The Physical Layer

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The Physical Layer

- The Physical Layer
  - The lowest layer in our protocol model, is the foundation on which the network is built.
  - It defines the electrical, timing and other interfaces by which **bits** are sent as signals over channels.
  - The performance of different kinds of physical channels: **throughput**, **latency (delay)** and **error rate**.

Outline

- The theoretical basis for data communication
- Three kinds of transmission media
- Digital modulation and multiplexing
- Three examples of communication examples

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- The theoretical basis for data communication
- Three kinds of transmission media
- Digital modulation and multiplexing
- Three examples of communication examples

Theoretical Basis — Fourier Series

- Information can be transmitted on wires by varying some physical property such as *voltage* or *current*.
  - By representing the value of this voltage or current as a single-valued function of time, $f(t)$, we can model the behavior of the signal of analyze it mathematically.
- Fourier Series [2] $g(t) = g(t + nT_0)$
  - In the early 19th century, the French mathematician Jean-Baptiste Fourier proved that any *reasonably behaved* **periodic** function $g(t)$ with the fundamental period T_0 can be represented as

$$\boxed{g(t) = \sum_{n=-\infty}^{+\infty} a_n e^{j2\pi f_0 n t}}$$

where $f_0 = 1/T_0$ is **the fundamental frequency** of the periodic signal $g(t)$

  - If the fundamental period T_0 is known and the amplitudes a_n are given, the original periodic signal $g(t)$ can be reconstructed.

$$\boxed{a_n = \frac{1}{T}\int_T g(t) e^{-j2\pi f_0 n t} dt}$$

Theoretical Basis — Fourier Series

$$\boxed{g(t)=\sum_{n=-\infty}^{+\infty}a_n e^{j2\pi f_0 nt}=\sum_{n=-\infty}^{+\infty}a_n(\cos(2\pi f_0 nt)+j\sin(2\pi f_0 nt))}$$

- If $g(t)$ is a **real** signal, then the coefficient a_{-n} is **the conjugate** of a_n.

$$\boxed{g(t)=C+\sum_{n=1}^{\infty}2A_n\cos(2\pi nf_0 t)+\sum_{n=1}^{\infty}2B_n\sin(2\pi nf_0 t)} \quad (2\text{-}1)$$

$$A_n=\frac{1}{T_0}\int_{T_0}g(t)\cos(2\pi nf_0 t)dt \quad B_n=\frac{1}{T_0}\int_{T_0}g(t)\sin(2\pi nf_0 t)dt \quad C=\frac{1}{T}\int_{T}g(t)dt$$

- But in real world, a data signal is **NOT** periodic and has **a finite duration**. We can imagine that it repeats the entire pattern over and over forever (i.e., the interval from T to 2T is the same as from 0 to T, etc.).

Theoretical Basis — Fourier Series

$$a_n e^{j2\pi f_0 nt} + a_{-n} e^{-j2\pi f_0 nt}$$

$$Let \quad a_n = A_n - jB_n$$

$$(A_n - jB_n)e^{j2\pi f_0 nt} + (A_n + jB_n)e^{-j2\pi f_0 nt}$$

$$= (A_n - jB_n)\{\cos(2\pi f_0 nt) + j\sin(2\pi f_0 nt)\} + (A_n + jB_n)\{\cos(2\pi f_0 nt) - j\sin(2\pi f_0 nt)\}$$

$$= 2A_n \cos(2\pi f_0 nt) + 2B_n \sin(2\pi f_0 nt)$$

$$\boxed{g(t) = C + \sum_{n=1}^{\infty} 2A_n \cos(2\pi n f_0 t) + \sum_{n=1}^{\infty} 2B_n \sin(2\pi n f_0 t)}$$

Theoretical Basis — Fourier Series

$$\boxed{g(t) = C + \sum_{n=1}^{\infty} 2A_n \cos(2\pi n f_0 t) + \sum_{n=1}^{\infty} 2B_n \sin(2\pi n f_0 t)} \quad (2\text{-}1)$$

- The B_n amplitudes can computed for any given $g(t)$ by multiplying both sides of Eq.(2-1) by $\sin(2\pi n f_0 t)$ and then integrating from 0 to T_0.

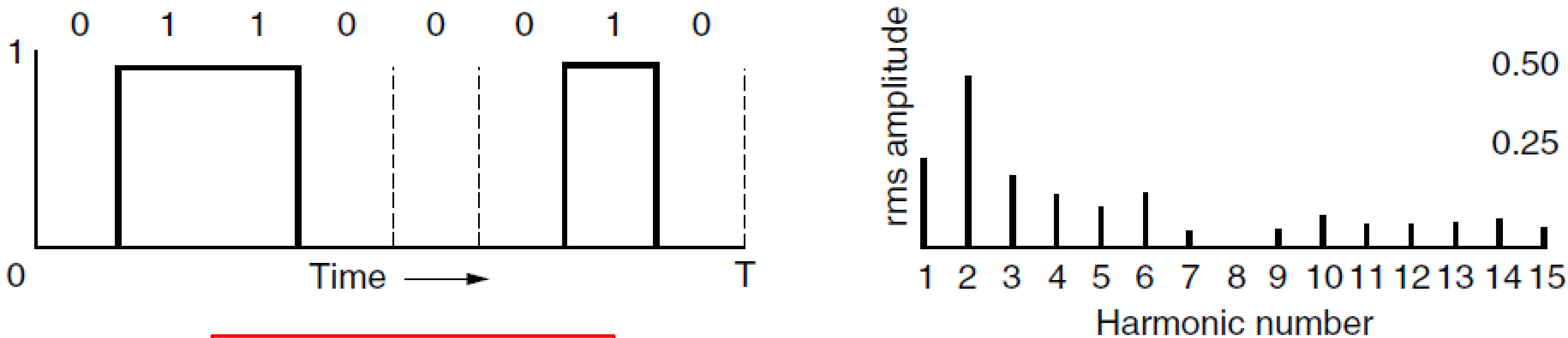
$$\int_0^{T_0} \sin(2\pi k f_0 t)\sin(2\pi n f_0 t)dt = \begin{cases} 0 & k \neq n \\ T_0/2 & k = n \end{cases}$$

$$\int_0^{T_0} \sin^2(2\pi k f_0 t)dt = \int_0^{T_0} \frac{1-\cos(4\pi k f_0 t)}{2} dt = \frac{T_0}{2} \qquad k = n$$

$$\int_0^{T_0} \frac{1}{2}\{\cos(2\pi(k-n)f_0 t) - \cos(2\pi(k+n)f_0 t)\}dt = 0 \qquad k \neq n$$

- Similarly, by multiplying Eq.(2-1) by $\cos(2\pi n f_0 t)$ and integrating between 0 and T_0, we can derive A_n.

Theoretical Basis — Fourier Series



$T_0 = 8 \Rightarrow f_0 = 1/8$

(a)

$$A_n = \frac{1}{T_0}\int_0^{T_0} g(t)\cos(2\pi n f_0 t)dt \qquad B_n = \frac{1}{T_0}\int_0^{T_0} g(t)\sin(2\pi n f_0 t)dt \qquad C = \frac{1}{T_0}\int_0^{T_0} g(t)dt$$

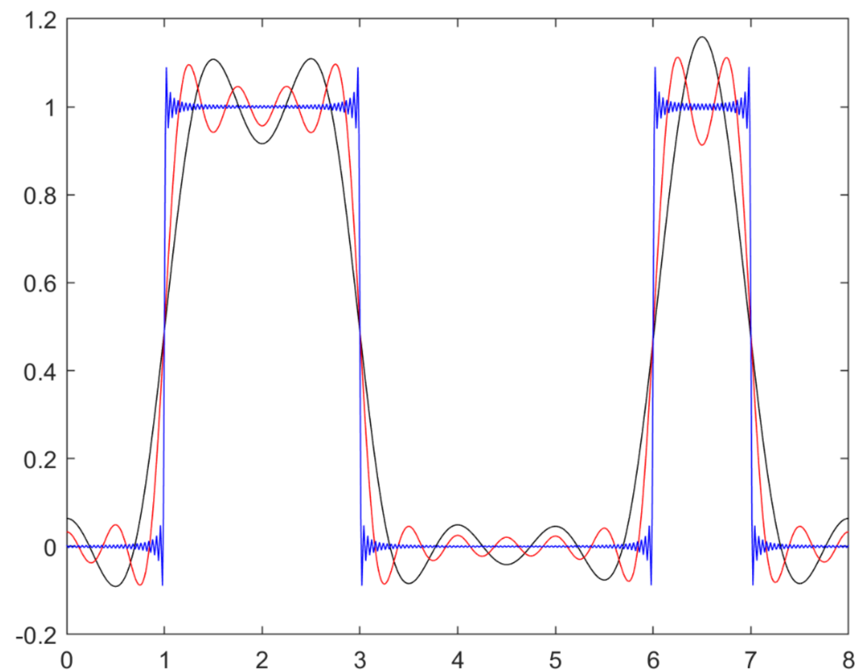
$$C = \frac{1}{T_0}\int_0^{T_0} g(t)dt = \frac{1}{8}\left(\int_1^3 dt + \int_6^7 dt\right) = \frac{1}{8}(2+1) = \frac{3}{8}$$

$$A_n = \frac{1}{T_0}\int_0^{T_0} g(t)\cos(2\pi n f_0 t)dt = \frac{1}{8}\left(\int_1^3 \cos(2\pi n\frac{1}{8}t)dt + \int_6^7 \cos(2\pi n\frac{1}{8}t)dt\right)$$

$$= \frac{1}{2\pi n}\left[\sin(\frac{3\pi n}{4}) - \sin(\frac{\pi n}{4}) + \sin(\frac{7\pi n}{4}) - \sin(\frac{3\pi n}{2})\right]$$

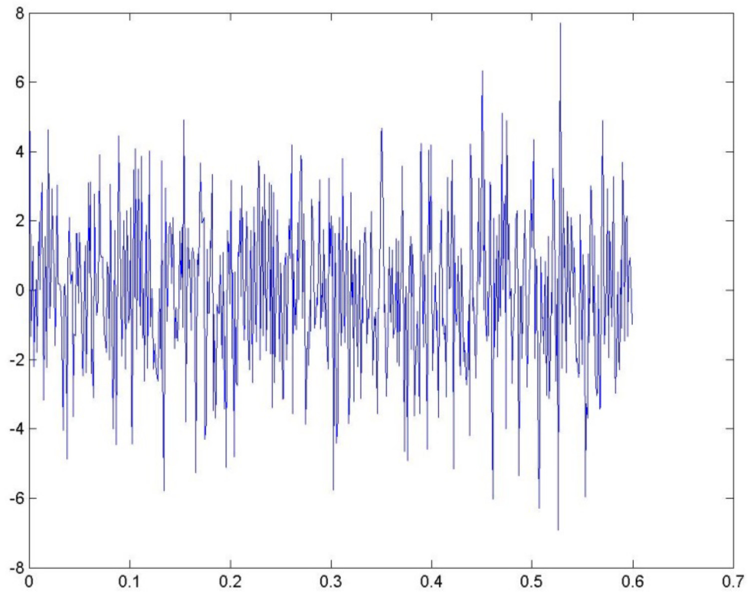
```
% To render the results presented in Fig.2-1
c = 3/8; % the DC component
t = 0:0.01:8;
f = 1/8;

N1 = 8;
g1 = c*ones(1, length(t));
for n = 1:N1
   bn = 1/(pi*n)*(cos(pi*n/4) - cos(3*pi*n/4) + cos(6*pi*n/4) -
cos(7*pi*n/4));
   an = 1/(pi*n)*(sin(3*pi*n/4) - sin(pi*n/4) + sin(7*pi*n/4) -
sin(6*pi*n/4));
   g1 = g1 + bn*sin(2*pi*n*f*t) + an*cos(2*pi*n*f*t);
end

N2 = 15;
g2 = c*ones(1, length(t));
for n = 1:N2
   bn = 1/(pi*n)*(cos(pi*n/4) - cos(3*pi*n/4) + cos(6*pi*n/4) -
cos(7*pi*n/4));
   an = 1/(pi*n)*(sin(3*pi*n/4) - sin(pi*n/4) + sin(7*pi*n/4) -
sin(6*pi*n/4));
   g2 = g2 + bn*sin(2*pi*n*f*t) + an*cos(2*pi*n*f*t);
end

N3 = 200;
g3 = c*ones(1, length(t));
for n = 1:N3
   bn = 1/(pi*n)*(cos(pi*n/4) - cos(3*pi*n/4) + cos(6*pi*n/4) -
cos(7*pi*n/4));
   an = 1/(pi*n)*(sin(3*pi*n/4) - sin(pi*n/4) + sin(7*pi*n/4) -
sin(6*pi*n/4));
   g3 = g3 + bn*sin(2*pi*n*f*t) + an*cos(2*pi*n*f*t);
end

plot(t, g1, 'k-', t, g2, 'r-', t, g3, 'b-');
```

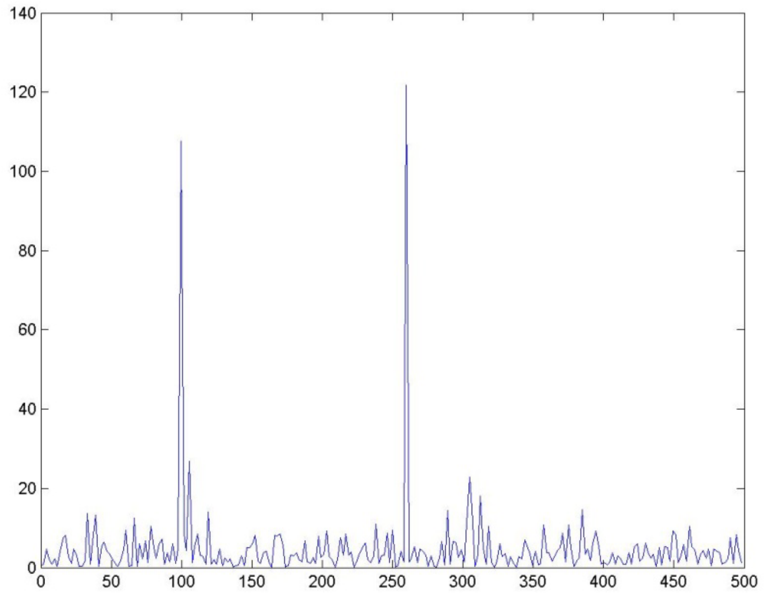
Reconstruction of the signal from the harmonics (terms)



这段代码就是我采用三种不同个数的正弦和余弦信号来逼近方形波。你们可以看到当正弦和余弦信号个数增加时，线性叠加合成波形越逼近原来的方形信号。你们自己可以把”N”参数变化一下，看看输出波形有什么样变化？

An Fourier Analysis Example





t = 0:0.001:0.6;   f = 1000*(0:255)/512;

x = **cos** (2*pi*100*t)+**sin**(2*pi*260*t);

y = x + 2*randn(size(t)); Y = fft(y, 512);

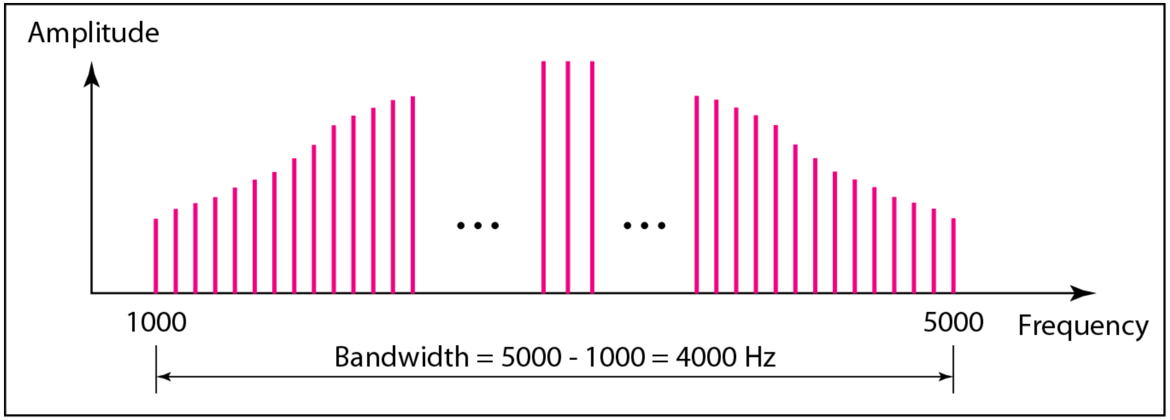
P = Y.*conj(Y)/512;

figure(1); plot(t, y); figure(2); plot(f, P(1:256));

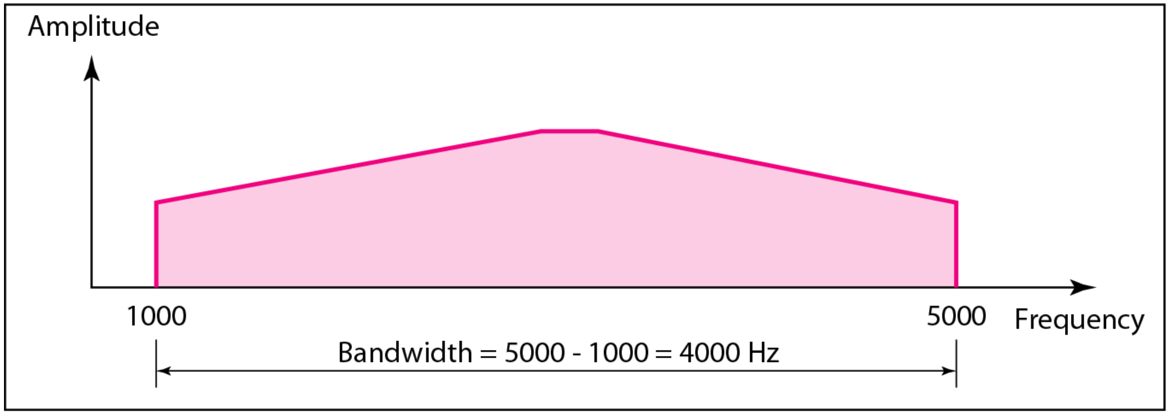
Theoretical Basis — Bandwidth-limited Signals

- **No** communication channels can transmit signals **without** losing some power in the process.
  - If all the Fourier components were equally diminished, the resulting signal would be reduced in amplitude but not distorted in shape.
- But, most of real communication channels *affect different frequency components differently*.
- Usually, for a wire, the amplitudes are transmitted mostly undiminished from 0 up to some frequency f_c (measured in cycles/sec or Hertz (Hz)), with all frequencies above this cutoff frequency attenuated.
  - f_c — the **cutoff** frequency (截止频率)
- <u>The width of the frequency range transmitted without being strongly attenuated is called the **bandwidth**</u>.
  - The bandwidth is *a physical property* of the transmission medium that depends on, for example, the construction, thickness, and length of wire or fiber.

The bandwidth of periodic and non-periodic composite signals



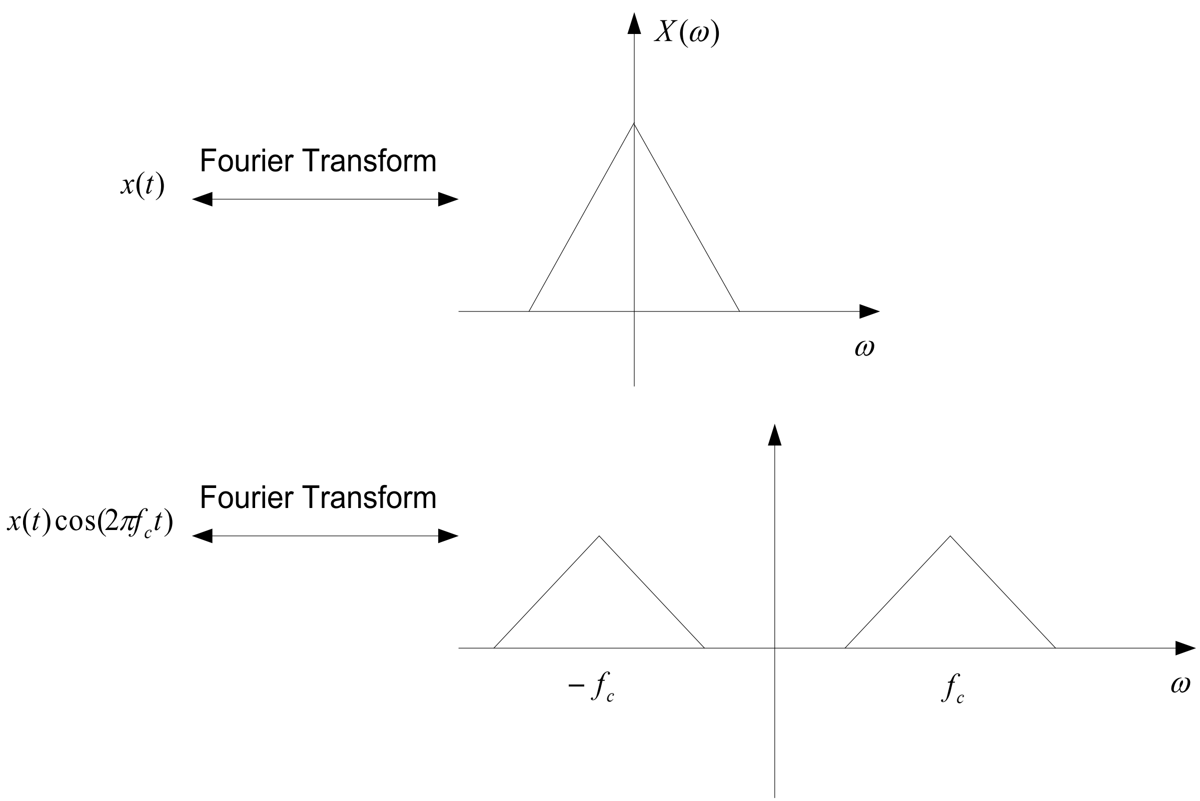
a. Bandwidth of a periodic signal



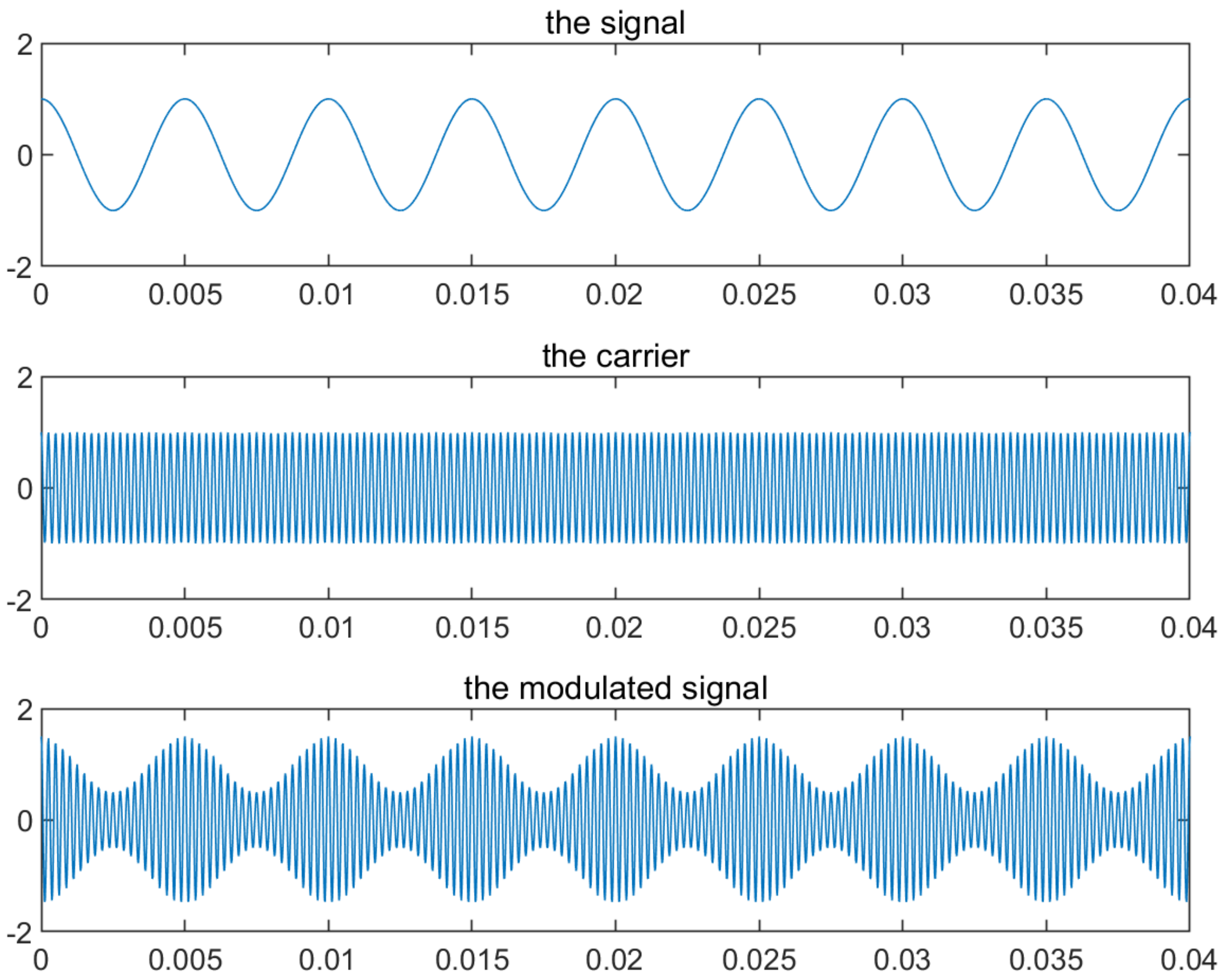
b. Bandwidth of a nonperiodic signal

Theoretical Basis — Bandwidth-limited Signals

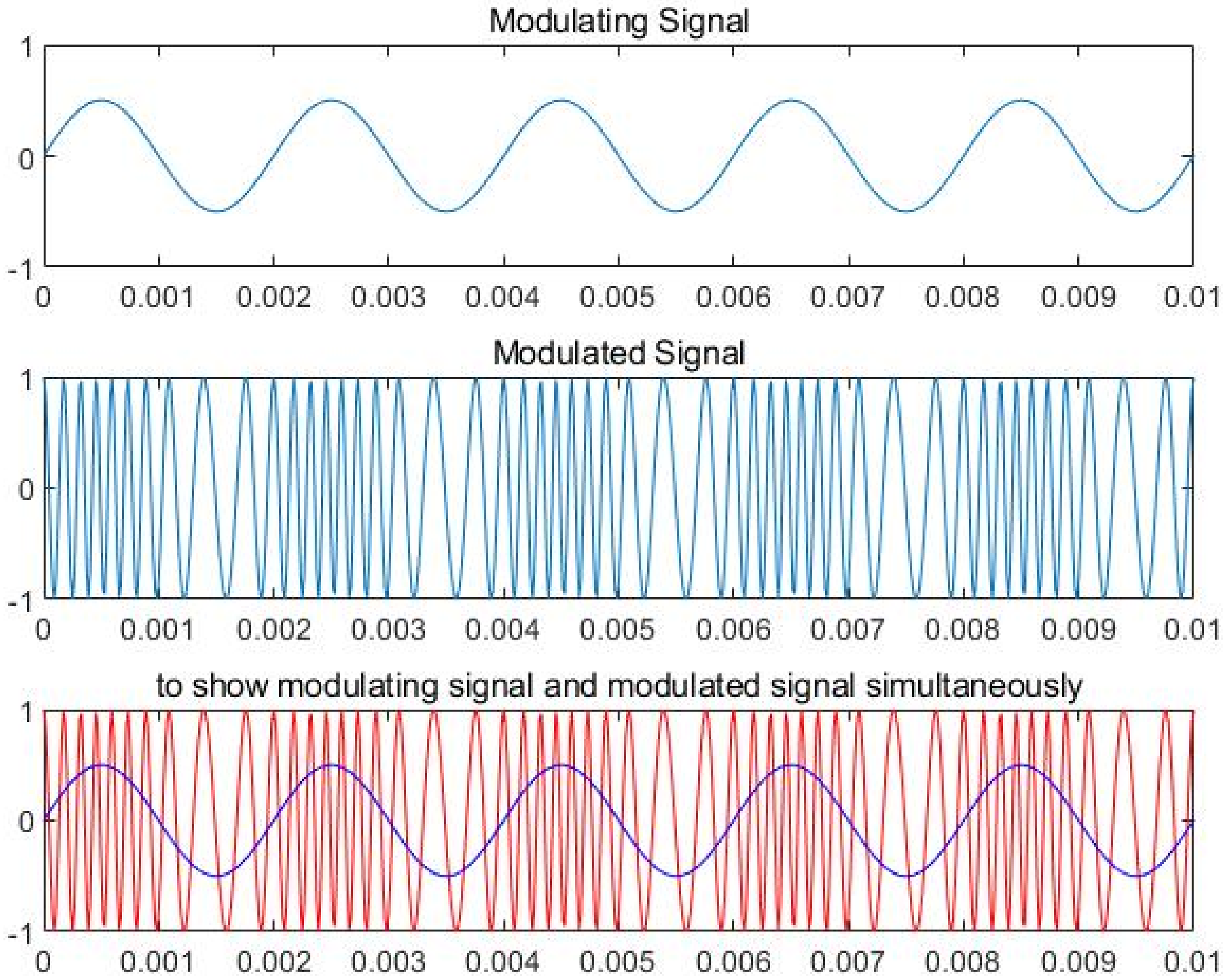
- **Baseband** Signals vs. **Passband** Signals
  - Signals that run from 0 up to a maximum frequency are called basedband signals.
  - Signals are shifted to occupy a higher range of frequencies, such as in the case of all wireless transmission, are called passband signals.



