up to 12 Mbps
- OFDM is used up to 1.1 MHz for ADSL2
  - Most bandwidth down





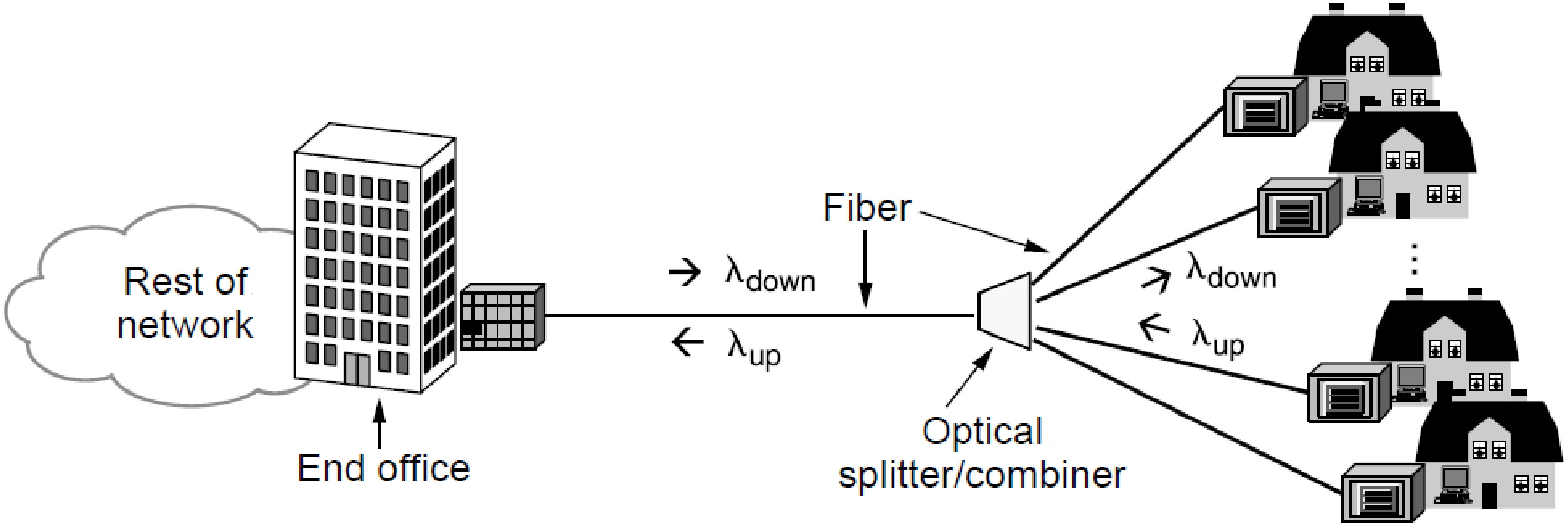
Bandwidth versus distance over Category 3 UTP for DSL



Local loop (3): Fiber To The Home

FTTH broadband relies on deployment of fiber optic cables to provide high data rates to customers

