Computer Networks

Chapter 02

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Contents

Physical Layer

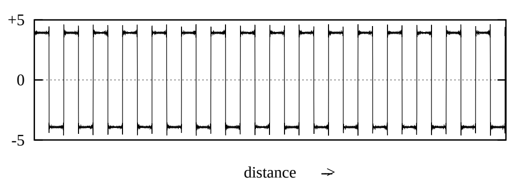
Essence: Provide the means to transmit bits from sender to receiver $\Rightarrow$ involves a lot on how to use (analog) signals for digital information

- Theoretical background: signal transmission and Fourier analysis
- Transmission media (wires and no wires)
- Modulation techniques (the actual encoding), multiplexing, and switching

Transmitting Signals (1/2)

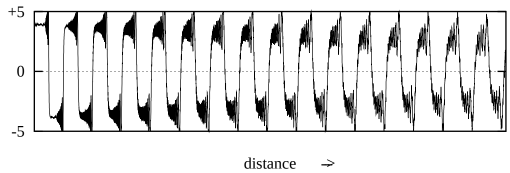
- We're living in a digital world, meaning that we'd preferably want to send digital (i.e. two-valued) signals through wires.
- Wires are pretty much physical, meaning that Mother Nature will probably impose a few constraints here and there.

Observation: Signals are not entirely transmitted through a wire as you would expect:

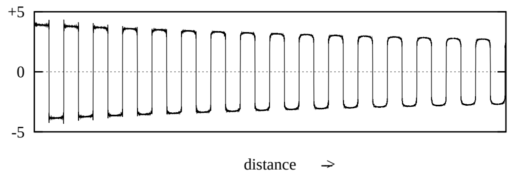


Transmitting Signals (2/2)

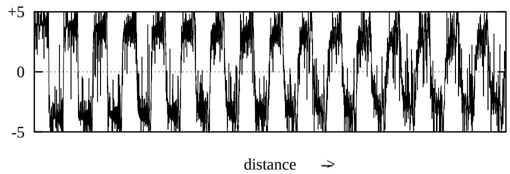
Effect of frequency-dependent **transmission delays**:



Effect of frequency-dependent **attenuation**:



Overall effect including **noise**:

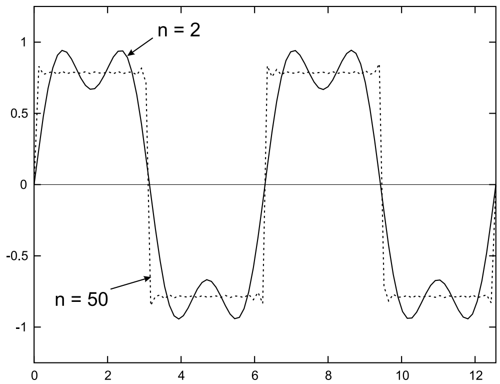


Fourier Analysis (1/2)

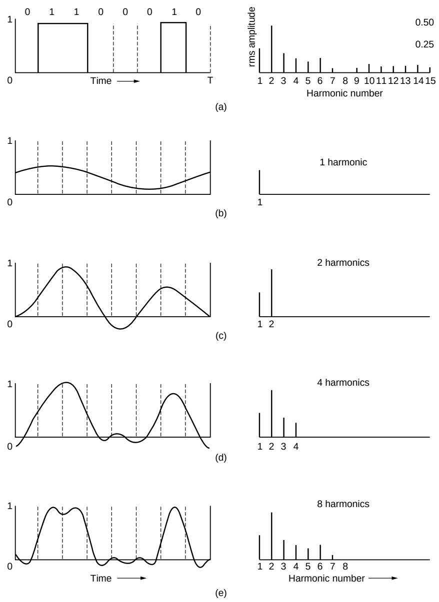
To understand what's going on, we need **Fourier Analysis.** A periodic function with period T (and frequency $f = 1/T$) $g(t)$ can be written as:

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

Example: $g(t) = \sum_{k=1}^{n} \frac{1}{2k-1} \sin[(2k-1)t]$ (n is the number of **harmonics** we take into account)



Fourier Analysis (2/2)



Note: root mean squares (on the right) reflect the dispersed energy at the given frequency.

Bandwidth (1/2)

What does this all mean?

- Digital signal transmission can be thought of as being constructed as an infinite number of periodic analog signals.
- The quality of transmission is frequency dependent $\Rightarrow$ not all parts of the digital signal get through the wire as you would expect.
- Digital signal transmission is subject to attenuation, distortion, etc. This is partly caused by disallowing high-frequency components to pass through (**bandwidth**).

Example: (We are trying to transmit a single byte):

- With a bit rate of b bits/sec, it takes 8/b seconds to send a byte.
- The frequency f_1 of the first harmonic is b/8 Hz.

Bandwidth (2/3)

bps	T (ms)	f_1	# har.
300	26.67	37.5	80
600	13.33	75.0	40
1200	6.67	150.0	20
2400	3.33	300.0	10
4800	1.67	600.0	5
9600	0.83	1200.0	2
19200	0.42	2400.0	1
38400	0.21	4800.0	0

Assumption: We are using a simple encoding technique based on the fact that the line supports only two signal values.