Amplitude Modulation Example



Frequency Modulation Example



Theoretical Basis — Bandwidth-limited Signals

- Bandwidth vs. Maximum Data Rate
  - To electrical engineers, (analogue) bandwidth is a quantity measured in Hz.
  - To computer scientists, (digital) bandwidth is the maximum data rate of a channel, a quantity measured in bits/sec.
  - The data rate is the end result of using the analog bandwidth of a physical channel for digital transmission, so the two are related.

Theoretical Basis — The Maximum Data Rate of a Channel

- Channel Capacity — the **maximum rate** at which data can be transmitted over a given communication path or channel under given conditions.
- *Four* related concepts:
  - **Data rate (bps)**
    - If the binary-input and binary-output channel is noise free, the data rate will be 1bps.
  - **Bandwidth**: determined by
    - The deliberate limitation at the transmitter to prevent the interference from other sources
    - The physical properties of the transmission medium (**Hz**). (the greater the bandwidth, the greater cost of the communication system)
  - **Noise**
  - **Error rate**: the rate at which errors occur, where an error is the reception of a "1" when a "0" was transmitted or the reception of a "0" when a "1" was transmitted.

Theoretical Basis — Nyquist Bandwidth

- As early as 1924, an AT&T engineer, Henry Nyquist, realized that even a **perfect** channel has a finite transmission capacity.
  - Investigate the problem of determining the maximum signaling rate that can be used over a telegraph channel of a given bandwidth without *inter-symbol interference*. $s(t) = \sum_n a_n g(t - nT_s)$ where $g(t)$ represents a basic pulse shape and $\{a_n\}$ is the binary sequence of $\{\pm 1\}$ transmitted at a rate of $1/T_s$ bits/s.
- The **question** is: to determine the *optimal pulse shape* that was band-limited to B Hz and maximize the bit rate under the constraint that the pulse caused no inter-symbol interference at the sampling time kT_s, k = 0, ± 1, ± 2, …

Theoretical Basis — Nyquist Bandwidth

- What is inter-symbol interference (**ISI**) ?
  - Suppose $g(t)$ is an ideal rectangular pulse: $g(t) = \begin{cases} 1 & -\frac{T}{2} \leq t \leq \frac{T}{2} \\ 0 & otherwise \end{cases}$
  - Then its spectrum will be: $G(f) = \int_{-\infty}^{+\infty} g(t)e^{-j2\pi ft}dt = \int_{-T/2}^{+T/2} e^{-j2\pi ft}dt = \frac{sin(\pi fT)}{\pi f}$
  - You see that the spectrum of a rectangular pulse extends infinitely. Although the main lobe's energy is concentrated at low frequencies, the side lobes extend to infinity.

Theoretical Basis — Nyquist Bandwidth

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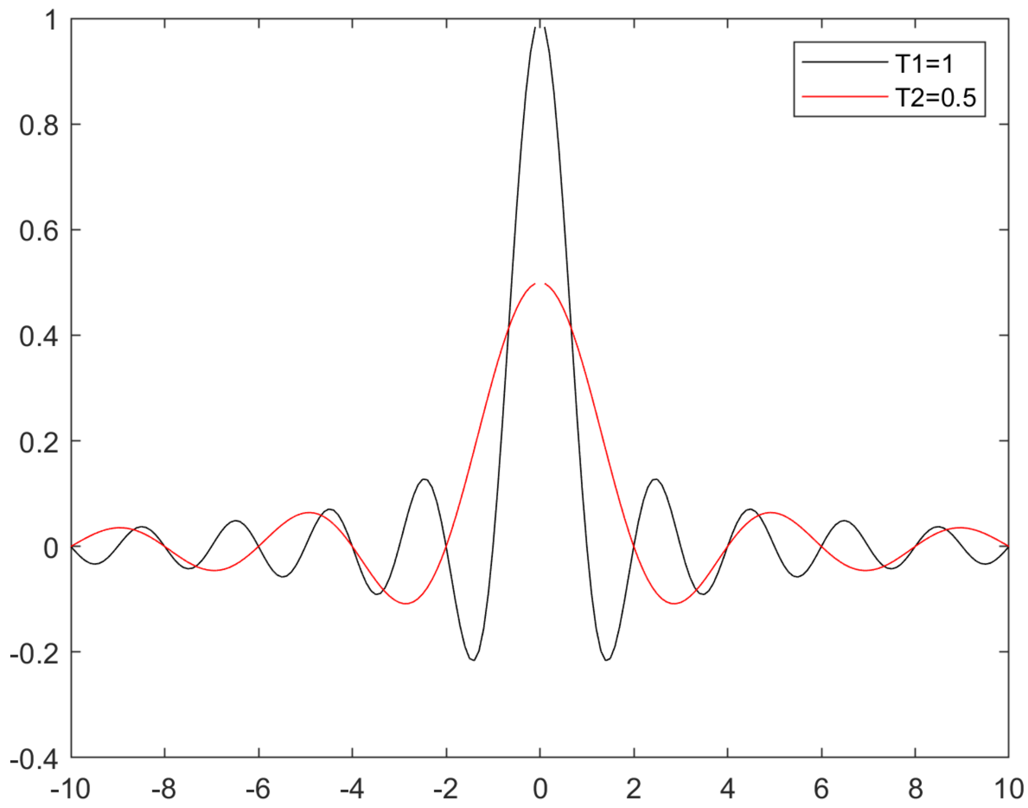
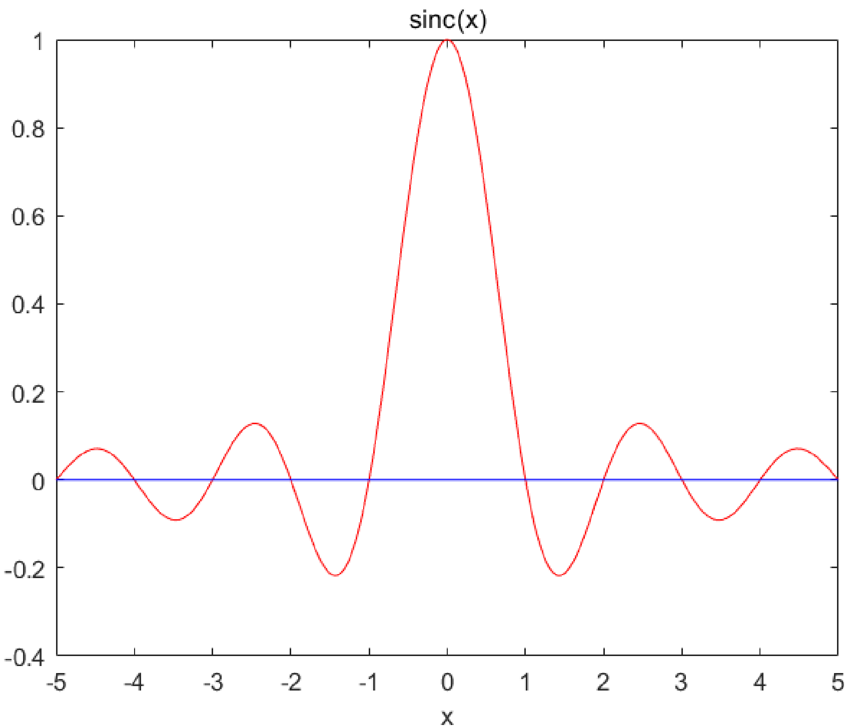


矩形脉冲的频谱无限延伸，虽然主瓣能量集中在低频，但旁瓣一直延伸到无穷远。注意这里横轴表示频率f，不是时间轴！

Sinc(x) = sin(πx)/(πx)

- Properties of sinc(x)
  - sinc(x) is an even function
  - $x = \ldots, -3, -2, -1, 1, 2, 3, \ldots$ sinc(x) = 0, sinc(0) = 1.

$$\int_{-\infty}^{+\infty} \frac{\sin(\pi x)}{\pi x} dx = 1$$



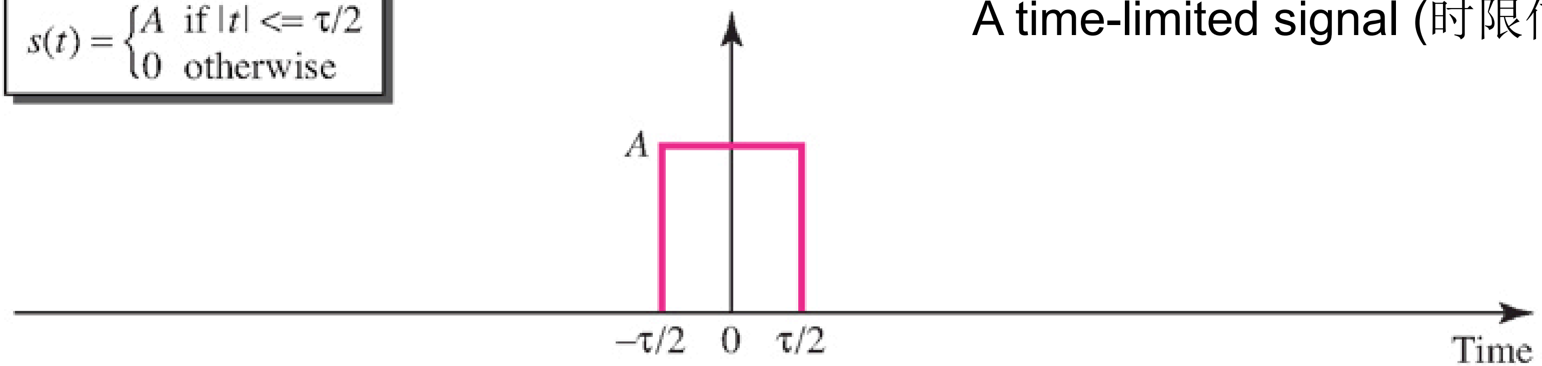
A Single Pulse Signal

$$S(f)=\int_{-\infty}^{+\infty} s(t)e^{-j2\pi ft}dt=\int_{-\frac{\tau}{2}}^{\frac{\tau}{2}} Ae^{-j2\pi ft}dt=\frac{2A}{j2\pi f}j\sin(2\pi f\frac{\tau}{2})=A\tau\frac{\sin(\pi f\tau)}{\pi f\tau}$$

Time domain

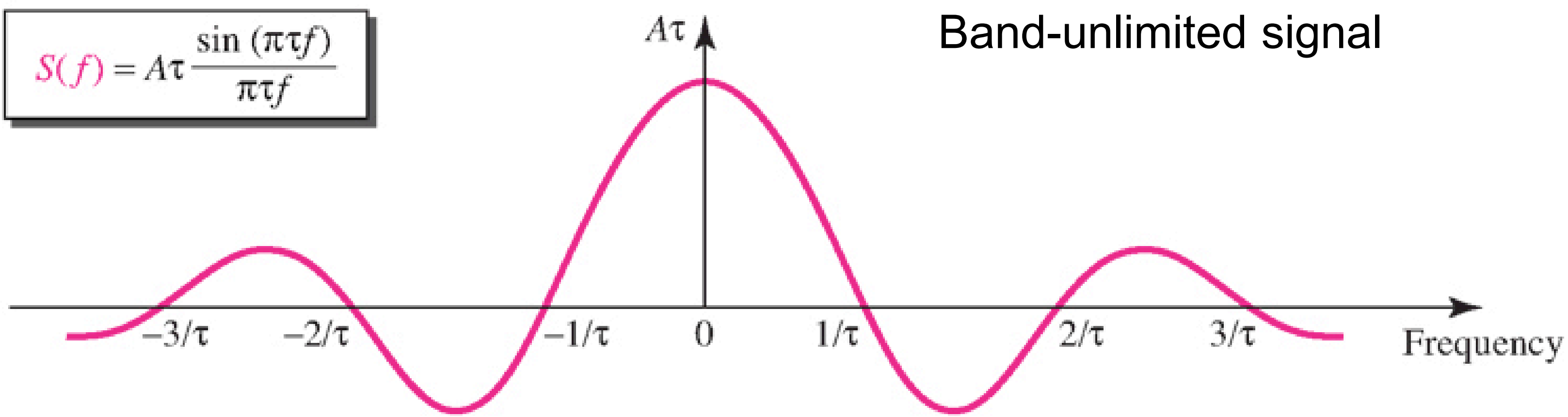
$$s(t)=\begin{cases}A & \text{if } |t| <= \tau/2\\ 0 & \text{otherwise}\end{cases}$$

A time-limited signal (时限信号)



$$S(f)=A\tau\frac{\sin(\pi\tau f)}{\pi\tau f}$$

Band-unlimited signal



Frequency domain

Theoretical Basis — Nyquist Bandwidth

- When this rectangular shaped pulse through a channel with bandwidth of *B*, the spectrum is truncated by the bandwidth-limited channel, distortion is introduced. After applying the inverse Fourier transform, the time-domain waveform is no longer an ideal rectangle but exhibits blurred edges and extended tails. (有限带宽导致矩形脉冲的“理想方形”不再保持，边沿过渡区会被拉长。)
  - Band-limited signals vs. Time-limited signals
- An ideal rectangular pulse is originally confined to the interval [−T/2, T/2], and when the sampling points are aligned, it does not interfere with other symbols. However, after through a channel with limited bandwidth, the waveform spreads in time and its tail extends to the sampling instants of adjacent symbols, thereby causing inter-symbol interference (**ISI**).

Theoretical Basis — Nyquist Bandwidth

- The Nyquist criterion for zero ISI: When transmitting digital symbols over a band-limited channel of bandwidth *B*
  - 1) Each symbol must be represented by a pulse shape that does not interfere with neighboring symbols at their sampling instants
    - The optimal pulse shape

$$\boxed{g(t) = \frac{\sin 2\pi B t}{2\pi B t}}$$

  - 2) Nyquist showed that *the maximum symbol rate* achievable without ISI is $R_s = 2B$ symbols per second
    - The Nyquist rate for band-limited channels

The Nyquist criterion for **zero ISI** (inter-symbol interference):

Suppose $s(t) = \sum_n a_n g(t - nT_s)$ is a digital signal sequence we want to transmit over a channel with one-sided bandwidth B, the optimal pulse should be $g(t) = \frac{sin2\pi Bt}{2\pi Bt}$, and the sampling rate should be $R_s = \frac{1}{T_s} = 2B$.

Its samples at integer multiples of T_s are $g(nT_s) = \frac{\sin(2\pi BnT_s)}{2\pi BnT_s} = \frac{\sin(n\pi)}{n\pi}$, then for any integer $n \neq 0$, $g(nT_s) = \frac{\sin(n\pi)}{n\pi} = 0$, while $g(0) = 1$. Hence symbols do not interfere at sampling instants → **zero ISI**.

However, the ideal sinc has infinite time support, so it's not physically realizable. In practice one uses pulses from the raised-cosine family.

Theoretical Basis — Nyquist Bandwidth

- From symbol rate to bit rate
  - Now suppose each symbol can take V discrete values (or levels). Then each symbol carries $\log_2 V$ bits of information
  - Therefore, the maximum bit rate is $C = 2B \log_2 V$
    - Binary: $C = 2B$
    - Multilevel: $C = 2B \log_2 V$
- For a given bandwidth, the data rate can be increased by increasing the number of different signal elements. How?
  - However, this will increase burden on receiver.
  - Noise and other impairment on the transmission line will limit the practical value of V.

Theoretical Basis — Shannon Capacity

- For a bandlimited additive white Gaussian noise (AWGN) channel,
  - **Shannon Capacity:** $C = Blog_2(1 + SNR)$ bits/second
    - B = channel bandwidth (Hz, one-sided)
    - Only assume white noise, not accounted for attenuation, delay or impulse noise.
    - SNR = signal-to-noise ratio (SNR) in linear scale (not dB)

$$\boxed{\mathrm{SNR}_{dB} = 10\log_{10}(\text{signal power / noise power}) = 10\log10(SNR)}$$

    - C = theoretical maximum reliable data rate (capacity)
    - **High *SNR***: capacity $\approx Blog_2(SNR)$. Wider bandwidth directly increases capacity.
    - **Low *SNR***: Since noise is assumed to be white, the wider bandwidth, the more noise is admitted to the system. When $SNR \ll 1$, $\ln(1+x) \approx x$, $C \approx \frac{B}{ln2} \cdot \frac{S}{N} = \frac{B}{ln2} \cdot \frac{P}{N_0 B} = \frac{P}{N_0 ln2}$, ($N_0$ is the single-sided noise power spectral density (PSD), P is the signal power).

Theoretical Basis — Shannon Capacity

- Relation among data rate, noise and error rate.
  - For a given noise pattern, if the data rate is increased, then the bits become “shorter” so that more bits are affected.
  - For a given noise level, the greater signal strength will improve the ability to receive data correctly.

- Key differences between Nyquist bandwidth and Shannon Capacity
  - Nyquist formula is about avoiding ISI (ideal pulses, noiseless), Nyquist says how fast you can push symbols without ISI (max 2B symbols/sec)
  - Shannon formula considers noise: not all $\log_2 M$ bits/symbol are reliable unless *SNR* supports it. Shannon says how many reliable bits each symbol can carry, depending on SNR.

Extension reading [4] R.L. Freeman, “Bits, symbols, bauds, and bandwidth,” IEEE Communication Magazine, pp.96-99, Apr. 1998.

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- The theoretical basis for data communication
- Three kinds of transmission media
- Digital modulation and multiplexing
- Three examples of communication examples

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- Three kinds of transmission media (Guided or Wired, Wireless, Satellite)
- Digital modulation and multiplexing
- Three examples of communication examples

Transmission Media I: Guided Transmission Media

- Guided transmission media
  - Persistent storage
  - Twisted pairs
  - Coaxial cable
  - Power lines
  - Fiber optics

Guided Transmission Media: Persistent Storage

- Consists of magnetic or solid-state storage
- Common way to transport data
  - Write to persistent storage
  - Physically transport the tape or disks to the destination machine
  - Read data back again
- Cost effective for applications where a high data rate or cost per bit transported is the key factor
- Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway
- The **delay** characteristics are poor: Transmission time is measured in hours or days, not milliseconds.
  - The web
  - Video conference
  - Online game

Guided Transmission Media: Twisted Pairs (I)

- Twisted Pairs
  - The oldest and still most common transmission media
  - A twisted pair consists of two insulated copper wires, typically about 1mm thick. The wires are twisted together <u>in a helical form</u>, just like a DNA molecule.
    - Twisting is done because two parallel wires constitute a fine antenna.
  - A signal is usually carried as <u>**the difference in voltage**</u> between the two wires in the pair.
    - This provides better immunity to <u>external noise</u> because the noise tends to affect both wires the same, leaving the difference unchanged.
  - Twisted pairs can be used for transmitting either analog or digital information.
  - The bandwidth depends on the thickness of the wire and the distance traveled, but several megabits/sec can be achieved for a few kilometers in many cases.

Guided Transmission Media: Twisted Pairs (II)

- Twisted Pairs
  - Different LAN standards may use the twisted pairs differently.
  - 100-Mbps Ethernet uses two (out of the four) pairs, one pair for each direction.
  - 1-Gbps Ethernet uses all four pairs in both directions simultaneously, but this requires the receiver to factor out the signal that is transmitted locally.

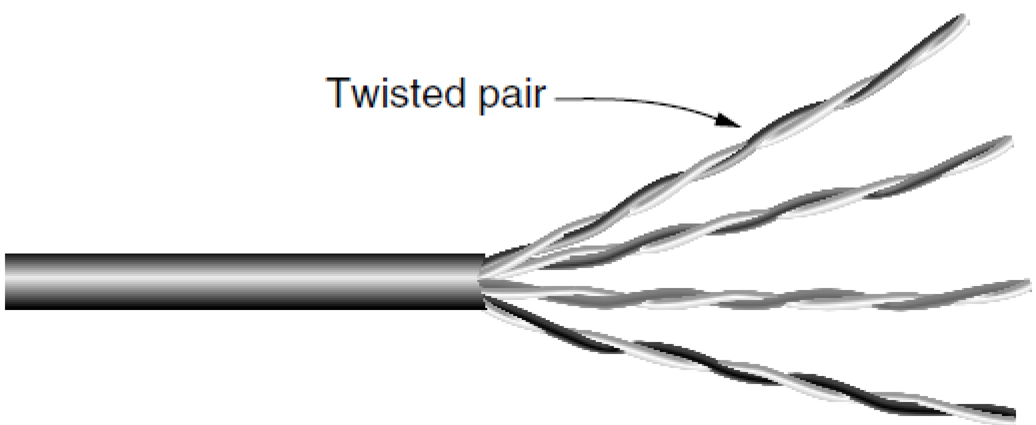


Figure 2-3. Category 5 UTP cable with four twisted pairs.

UTP — Unshielded Twisted Pair

Category 7 cables have shielding on the individual twisted pair to reduce the susceptibility to external interference and crosstalk with other nearby cables.

Guided Transmission Media: Twisted Pairs (III)

- Twisted Pairs
  - Full duplex links (1-Gbps Ethernet, all four pairs in both directions).
  - Half duplex links (100-Mbps Ethernet, one pair for each direction)
  - Simplex links (one-way street)

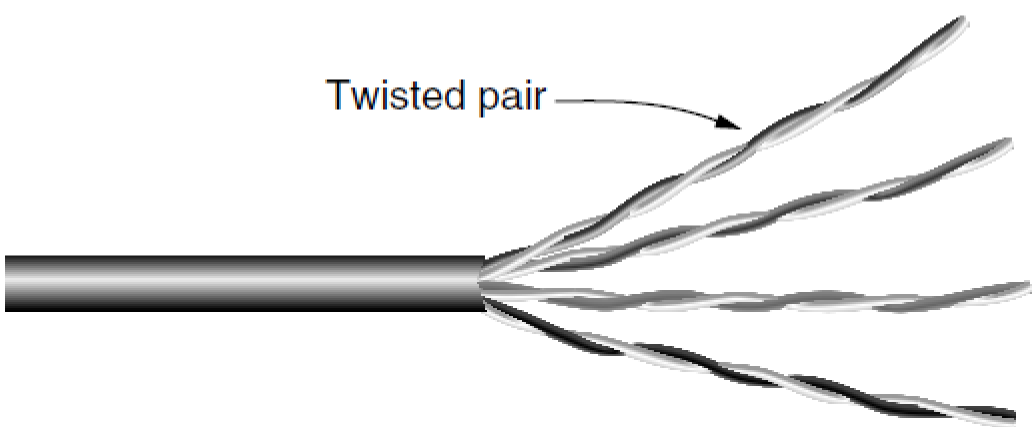


Figure 2-3. Category 5 UTP cable with four twisted pairs.

UTP — Unshielded Twisted Pair

Category 7 cables have shielding on the individual twisted pair to reduce the susceptibility to external interference and crosstalk with other nearby cables.

Guided Transmission Media: Coaxial Cable

- Coaxial Cable
  - Commonly used for cable television and metropolitan area network (MAN), and delivering high-speed Internet connectivity to homes.
  - Modern cables have a bandwidth of up to a few GHz.

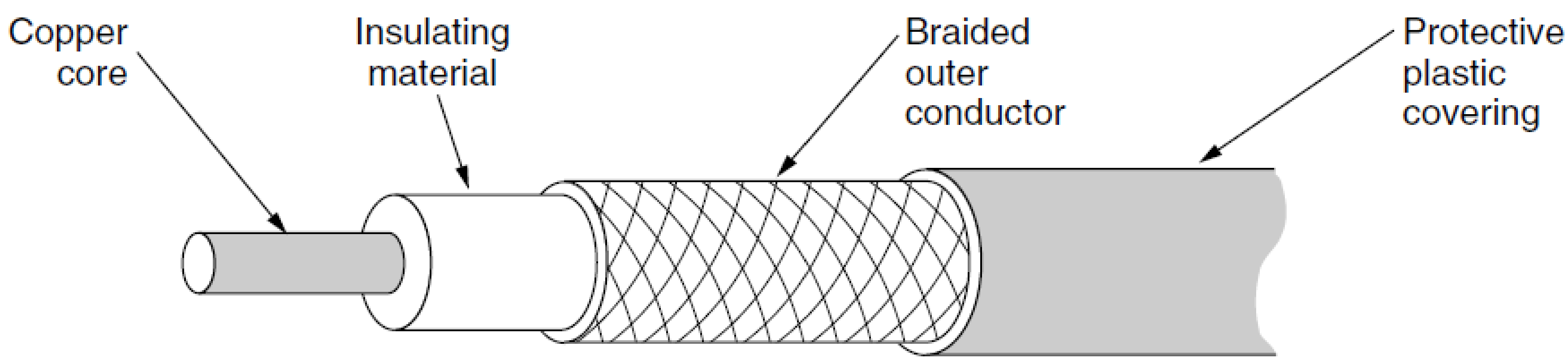


Figure 2-4. A coaxial cable.

Guided Transmission Media: Power Lines

- Power Lines
  - The data signal is superimposed on the low-frequency power signal.
  - The difficulties with using household electrical wiring for a network is that it is was designed to distribute power signals.
    - The electrical properties of the wiring vary from one house to the next and changes as appliances are turned on and off, which causes data signals to bounce around the wiring.
    - Transient currents when appliances switch on and off create electrical noise over a wide range of frequencies.

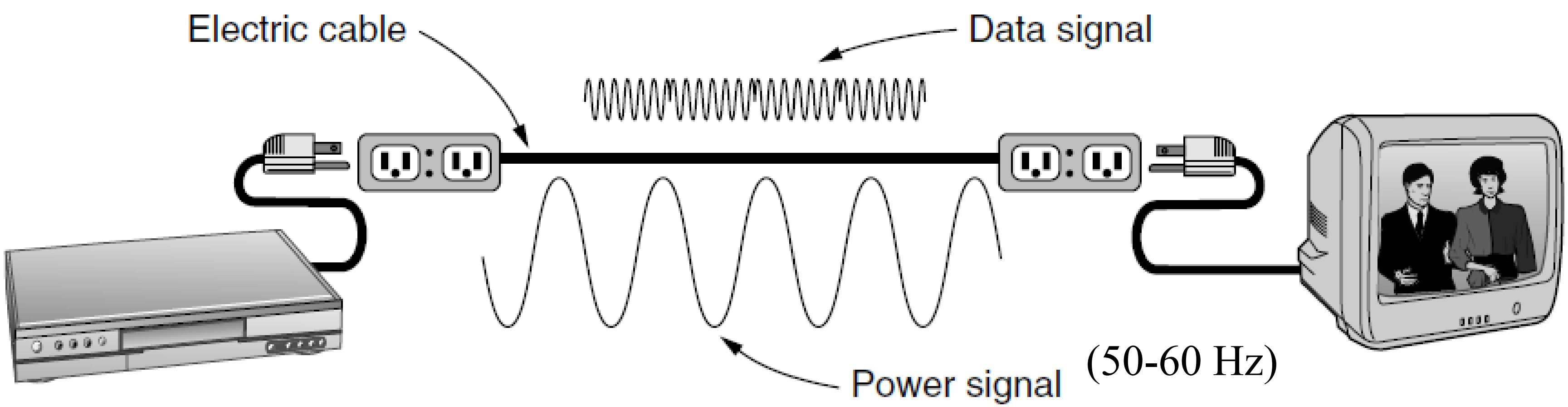


Figure 2-5. A network that uses household electrical wiring.