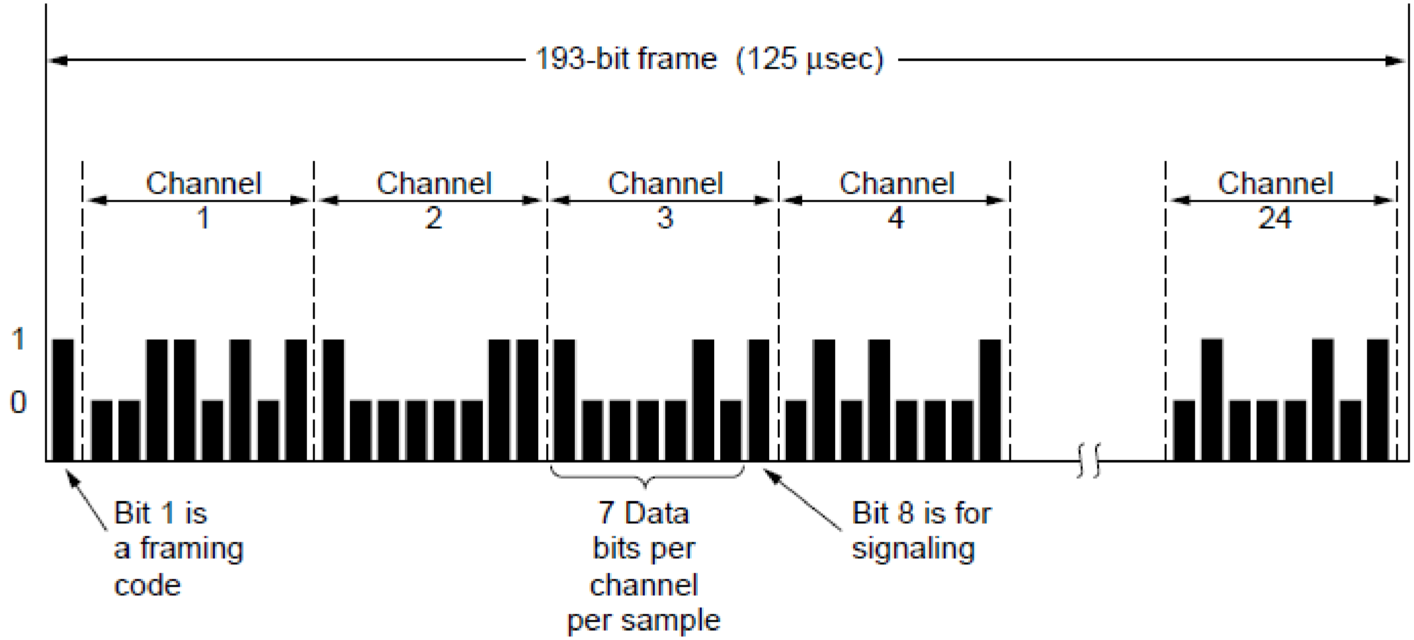
- One wavelength can be shared among many houses
- Fiber is passive (no amplifiers, etc.)



Trunks and Multiplexing (1)

Calls are carried digitally on PSTN trunks using TDM

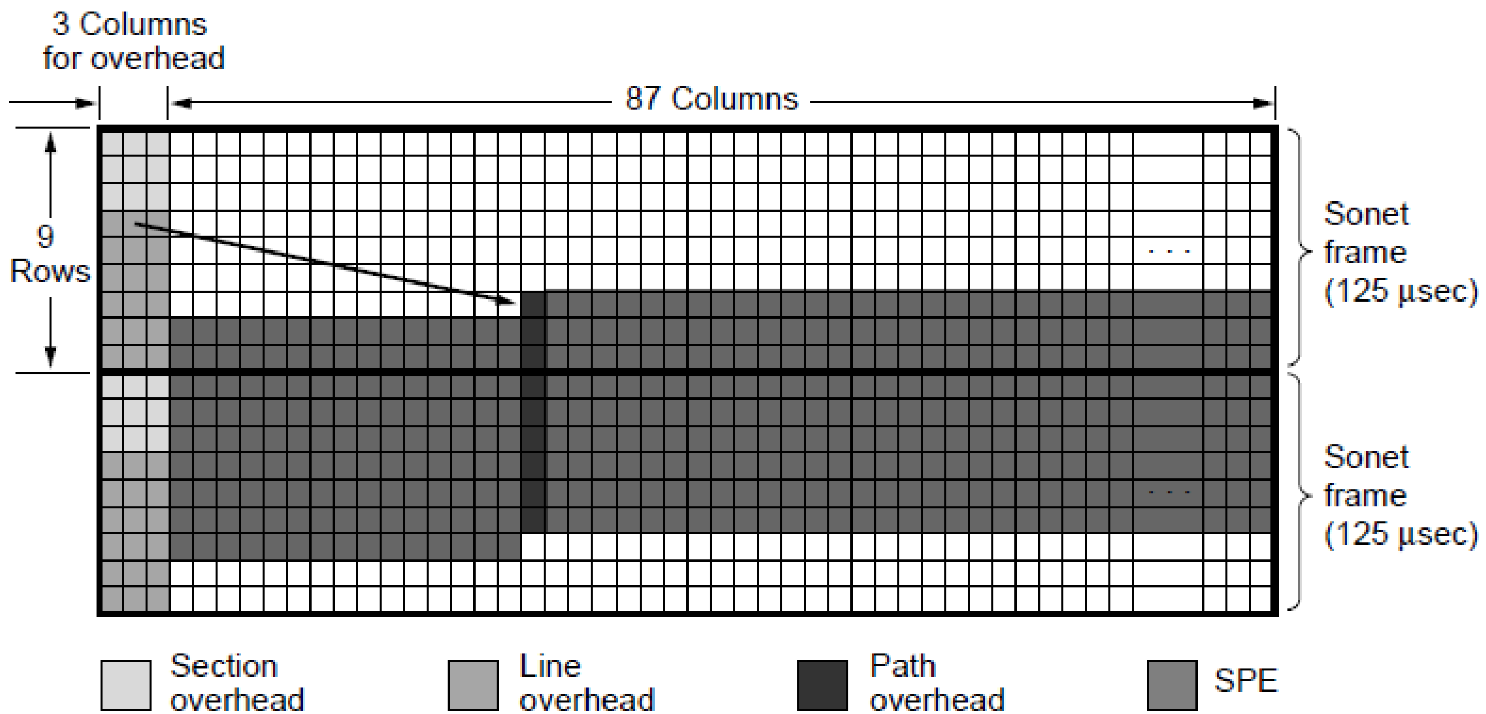
- A call is an 8-bit PCM sample each 125 μs (64 kbps)
- Traditional T1 carrier has 24 call channels each 125 μs (1.544 Mbps) with symbols based on AMI