Observation: Most telephone carriers cut off the highest frequency at 3000 Hz $\Rightarrow$ we can never transmit at a higher speed than 9600 bps (and without special encoding, it's much lower)

Bandwidth (3/3)

Improvement: If there are four signal values available, we could encode 2 bits at a time:

$$00 \rightarrow 0 \text{ volt} \quad 01 \rightarrow 2 \text{ volt}$$
$$10 \rightarrow 4 \text{ volt} \quad 11 \rightarrow 6 \text{ volt}$$

The number changes in a signal per second is called the **baud**.

Example 2: A 2400 bauds line (modem) can make a bit rate of 9600 bps provided it uses 16 (2^4) signal values:

S	bits	S	bits	S	bits	S	bits
0	0000	4	0100	8	1000	12	1100
1	0001	5	0101	9	1001	13	1101
2	0010	6	0110	10	1010	14	1110
3	0011	7	0111	11	1011	15	1111

Nyquist & Shannon

Nyquist showed that if the cut-off frequency is H Hz, the filtered signal can be reconstructed by making $2H$ samples. No more, no less. **Consequence:**

maximum transmission rate = $2H\log_2 V$ bps

(where V is the number of signal values)

Shannon showed that a *noisy* channel with a signal-to-noise ration S/R, has a limit with respect to the bit rate:

maximum transmission rate = $H\log_2(1+S/R)$ bps

Example: A telephone line with H = 3000 and $10\log_{10}(S/R) = 30$ dB, can do no better than 30 kbps, no matter how you do your encoding (excluding compression).

Transmission Media Magnetic Tape

Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway

- Take a standard videotape that can carry about 7 gigabytes of data.
- A box of 50 × 50 × 50 cm can hold about 1000 tapes, which corresponds to 7000 gigabytes.
- Sending such a box can be done within 24 hours, worldwide.

We've got a transmission rate of 648 Mbps!

Question: What is overlooked in this reasoning?

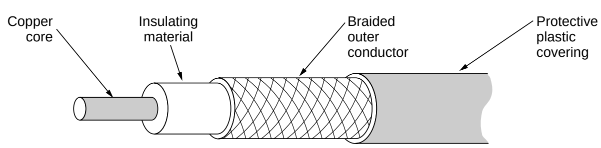
Copper Wires (1/2)

Twisted pair: Two insulated copper wires, twisted like a DNA string (reduces electrical inference). Often, twisted pairs go by the bundle. Comparable to telephone wiring at home.

Further distinction between shielded (STP) and unshielded (UTP) versions, but the shielded ones are primarily used only with IBM installations.

Copper Wires (2/2)

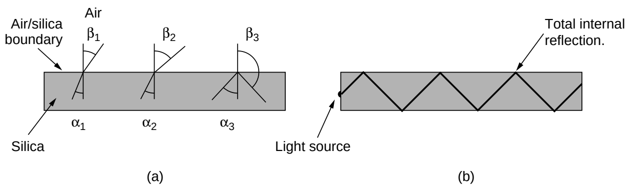
Coax cable: Exactly like the one you use for your TV Set:



Coax is better than twisted pair when you need more bandwidth, but is now rapidly being replaced with fiber.

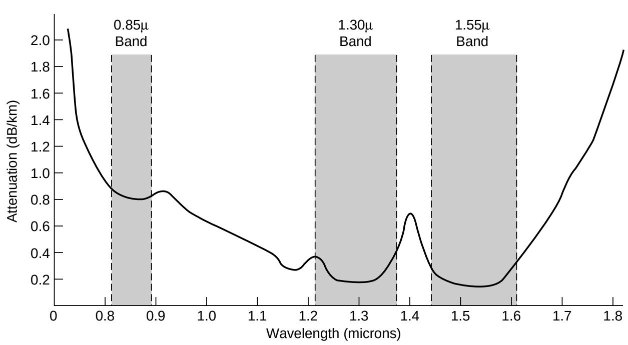
Fiber Optics (1/2)

Principle: Rather than using electrical signals, we use optical ones that are passed through optical fiber. Principal working is based on the refraction property of light:



Fiber Optics (2/2)

As it turns out, attenuation is extremely well in optical fiber. This means that they can be used for long distances. In addition, the bandwidth is enormous.

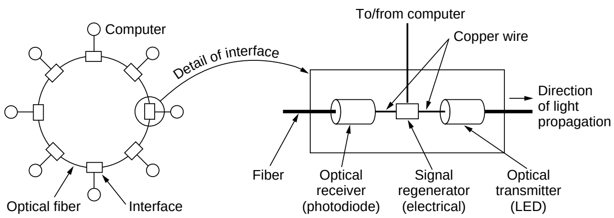


Fiber Connections

Observation: An interface consists of a receiver (photodiode) which transforms light into electrical signals, and/or a transmitter (LED or laserdiode)

Passive interface: A computer is directly connected to the optical fiber

Active interface: There's an ordinary electrical repeater connected to two fiber segments and the computer:



Optical Fiber vs Copper Wire

Bandwidth: Fiber can support enormous bandwidths, exactly what we need with upcoming image-based applications (video-on-demand).