Guided Transmission Media: Fiber Optics (I)

- Allows essentially infinite bandwidth
- Must consider costs
  - For installation over the last mile and to move bits
- Uses
  - Long-haul transmission in network backbones
  - High-speed LANs
  - High-speed Internet access
- **Key components**
  - Light source, transmission medium, and detector
- Transmission system uses physics

Guided Transmission Media: Fiber Optics (II)

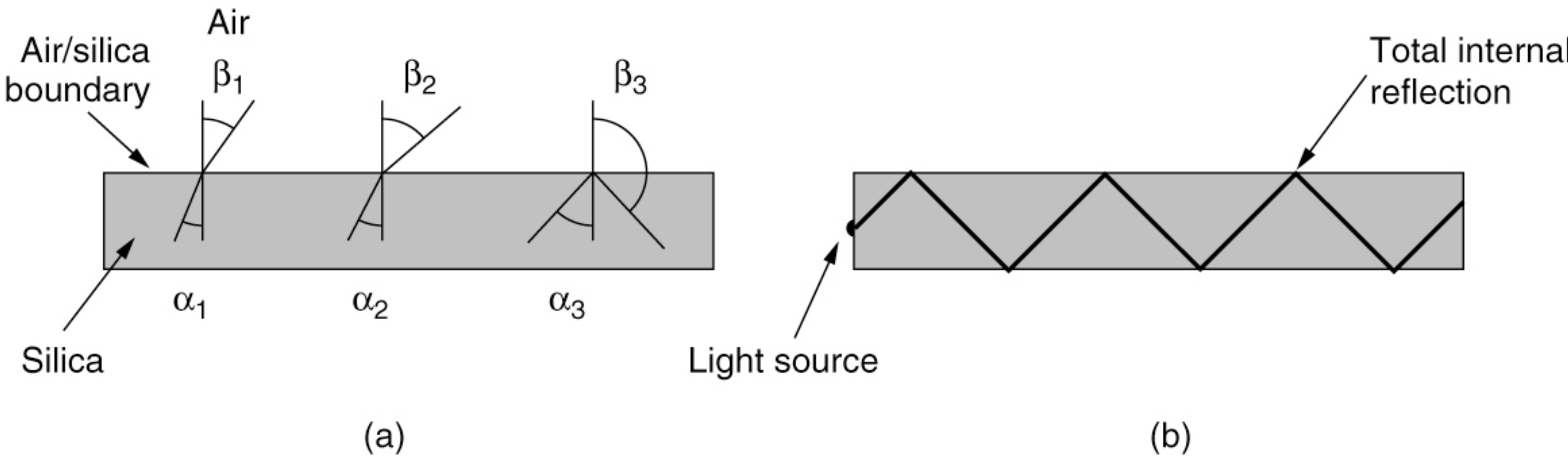
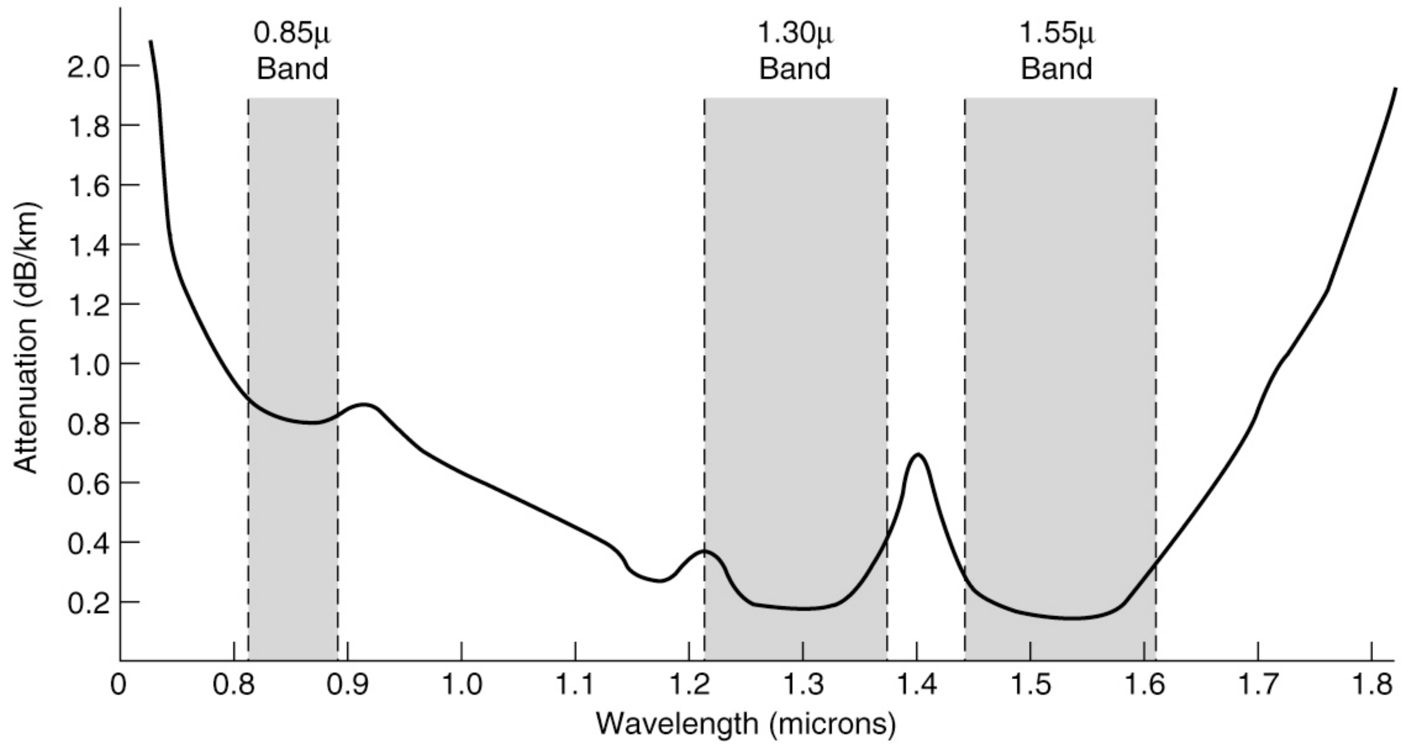


Figure (a) illustrates a light ray inside a silica fiber impinging on the air/silica boundary at different angles. Figure (b) illustrates light trapped by total internal reflection.

Guided Transmission Media: Fiber Optics (III)

- Transmission of light through fiber
  - Attenuation of light through glass
    - Dependent on the wavelength of the light
    - Defined as the ratio of input to output signal power
- Fiber cables
  - Similar to coax, except without the braid
- Two kinds of signaling light sources
  - LEDs (Light Emitting Diodes)
  - Semiconductor lasers

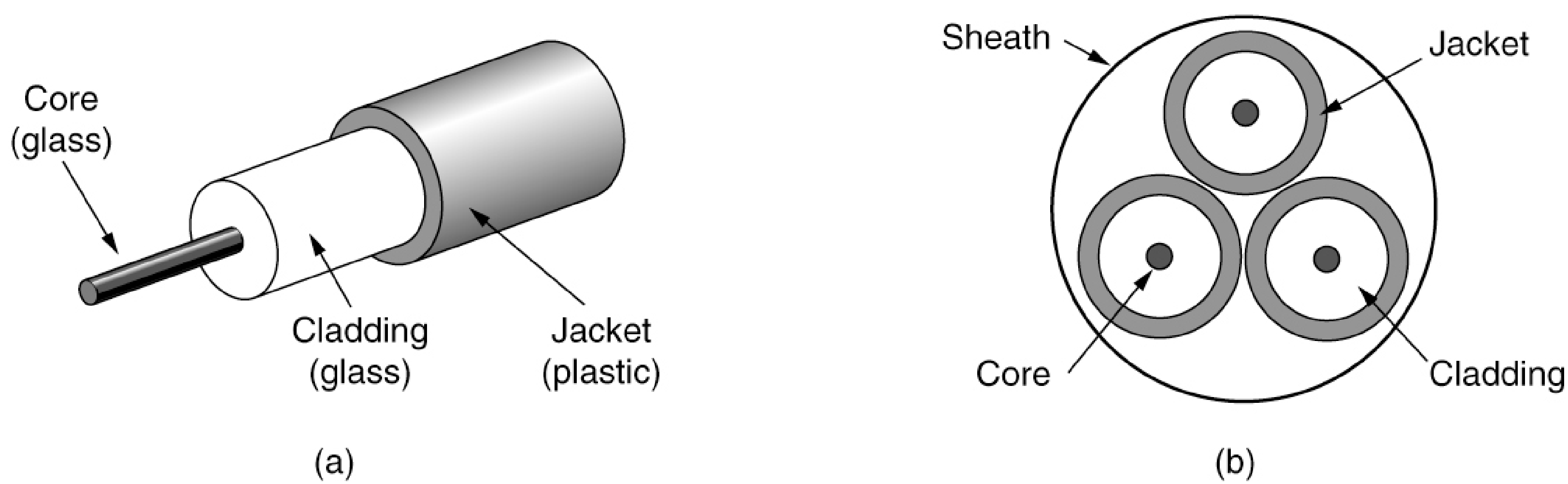
Guided Transmission Media: Fiber Optics (IV)



♦ Three wavelength bands are mostly commonly used at present for optical communication. They are centered at 0.85, 1.30 and 1.55 microns, respectively.

♦ Attenuation of light through fiber in the infrared region is measured in units of decibels (dB) per linear kilometer of fiber. 0.85-micron band has higher attenuation and is used for short distances.

Guided Transmission Media: Fiber Optics (V)



Views of a fiber cable

- The core is surrounded by a glass cladding with a lower index of refraction than the core, to keep all the light in the core. (镀层的折射率比内部材质的折射率低保证光线一直在内部中传输)
- **A multimode fiber** (diameter ~ 50 microns): many different rays will be bouncing around at different angles.
- **A single-mode fiber** (diameter less than 10 microns): the light can propagate only in a straight line.

Guided Transmission Media: Fiber Optics (VI)

Item	LED	Semiconductor laser
Data rate	Low	High
Fiber type	Multi-mode	Multi-mode or single-mode
Distance	Short	Long
Lifetime	Long life	Short life
Temperature sensitivity	Minor	Substantial
Cost	Low cost	Expensive

A comparison of semiconductor diodes and LEDs as light sources.

Guided Transmission Media: Fiber Optics (VII)

- Fiber advantages over copper
  - Handles higher bandwidth
  - Not affected by power surges, electromagnetic interference, power failures, corrosive chemicals
  - Thin and lightweight
  - Do not leak light
  - Difficult to tap (窃听)
- Fiber disadvantage
  - Less familiar technology that requires specific engineering skills
  - Fibers damaged easily by being bent too much

Transmission Media II: **Wireless**

- The Electromagnetic Spectrum

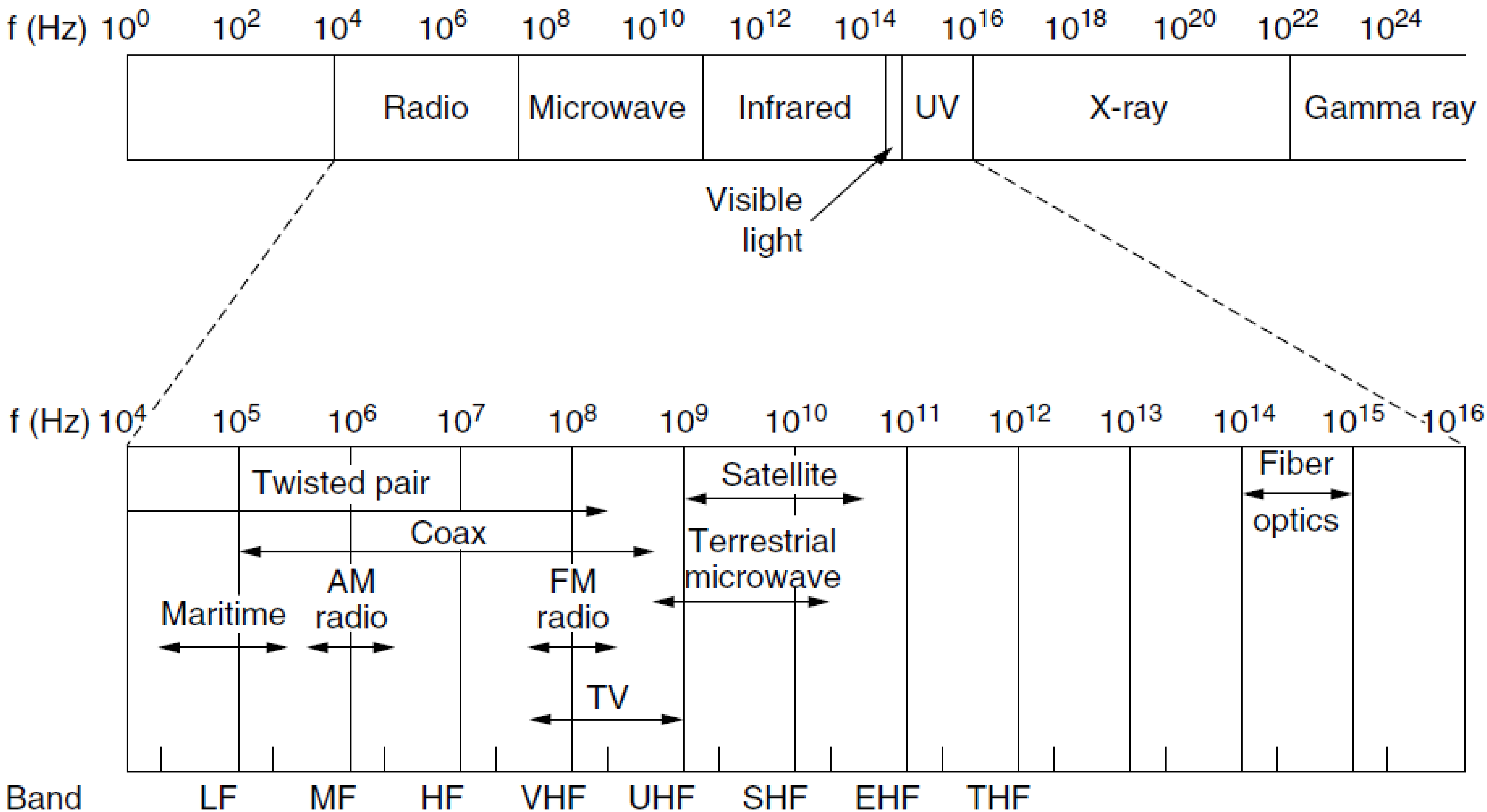


Figure 2-10. The electromagnetic spectrum and its uses for communication.

Transmission Media II: **Wireless**

- Most transmissions use a relatively narrow frequency band (i.e., $\Delta f/f << 1$)
  - They concentrate their signals in this narrow band to use the spectrum efficiently and obtain reasonable data rates by transmitting with enough power.
- However, in some cases, a wider band is used, with three variations.
  - Frequency hopping spread spectrum (Austrian-born sex goddess Hedy Lamarr)
    - A transmitter hops from frequency to frequency hundreds of times per second.
    - This technique is used commercially, for example, in Bluetooth and older versions of 802.11

Nov. 9, 1914 – Jan. 19, 2000

  - Direct sequence spread spectrum
    - CDMA
  - UWB (Ultra WideBand)
    - UWB sends a series of rapid pulses, varying their position to communicate information. The rapid transitions lead to a signal that is spread thinly over a very wide frequency band.

Transmission Media II: **Wireless**

- Radio Transmission
  - Radio frequency (RF) waves are easy to generate, can travel long distances, and can penetrate buildings easily, so they are widely used for communications, both indoors and outdoors.
  - Radio waves are omnidirectional, meaning that they travel in all directions from the source, so the transmitter and receiver do not have to be carefully aligned physically.
  - The properties of radio waves are frequency dependent.
    - At low frequencies, radio waves pass through obstacles well, but the power falls off sharply with distance from the source, at least as fast as $1/r^2$ in air. This attenuation is called path loss.
    - At high frequencies, radio waves tend to travel in straight lines and bounce off obstacles.

Transmission Media II: **Wireless**

- Radio Transmission
  - With fiber, coax, and twisted pair, the signal drops by the same fraction per unit distance, for example 20dB per 100m for twisted pair. With radio, the signal drops by the same fraction as the distance doubles.
    - This behavior means that radio waves can travel long distances, and interference between users is a problem

电离层

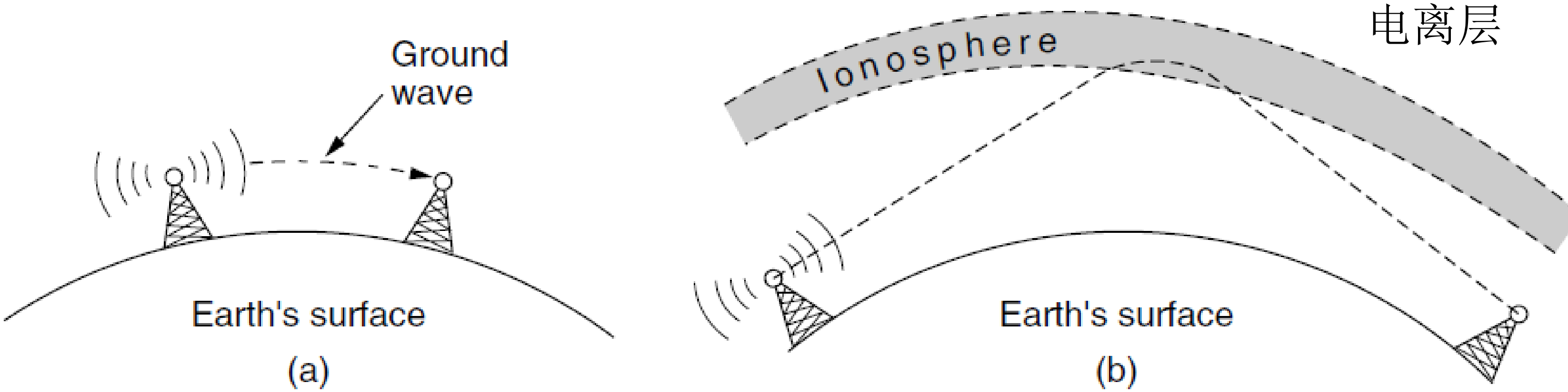


Figure 2-12. (a) In the VLF, LF, and MF bands, radio waves follow the curvature of the earth. (b) In the HF band, they bounce off the ionosphere.

Transmission Media II: **Wireless**

- Microwave Transmission
  - Above 100 MHz, the waves travel in nearly straight lines and can therefore be narrowly focused.
  - Concentrating all the energy into a small beam by means of parabolic antenna gives a much higher signal-to-noise ratio, but the transmitting and receiving antennas must be accurately aligned with each other.
  - Microwaves travel in a straight line, so if the towers are too far apart, the earth will get in the way. Thus, repeater are needed periodically.
    - The distance between repeaters goes up very roughly with the square root of the tower height.
  - The delayed waves may arrive out of phase with the direct wave and thus cancel the signal.
    - This effect is called **multipath fading**

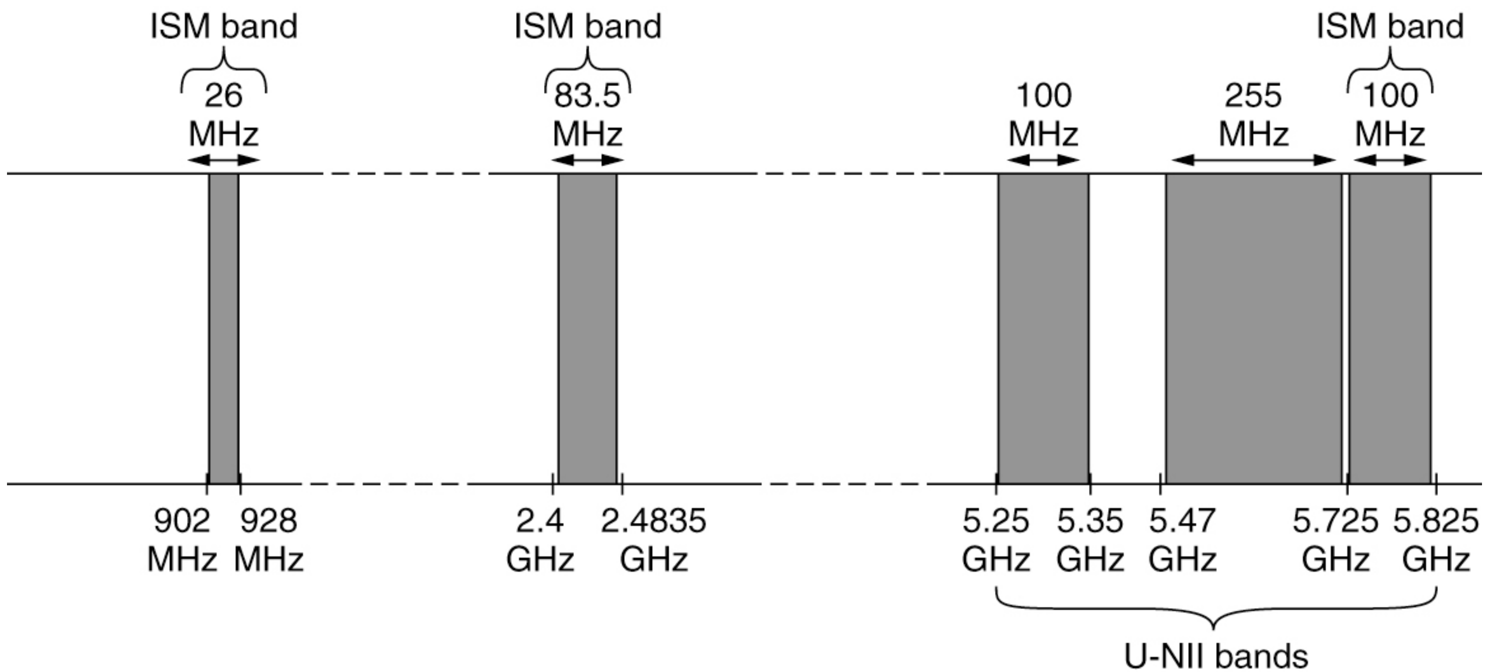
Transmission Media II: **Wireless**

- The politics of the Electromagnetic spectrum
  - ITU-R (International Telecommunication Union)
  - The FCC (Federal Communication Commission in US)

- Three algorithms were widely used in the past
  - Beauty contest
  - Lottery
  - Auction

Transmission Media II: **Wireless**

- Spectrum allocation



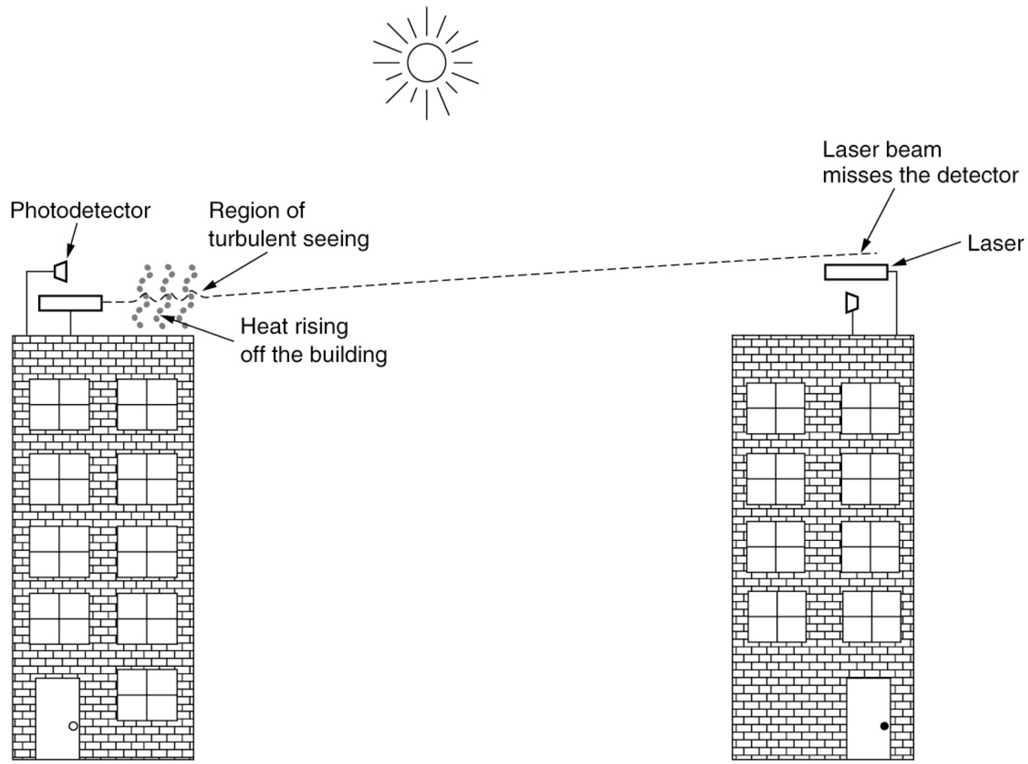
- ISM and U-NII (Unlicensed National Information Infrastructure) bands used in the United States by wireless devices.
- The 5-GHz bands are relatively undeveloped but, since they have the most bandwidth and are used by WiFi specifications such as 802.11 ac.

Transmission Media II: **Wireless**

- Infrared Transmission
  - Unguided infrared waves are widely used for short-range communication
    - Remote controls used for televisions
  - They are relatively directional, cheap and easy to build but have a major drawback: they do not pass through solid objects.
  - No government license is needed to operate an infrared system, in contract to radio systems, which must be licensed outside the ISM bands.

Transmission Media II: **Wireless**

- Light Transmission



♦ Unlike microwave transmission, light transmission does not require a license from government.

♦ Convection currents (wind, temperature, fog, etc.) can interfere with laser communication systems. A bidirectional system with two lasers is pictured here.

Transmission Media III: **Satellites**

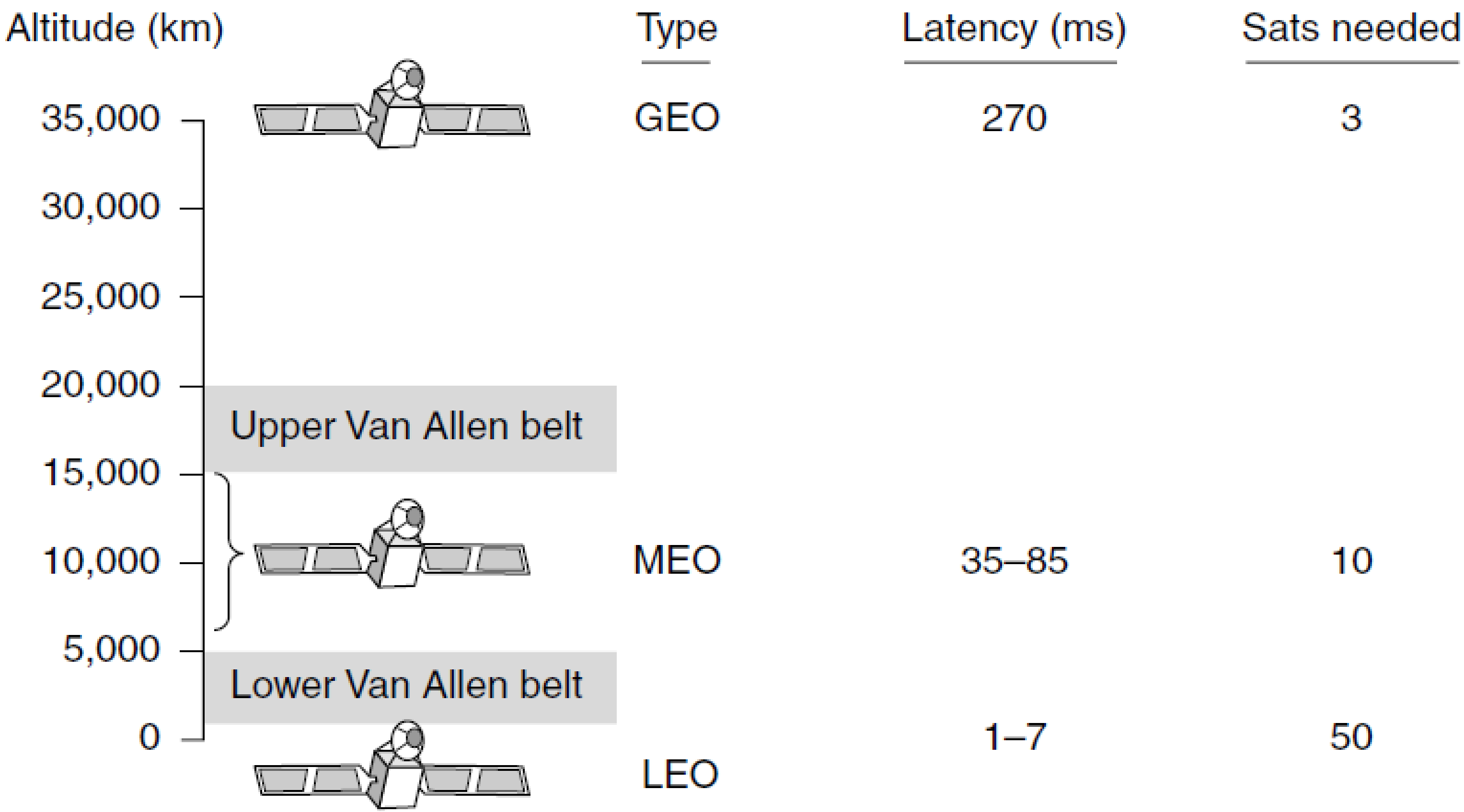


Figure 2-15. Communication satellites and some of their properties, including altitude above the earth, round-trip delay time, and number of satellites needed for global coverage.