Trunks and Multiplexing (2)

SONET (Synchronous Optical NETwork) is the worldwide standard for carrying digital signals on optical trunks

- Keeps 125 μs frame; base frame is 810 bytes (52Mbps)
- Payload “floats” within framing for flexibility



Trunks and Multiplexing (3)

Hierarchy at 3:1 per level is used for higher rates

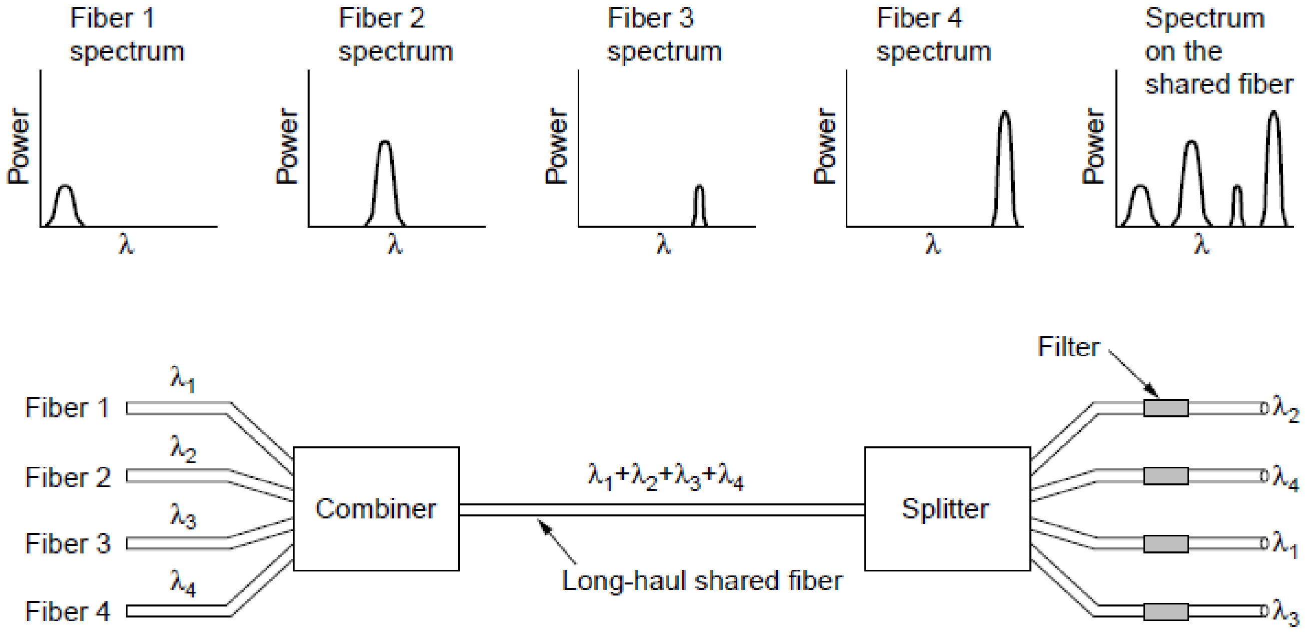
- Each level also adds a small amount of framing
- Rates from 50 Mbps (STS-1) to 40 Gbps (STS-768)