Attenuation: Because the attenuation in fiber is less than in copper (can you imagine why?), we don't need to boost the signal as often. In practice, fiber requires an *active repeater* every 30 km, copper every 5 km.

External influences: That's right, no more interference from other cables, radios, power failures, etc. Crosstalk (you hearing another conversation) is out of the question.

Weight: Fiber simply doesn't weigh as much. Good for backs, bones, and the use of heavy maintenance equipment.

Wireless Transmission (1/3)

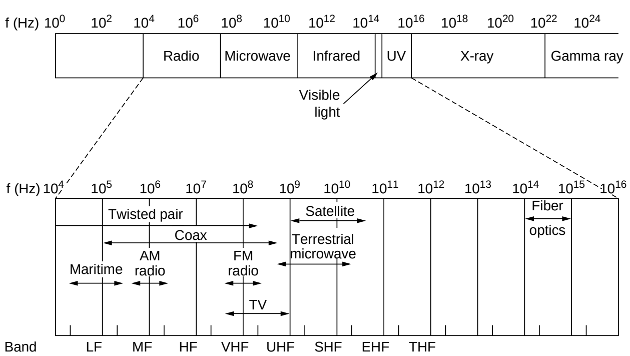
Wireless transmission is really great for all of us who can't sit still, or feel they have to be on-line all the time (watch it – you may miss something). It's also convenient when wiring is needed where it can't be done, or isn't really worth the trouble (jungles, islands, mountains), or because it's just user-unfriendly (homes).

Wireless transmissions travel at the speed of light (c), uses a frequency (f) which has a wavelength (λ):

$$c = \lambda \cdot f$$

The larger the wavelength is, the longer the distance it can travel without attenuation. Also, the dispersion of higher frequencies is much lower.

Wireless Transmission (2/3)



Note: We can encode only a few bits per Hertz in the low frequency range, but much more in the higher ranges. This means that wireless transmission will generally have a much lower bandwidth (in practice: 1-2 Mbps).

Observation: Fiber optics operate in the high frequency range, which explains the transmission rates of gigabits per second.

Wireless Transmission (3/3)

$$c = \lambda \cdot f \Rightarrow \frac{df}{d\lambda} = -\frac{c}{\lambda^2} \Rightarrow \Delta f = -\frac{c \cdot \Delta\lambda}{\lambda^2}$$

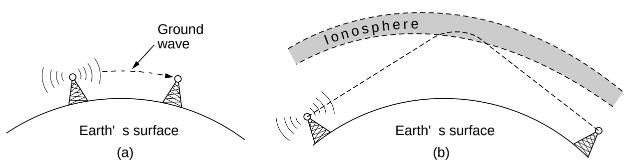
Conclusion: the wider the range, and the shorter the wavelength, the higher the bandwidth. **Example:** Fiber optics often work at $\lambda = 1.3 \times 10^{-6}$ with $\Delta\lambda = 0.17 \times 10^{-6}$ leading to 30 THz bandwidth!

Frequency hopping: Use a wide band, but let the transmitter hop from frequency to frequency (hundreds of times per second). Good for avoiding continuous interference and reducing the effect of reflected signals (you won't be listening to them).

Direct sequence: Simply spread the signal over a wide frequency band (and allow several signals with different encoding/modulation techniques to be transmitted simultaneously).

Wireless Transmission (4/4)

Observation: Radio transmission (VLF–VHF) is extremely popular for its cheapness and range. Also, waves just go all over the place.

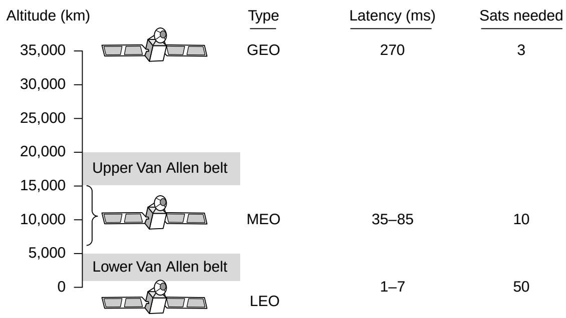


Observation: Microwave transmission is also popular and is good for long distances, as long as it's directed. Problem is the density in the spectrum, requiring higher frequency ranges (which are hard for unguided transmissions)

Communication Satellites

Observation: Satellites are attractive because they provide a relatively simple model of communication: one signal up can be broadcast to many receivers downwards.