Transmission Media III: **Satellites**

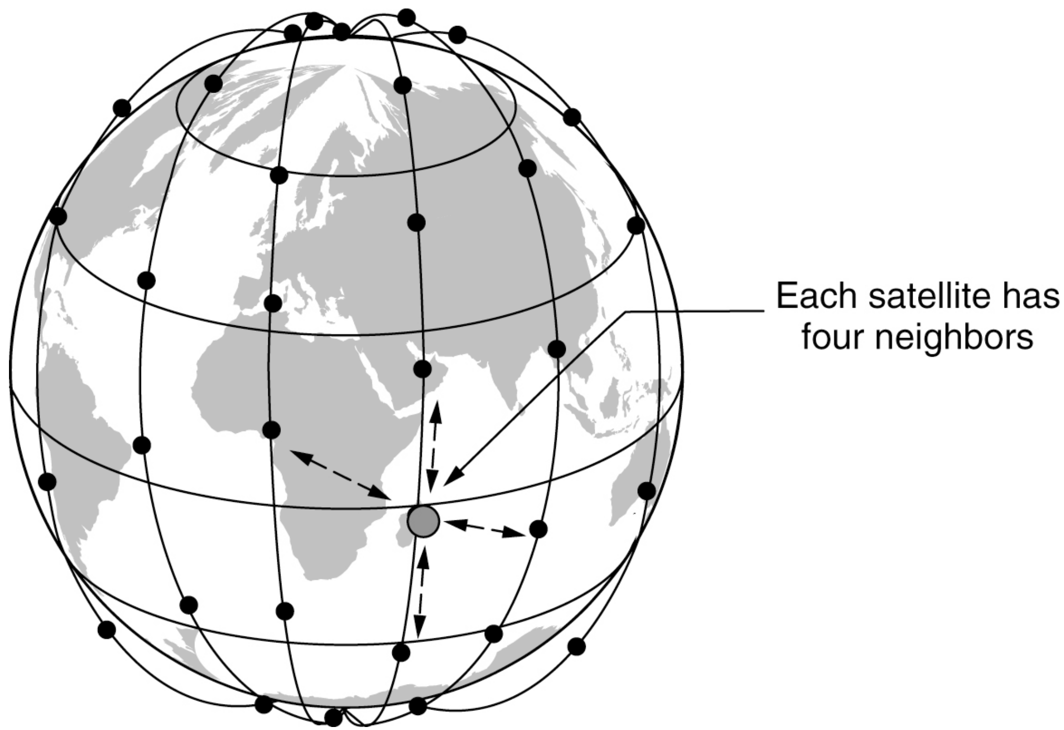
- The principal satellite bands.

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

Transmission Media III: Satellites

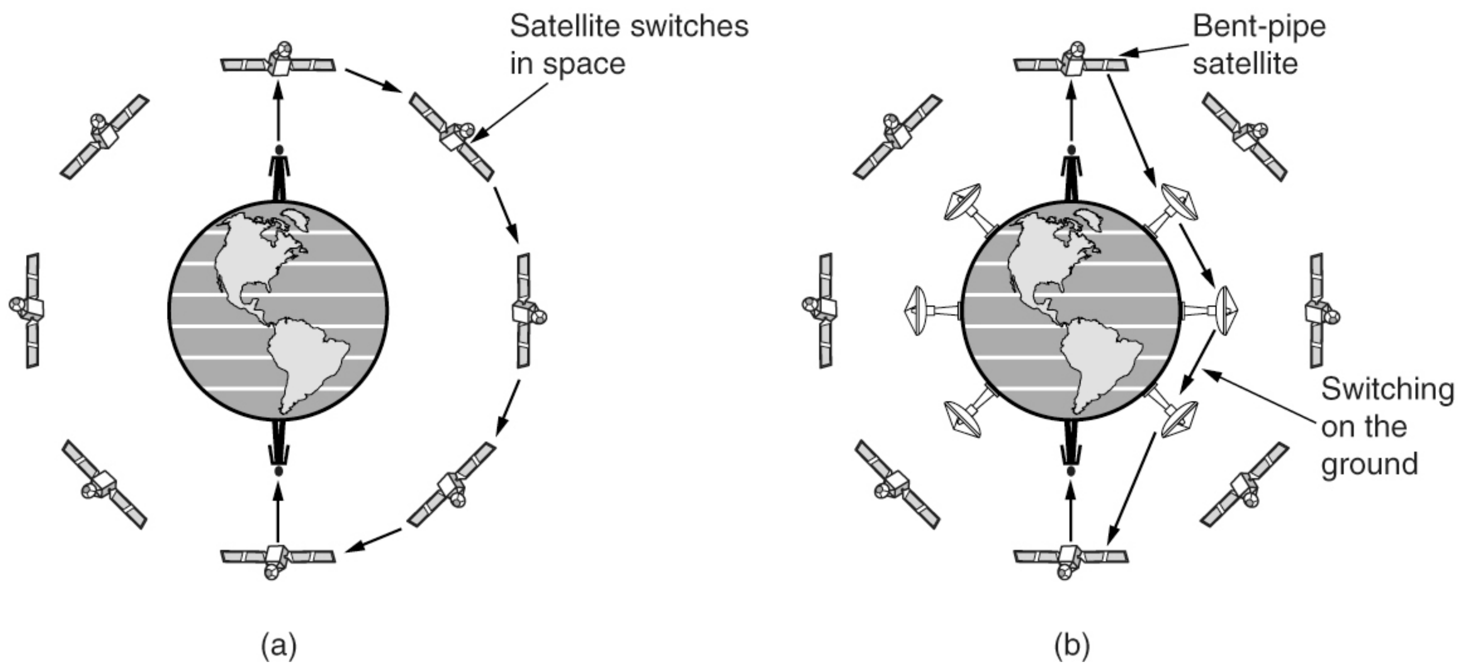
- MEO (Medium-Earth Orbit) satellites
  - Found at lower altitudes - between the two Van Allen belts
  - Drift slowly in longitude (6 hours to circle the earth)
  - Must be tracked as they move through the sky
  - Have a smaller footprint on the ground
  - Require less powerful transmitters to reach them
- Used for navigation systems
- Example:
  - Constellation of roughly 30 GPS (Global Positioning System) satellites orbiting at about 20,200 km

Low-Earth Orbit Satellites (1 of 2)



The Iridium satellites form six necklaces around the earth.

Low-Earth Orbit Satellites (2 of 2)



(a) Relaying in space. (b) Relaying on the ground.
星链，是美国太空探索技术公司的一个项目，太空探索技术公司计划在2019年至2024年间在太空搭建由约1.2万颗卫星组成的“星链”网络提供互联网服务

Transmission Media III: **Satellites**

- Satellites vs. Fiber
  - Communication satellites have some major niche markets that fiber does not
    - Rapid deployment
    - For communication in places where the terrestrial infrastructure is poorly developed.
    - When broadcasting is essential

Outline

- The theoretical basis for data communication
- Three kinds of transmission media
- Digital modulation and multiplexing
- Three examples of communication examples

Outline

- The theoretical basis for data communication
- Three kinds of transmission media
- Digital modulation and multiplexing
- Three examples of communication examples

Digital Modulation and Multiplexing

- Wires and wireless channels carry **analog signals** such as continuously varying voltage, light intensity, or sound intensity.
- To send digital information, we must <u>devise analog signals to represent bits</u>.
  - The process of converting between bits and signals that represent them is called **digital modulation**.
- There are about two schemes to convert bits into a signal
  - 1) Baseband transmission (for wired channels)
    - The signal occupies frequencies from zero up to a maximum that depends on the signaling rate
  - 2) Passband transmission (for wireless and optical channels)
    - To regulate **amplitude**, **phase** and **frequency** of a carrier signal to convey bits. (The signal occupies a band of frequencies around <u>**the frequency of the carrier signal**</u>)
- Channels are often shared by multiple signals
  - To use a single wire to carry several signals — **Multiplexing**

Digital Modulation: Baseband Transmission

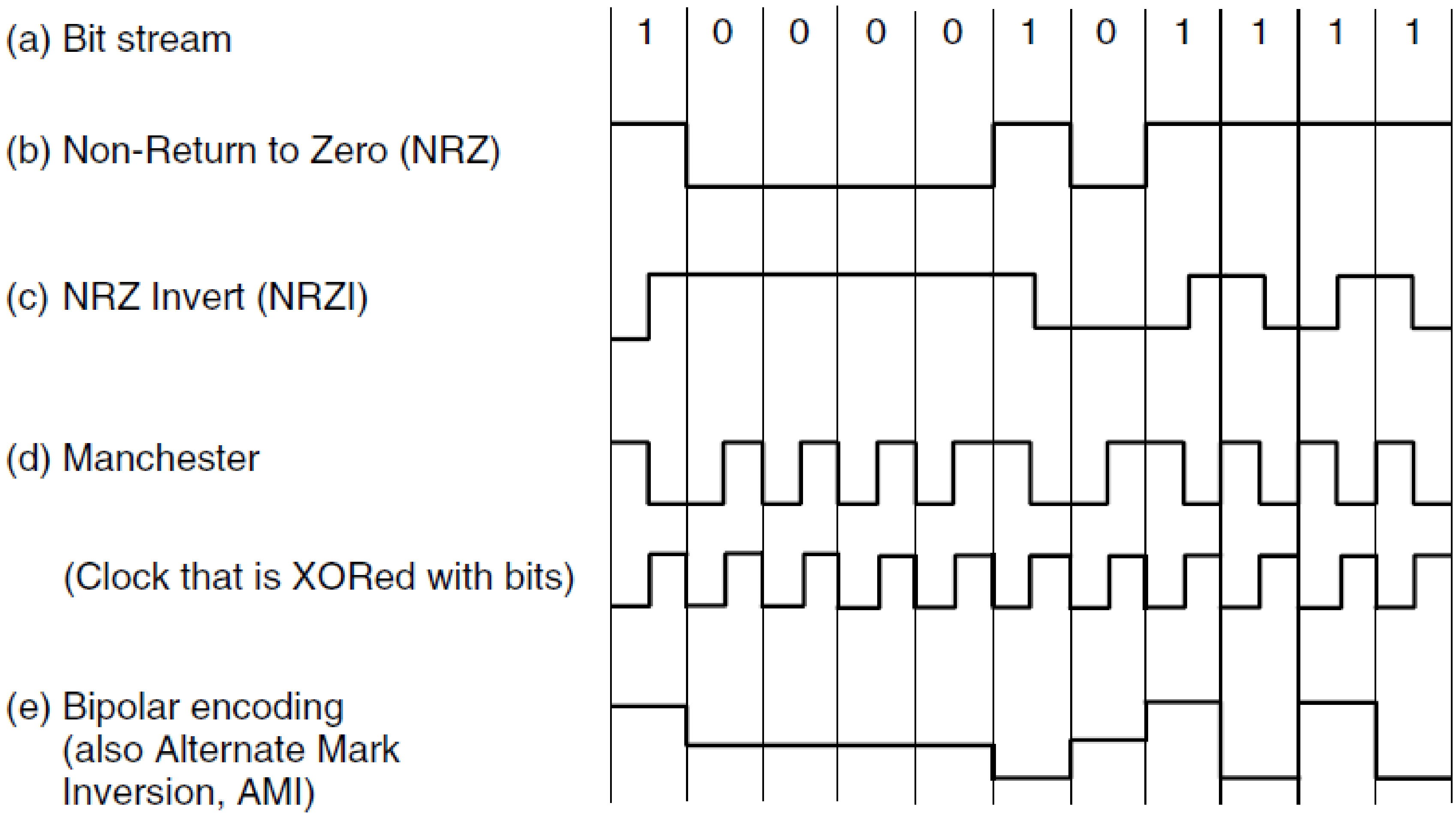


Figure 2-20. Line codes: (a) Bits, (b) NRZ, (c) NRZI, (d) Manchester, (e) Bipolar or AMI.

Digital Modulation: Baseband Transmission

- **NRZ** (Non-Return-to-Zero)
  - The most straightforward form of digital modulation is to use **a positive voltage** to represent a **1** and **a negative voltage** to represent a **0**. For an optical fiber, the presence of light might represent a 1 and the absence of light might represent a 0.
  - At the receiver, the receiver converts it into bits by sampling the signal at regular intervals of time.
    - The signal will **not** look exactly like the signal that was sent. It will be *attenuated* and *distorted* by the channel and noise at the receiver.
    - To decode the bits, the receiver maps the signal samples to the **closest** symbols.
  - With NRZ, the signal may cycle between the positive and negative levels up to every 2 bits. This means that we need a bandwidth of at least of B/2 Hz when the bit rate is B bits/sec. $C = 2B \log_2 V$ (V = 2)
    - Nyquist Bandwidth

Digital Modulation: Baseband Transmission

- One strategy for using limited bandwidth more efficiently is to use more than two signaling levels.
  - For example, by using four voltages, we can send 2 bits at once as a single symbol.
  - But at the receiver end, the receiver should be strong enough to distinguish the four levels.
  - The rate at which the signal changes is then half the bit rate, so the needed bandwidth has been reduced.

- <u>The bit rate = the symbol rate × the number of bits per symbol</u>
  - Bauds and bits per second are synonymous only in the binary domain.
  - The baud rate = the symbol rate

Digital Modulation: Baseband Transmission

- For all schemes that encodes bits into symbols, the receiver must know when one symbol ends and the next symbol begins to correctly decode the bits.
  - Accurate clock would help with this problem.
- Strategies
  - 1) to send a separate clock signal to the receiver.
  - 2) a clever trick is to mix the clock signal with the data signal by XORing them together so that no extra line is needed.
- **Manchester Encoding**: 0 — a low-to-high transition; 1 — a high-to-low transition.
  - The downside of Manchester encoding is that it requires twice as much bandwidth as NRZ because of clock.
  - Many Ethernet technologies use Manchester encoding.

Digital Modulation: Baseband Transmission

- **NRZI** (Non-Return-to-Zero Inverted)
  - By encoding a 1 as a transition and a 0 as no transition, or vice verse.
  - The popular **USB** (Universal Serial Bus) standard for connecting computer peripherals use NRZI.
- **Scrambling**
  - To make data look random by XORing the data with a **pseudorandom** sequence before it is transmitted.
  - Scrambling prevents to have dominant frequency components (caused by repetitive data patterns) that might radiate electromagnetic interference.
    - Scrambling helps because random signals tend to be “white”, or have energy spread across the frequency components.

Digital Modulation: Baseband Transmission

- **Balanced signals**
  - Signals that have as much positive voltage as negative voltage even over short periods of time are called balanced signals. — They average to zero (have no DC component).
  - The lack of a DC component is an advantage because some channels, such as coaxial cable or lines with transformers, strongly attenuate a DC component due to their physical properties.
  - One method of connecting the receiver to the channel called capacitive coupling passes only the AC components of a signal.
  - A straightforward way to construct a balanced code is to use two voltage levels to represent a logical 1 (say +1 V or –1 V) with 0 V representing a logical 0. — **bipolar encoding**

Digital Modulation: Baseband Transmission

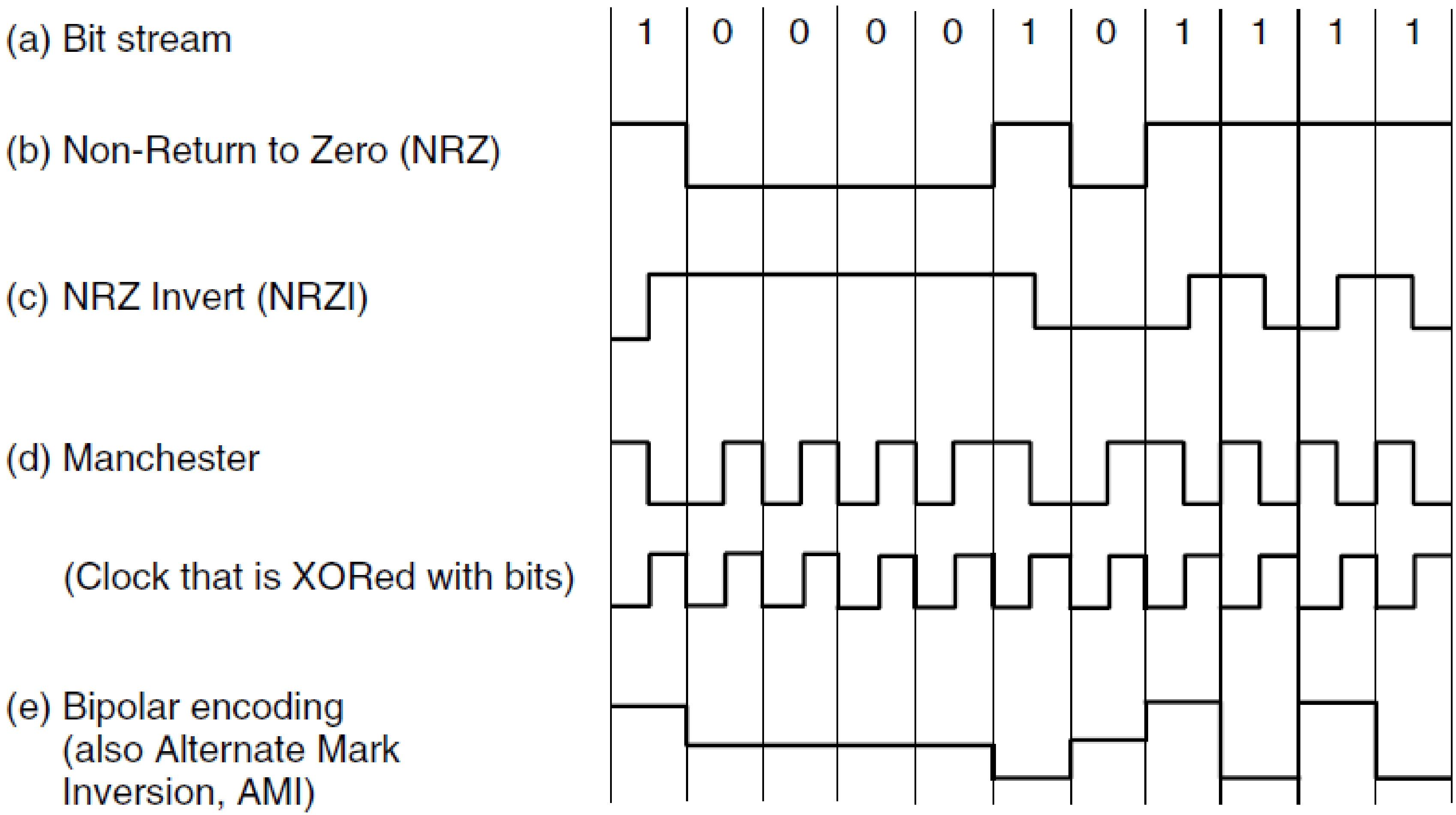


Figure 2-20. Line codes: (a) Bits, (b) NRZ, (c) NRZI, (d) Manchester, (e) Bipolar or AMI.

Digital Modulation: Passband Transmission

- Passband transmission: an arbitrary band of frequencies is used to transmit the signal.
  - To shift a baseband signal that occupies 0 to *B* Hz to occupy a passband of *S* to *S*+*B* Hz without changing the amount of information it carries.
  - At the receiver, it can be shifted back to baseband.
- Why passband transmission?
  - For wireless channels, it is NOT practical to send very low frequency signals because <u>the size of the antenna needs to be a fraction of the signal wavelength</u>, which becomes large.

$$\boxed{\lambda f = c = 3\times 10^{8}\, m/s}$$

  - Regulatory constraints and the need to avoid interference usually dictate the choice of frequencies.
  - <u>Even for wires, placing a signal in a given frequency band is useful to let different kinds of signals coexist on the channel.</u> — **FDMA** for multiplexing

Digital Modulation: Passband Transmission

- Digital modulation is accomplished with passband transmission by regulating or modulating a carrier signal that sits in the passband.
- We can modulate the **amplitude**, **frequency** or **phase** of the carrier signal.
  - **ASK** (Amplitude Shift Keying): two different amplitudes are used to represent 0 and 1. $s_m(t) = A_m g(t)\cos(2\pi f_c t) \quad m = 1, 2\cdots, M$
  - **FSK** (Frequency Shift Keying): two or more different tones are used ($f_c \pm \Delta f, f_c \pm 2\Delta f, \ldots$)
  - **PSK** (Phase Shift Keying): the carrier wave is systematically shifted 0 or 180 degrees at each symbol period.
    - **BPSK** (Binary PSK): 0 and 180 degrees
    - **QPSK** (Quadrature PSK): 45, 135, 225 and 315 degrees

Digital Modulation: Passband Transmission

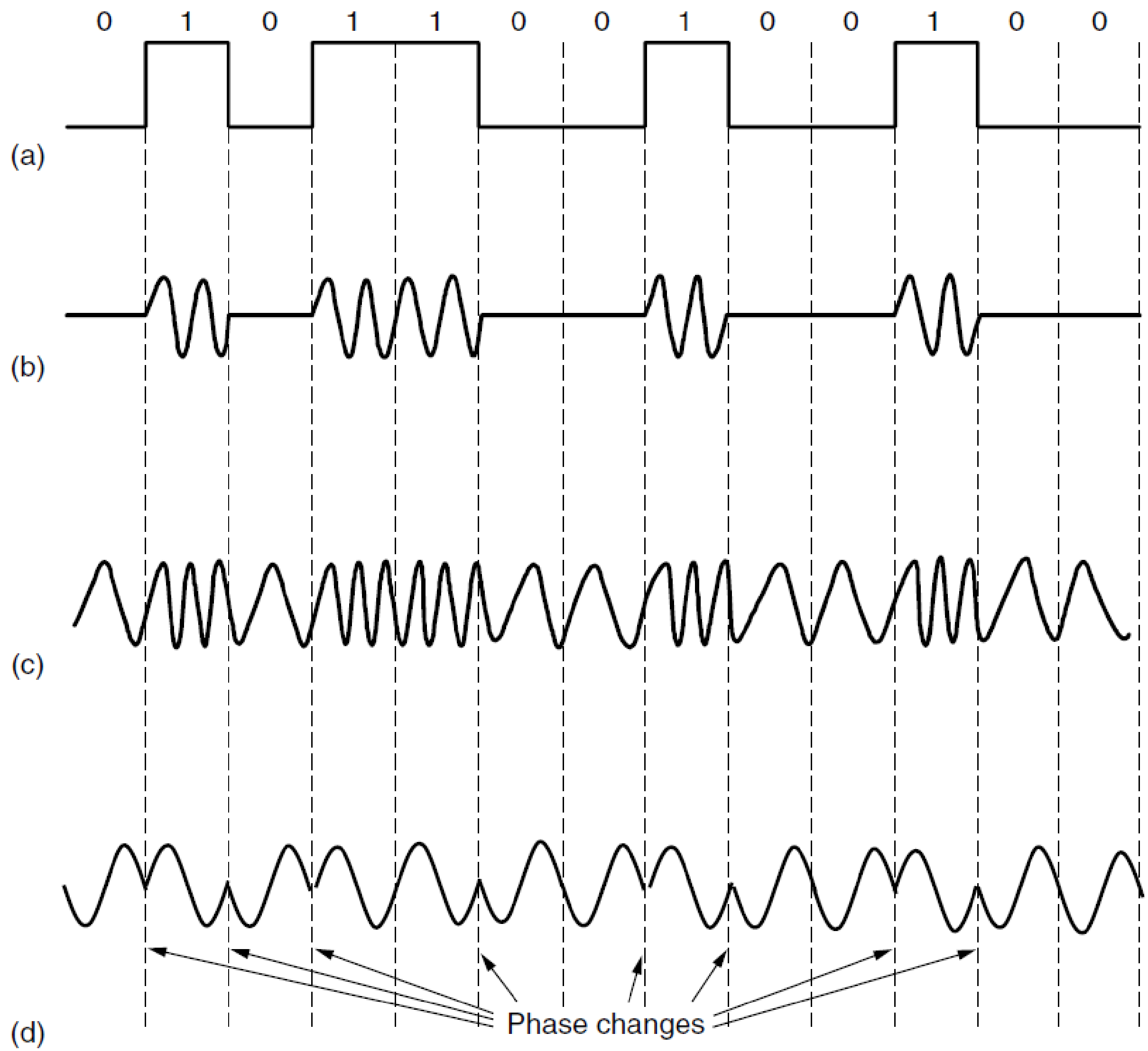


Figure 2-22. (a) A binary signal. (b) Amplitude shift keying. (c) Frequency shift keying. (d) Phase shift keying.

Digital Modulation: Passband Transmission

- We can combine these schemes and use more levels to transmit more bits per symbol.
  - Constellation diagram

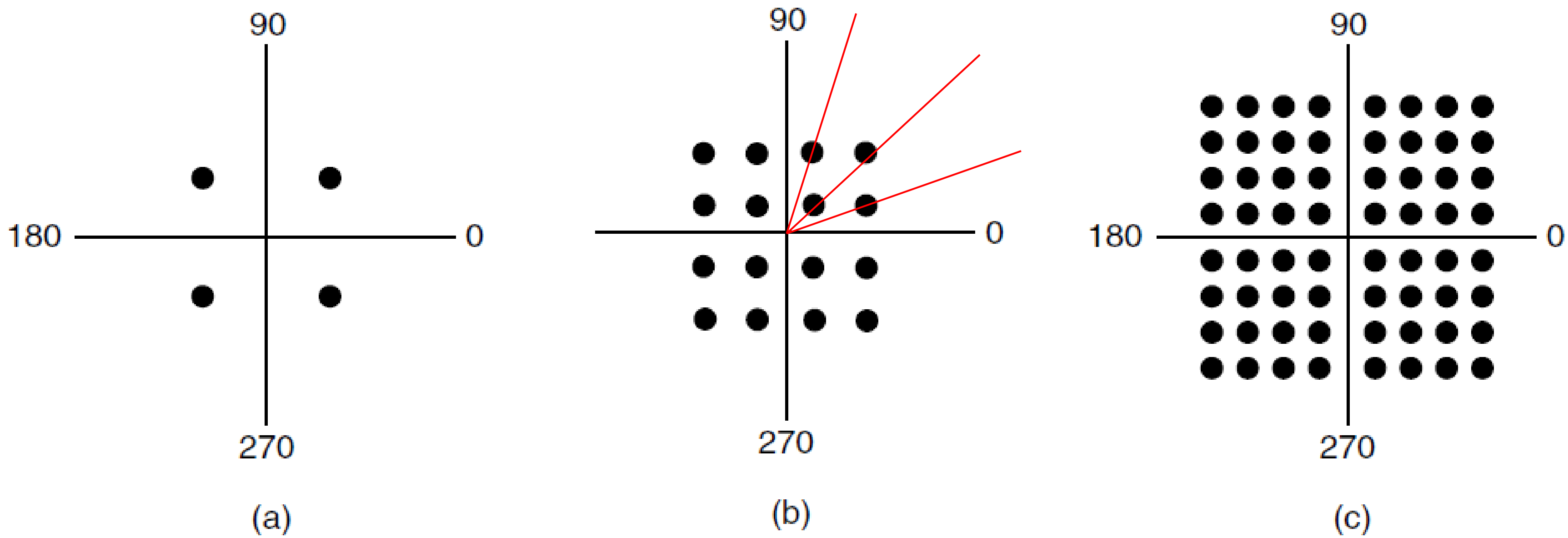
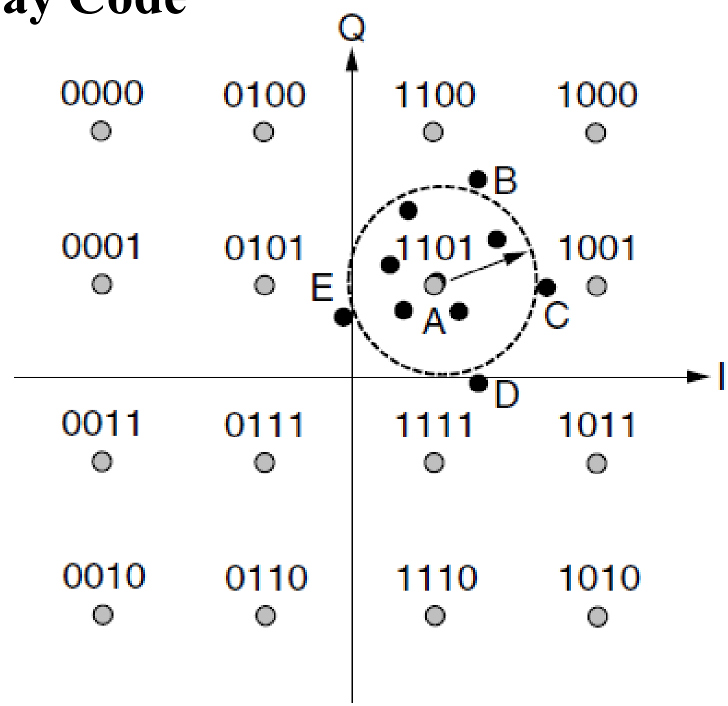


Figure 2-23. (a) QPSK. (b) QAM-16. (c) QAM-64.

It is easier to build electronics to produce symbols as a combination of values on each axis than as a combination of amplitude and phase values. That is why the patterns look like squares rather than concentric circles.

Digital Modulation: Passband Transmission

- The constellations we have seen so far do not show how bits are assigned to symbols. When making the assignment, an important consideration is that <u>*a small burst of noise* at the receiver **not** lead to many bit errors.</u>
  - **Gray Code**



When 1101 is sent:

Point	Decodes as	Bit errors
A	1101	0
B	1100	1
C	1001	1
D	1111	1
E	0101	1

Figure 2-24. Gray-coded QAM-16.

Digital Modulation: FDM

- **FDM** (Frequency Division Multiplexing)
  - To divide the spectrum into frequency bands, with each user having exclusive possession of some band in which to send their signal.
  - Example: AM radio broadcasting — The allocated spectrum is about 1 MHz, roughly 500 kHz to 1500 kHz. Different frequencies are allocated to different logical channels (stations), each operating in a portion of the spectrum, with the interchannel separation great enough to prevent interference.