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-12	OC-12	STM-4	622.08	601.344	594.432
STS-48	OC-48	STM-16	2488.32	2405.376	2377.728
STS-192	OC-192	STM-64	9953.28	9621.504	9510.912
STS-768	OC-768	STM-256	39813.12	38486.016	38043.648

SONET/SDH rate hierarchy

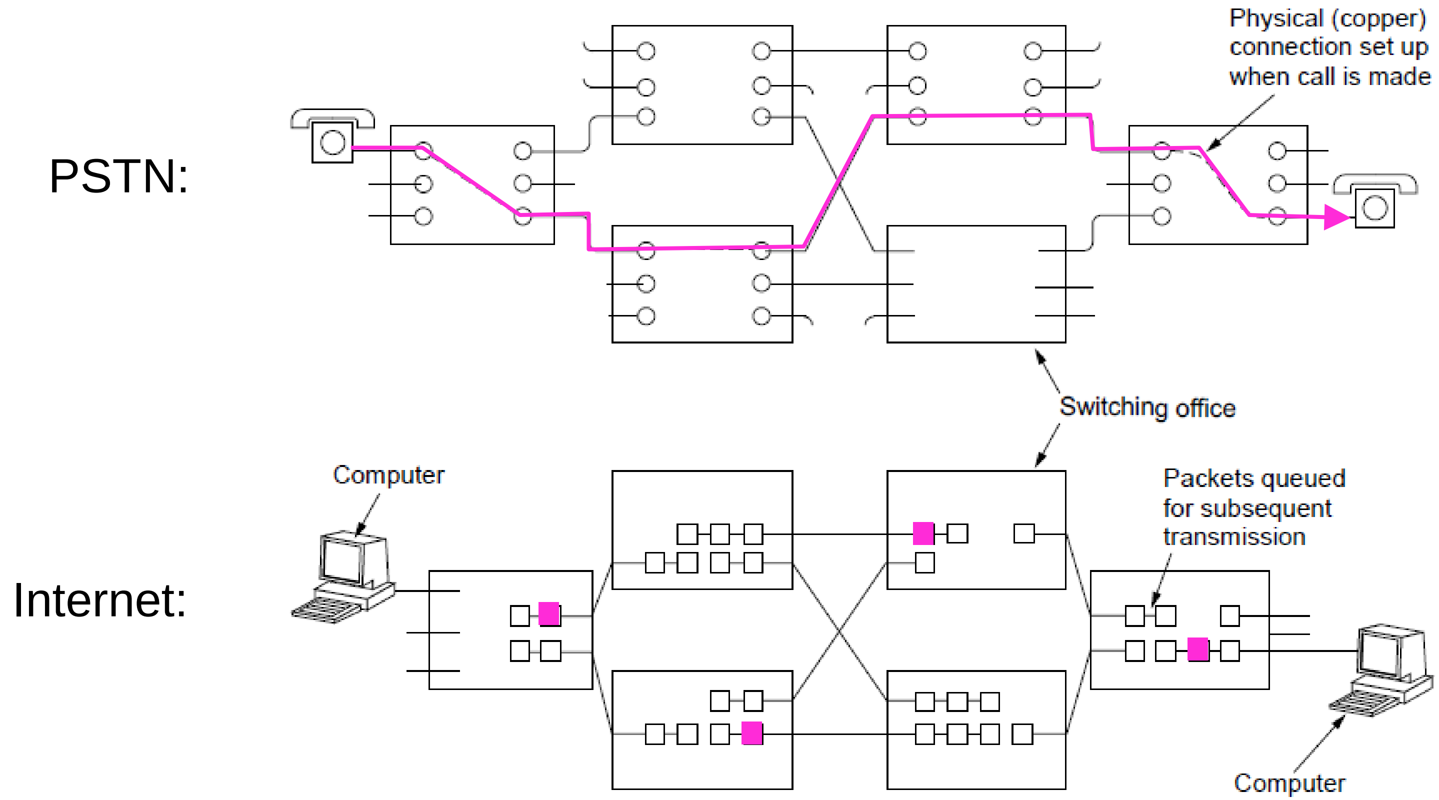
Trunks and Multiplexing (4)