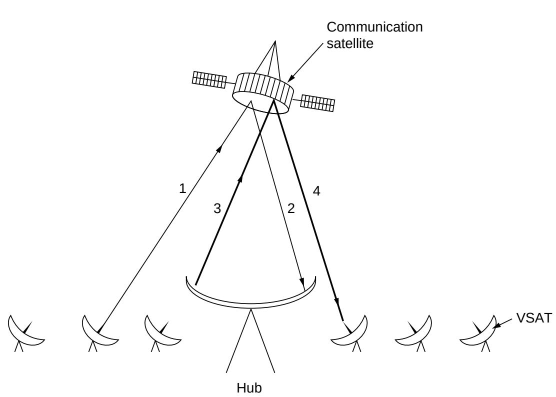
Taking Mother Nature into account (i.e., avoiding belts around the earth consisting of highly-charged particles that would destroy a satellite), there are three types of satellites:



Geostationary Orbit Satellites

Feature: GEO satellites are placed at 35,800 km above the earth where their rotational speed is the same as that of the earth. The effect is that they appear to remain motionless in the sky.

VSATs: Very Small Aperture Terminals – simple systems that output 1 Watt at 19.2 kbps but can download as much as 512 kbps. To allow the VSATs to communicate with each other, hubs are used:

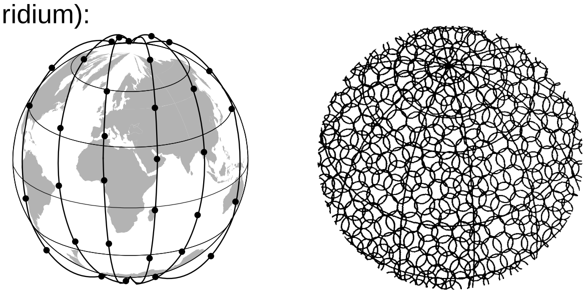


Medium-Earth Orbit Satellites

Example: The Global Positioning System (GPS) orbit at 18,000 km. It takes about 6 hours for a satellite to circle the earth. They are not used for telecommunications.

Low-Earth Orbit Satellites (1/2)

Essence: We throw in a relatively large number of low-orbit satellites which jointly cover the surface of the earth; when you are out of your current satellite's **spot beam**, you should be in that of the next satellite (Iridium):



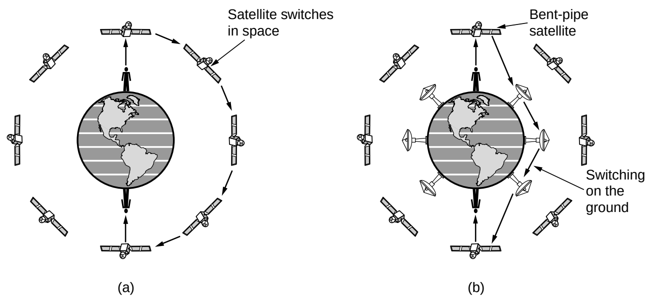
(a) (b)

Note: Iridium uses 66 satellites, each having a maximum of 48 cells (i.e., spot beams), totaling 1628 cells.

Observation: This approach is virtually the same as that of cellular radio, except that the cells are moving instead of the subjects.

Low-Earth Orbit Satellites (2/2)

Alternative: In Globalstar, much of the complexity is handled by ground stations that pick up a connection from a satellite, and pass it on to the one closest to the receiver:



Observation: This scheme avoids much of the complexity for (managing) inter-satellite communication.

Where (not) to use Satellites

Bandwidth: Fiber wins, but not everyone has access to all the available bandwidth. Satellites may make it easier to transfer data anyway

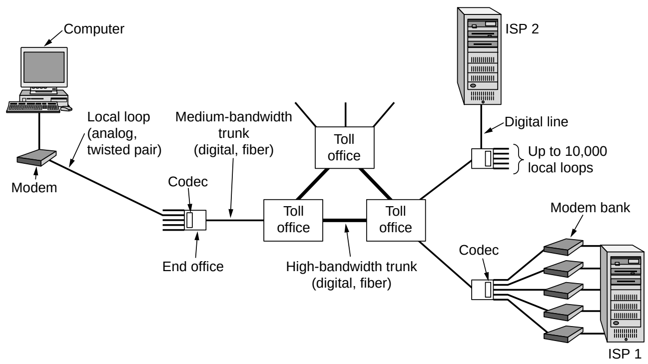
Mobility and remote locations: Satellites win, although it isn't clear whether simple cellular techniques may do just fine

Broadcasting: Satellites win easily: broadcasting essentially comes for free

Fast and reliable: Give credits to fiber: satellites are pretty bad due to inherent high latency (230 ms round-trip for geostationary satellites), and too much Mother Nature (rain!)