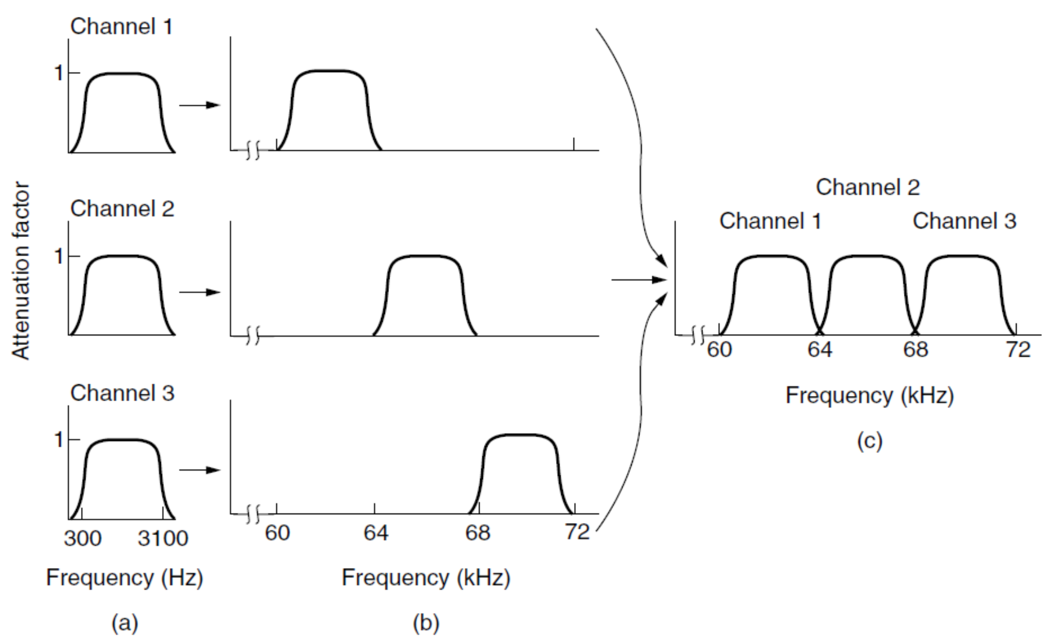


Figure 2-25. Frequency division multiplexing. (a) The original bandwidths. (b) The bandwidths raised in frequency. (c) The multiplexed channel.

Digital Modulation: OFDM

- **OFDM** (Orthogonal FDM)

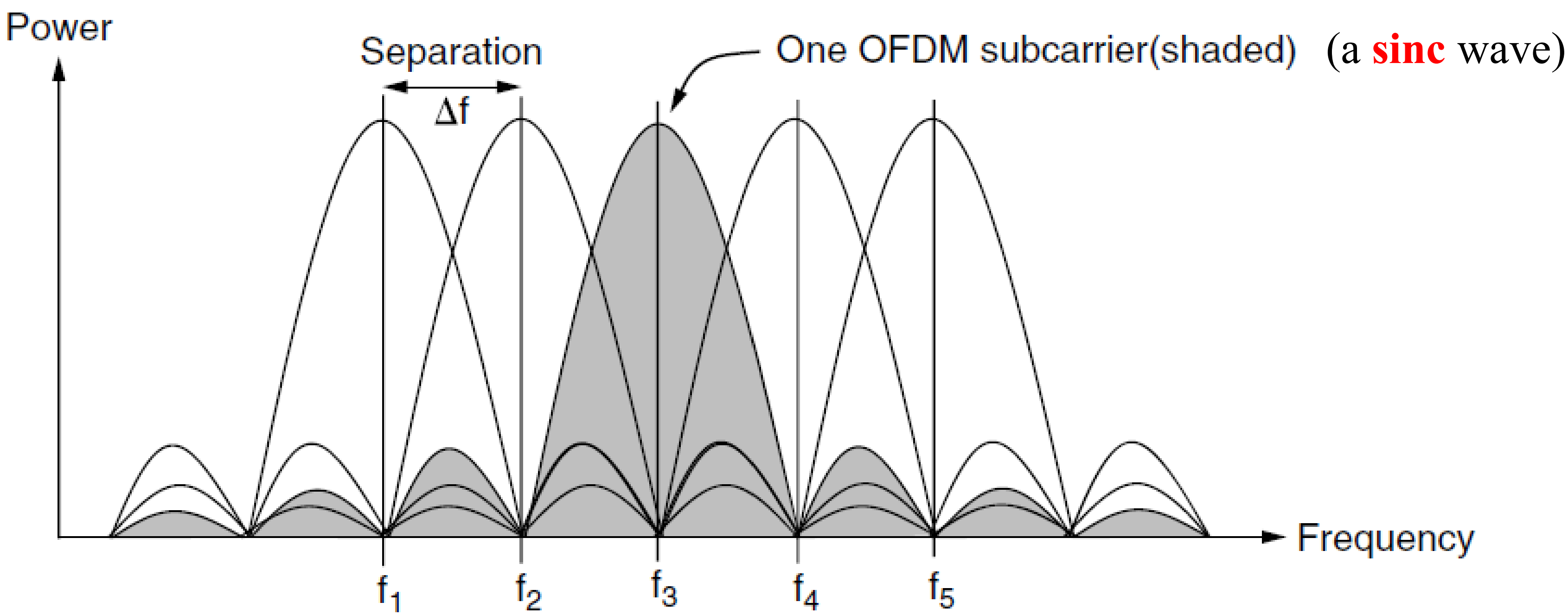


Figure 2-26. Orthogonal frequency division multiplexing (OFDM).

The channel bandwidth is divided into many subcarriers that independently send data. The frequency response of each subcarrier is designed so that **it is zero at the center of the adjacent subcarriers**. To make this work, a guard time is needed to repeat a portion of the symbol signals in time so that they have the desired frequency response.

Digital Modulation: TDM

- **TDM** (Time Division Multiplexing) — the users take turns (in a round-robin fashion), <u>each one *periodically* getting **the entire bandwidth** for a little burst of time</u>.
  - Time slot

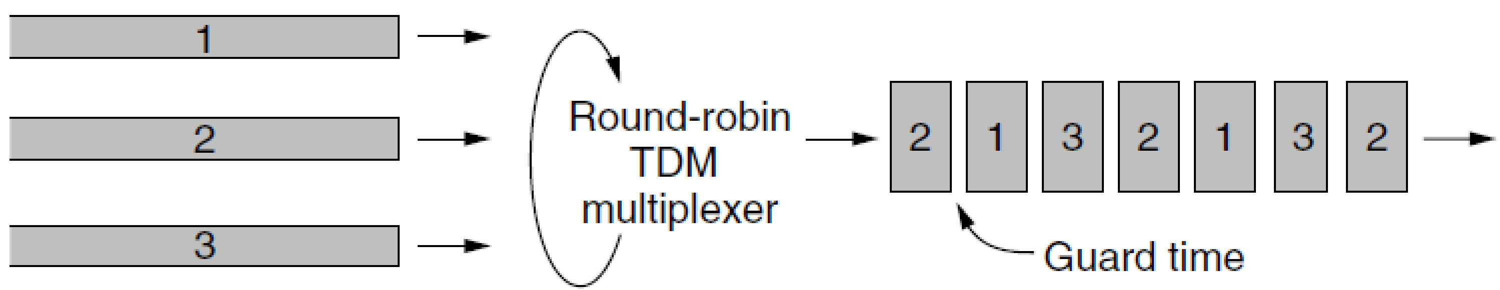


Figure 2-27. Time Division Multiplexing (TDM).

This stream runs at the sum rate of the individual streams. For this to work, the streams must be **synchronized** in time.

Digital Modulation: CDM

- **CDM** (Code Division Multiplexing)
  - A form of spread spectrum communication in which a narrowband signal is *spread out* over a wider frequency band.
  - More tolerant of interference.
  - Allows each station to transmit over the entire frequency spectrum all the time. Multiple simultaneous transmissions are separated using coding theory.
  - In CDMA, each bit time is subdivided into *m* short intervals called **chips**.
    - Typically, there are 64 or 128 chips per bit.
    - Each station has its own **unique** chip sequence — **Walsh codes**

Digital Modulation: CDM

- Increasing the amount of information to be sent from *b* bits/sec to *mb* bits/sec for each station means that the bandwidth needed for CDMA is greater by a factor of *m* than the bandwidth needed for a station not using CDMA.
  - If we have a 1-MHz band available for 100 stations, with FDMA each one would have 10 kHz and could send at 10 kbps.
  - With CDMA, each station use the full 1-MHz, so the chip rate is 100 chips per bit to spread the station's bit rate of 10 kbps across the channel.
    - With good pseudo-noise codes (Gold codes, Walsh codes, etc.), users interfere like additional noise.
    - CDMA capacity is then **interference-limited**, not bandwidth-limited.
  - One significant limitation is that we have assumed that all the chips are **synchronized** in time at the receiver.

Digital Modulation: CDM

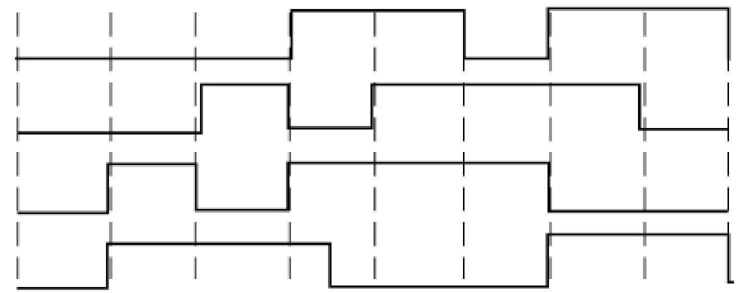
$A = (-1\ -1\ -1\ +1\ +1\ -1\ +1\ +1)$

$B = (-1\ -1\ +1\ -1\ +1\ +1\ +1\ -1)$

$C = (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$

$D = (-1\ +1\ -1\ -1\ -1\ -1\ +1\ -1)$

(a)



(b)

$$
\begin{aligned}
S_1 &= C &&= (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)\\
S_2 &= B+C &&= (-2\ \ 0\ \ 0\ \ 0\ +2\ +2\ \ 0\ -2)\\
S_3 &= A+\overline{B} &&= (\ 0\ \ 0\ -2\ +2\ \ 0\ -2\ \ 0\ +2)\\
S_4 &= A+\overline{B}+C &&= (-1\ +1\ -3\ +3\ +1\ -1\ -1\ +1)\\
S_5 &= A+B+C+D &&= (-4\ \ 0\ -2\ \ 0\ +2\ \ 0\ +2\ -2)\\
S_6 &= A+B+\overline{C}+D &&= (-2\ -2\ \ 0\ -2\ \ 0\ -2\ +4\ \ 0)
\end{aligned}
$$

(c)

$$
\begin{aligned}
S_1 \bullet C &= [1+1+1+1+1+1+1+1]/8 = 1\\
S_2 \bullet C &= [2+0+0+0+2+2+0+2]/8 = 1\\
S_3 \bullet C &= [0+0+2+2+0-2+0-2]/8 = 0\\
S_4 \bullet C &= [1+1+3+3+1-1+1-1]/8 = 1\\
S_5 \bullet C &= [4+0+2+0+2+0-2+2]/8 = 1\\
S_6 \bullet C &= [2-2+0-2+0-2-4+0]/8 = -1
\end{aligned}
$$

(d)

- Each station has its own ***unique*** chip sequence. Let the symbol **S** denotes the *m*-chip vector for station S, and $\overline{\mathbf{S}}$ for its negation.
  - During each bit time, a station can transmit a 1 (by sending its chip sequence), it can transmit a 0 (by sending the negative of its chip sequence)

Digital Modulation: CDM

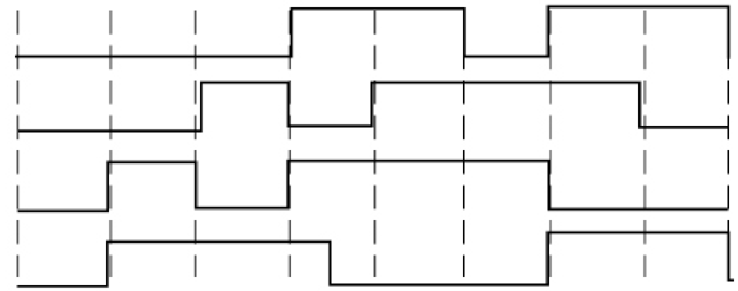
A = (−1 −1 −1 +1 +1 −1 +1 +1)

B = (−1 −1 +1 −1 +1 +1 +1 −1)

C = (−1 +1 −1 +1 +1 +1 −1 −1)

D = (−1 +1 −1 −1 −1 −1 +1 −1)

(a)



(b)

$S_1 = C \quad = (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$

$S_2 = B+C \quad = (-2\ \ 0\ \ 0\ \ 0\ +2\ +2\ \ 0\ -2)$

$S_3 = A+\overline{B} \quad = (\ 0\ \ 0\ -2\ +2\ \ 0\ -2\ \ 0\ +2)$

$S_4 = A+\overline{B}+C \quad = (-1\ +1\ -3\ +3\ +1\ -1\ -1\ +1)$

$S_5 = A+B+C+D = (-4\ \ 0\ -2\ \ 0\ +2\ \ 0\ +2\ -2)$

$S_6 = A+B+\overline{C}+D = (-2\ -2\ \ 0\ -2\ \ 0\ -2\ +4\ \ 0)$

(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)

- If all chip sequences are *orthogonal*, by which we mean that the normalized inner product of any two *distinct* chip sequences **S** and **T** is 0, that is $S \cdot T = \frac{1}{m}\sum_{i=1}^{m} S_i T_i = 0$

$$\boxed{\mathbf{S}\bullet\mathbf{S} = \frac{1}{m}\sum_{i=1}^{m} S_i S_i = \frac{1}{m}\sum_{i=1}^{m} S_i^2 = \frac{1}{m}\sum_{i=1}^{m} (\pm 1)^2 = 1, \quad \mathbf{S}\bullet\overline{\mathbf{S}} = \frac{1}{m}\sum_{i=1}^{m} S_i \overline{S}_i = -1}$$

Outline

- The theoretical basis for data communication
- Three kinds of transmission media
- Digital modulation and multiplexing
- Three examples of communication examples

Outline

- The theoretical basis for data communication
- Three kinds of transmission media
- Digital modulation and multiplexing
- Three examples of communication examples
  - Public Switch Telephone Network
  - Cellular Networks
  - Cable Networks

Example I: PSTN (I)

- Alexander Graham Bell patented the telephone in 1876.
- The Bell Telephone Company opened its first switching office in 1878.

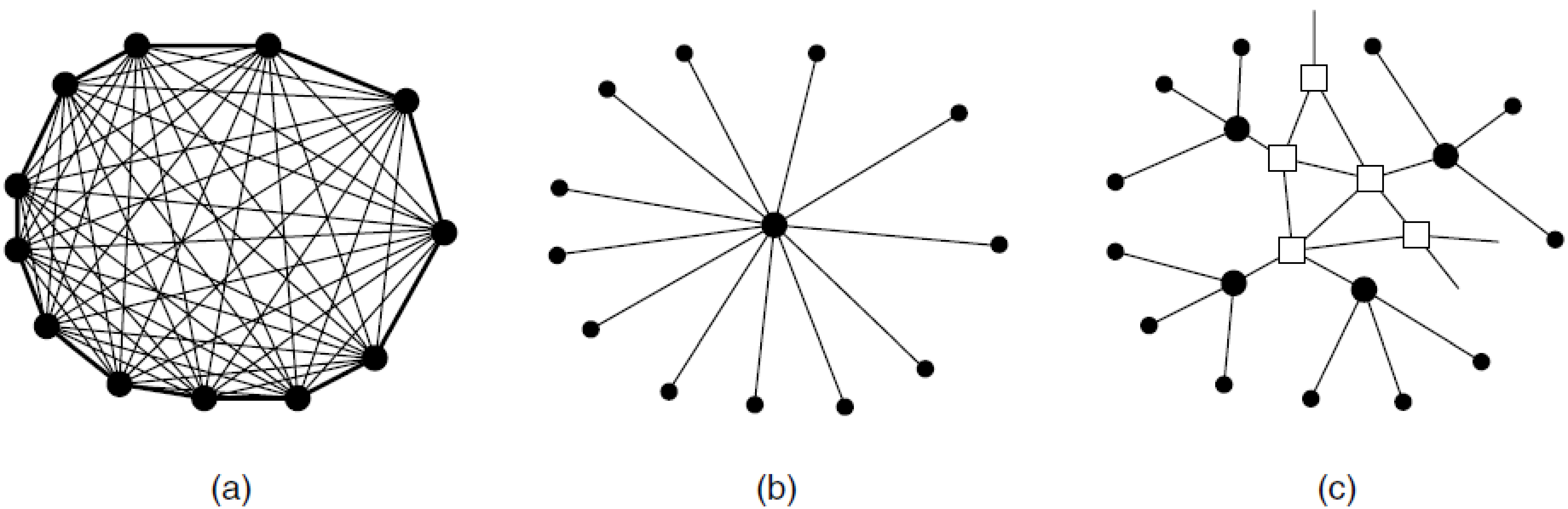


Figure 2-29. (a) Fully interconnected network. (b) Centralized switch. (c) Two-level hierarchy.

Example I: PSTN (II)

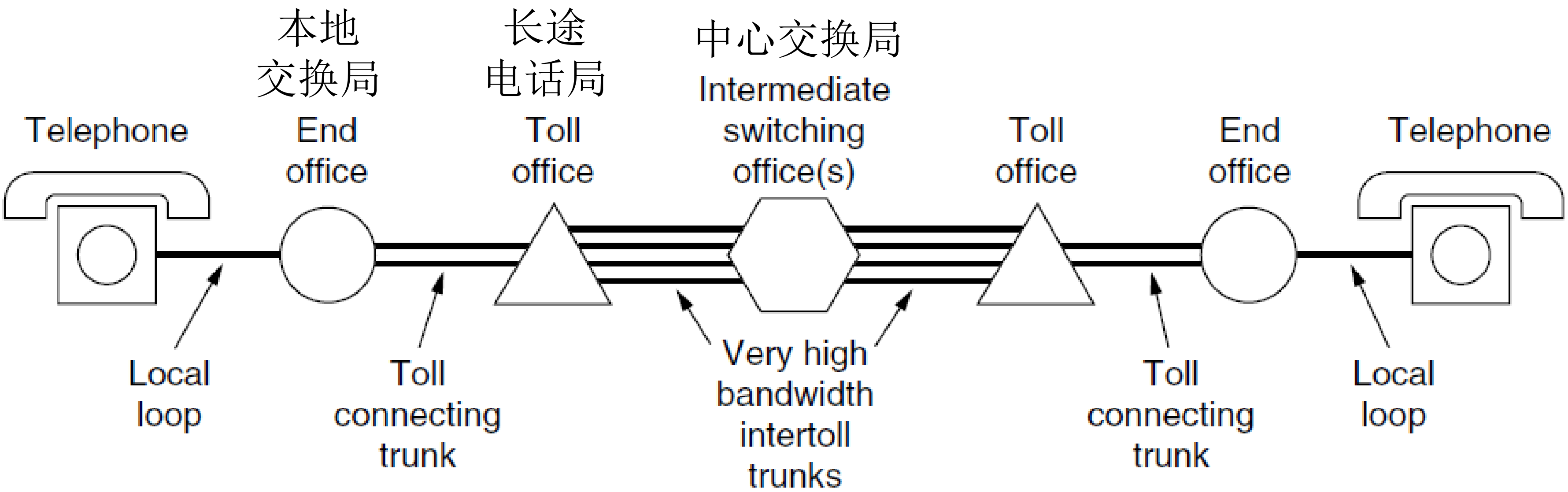


Figure 2-30. A typical circuit route for a long-distance call.

The telephone system consists of *three* major components:

1. **Local loops**: telephone modem, ADSL, fiber
2. **Trunks** (digital fiber optic links connecting switching offices) — main consideration problem is multiplexing (FDM and TDM)
3. **Switching offices** (where calls are moved from one trunk to another) — two switching ways

Example I: PSNT: Local Loop

- Telephone **modems**
  - A device that converts between a stream of digital bits and an analog signal that represents the bits is called a **modem**, which is short for "modulator demodulator"

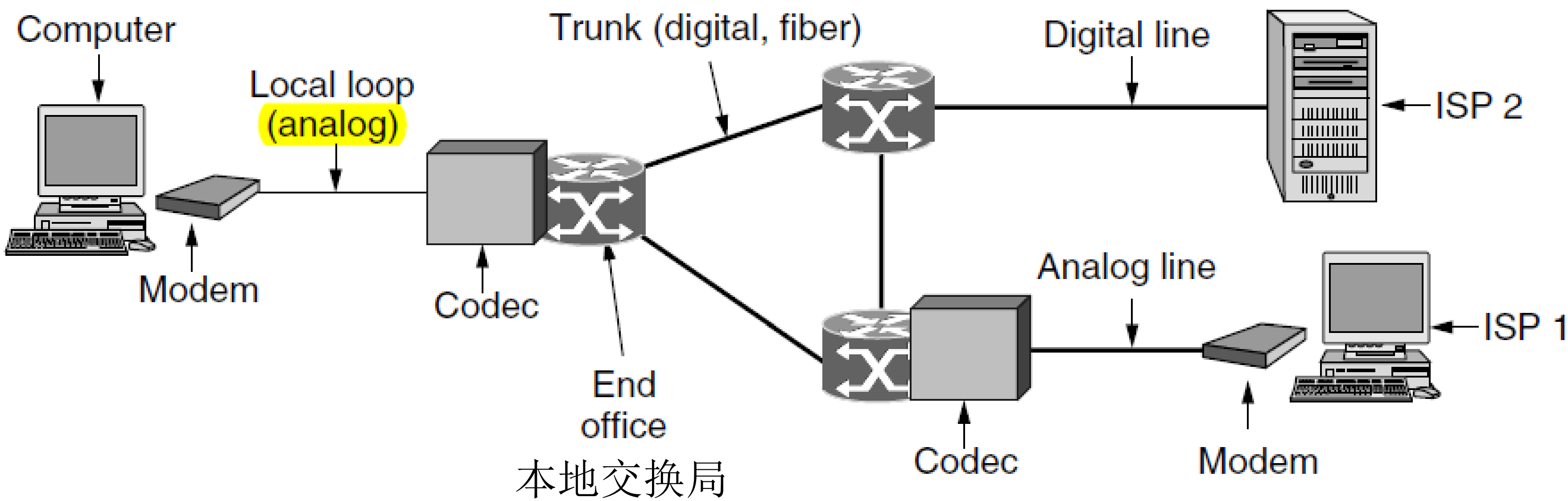
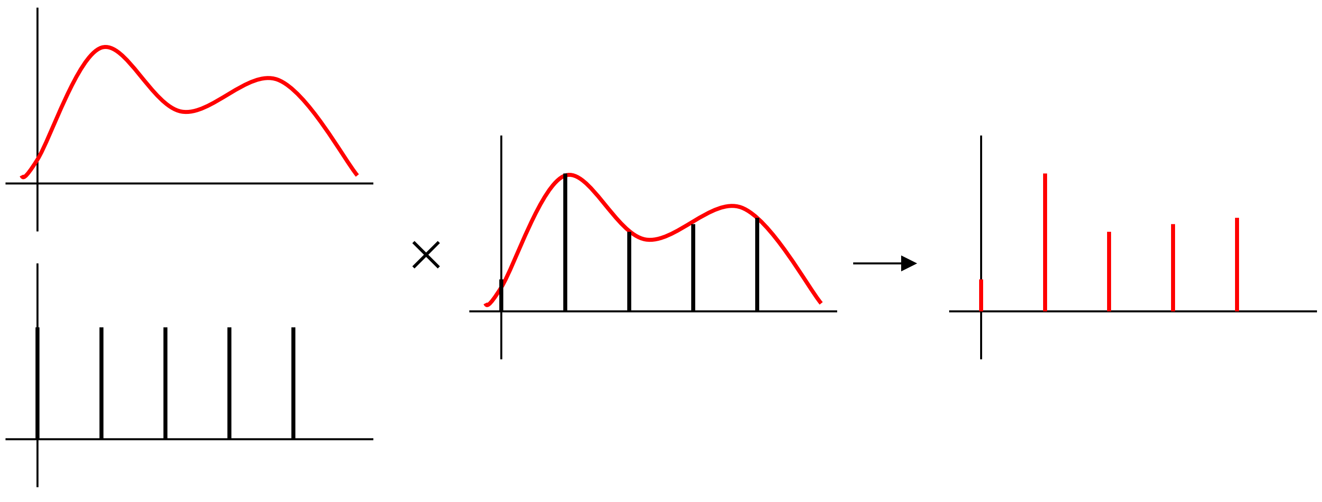


Figure 2-32. The use of both analog and digital transmission for a computer-to-computer call. Conversion is done by the modems and codecs.

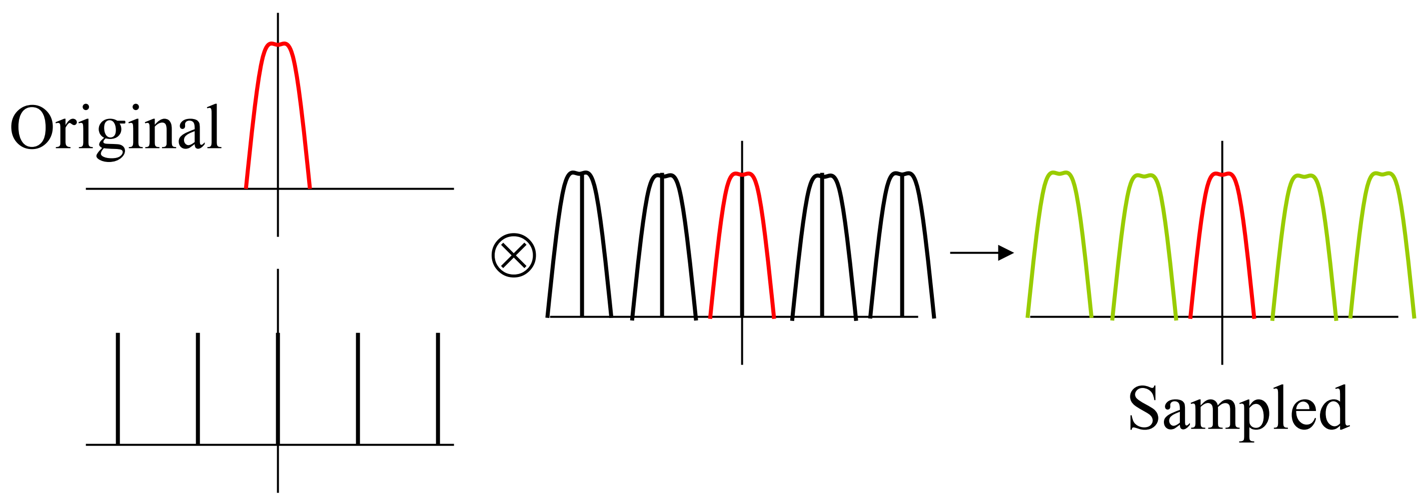
Sampling in Spatial Domain*

- Sampling in the spatial domain is like **multiplying** by a comb function
- You take some ideal function and get data for a regular grid of points



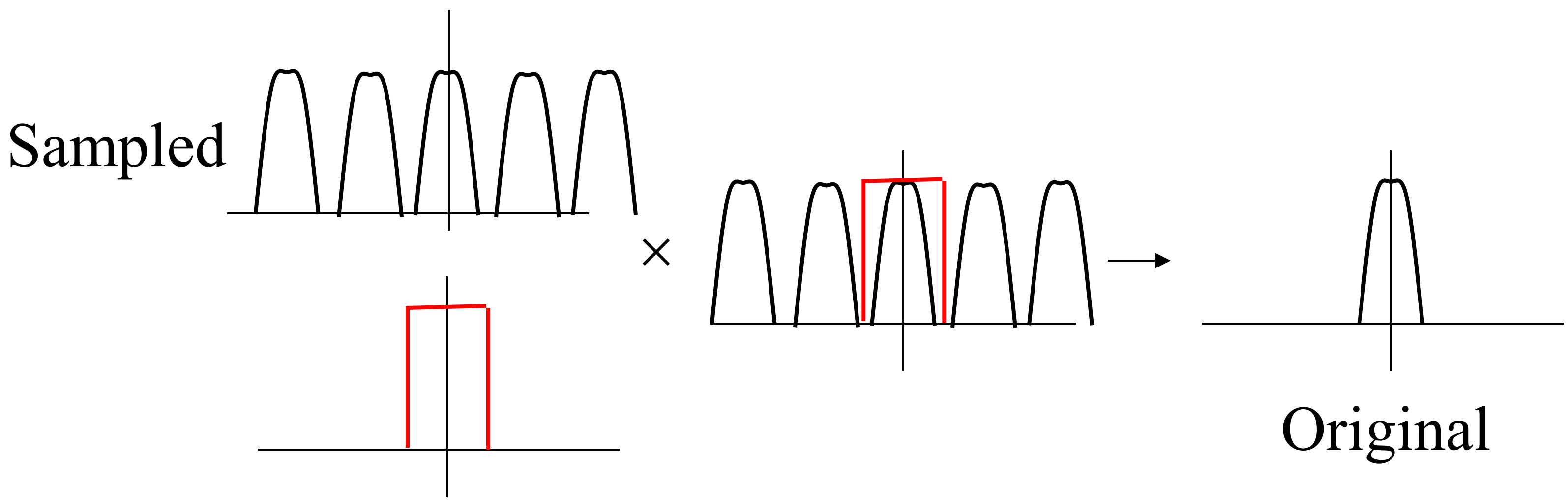
Sampling in Frequency Domain*

- Sampling in the frequency domain is like **convolving** with a comb function
  - Follows from the convolution theory: multiplication in spatial equals convolution in frequency
  - Spatial comb function in the frequency domain is also the comb function



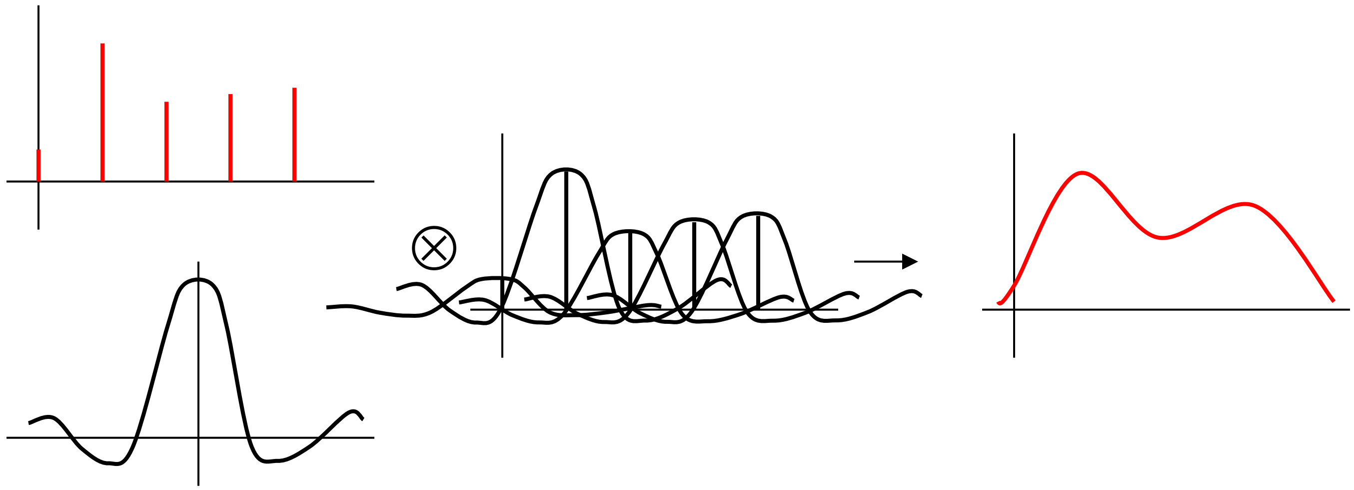
Reconstruction (Frequency Domain)*

- To reconstruct, we must restore the original spectrum
- That can be done by multiplying by a square pulse – **an ideal low-passing filter**.