WDM (Wavelength Division Multiplexing), another name for FDM, is used to carry many signals on one fiber:



Switching (1)

PSTN uses circuit switching; Internet uses packet switching



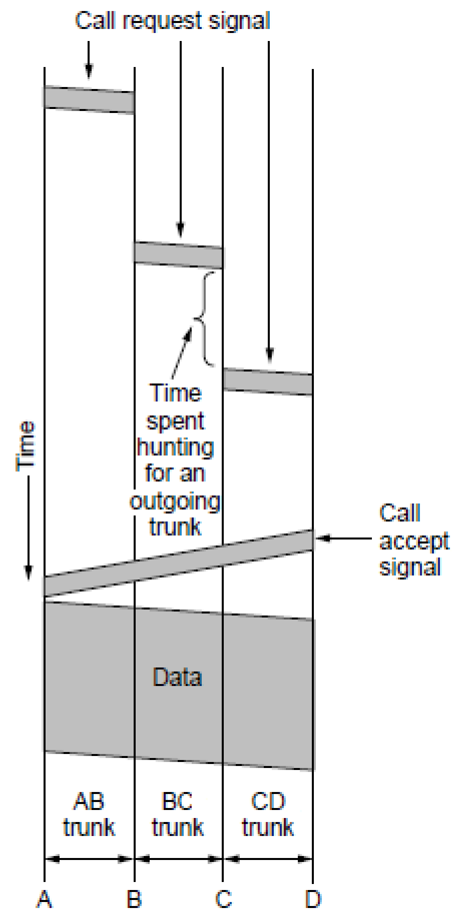
Switching (2)

Circuit switching requires call setup (connection) before data flows smoothly

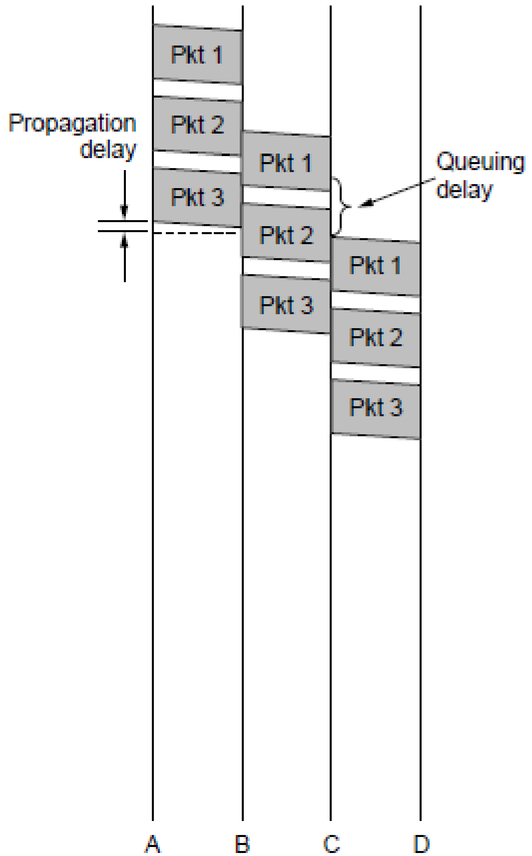
- Also teardown at end (not shown)

Packet switching treats messages independently

- No setup, but variable queuing delay at routers



Circuits



Packets

Switching (3)