The Local Loop

Observation: When it comes the telephone system, from a networking perspective the local loop is the most interesting to look at. The general structure is as follows:

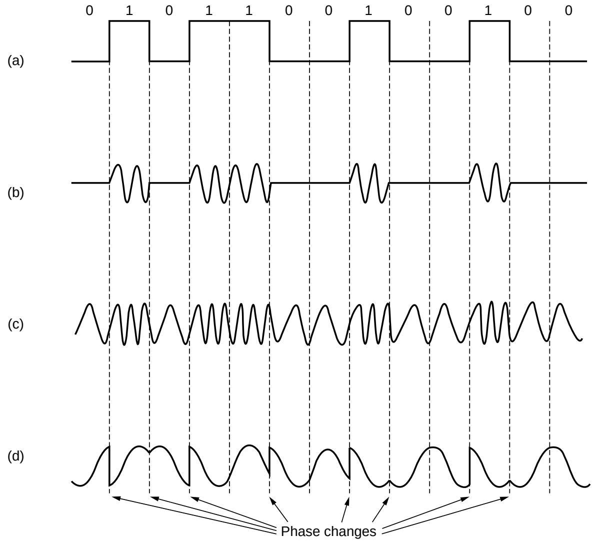


Modulation Techniques (1/3)

Problem: How can we encode our signals when we can effectively use only a single frequency (or better: small frequency range)? **Answer:** Apply **modulation techniques**:

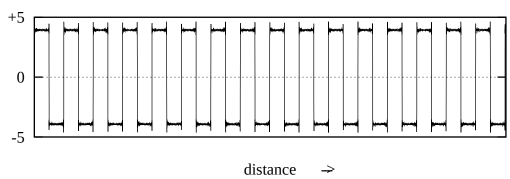
- Change the amplitude (strength) of the signal: changing amplitude means a binary 1, constant amplitude a binary 0.
- Use *two* frequencies to encode your bits (these frequencies can be put “on top” of your base frequency).
- Change the phase of the wave (cf. sine and cosine) to do signal encoding.

Modulation techniques (2/3)

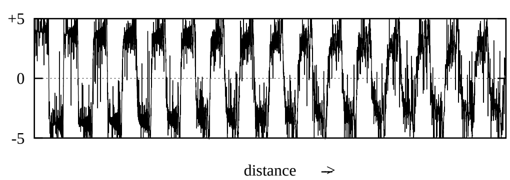


Modulation techniques (3/3)

Observation: Modulation is strongly related to not being able to set a (wide-frequency-ranges) DC signal value on the wire as direct encoding of binary signals:

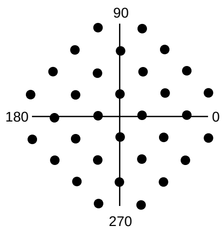


becomes

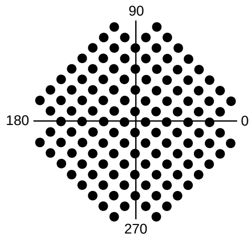


Increasing Transmission Rates

Observation: An important issue is to use low-baud modems for high transmission rates, by increasing the number of signal values $\Rightarrow$ Combine different modulation techniques



(b)



(c)

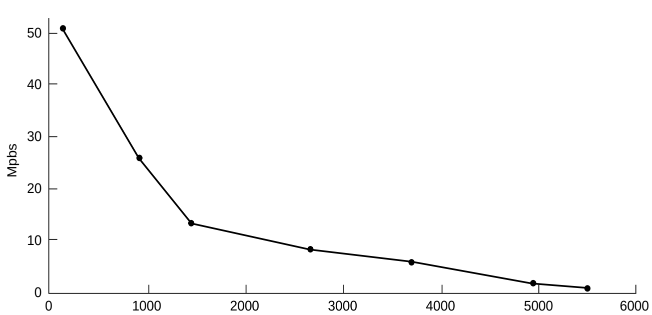
Example: V.32 uses phase-shifting combined with amplitude modulation

Observation: We have to be extremely accurate in being able to detect changes in a signal value. Further improvements are made by also using compression techniques

Digital Subscriber Lines

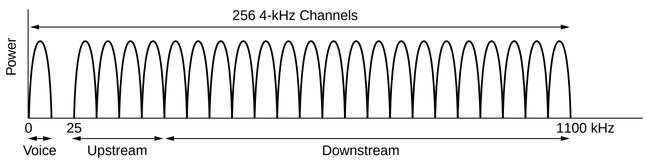
Observation: Traditional telephone modems are artificially limited to a 3000 Hz bandwidth, used to carry voice over analog lines. If we can direct signals to a different switch that does not narrow the bandwidth, much higher transmission rates can be achieved.

Snag: The actual bandwidth capacity that a copper wire can support, is dependent on the distance that a signal needs to be carried:



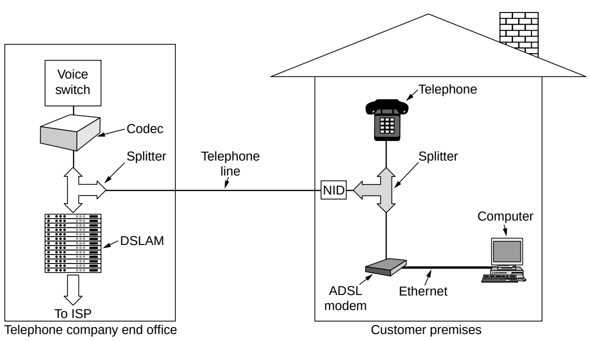
Asymmetric DSL (1/2)

Essence: Considering that the local loop has a 1.1 MHz spectrum, we can divide the spectrum into 256 4kHz channels (like in traditional telephone systems), and divide these into several **logical channels**:



Note: It is up to the provider to decide how it will arrange its channels. Different combinations are possible.