Reconstruction (Spatial Domain)*

- Multiplying by a square pulse in the frequency domain is the same as convolving with a **sinc** function in the spatial domain



Nyquist Sampling

- **Aliasing** cannot happen if you sample at a frequency that is twice the original frequency – **the Nyquist Sampling Limit**
  - You cannot accurately reconstruct a signal that was sampled below its Nyquist frequency – you do not have the enough information.
  - There is no point sampling at higher frequency – you do not gain extra information
- Signals that are not **bandlimited** cannot be accurately sampled and reconstructed
  - They would require an infinite sampling frequency

Example I: PSNT: Local Loop

- Telephone **modems**
  - A voice-grade telephone line is limited to 3100 Hz, and each telephone channel is 4000 Hz wide when the guard bands are included.
  - According to **the Nyquist Theorem**, the number of samples per second needed to reconstruct it is thus 8000.
  - The number of bits per sample in the U.S. is 8, one of which may be used for control purposes, allowing 56 kbps for user data
  - In Europe, all 8 bits are available to users, so 64 kbps modems could have been used.
  - The downstream channel (ISP to user) provides a higher bit rate than that of the upstream channel (user to ISP) because there is usually more data transported from the ISP to the user than the other way.

Example I: PSNT: Local Loop

- Telephone **modems**

Data (4B)	Codeword (5B)	Data (4B)	Codeword (5B)
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

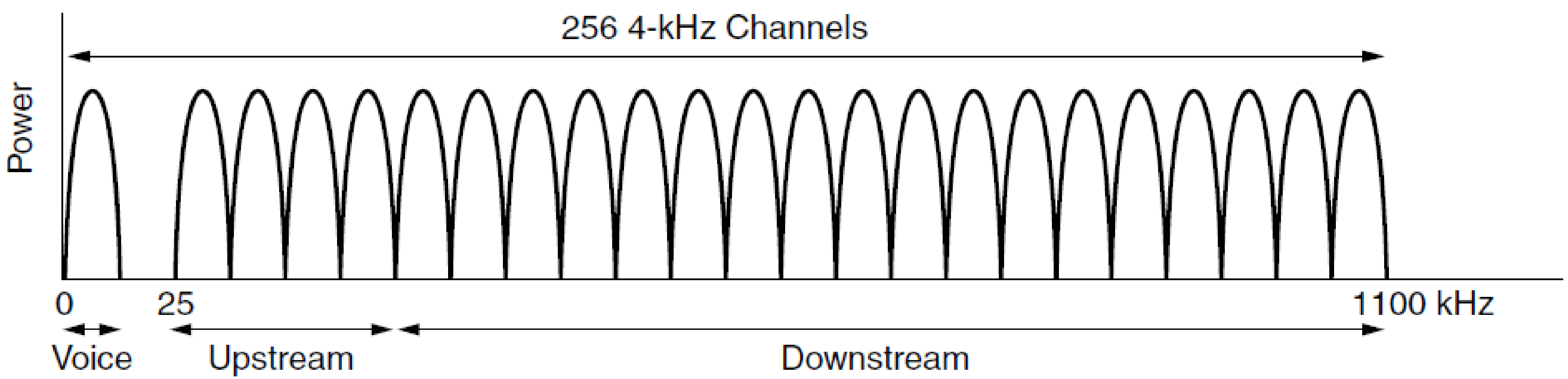
Some modem standards and their bit rate.

Example I: PSNT: Local Loop

- Digital Subscriber Lines
  - Telephones were invented for carrying the human voice and the entire system has been carefully *optimized* for this purpose.
  - The wire runs through **a filter** that attenuates all frequencies below 300 Hz and above 3400 Hz, quoted as 4000 Hz.
  - The trick that makes xDSL work is that without the filter, the entire capacity of the local loop available. The limiting factor then becomes the physics of the local loop, which supports roughly **1 MHz**, not the artificial 3100 Hz bandwidth created by the filter.

Example I: PSNT: Local Loop

- The available 1.1 MHz spectrum on the local loop is divided into 256 independent channels of around 4 kHz each.
- The OFDM scheme is used to send data over these channels, though it is often called **DMT** (Discrete MultiTone) in the context of ADSL.
- Channel 0 is used for POTS (Plain Old Telephone Service)
- Channels 1-5 are not used to keep the voice and data signals from *interfering* with each other.
- Of the remaining 250 channels, one is used for **upstream control** and one is used for **downstream control**. The rest are available for **user data**.



Most users download more data than their upload.

Figure 2-34. Operation of ADSL using discrete multitone modulation.

Example I: PSNT: Local Loop

- The international ADSL standard, known as G.dmt (Discrete MultiTone), was approved in 1999: 8 Mbps downstream and 1 Mbps upstream.
- It was superseded by a second generation in 2002, called ADSL: 12 Mbps downstream and 1 Mbps upstream.
- ADSL2+: doubles the downstream speed to 24 Mbps by doubling the bandwidth to use 2.2 MHz over the twisted pair.

Example I: PSNT: Local Loop

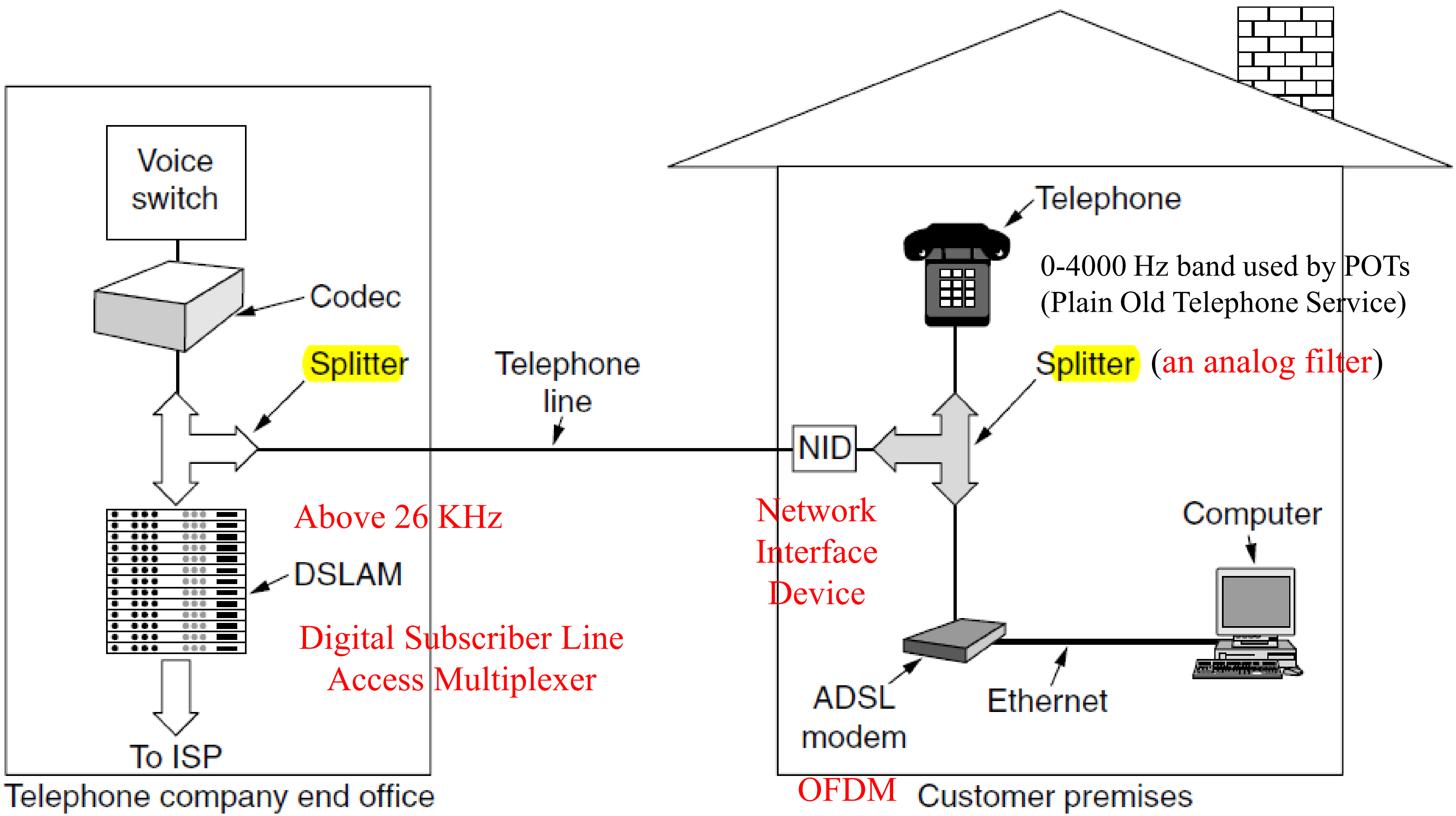


Figure 2-35. A typical ADSL equipment configuration.

Example I: PSNT: Local Loop

- Fiber to the Home
  - Deployed copper local loops limit the performance of ADSL and telephone modems. To let them provide faster and better network services, telephone companies are upgrading local loops at every opportunity by installing optical fiber all the way to houses and offices.
  - Usually, the fibers from the houses are joined together so that only a single fiber reaches the end office per group of up to 100 houses.
    - In the downstream direction, **optical splitter** divide the signal from the end office so that is reaches all the houses. Encryption is needed for security if only one house should be able to decode the signal.
    - In the upstream direction, **optical combiners** merge the signals from the houses into a single signal that is received at the end office. — **synchronization**
  - **PON** (Passive Optical Network)
    - <u>It is common to use one wavelength shared between all the houses for downstream transmission, and another wavelength for upstream transmission.</u>

Example I: PSNT: Local Loop

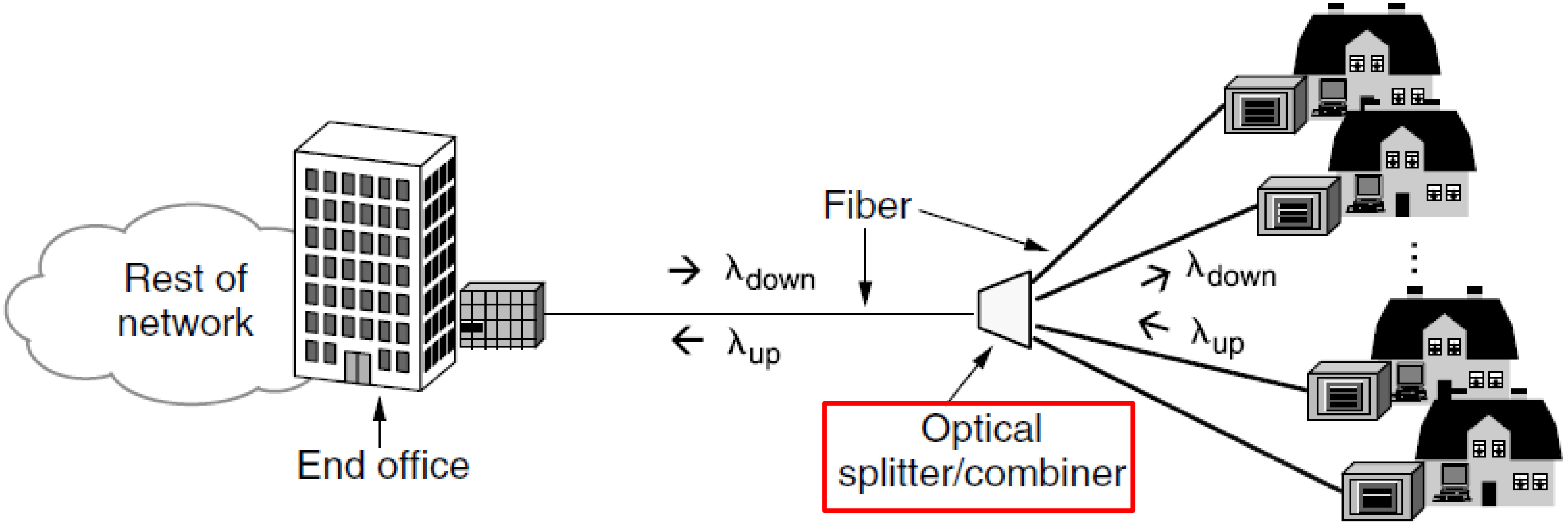


Figure 2-36. Passive optical network for Fiber To The Home.

Example I: PSNT: Trunks

- Trunks in the telephone network are not only much faster than the local loops, they are different in two other respects.
  - The core of the telephone network carries digital information, not analog information; that is, **bits not voice**.
  - The trunks carry thousands, even millions, of calls *simultaneously*.
    - This sharing is important for achieving economies of scale.
    - It is accomplished with versions of **TDM** and **FDM** multiplexing.
      - **SONET**: the TDM system used for fiber optics
      - FDM is applied to fiber optics (**wavelength division multiplexing**)

Example I: PSNT: Trunks

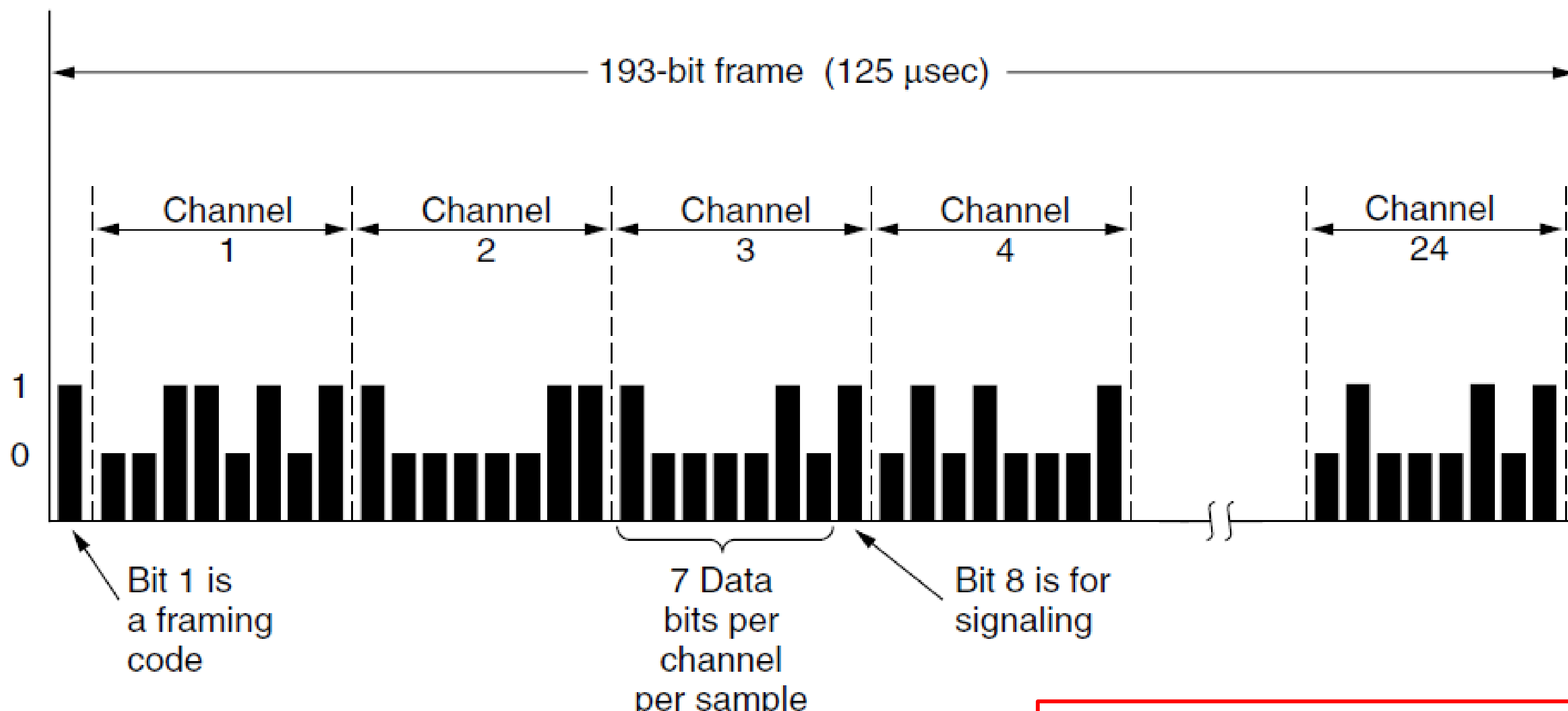
- Early in the development of the telephone network, the core handled voice calls as analog information.
- FDM techniques were used for many years to multiplexing 4000-Hz voice channels (comprised of 3100 Hz plus guard bands) into larger and larger units.
  - For example, 12 calls in the 60 kHz-to-108 kHz band is know as a group and five groups (a total of 60 calls) are known as a supergroup, and so on.
- FDM requires *analog* circuitry. In contrast, TDM can be handled entirely by *digital* electronics.

Example I: PSNT: Trunks

- Digitizing Voice Signals
  - **Sampling Theorem** (Nyquist Theorem) — If a signal $f(t)$ is sampled at regular intervals of time and at a rate higher than twice the highest signal frequency, then the samples contain all the information of the original signal. The function $f(t)$ may be reconstructed from the samples by the use of a low-passing filter.
  - According to the Nyquist theorem, the codec makes 8000 samples per second for the 4 kHz telephone channel bandwidth. Each sample of the amplitude of the signal is **quantized** to an 8-bit number (**PCM**).
    - The data rate is 8000 samples/sec *8 bits /sample = 64 kbps
    - The sample rate is 125 μsec/sample. (10^{-6} sec)

Example I: PSNT: Trunks

- TDM (Time Division Multiplexing)
  - The format is called DS1 and the carrier is called T1 (North America and Japan).
  - The T1 carrier consists of 24 voice channels multiplexing together.



193 bits/ 125 μsec = 1.544 Mbps

Figure 2-37. The T1 carrier (1.544 Mbps).

Example I: PSNT: Trunks

- Time division multiplexing allows multiple T1 carriers to be multiplexed into higher-order carriers.
  - **Four** T1 streams at 1.544 Mbps should generate 6.176 Mbps, but T2 is actually 6.312 Mbps. The extra bits are used for framing and recovery in case the carrier slips.

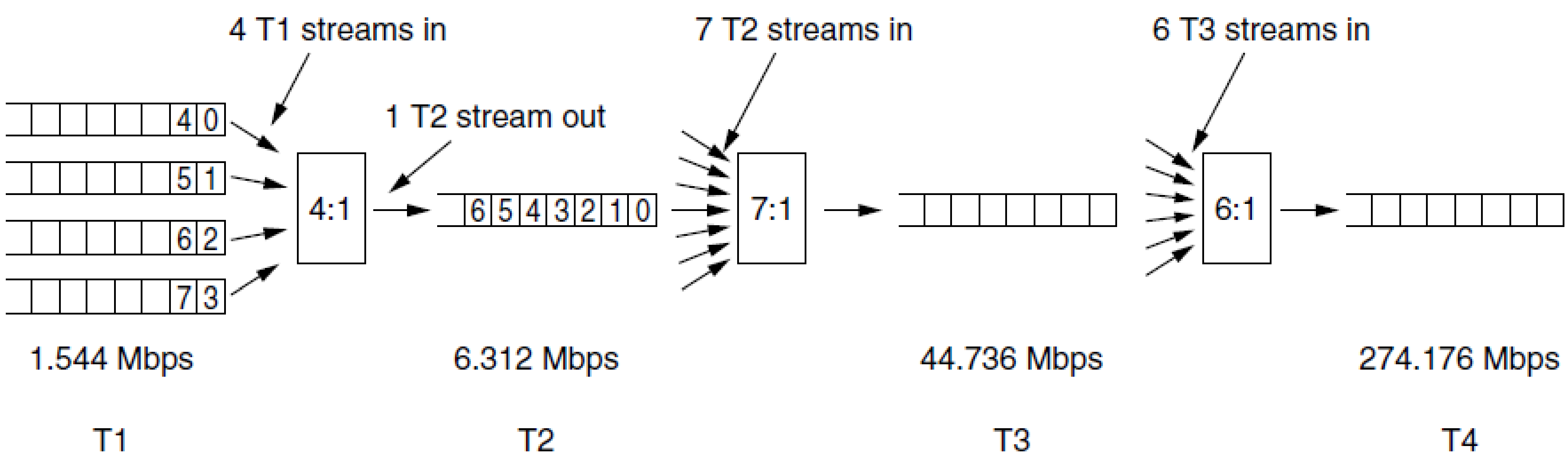
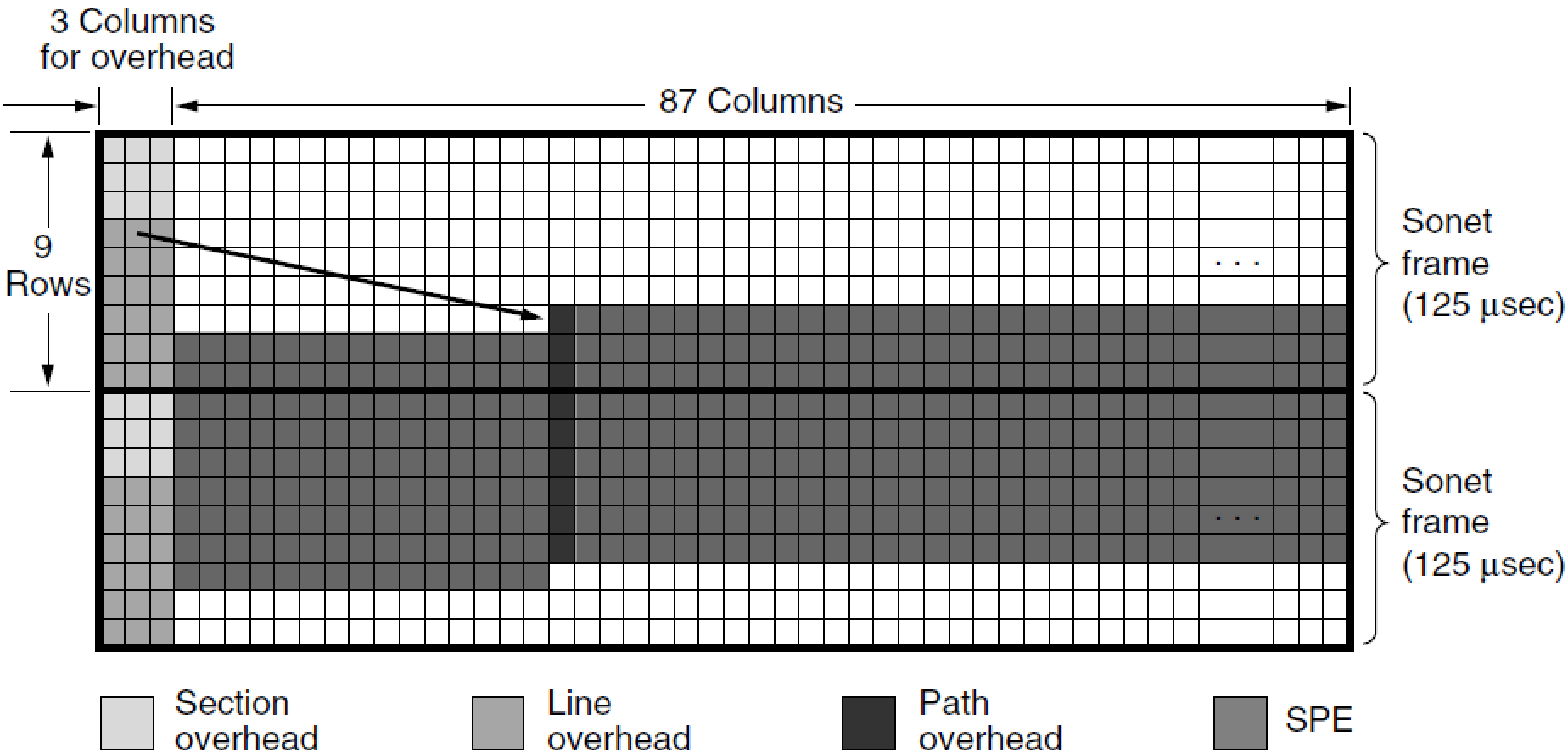


Figure 2-38. Multiplexing T1 streams into higher carriers.

Example I: PSNT: Trunks

- **SONET/SDH** (Synchronous Optics NETwork, Bellcore, 1985) — a standardization of optical TDM system.
  - The basic SONET frame is a block of 810 bytes put out every 125μsec.
  - The 810-byte SONET frames are best described as a rectangle of bytes, <u>90 columns wide by 9 rows high</u>.
  - $8 \times 810 = 6480$ bits are transmitted 8000 times per second, thus a gross data rate 51.84 Mbps. ($6480 \times 8000 = 51.84 \times 10^6$ bits/s)
  - This layout is the basic SONET channel, called STS-1 (Synchronous Transport Signal-1)
  - All SONET trunks are multiples of STS-1.

Example I: PSNT: Trunks



Synchronous Payload Envelope

Figure 2-39. Two back-to-back SONET frames.

Example I: PSNT: Trunks

- **WDM** (Wave-length Division Multiplexing)

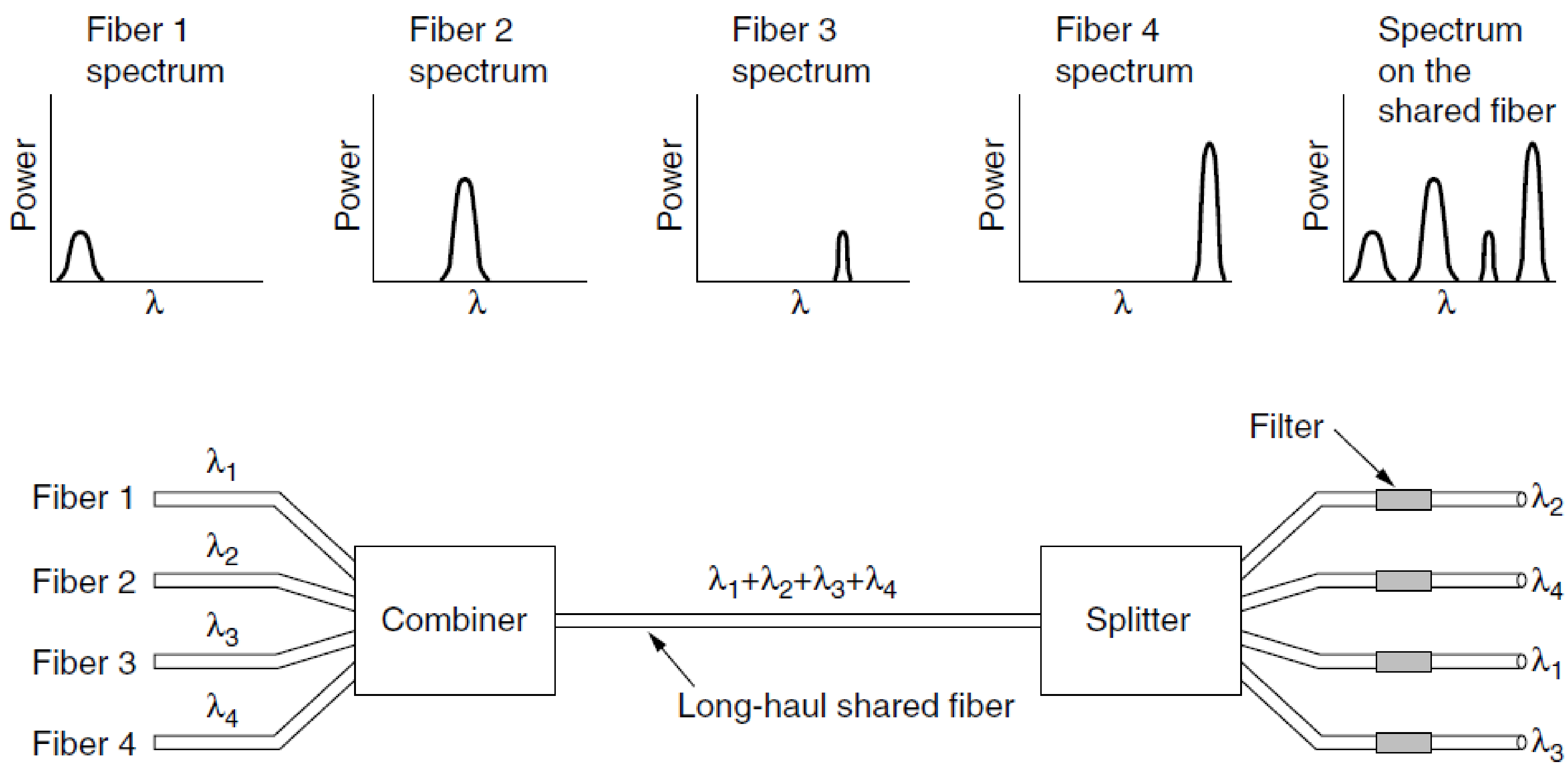


Figure 2-41. Wavelength division multiplexing.

Compared to FDM, the description of fiber optic channels by their wavelength or "color" rather than frequency.

Example I: PSNT: Switching

- Circuit Switching
  - Once a call has been set up, **a dedicated physical path** between both ends exists and will continue to exist until the call is finished.
    - The need to set up and end-to-end path before any data can be sent.
    - The only delay for data is the propagation time for the electromagnetic signal, about 5 msec per 1000 km.
  - Automatic circuit switching equipment was invented by a 19th century Missouri undertaker name Almon B. Strowger.

Example I: PSNT: Switching

- Packet Switching
  - There is no need to set up a dedicated path in advance.
  - It is up to routers to use **store-and-forward** transmission to send each packet on its way to the destination on its own.
    - There is no fixed path.
  - Packet-switching networks place a tight upper limit on the size of packets.
  - Queuing delay and congestion

Example I: PSNT: Switching

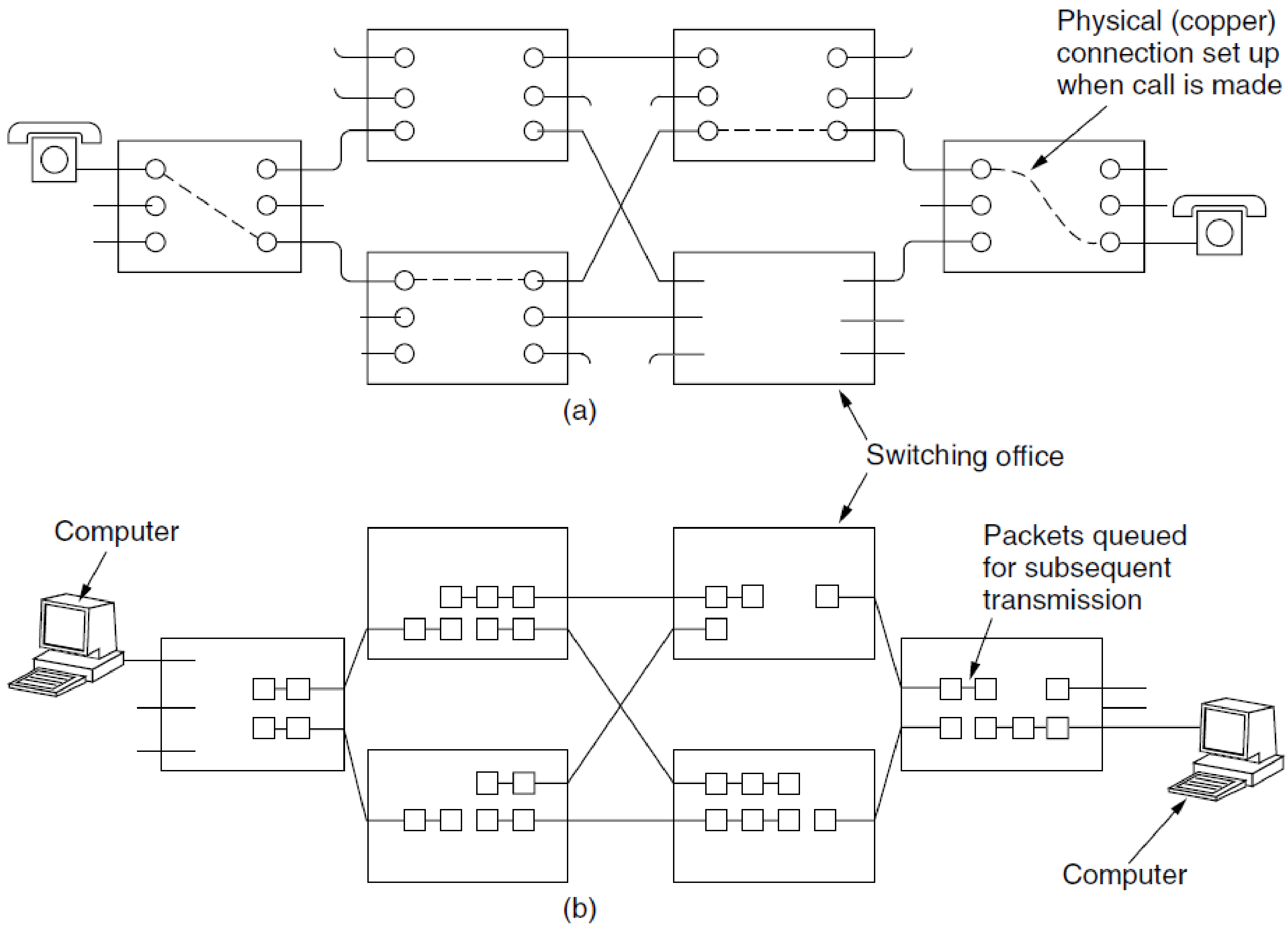


Figure 2-42. (a) Circuit switching. (b) Packet switching.

Example I: PSNT: Switching

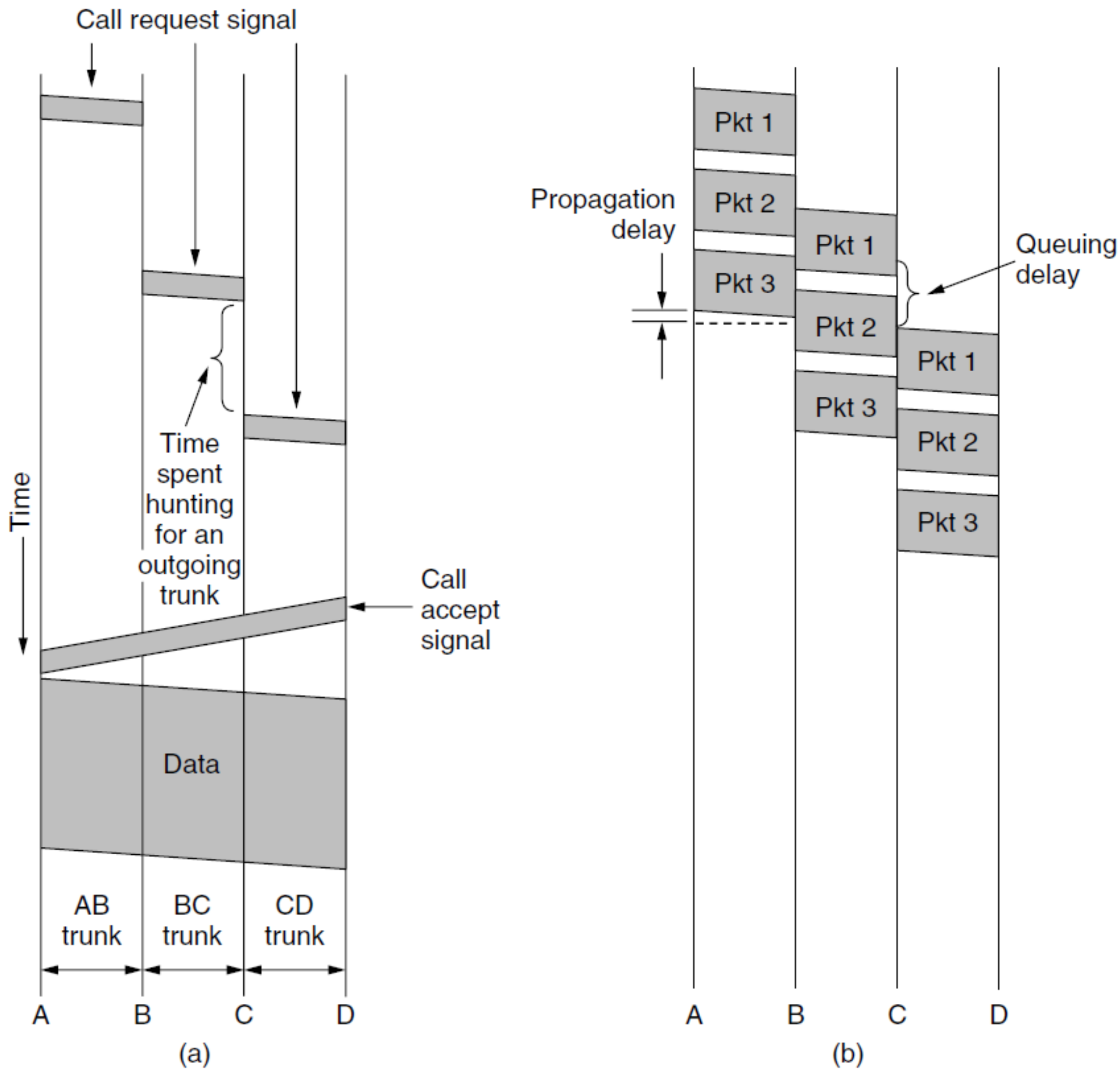


Figure 2-43. Timing of events in (a) circuit switching, (b) packet switching.

Circuit Switching vs. Packet 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
Charging	Per minute	Per packet

Figure 2-44. A comparison of circuit-switched and packet-switched networks.

Circuit Switching vs. Packet Switching [6]

- Circuit switching *pre-allocates* use of the transmission link regardless of demand, with allocated but unneeded link time going unused. Packet switching on the other hand allocates link use *on demand*. Such on-demand (rather than pre-allocated) sharing of resources is sometimes referred to as **the statistical multiplexing** of resources.
- Although packet switching and circuit switching are both prevalent in today's telecommunication networks, the trend has certainly been in the direction of packet switching.
- Why is packet switching more efficient? Let's look at a simple example: Suppose there are 10 users and they share a 1Mbps link, then one user suddenly generates one thousand 1000-bit packets, while other users remain quiescent and do not generate packets.
  - Circuit switching: for example we use a TDM circuit switching with 10 time slots per frame.
  - Packet switching:

Circuit Switching vs. Packet Switching [6]

- Why is packet switching more efficient? Let's look at a simple example: Suppose there are 10 users and they share a 1Mbps link, then one user suddenly generates *one thousand* 1000-bit packets, while other users remain quiescent and do not generate packets.
  - Circuit switching: for example, we use a TDM circuit switching with 10 time slots per frame. Since the active user can only use its own time slot to transmit data, and the transmission rate is 1Mbps/10 = 100kbps, so it will take 10 seconds before all the active user's one million bits of data has been transmitted.
  - Packet switching: the active user can continuously send its packets at the full link rate of 1Mbps, since there are no other users generating packets. So, in this case, all of the active user's packets will be transmitted within 1 second.

Circuit Switching vs. Packet Switching [6]

- Based on the above example, let's look at a more complicated situation: the probability that a specific user is **active** is 0.1 (that is, 10 percent).
  - Circuit switching: for example, we use a TDM circuit switching with 10 time slots per frame. The circuit switching link can support only 10 simultaneous users.
  - Packet switching: If there are 35 users, the probability that there are 10 or fewer simultaneously active users is as follows

$$p = 0.1 \qquad 1 = \sum_{n=0}^{35} C_{35}^{n} (1-p)^{35-n} p^{n}$$

$$C_{35}^{0}(1-p)^{35} + C_{35}^{1}(1-p)^{34} p + \cdots C_{35}^{10}(1-p)^{25} p^{10} = 0.9996$$

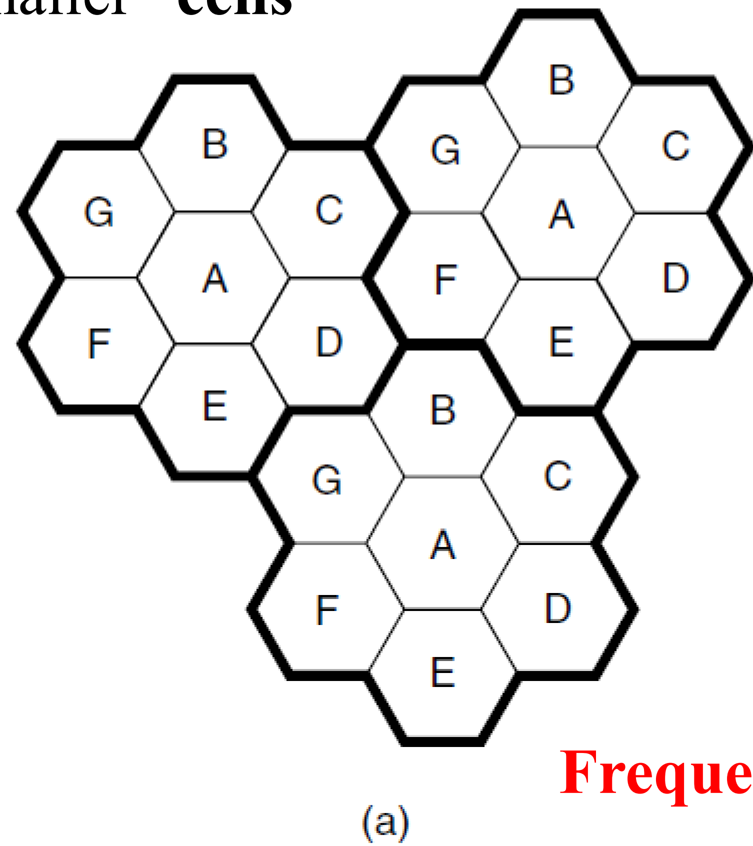
Thus, the probability that there are 11 or more simultaneously active users is approximately 0.0004. When there are 10 or fewer active users, users' packets flow through the link essentially without delay, as is the case with circuit switching. Because the probability of having more than 10 simultaneously active users is minuscule in this example, packet switching provides essentially the same performance as circuit switching, but does so while allowing for more than three times the number of users.

Example II: Cellular Networks

- Mobile phone distinct generations
- The initial three generations: 1G, 2G, 3G
  - Provided analog voice, digital voice, and both digital voice and data (Internet, email, etc.) respectively
- 4G technology adds capabilities
  - Physical layer transmission techniques and IP-based femtocells
  - 4G is based on **packet switching** only (no circuit switching)
- 5G being rolled out now
  - Supports up to 20 Gbps transmissions and denser deployments
  - Focus on reducing network latency

Cellular Concept

Proposed by Bell Labs in 1947 — Geographic service divided into smaller "**cells**"



Frequency Reuse

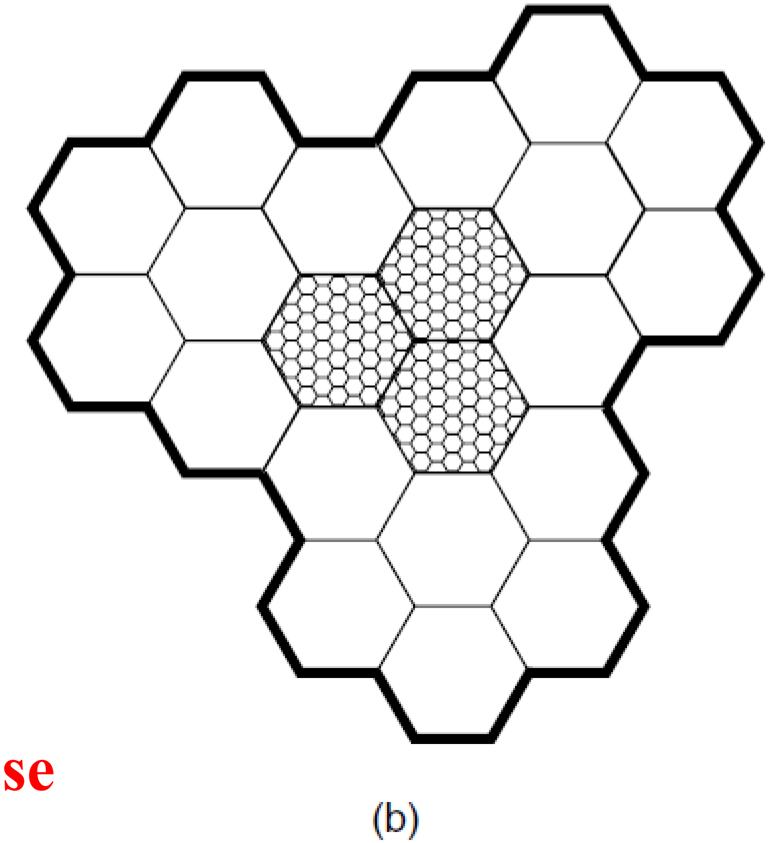
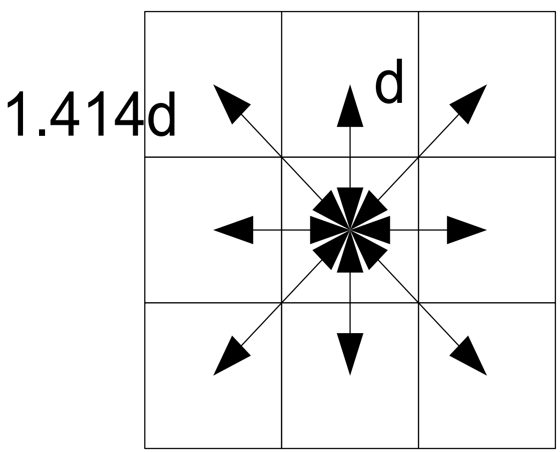


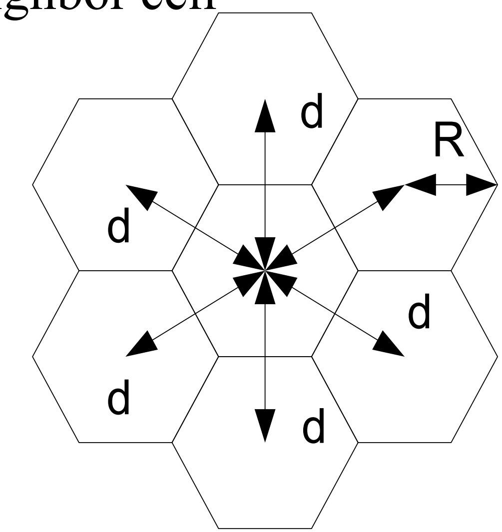
Figure 2-45. (a) Frequencies are not reused in adjacent cells. (b) To add more users, smaller cells can be used.

Shape of Cells

- Each cell use of several carrier frequencies
  - not the same frequencies in **adjacent** cells
  - **Cluster** of cells N = group of adjacent cells which use all the system frequency assignment.
- If a mobile user changes cell
  - **handover** of the connection to the neighbor cell



Square pattern



Hexagonal pattern

Cellular Networks: GSM

- SIM card (Subscriber Identity Module)
- VLR (Visitor Location Register)
- HLR (Home Location Register)
- Both databases must be kept up to date as mobiles move from cell to cell.

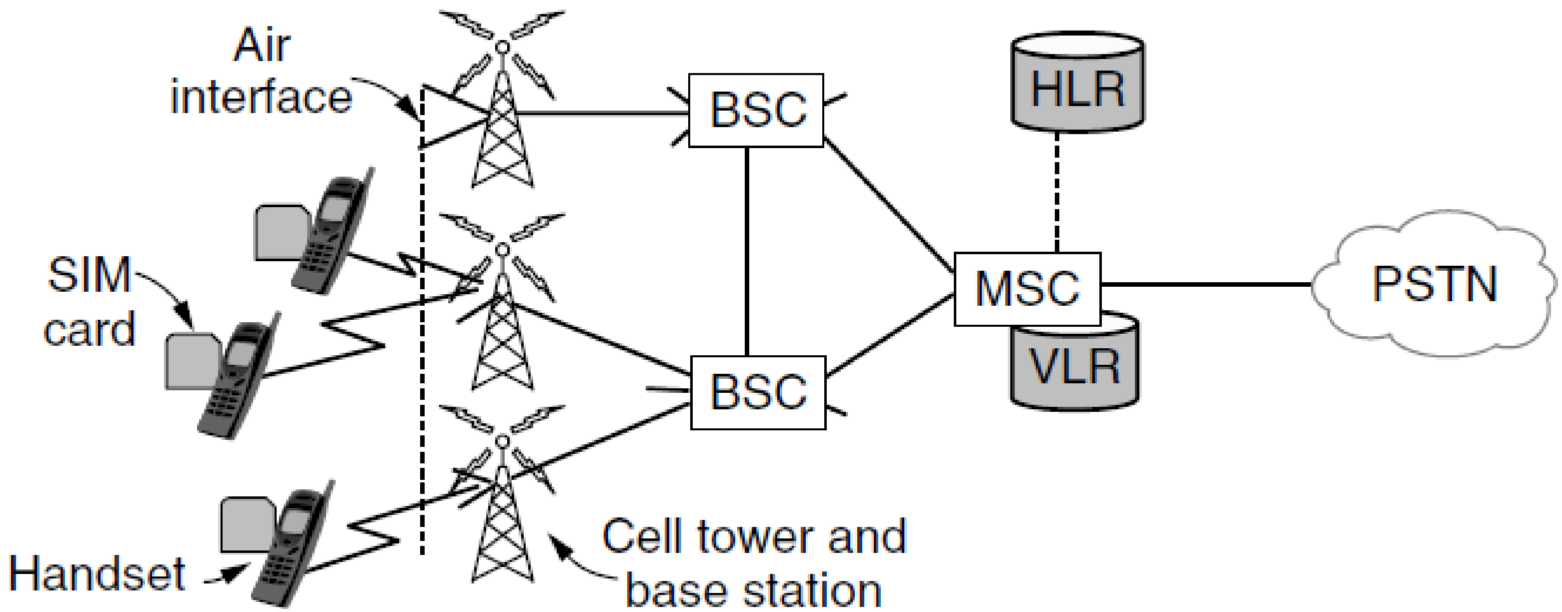


Figure 2-46. GSM mobile network architecture.

Base Station

Cellular Networks: GSM

Each GSM channel is with 200 kHz. (959.8 – 935.2) MHz / 124 $\cong$ 200 kHz

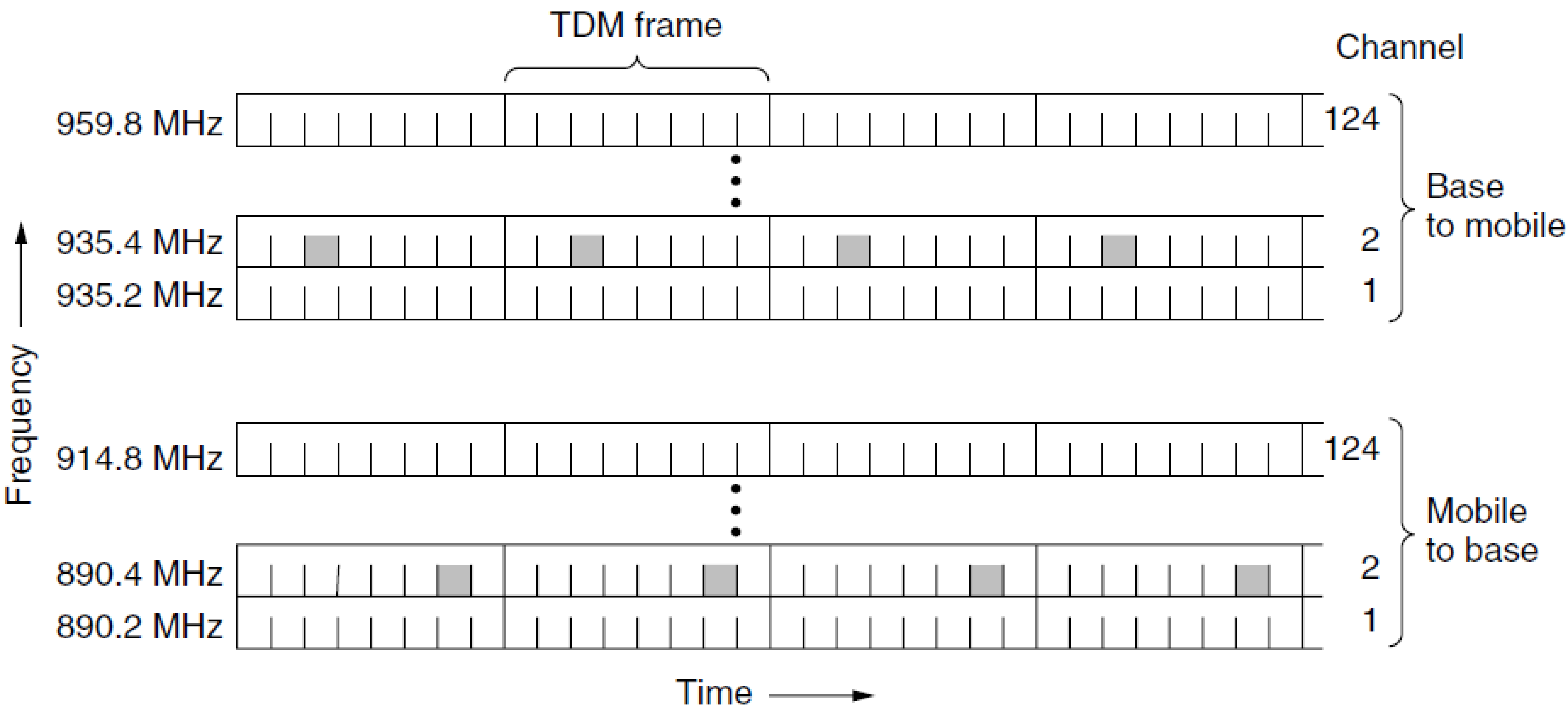


Figure 2-47. GSM uses 124 frequency channels, each of which uses an eight-slot TDM system.

Cellular Networks: GSM

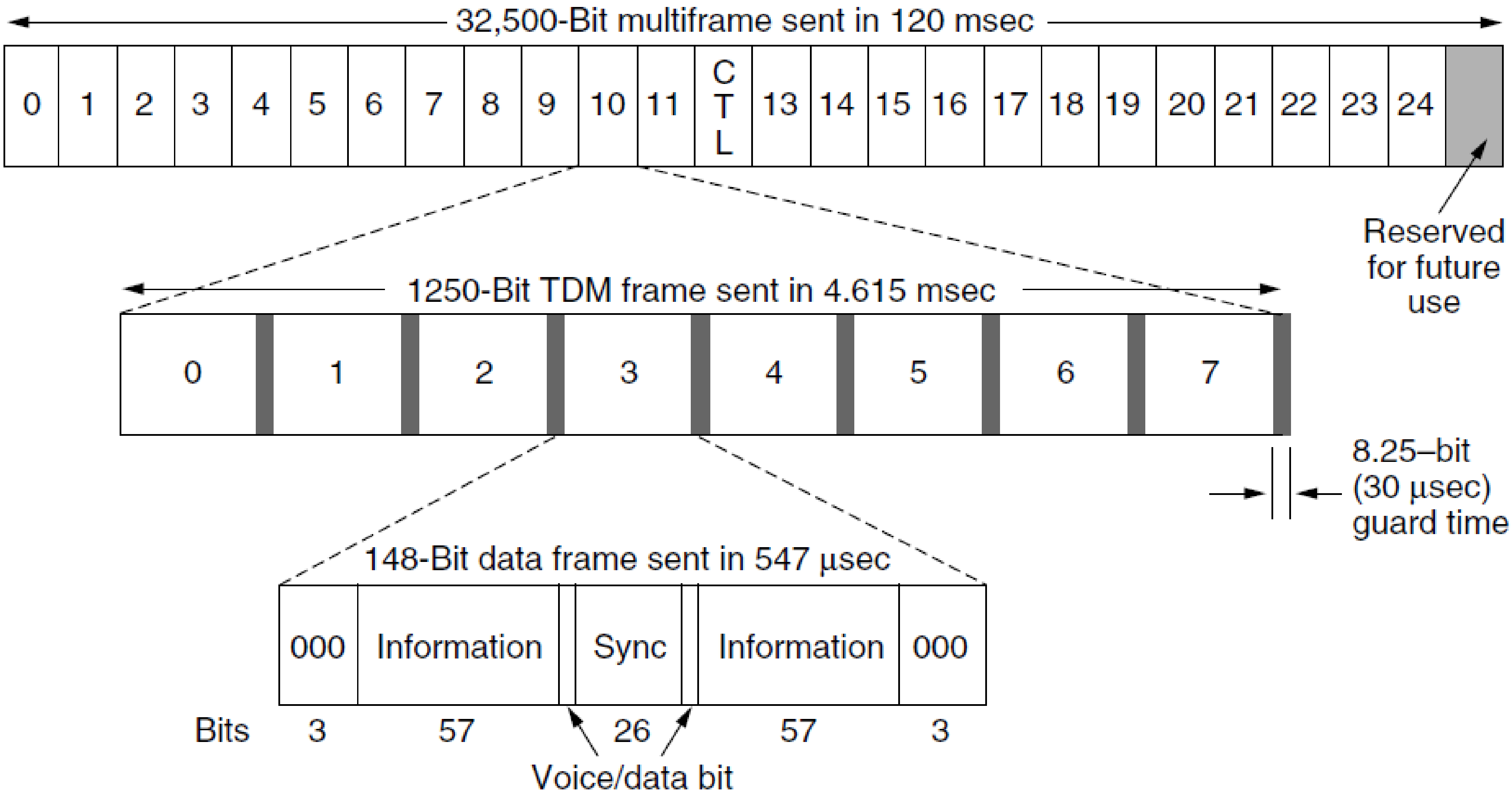


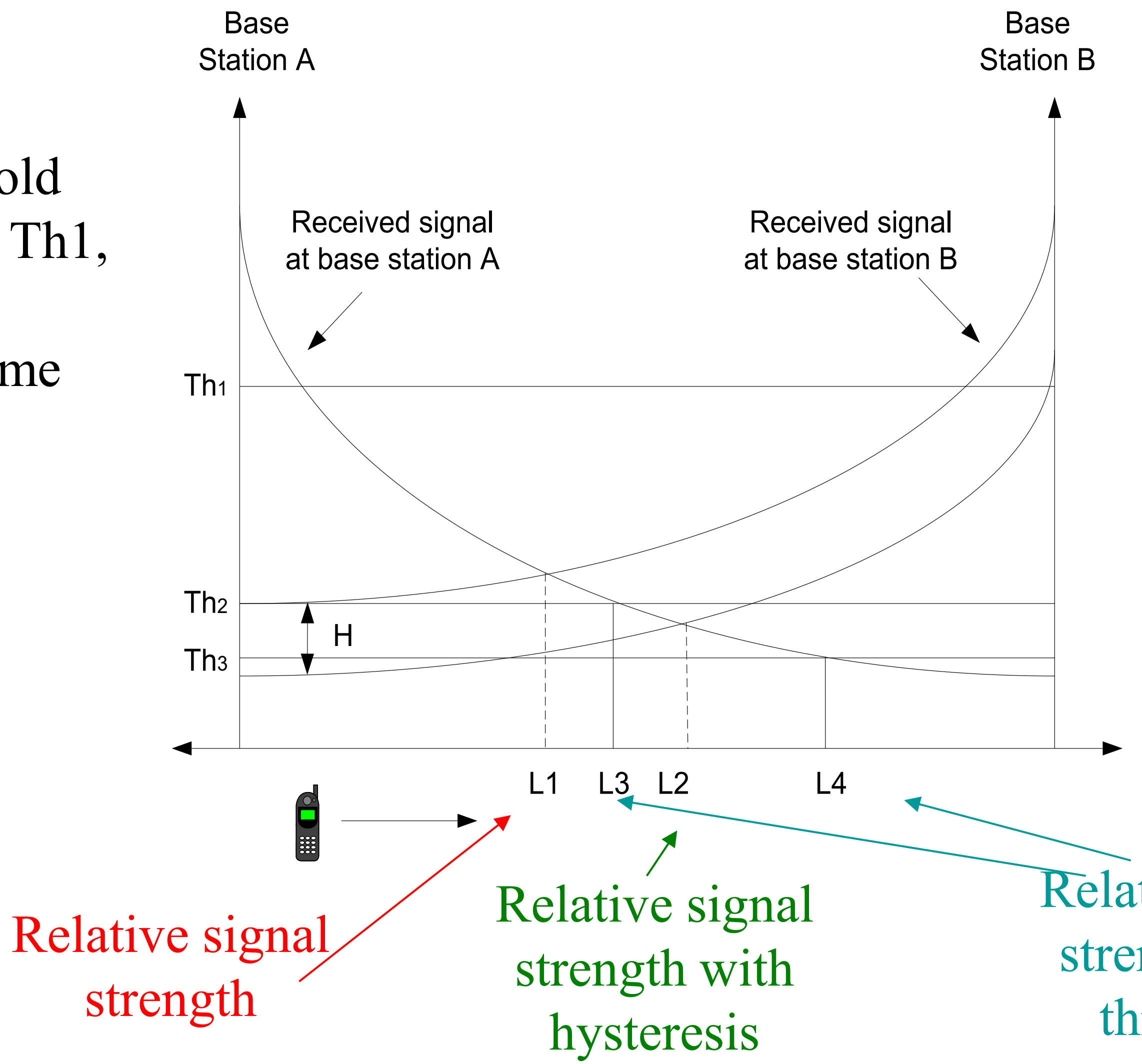
Figure 2-48. A portion of the GSM framing structure.

Issues for Handoff *

- Making handoffs "seamless"
  - Minimize handoff latency
  - Minimize frequency of handoff and its effects on QoS
  - Minimize probability of dropping connections across handoffs
  - Minimize "call blocking" effects of admission control
- Handoff Strategies
  - Relative signal strength
  - Relative signal strength with threshold
  - Relative signal strength with hysteresis
  - Relative signal strength with hysteresis and threshold
  - Prediction techniques

Handoff Decision as a Function of Handoff Scheme *

If a high threshold is used, such as Th1, this scheme performs the same as the relative signal strength.



Cellular Networks: CDMA

- Soft handoff

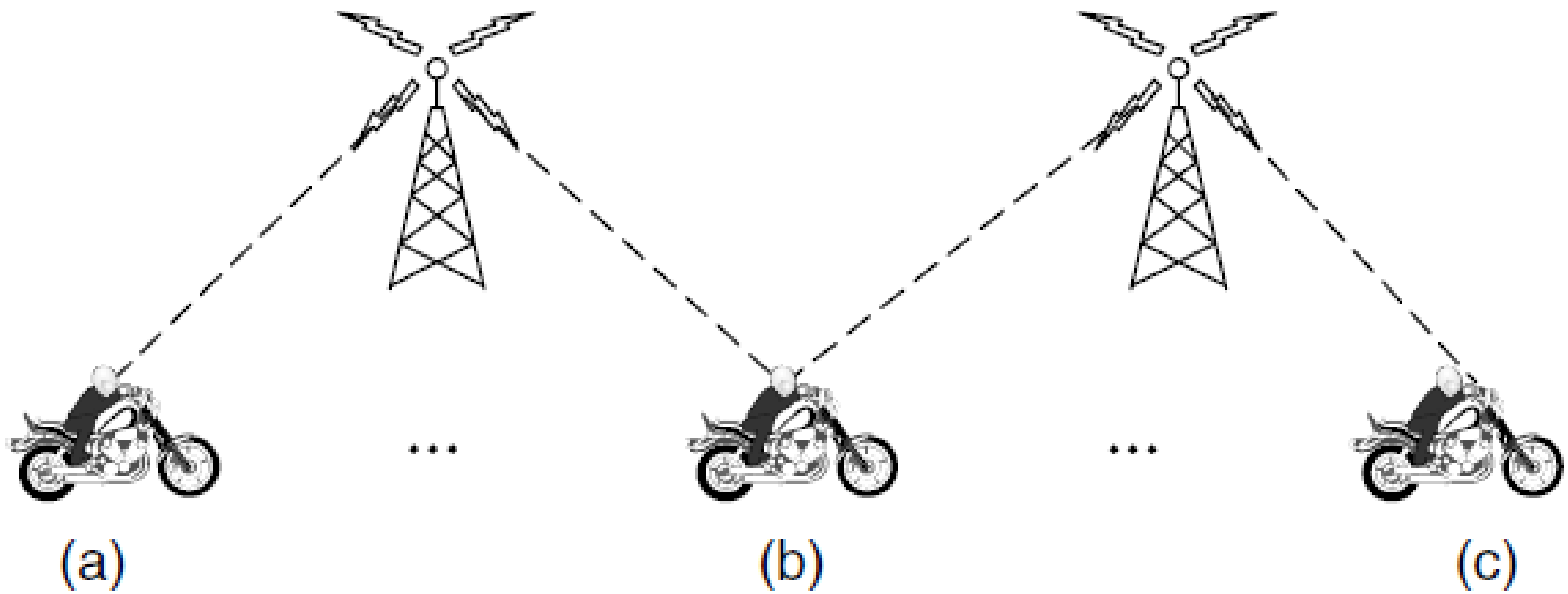


Figure 2-49. Soft handoff (a) before, (b) during, and (c) after.

Fourth-Generation (4G) Technology: Packet Switching

- Also called IMT Advanced
- Based completely on **packet-switched** technology
- EPC (Evolved Packet Core) allows packet switching
  - Simplified IP network separating voice traffic from the data network
  - Carries both voice and data in IP packets
  - Voice over IP (VoIP) network with resources allocated using the statistical multiplexing approaches
  - The EPC must manage resources in such a way that voice quality remains high in the face of network resources that are shared among many users

Fifth-Generation (5G) Technology

- Two main factors
  - Higher data rates and lower latency than 4G technologies
- Technology used to increase network capacity
  - Ultra-densification and offloading
  - Increased bandwidth with millimeter waves (毫米波)
  - Increased spectral efficiency through advances in massive MIMO (Multiple-Input Multiple-Output) technology
- Network slicing feature
  - Lets cellular carriers create multiple virtual networks on top of the same shared physical infrastructure
  - Can devote network portions to specific customer use cases
- Rise of MVNOs (Mobile Virtual Network Operators)

Example III: Cable Networks (I)

- Many people nowadays get their telephone and internet service over cable.
- Community Antenna Television
  - The system initially consisted of a big antenna on top of a hill to pluck the television signal out of the air, an amplifier, called the **headend**, to strengthen it, and a coaxial cable to deliver it to people's houses.

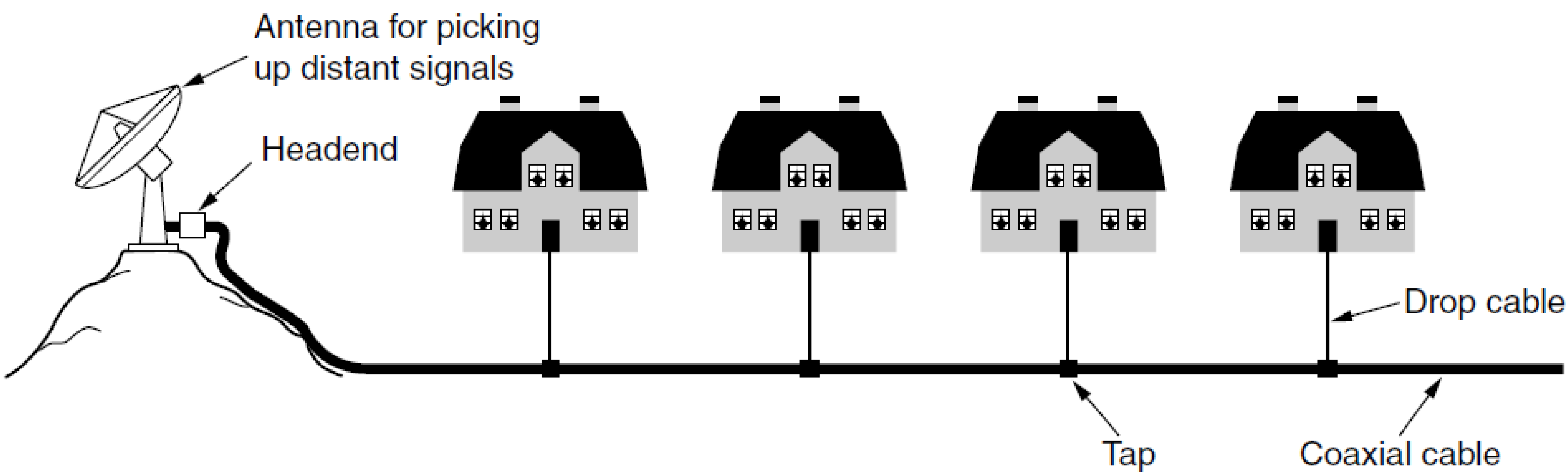
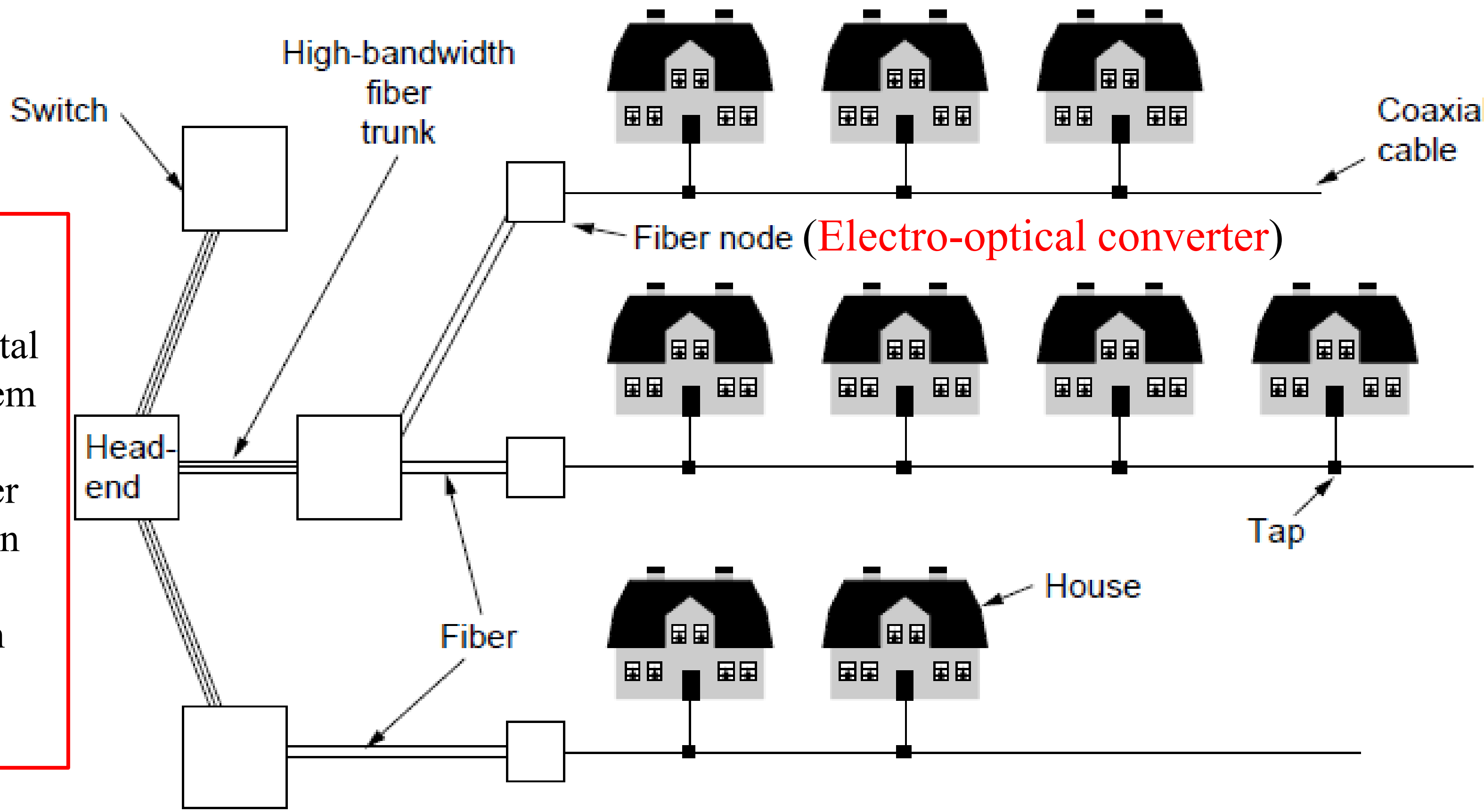


Figure 2-50. An early cable television system. — **A broadcast system**

Example III: Cable Networks (II)

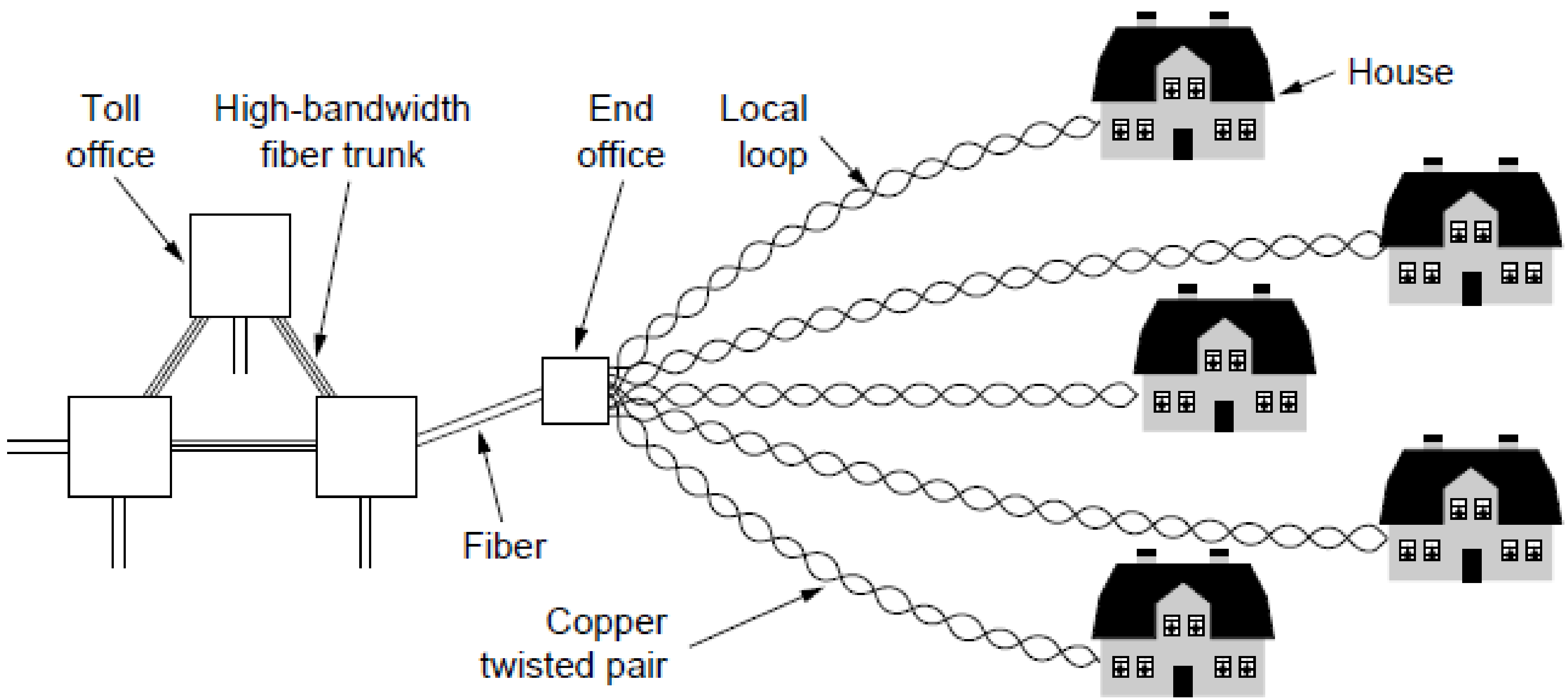
- Hybrid Fiber-Coax cable network (**HFC**)
  - Because the bandwidth of fiber is much greater than that of coax, a fiber node can feed multiple coaxial cables.
  - All one-way amplifiers had to be replaced by two-way amplifier to support upstream as well as downstream transmissions.



The upgraded headend is an intelligent digital computer system with a high-bandwidth fiber interface and an ISP — CMTS (Cable Modem Termination System)

Example III: Cable Networks (III)

- The fixed telephone system



(b)

Example III: Cable Networks (IV)

- To have television and Internet peacefully coexist on the same cable, the solution is built on **frequency division multiplexing**.
  - Cable television channels in North America occupy the 54-550 MHz region (except for FM radio, from 88 to 108MHz).
  - To introduce upstream channels in the 5-42 MHz band and use the frequencies at the high end for the downstream signals. — **asymmetric**

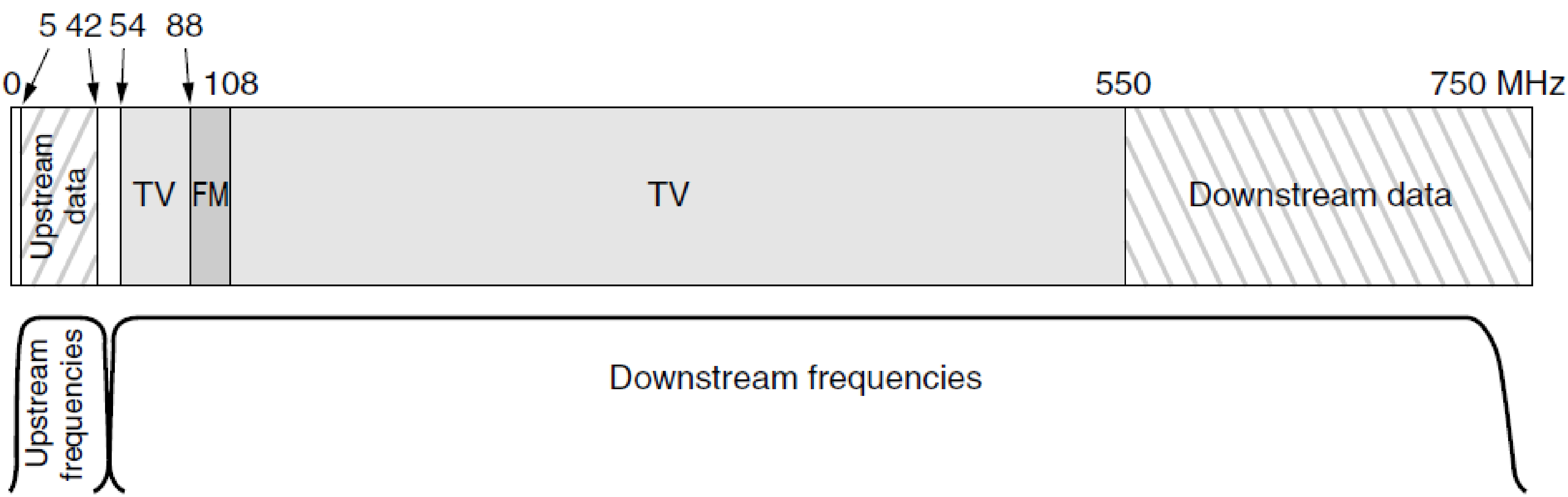


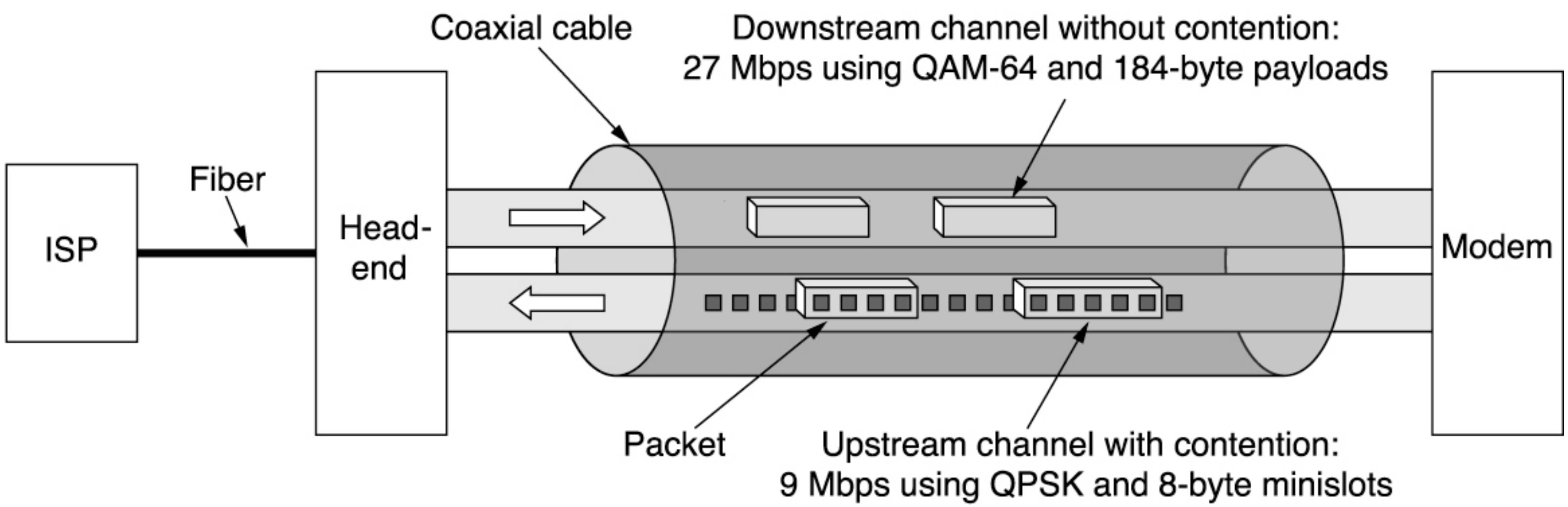
Figure 2-52. Frequency allocation in a typical cable TV system used for Internet access.

Example III: Cable Networks (V)

- Last-mile connectivity technology of Cable companies operator includes
  - HFC physical-layer technology (Fig 2-45(a) in 6th Edition)
  - fiber
  - wireless last mile connectivity (it is typically an Ethernet connection)
- DOCSIS (Data Over Cable Service Interface Specification) 3.1 latest version
  - Introduced Orthogonal Frequency Division Multiplexing (OFDM)
  - Introduced wider channel bandwidth and higher efficiency
  - Enable over 1Gbps of downstream capacity per home
- Extensions to DOCSIS 3.1
  - Full Duplex operation (2017) and DOCSIS Low Latency (2018)
- Cable Internet subscribers require a DOCSIS cable modem (QAM-64, QAM-256)

Resource Sharing in DOCSIS Networks: Nodes and Minislots

- One important fundamental difference between the HFC system (Fig. 2-45 (a)) and the telephone system (Fig. 2-45 (b)) is that: In a given residential neighborhood, a single cable is shared by many houses, whereas in the telephone system, every house has its own private local loop.
  - **Contention** (CDMA — no collision, ALOHA — collision)
  - The downstream channels are managed differently from the upstream channels.



ADSL vs. Cable

- What is better, ADSL or cable?
  - This is like asking which operating system is better, or which language is better?
  - Cable uses coax; ADSL uses twisted pair.
    - The theoretical carrying capacity of coax is hundreds of times more than twisted pair. However, the full capacity of the cable is not available for data users because much of the cable’s bandwidth is spent on television programs.

Main Points

- Bandwidth, bit rate, symbol rate, baud [4]
- Nyquist Bandwidth ~ Shannon's Capacity
- Transmission media: guided (wired), wireless, satellite
- Baseband transmission ~ Passband transmission
  - Baseband signal ~ passband signal
  - NRZ, NRZI, Manchester encoding, Bipolar encoding
  - ASK, FSK, PSK, QAM,
- Multiplexing
  - TDM, FDM, CDM
- Three widely deployed communication systems: PSTN, cellular network, cable system

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