Comparison of circuit- and packet-switched networks

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

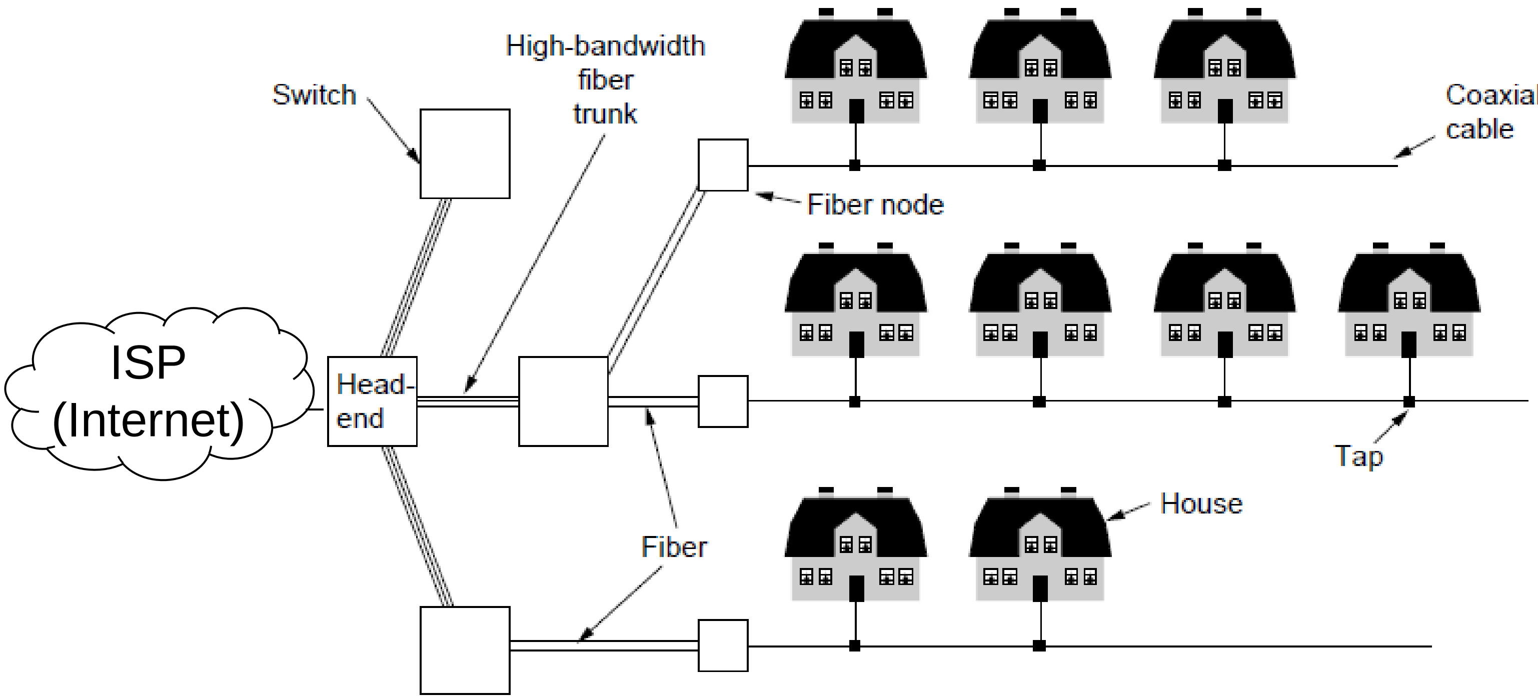
Cable Television

- Internet over cable »
- Spectrum allocation »
- Cable modems »
- ADSL vs. cable »

Internet over Cable

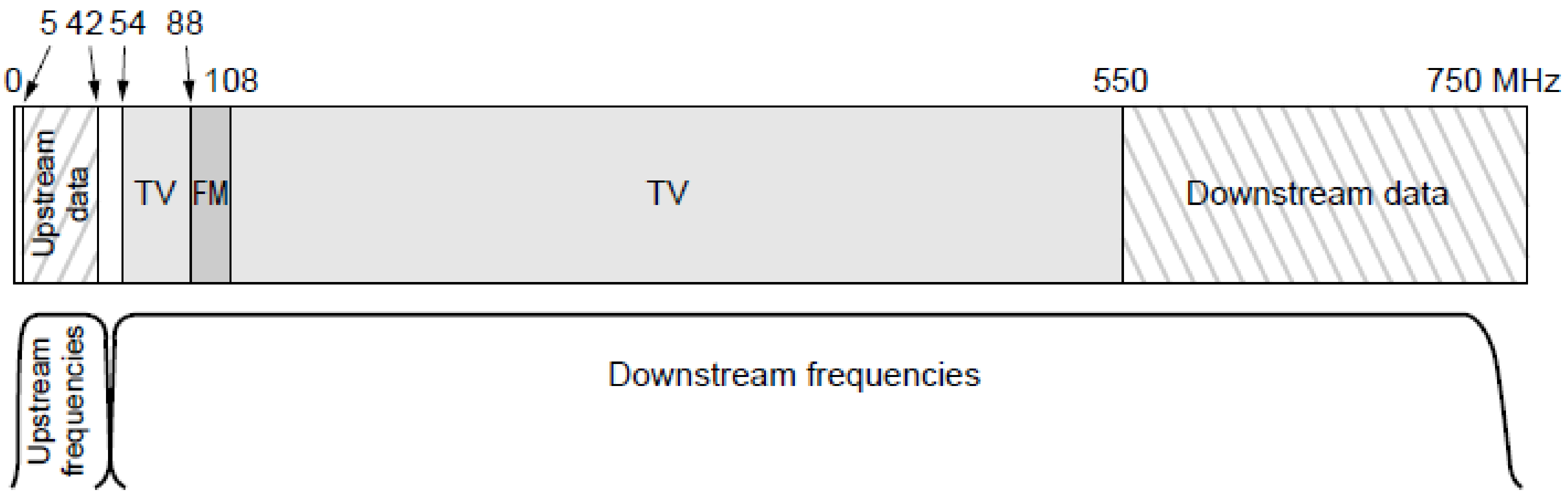
Internet over cable reuses the cable television plant