Asymmetric DSL (2/2)

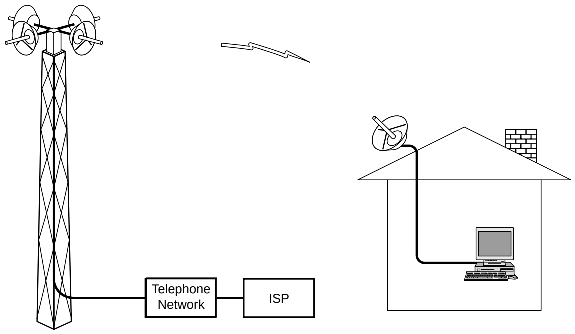


NID	Network Interface Device
DSLAM	DSL Access Multiplexer

Wireless Local Loop

Problem: Suppose you want to start an ISP but using the local loop is out of the question because it is owned by your competitor.

Solution: Set up a wireless direct connection between one of your antennas and your subscribers (in a so-called **sector**):

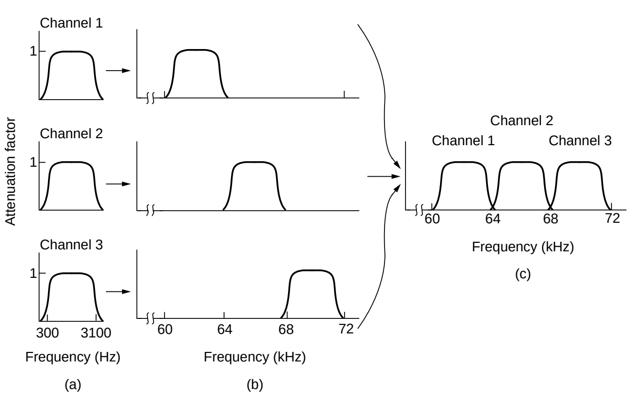


Note: A sector can operate at 36 Gbps downstream bandwidth and 1 Mbps upstream, to be shared by subscribers. The range is about 2–5 km.

Multiplexing: FDM

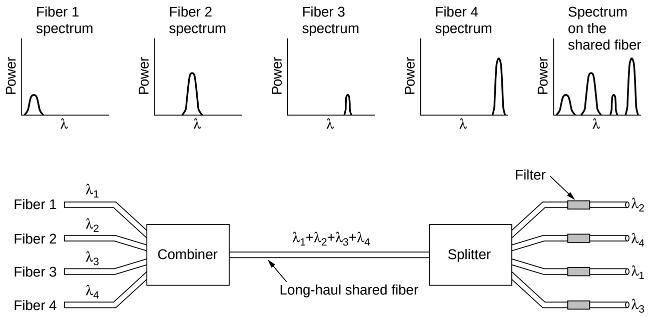
Problem: Considering that the bandwidth of a channel can be huge, wouldn't it be possible to *divide* the channel into sub-channels?

Frequency Division Multiplexing: Divide the available bandwidth into channels through frequency filtering, and apply modulation techniques per channel:



Multiplexing: WDM

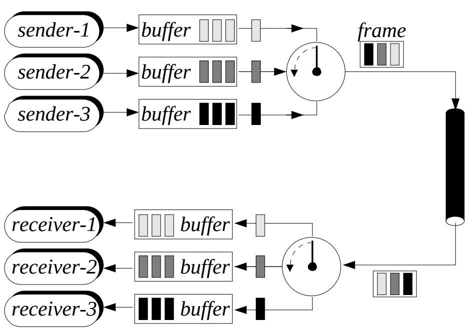
Wavelength Division Multiplexing: Actually the same as FDM, but used for fiber optics.



Observation: Light waves have their own frequency range; they are simply combined and separated using standard (de)fraction properties

Multiplexing: TDM (1/3)

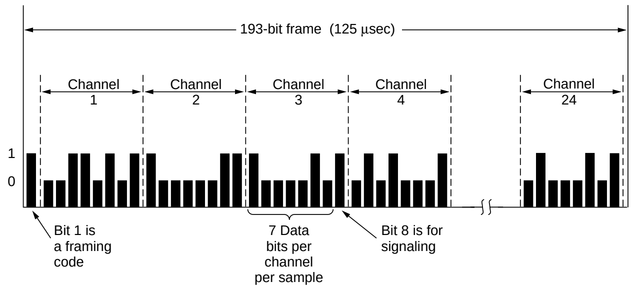
Time Division Multiplexing: Simply merge/split streams of digital data into a new stream. Data is handled in **frames** – a fixed series of consecutive bits:



Observation: This is full-digital solution in contrast to FDM and WDM

Multiplexing: TDM (2/3)

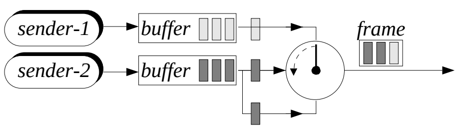
Example: The T1 system samples at 8000 Hz, and encodes each sample as a 7-bit number (i.e. 128 different values). With some extra control bits, we merge samples into 193-bit frames, every 125 μsec:

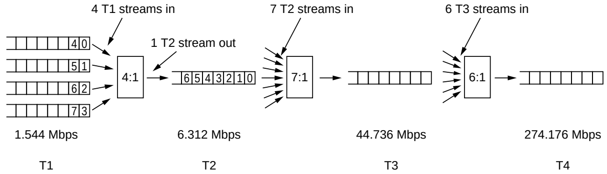


Observation: T1 supports a total of $193 \times \frac{1}{125} \times 10^6$ = 1.544 Mbps

Multiplexing: TDM (3/3)

Observation: TDM also makes it easy to offer individual senders higher bandwidth, by simply putting more data into a frame, or to combine several trunks into higher-bandwidth trunks:

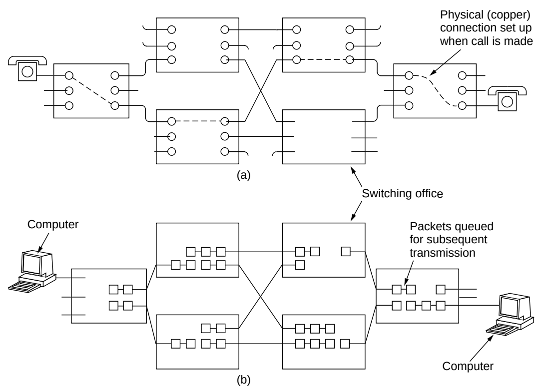




Switching (1/2)

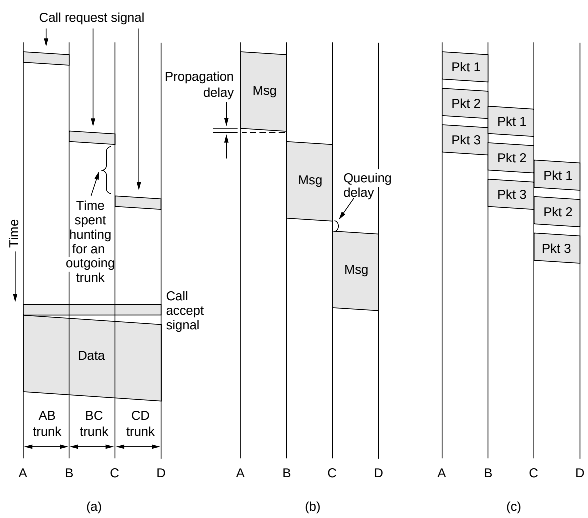
Circuit switching: Make a true **physical** connection from sender to receiver. This is what happens in traditional telephone systems.

Packet switching: (1) Split any data (i.e. message) into small **packets**, (2) route those packets separately from sender to receiver, and (3) assemble them again.



Switching (2/2)

Variation: Store-and-forward switching – a message is completely received at a router, stored, and then put into an outgoing queue for further routing



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

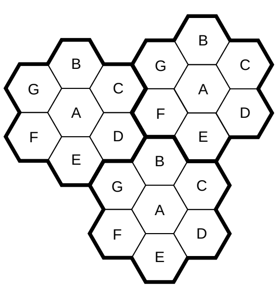
Switching: Comparison

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

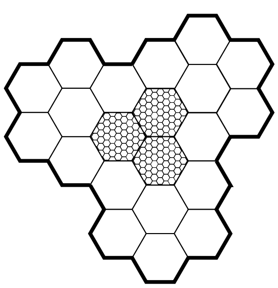
Advanced Mobile Phone System

Cells: The whole idea is to break up an area into small regional cells, each having their own frequency range, and such that no two adjacent cells have the same frequency.

Observation: The approach is pretty good for handling different densities; the problem is frequency allocation and energy emission (you can't "stop" a signal at a cell border)



(a)

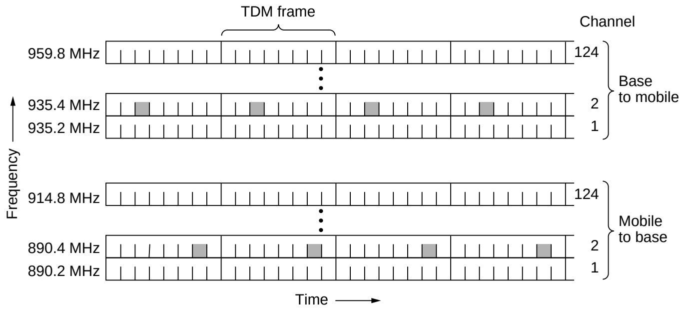


(b)

GSM (1/2)

GSM: Global System for Mobile communications, is used in Europe and is a full-blown digital cellular radio transmission system. A cell has one or more base stations, and uses a unique set of frequencies.

GSM uses 124 **downlink channels**, and 124 **uplink channels** per cell, each channel multiplexed by TDM:



Note: this gives $8 \times 124 = 992$ full duplex channels. A lot of them are not used to avoid interference with neighboring cells.