- Data is sent on the shared cable tree from the head-end, not on a dedicated line per subscriber (as with DSL)



Spectrum Allocation

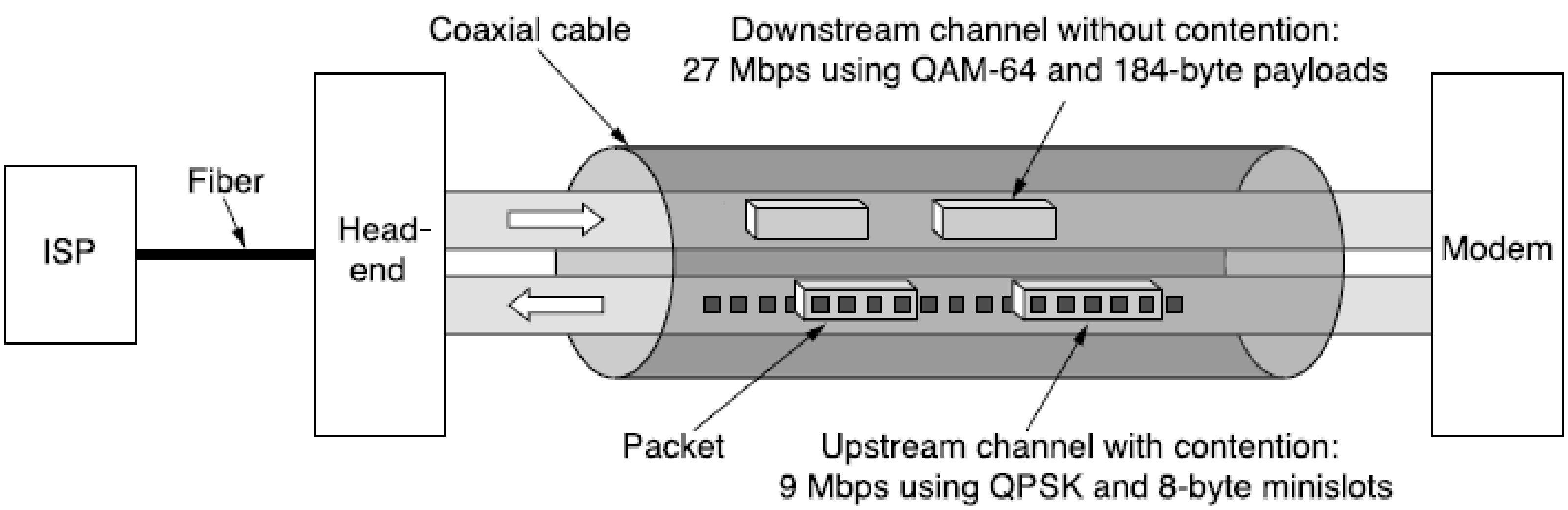
Upstream and downstream data are allocated to frequency channels not used for TV channels:



Cable Modems

Cable modems at customer premises implement the physical layer of the DOCSIS standard

- QPSK/QAM is used in timeslots on frequencies that are assigned for upstream/downstream data



Cable vs. ADSL

Cable:

- \+ Uses coaxial cable to customers (good bandwidth)
- − Data is broadcast to all customers (less secure)
- − Bandwidth is shared over customers so may vary

ADSL:

- \+ Bandwidth is dedicated for each customer
- \+ Point-to-point link does not broadcast data
- − Uses twisted pair to customers (lower bandwidth)