GSM (2/2)

There are also separate channels for:

- broadcasting cell info (so that a mobile station can see whether it has changed cells).
- cell maintenance (the base station has to know who's in its cell).
- call setup (incoming, and outgoing).

CDMA (1/2)

Code Division Multiple Access allows transmissions to be interleaved, but avoids interference. Note that this means inherently no message collision.

Principle: Assign a **chip sequence** to a station, which is just an m-bit code. Make sure that all chip sequences are pairwise orthogonal:

- rewrite a binary 0 as -1, and a binary 1 as +1.
- for every two chip sequences $\mathbf{S}$ and $\mathbf{T}$: $\frac{1}{m}\sum_{i=1}^{m} S_i T_i = 0$.
- send a 1 bit as yo<u>ur</u> chip sequence ($\mathbf{S}$), and a 0 bit as the inverse ($\mathbf{S}$).
- just transmit your bits when a new bit time slot starts $\Rightarrow$ the (possibly inversed) chip sequences are just added.
- getting the original value means taking the inner product of the original chip sequence with the signal sent.

CDMA (2/2)

(a)	(b)
A: 0 0 0 1 1 0 1 1	A: (–1 –1 –1 +1 +1 –1 +1 +1)
B: 0 0 1 0 1 1 1 0	B: (–1 –1 +1 –1 +1 +1 +1 –1)
C: 0 1 0 1 1 1 0 0	C: (–1 +1 –1 +1 +1 +1 –1 –1)
D: 0 1 0 0 0 0 1 0	D: (–1 +1 –1 –1 –1 –1 +1 –1)

Six examples:

– – 1 –	**C**	S_1 = (–1 +1 –1 +1 +1 +1 –1 –1)
– 1 1 –	**B** + $\underline{\mathbf{C}}$	S_2 = (–2 0 0 0 +2 +2 0 –2)
1 0 – –	**A** + $\underline{\mathbf{B}}$	S_3 = (0 0 –2 +2 0 –2 0 +2)
1 0 1 –	**A** + **B** + **C**	S_4 = (–1 +1 –3 +3 +1 –1 –1 +1)
1 1 1 1	**A** + **B** + **C** + **D**	S_5 = (–4 0 –2 0 +2 0 +2 –2)
1 1 0 1	**A** + **B** + $\overline{\mathbf{C}}$ + **D**	S_6 = (–2 –2 0 –2 0 –2 +4 0)

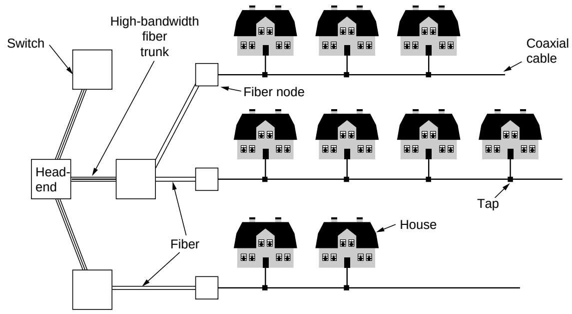
(c)

$S_1 \bullet C = (1 +1 +1 +1 +1 +1 +1 +1)/8 = 1$
$S_2 \bullet C = (2 +0 +0 +0 +2 +2 +0 +2)/8 = 1$
$S_3 \bullet C = (0 +0 +2 +2 +0 -2 +0 -2)/8 = 0$
$S_4 \bullet C = (1 +1 +3 +3 +1 -1 +1 -1)/8 = 1$
$S_5 \bullet C = (4 +0 +2 +0 +2 +0 -2 +2)/8 = 1$
$S_6 \bullet C = (2 -2 +0 -2 +0 -2 -4 +0)/8 = -1$

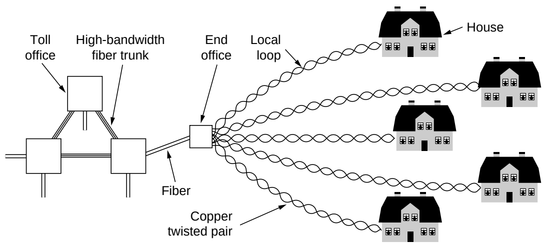
(d)

Question: doesn't this look a lot like linear algebra?

Cable Television



(a)

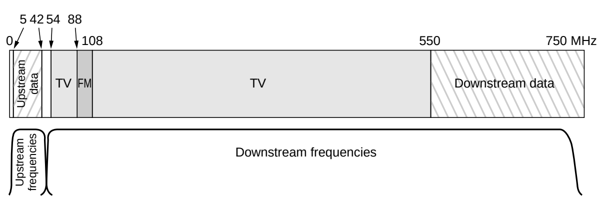


(b)

Observation: Cable requires sharing whereas the telephone system does not.

Cable Television: Principle

Essence: It's quite simple: there's a lot of unused bandwidth that can be allocated to sending bits over the wire:



Note: Because downstream (television) starts at 54 MHz, there is limited bandwidth that can be used for upstream data.

Cable Television Streams

Observation: The downstream data always comes from one source, which makes it easier to handle. Upstream data requires that subscribers contend for available slots: