BEng Course B38CN2: Introduction to Communications and Networks

Chapter 2. The Physical Layer

Sheng Tong

Xidian University

School of Telecommunications Engineering

Room: I-304, Main Building, North Campus

E-mail: ts_xd@163.com

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2. The Physical Layer

- The physical layer defines the mechanical, electrical, and timing interfaces to the network.
- Modern communication networks are mostly based on digital transmission systems and have the potential to carry all types of information.
- The application generates flows of information that need to be carried across the network. The digital transmission systems at the physical layer provide the pipes that actually carry the information flows across the network.

2.1 Digital Representation of Information

- Two categories of information:
  - Block-oriented information (digital): information that occurs in a single block, e.g., data files, e-mails, and pictures.
    - Data compression: exploits the reduncdancies to encode the original information into files that require fewer bits to transfer and less disk storage space.
    - Compression ratio: the ratio of the number of bits in the original file to the number of bits in the compressed file.
  - Stream information (analog): information that is produced continuously and needs to be transmitted as it is produced, such as voice, music or video.
    - Needs to be digitalized.

Digitalizing an Analog Signal

- Two Steps
  - Obtain sample values of the analog signal every T seconds
    - Signal bandwidth W_s: the range of frequencies contained in the signal; a measure of how fast the signal varies, W_s Hz.
    - Nyquist sampling theory: The sampling rate $f_s=1/T \geq 2W_s$ samples/second.
  - Quantize each of the sample values: How many (2^m) levels are used to approximate the sample value, i.e., represent each sample value using a finite number m of bits?
    - The accuracy of the reproduced signal increases as the number of bits used to represent each sample is increased.
    - Bit rate R_s: number of bits/second= number of bits/sample * number of samples/second.

Example: Pulse Code Modulation (PCM) Telephone-Quality Voice

- Signal bandwidth: W_s=4 KHz.
- The minimum sampling rate f_s:
  - ⇨ $f_s=2W_s$=8000 samples/second.
- The sample duration T:
  - ⇨ $T=1/f_s$=1/8000=125μs.
- Each PCM voice sample is reprented by 8 bits in resolution, resulting in a bit rate R_s:
  - ⇨ R_s=8000 samples/second * 8 bits/sample=64 kb/s.

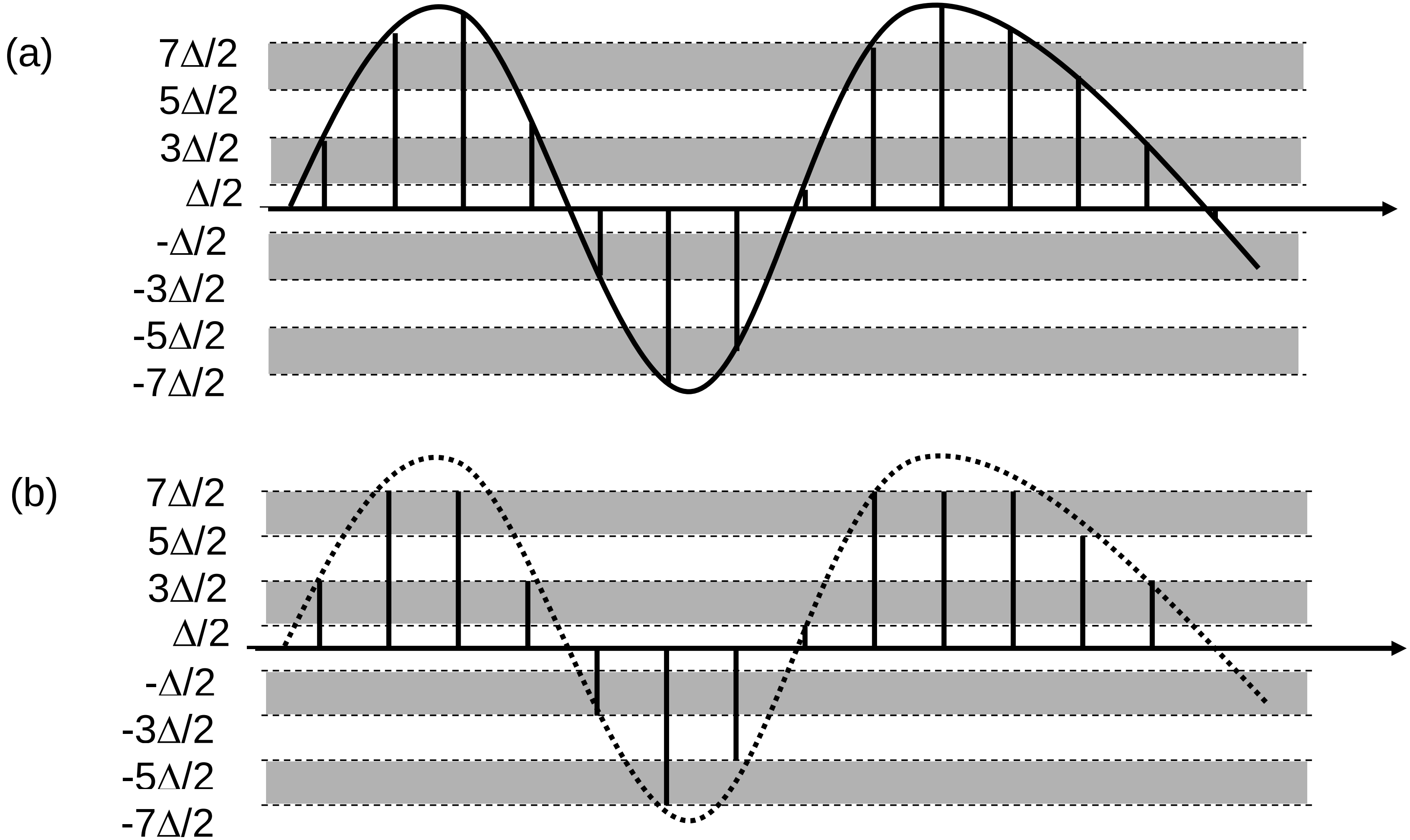


Fig. 2.1: Digitalizing a speech signal: (a) original waveform and the sample values; (b) original waveform and the quantized values.

2.2 Why Digital Transmissions?

Fig. 2.2: A general transmission system.

- A **transmission system**: makes use of a physical transmission medium or channel that allows the propagation of energy in the form of pulses or variations in voltage, current or light intensity.
- **Transmitter**: converts information into *signal* suitable for transmission; injects energy into communications medium or channel.
  - Telephone converts voice into electric current.
- **Receiver**: receives energy from medium; converts received signal into form suitable for delivery to user.
  - Telephone converts current into voice.

Analog and Digital Transmission

- **Analog transmission**: The objective is to transmit a waveform, which is a function that varies continuously with time.
  - **Problem**: This function of time must be reproduced exactly at the output of the analog communication system. However, communication channels cannot achieve perfect reproduction in practice, so distortion is unavoidable.
- **Digital transmission**: The objective is to transmit a given symbol that is selected from some finite set of possibilities.

Examples of Analog and Digital Transmission

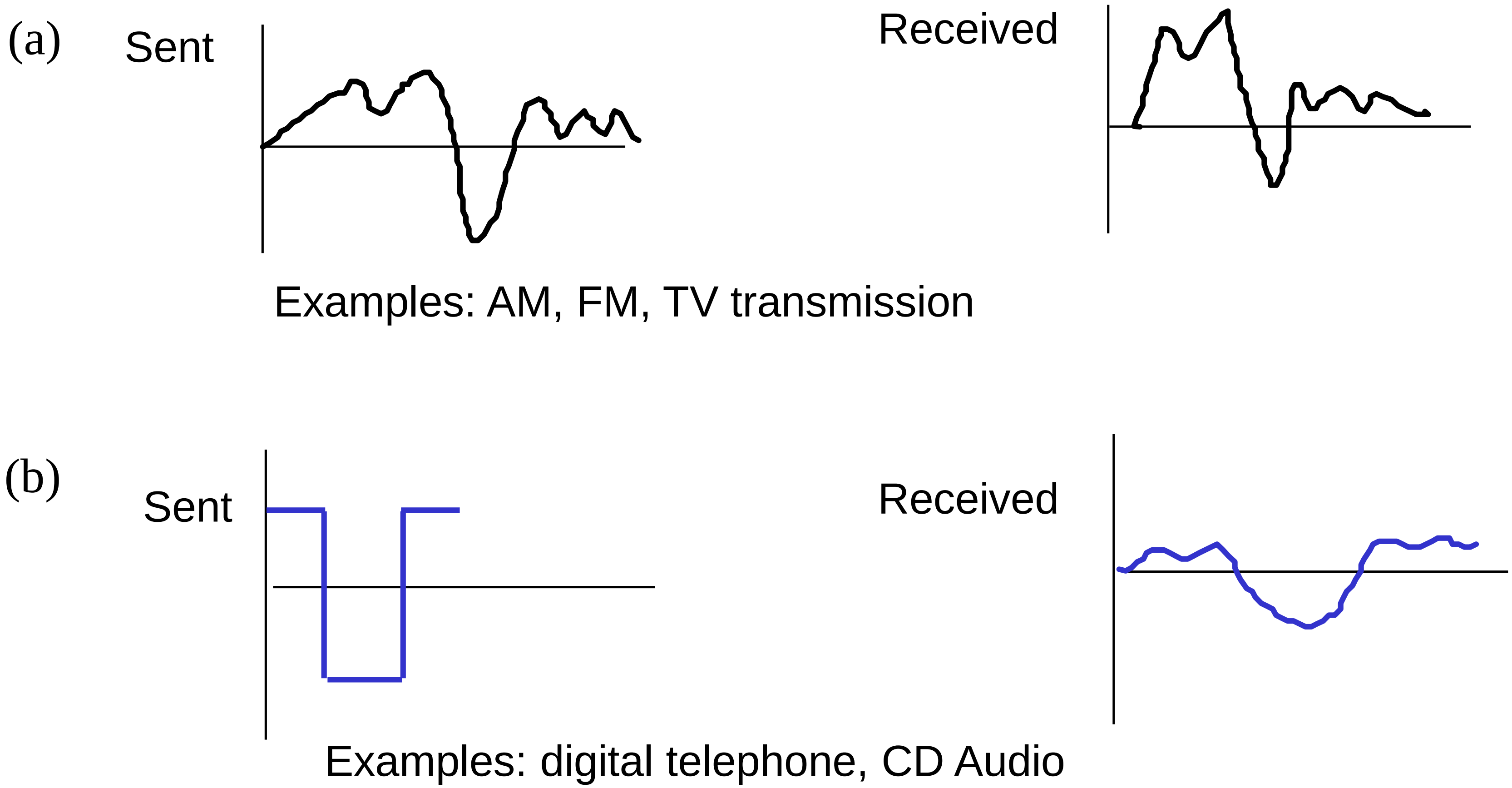


Fig. 2.3: (a) Analog transmission requires an accurate replica of the original signal whereas (b) digital transmission reproduces discrete levels.

2.2.1 Comparison of Analog and Digital Transmission

Advantages of digital transmission over analog transmission:

- Superior performance
  - Digital regenerators eliminate the accumulation of noise.
- Lower overall system cost
  - Can operate with lower signal levels or with greater distances between regenerators.
- Can monitor the quality of a transmission channel while the channel is in service.
- Digital networks can multiplex and switch any type of information that can be represented in digital form, and hence, are suitable for handling many types of services.
- Digital transmission also allows networks to exploit the advances in digital computer technology.

Superior Performance of Digital Transmission over Analog Transmission

- Repeaters are introduced periodically to compensate for the attenuation and distortion of the signal when transmitted over a long distance.

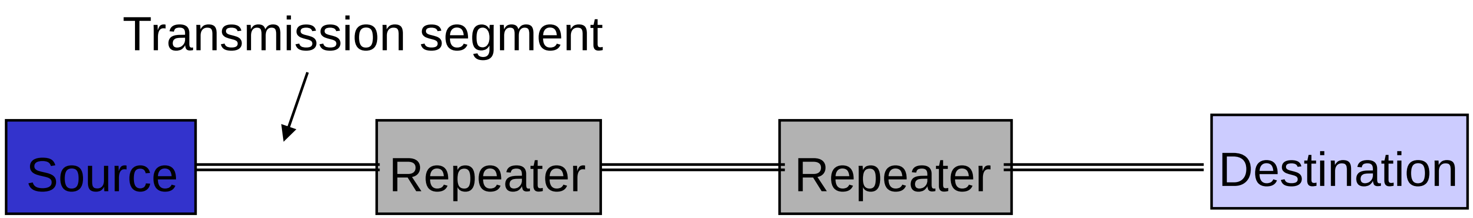


Fig. 2.4: Typical long distance link.

Analog Repeater

- Each repeater attempts to restore analog signal to its original form.
- Restoration is imperfect: Distortion is not completely eliminated; Noise and interference are only partially removed.
- Signal quality decreases with the number of repeaters.
- Communication is distance-limited.
- Still used in analog cable TV systems.
- Analogy: copy a song using a cassette recorder.

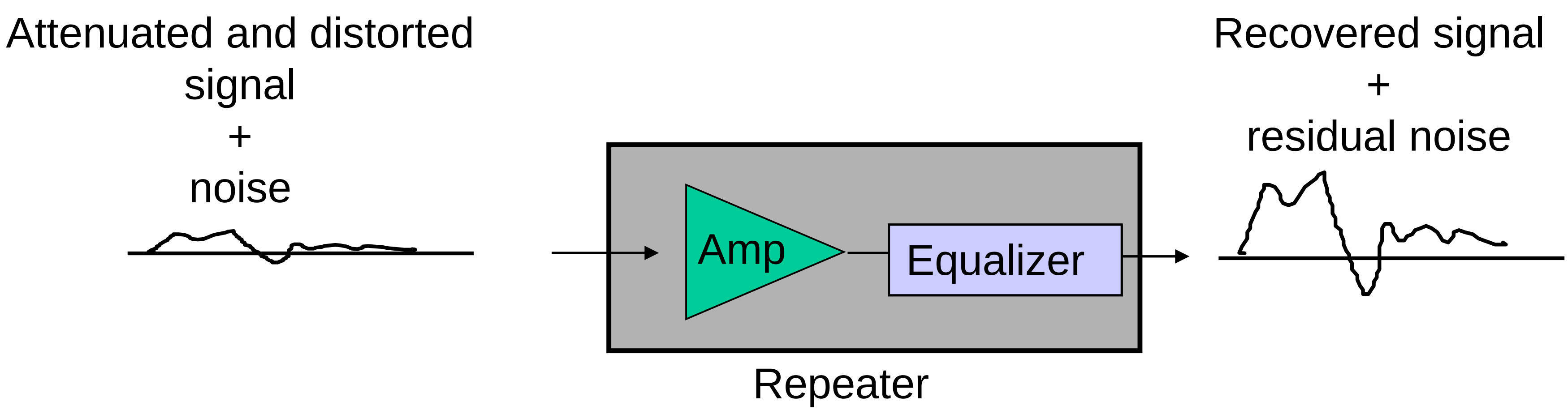


Fig. 2.5: An analog repeater.

Digital Regenerator

- Regenerator recovers original data sequence and retransmits on next segment.
- Can be designed in such a way that error probability is very small.
- Then each regeneration is like the first time!
- Communication is possible over very long distances.
- Analogy: copy an MP3 file.

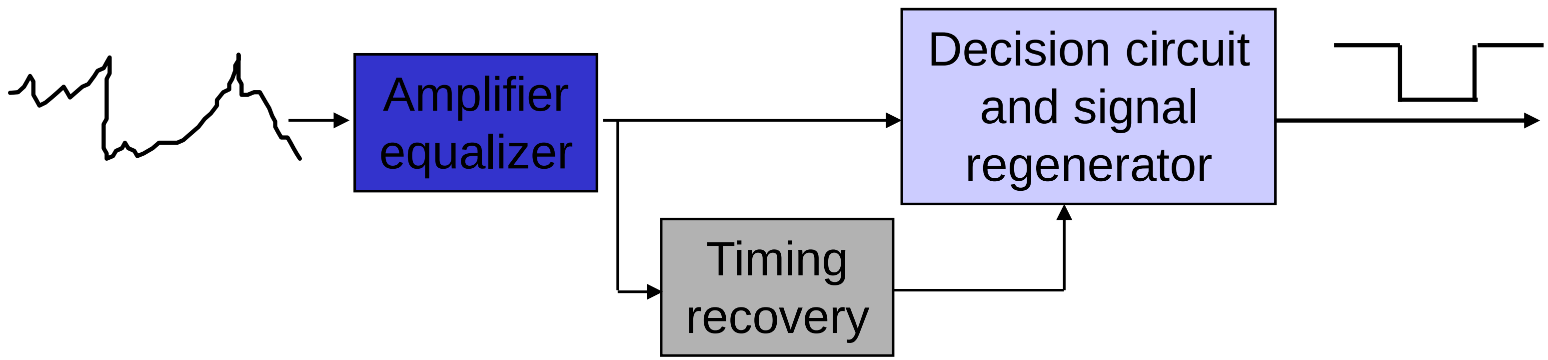


Fig. 2.6: A digital regenerator.

2.2.2 Basic Properties of Digital Transmission Systems

- The purpose of a binary digital transmission system is to transfer a sequence of 0s and 1s from a transmitter to a receiver.
- The **transmission speed** or **bit rate** ***R***: measured in **bits/second (b/s)**, can be viewed as the cross-section of the information pipe that connects the transmitter to the receiver.
- The transmission system uses pulses or sinusoids to transmit binary information over a physical transmission medium.
- A fundamental question: How fast can bits be transmitted reliably over a given media?
  - The amount of energy put into transmitting each signal.
  - The distance that the signal has to traverse.
  - The amount of noise that the receiver needs to contend with.
  - The bandwidth of the transmission channel.

Amplitude-Response Function

- **Amplitude-response function *A(f)* of a transmission channel**: the ratio of the amplitude of the output signal to the amplitude of the input signal.

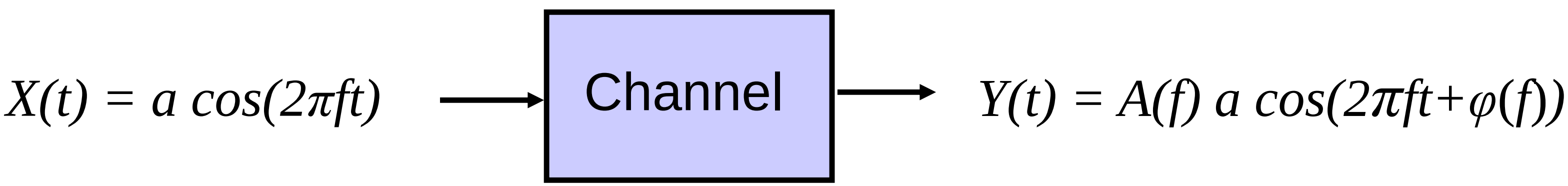


Fig. 2.7: Amplitude-response function.

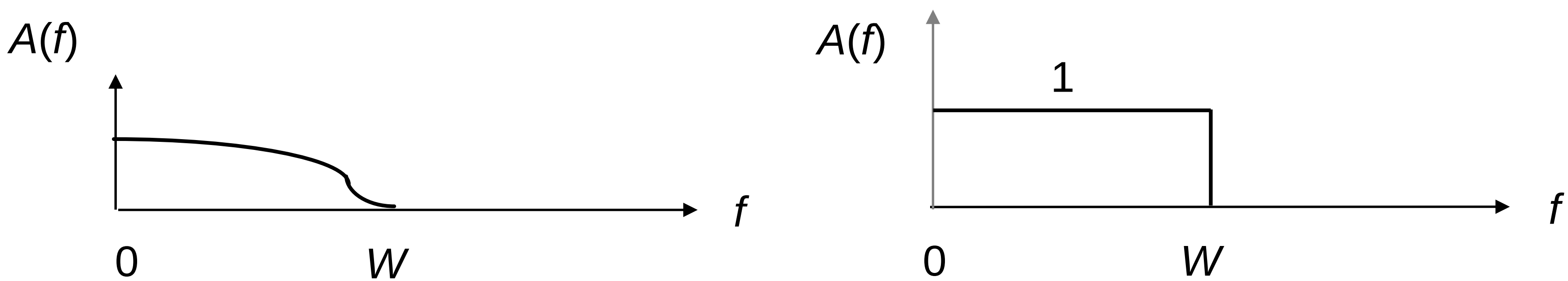


Fig. 2.8: Typical amplitude-response functions for low-pass and idealized low-pass channels.

Channel/Signal Bandwidth and Pulse Rate

- **Bandwidth W_c of a channel**: the range of input frequencies passed by the channel.
- **Bandwidth W_s of a signal**: the range of frequencies contained in the signal; a measure of how fast of the signal varies.
  - ⇨ The bandwidth W_c of a channel limits the **bandwidth** of the signals that can pass through the channel.
  - ⇨ The bandwidth W_c of a channel limits the **rate** at which we can send pulses through the channel, since higher signaling speed (pulse **rate**) translates into higher signal **bandwidth**.
- **Nyquist signaling rate**: The **maximum pulse rate (baud rate)** at which pulses can be transmitted through the channel is $r_{max}=2W_c$ pulses/second.
  - Channel bandwidth: W_c
  - The narrowest pulse that can be transmitted over the channel: $1/(2W_c)$ seconds.

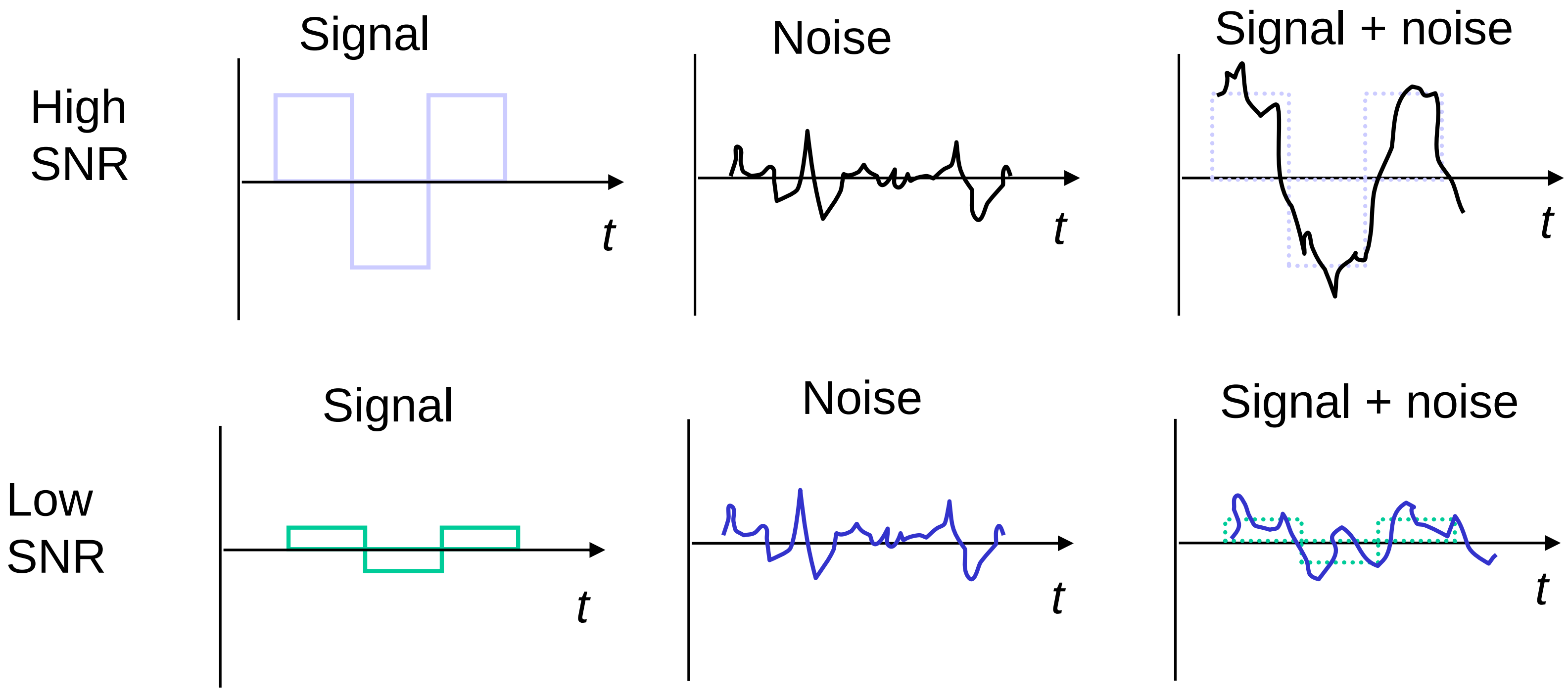
Single-Level and Multilevel Transmissions

- **Single-level (binary) transmission**: M=2^m $(m$=1$)$=2 amplitude levels; 1 bit/pulse.
  - **Bit rate**: $R=2W_c$ pulse/second*1 bit/pulse=$2W_c$ bps.
- **Multilevel transmission**: M=2^m $(m>1)$ amplitude levels; m bits/pulse.
  - **Bit rate**: $R=2W_c$ pulse/second*m bit/pulse=$2W_c m$ bps.
- **Without noise, the bit rate can be increased without limit by increasing the number of signal levels *M*.**

Noise and Reliable Communications

- Noise is an impairment encounted in all communication channels.
  - Electrons always vibrate at non-zero temperature.
  - Motion of electrons induces noise.
- **Signal-to-noise ratio (SNR):** the ratio of the average signal power to the average noise power; measures the relative amplitudes of the desired signal and noise.
  - SNR (dB)=10 $\log_{10}$SNR
- For multilevel transmission, the increase of the number of levels while keeping the same maximum signal levels $\pm A$, will imply significant increase in the probability of detection errors.
  - ⇨ The presence of noise limits the reliability with which the receiver can correctly determine the transmitted information.

Signal-To-Noise Ratio



$$\text{SNR} = \frac{\text{Average signal power}}{\text{Average noise power}}$$

$$\text{SNR (dB)} = 10 \log_{10} \text{SNR}$$

Fig. 2.9: Signal-to-noise ratio.

Shannon Channel Capacity

- **Channel capacity** of a transmission system: the maximum bit rate at which bits can be transferred reliably.
- **Shannon channel capacity** C: $C = W \log_2(1+\mathrm{SNR})$ bits/second
  - Affected by the channel bandwidth W and the received SNR.
  - Arbitrarily reliable communication is possible if the transmission rate $R < C$.
  - If $R > C$, then arbitrarily reliable communication is not possible.
  - "Arbitrarily reliable" means the BER can be made arbitrarily small through sufficiently complex coding.
  - C can be used as a measure of how close a system design is to the best achievable performance.

Fourier Series (1/2)

- The **Fourier series**: a decomposition process, resolves a peroidic signal *x(t)* with peroid *T* into an infinite sum of sine and cosine terms:

$$x(t) = a_0 + \sum_{n=1}^{\infty}[a_n \cos(2\pi n f_0 t) + b_n \sin(2\pi n f_0 t)]$$

where $f_0 = \frac{1}{T}$: fundamental frequency.

a_n, b_n : the cosine and sine amplitudes of the *n*th harmonics (terms), respectively.

a_0 : a constant.

- The **time average** of the signal over one peroid:

$$a_0 = \frac{1}{T}\int_0^T x(t)dt,$$

$$a_n = \frac{2}{T}\int_0^T x(t)\cos(2\pi n f_0 t)dt, \quad n=1, 2, \ldots$$

$$b_n = \frac{2}{T}\int_0^T x(t)\sin(2\pi n f_0 t)dt, \quad n=1, 2, \ldots$$

Fourier Series (2/2)

$$x(t) = a_0 + \sum_{n=1}^{\infty} \sqrt{a_n^2 + b_n^2} \cos(2\pi n f_0 t - \tan^{-1} \tfrac{b_n}{a_n})$$
$$= a_0 + \sum_{n=1}^{\infty} |c_n| \cos(2\pi n f_0 t + \theta_n).$$

- A periodic function $x(t)$ is said to have a **discrete spectrum** with components at the frequencies 0, f_0, $2f_0$, $3f_0$, …
- The **magnitude** of the discrete spectrum at the frequency components nf_0:

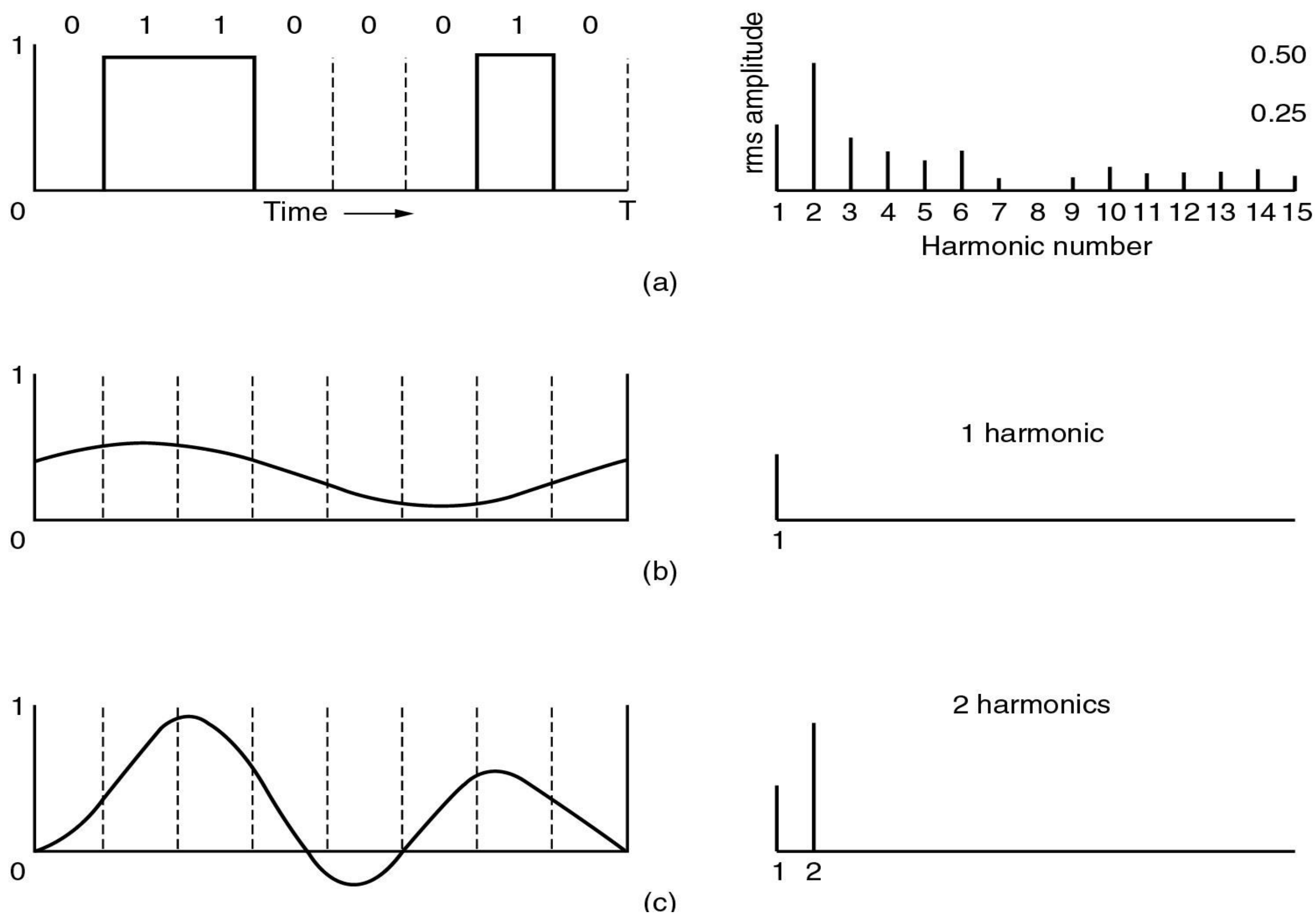
$$|c_n| = \sqrt{a_n^2 + b_n^2}.$$

- The **phase** of the discrete spectrum at the frequency components nf_0:

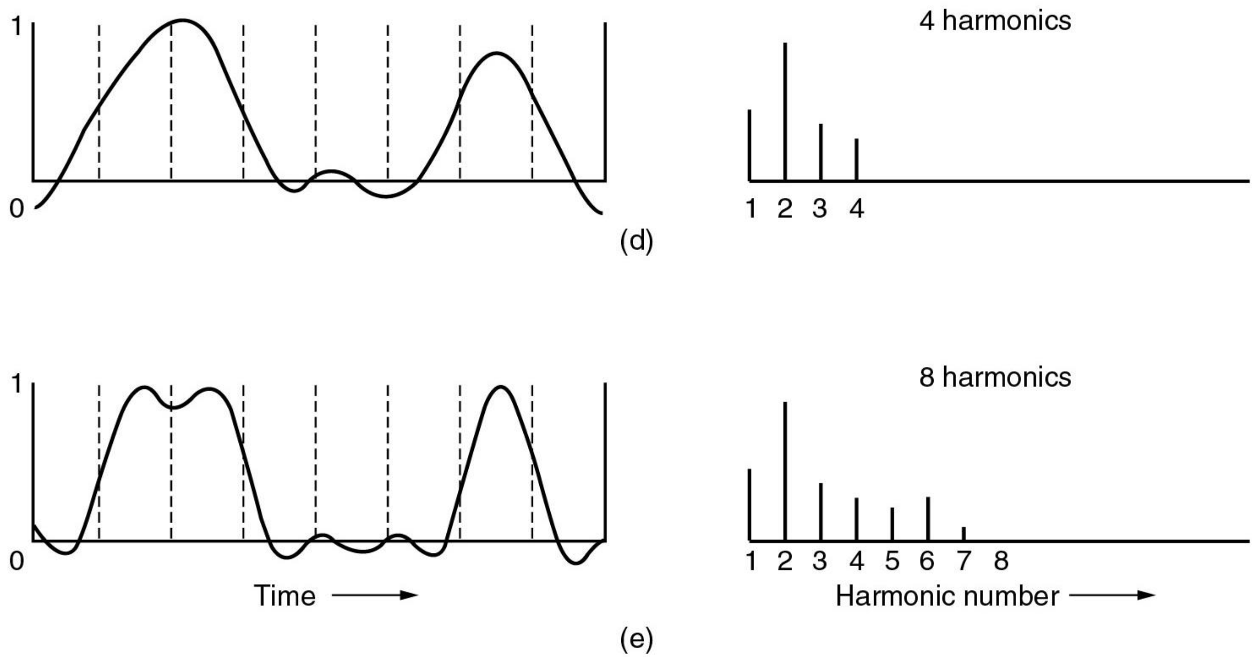
$$\theta_n = -\tan^{-1} \tfrac{b_n}{a_n}.$$

Example (1/3)

- Consider the transmission of the character “b”, whose 8-bit ASCII codeword is given by 01100010.



Example (2/3)



- Assume that the bit rate is b bits/sec. The time taken to transmit 8 bits is calcuated as 8/b sec. Then the fundamental frequence is given by f = b/8 Hz.

Example (3/3)

- Consider a telephone line, which has a cutoff frequency of 3000 Hz. Denote the number of highest harmonic as n. Then, we have $nf \le 3000 \text{ Hz} \rightarrow n \le 3000/f = 24000/b$.

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

2.3 Digital Representation of Analog Signals

- **Analog signals**: Signal levels vary continuously with time and/or space and therefore, have infinite number of values and cannot be represented exactly in practice.
- Examples: speech, audio, image, video.
- The **digitalization** of analog signals (2 steps):
  - Measuring sampling at evenly spaced instants of time, say T seconds.
  - Representing each sample value using a finite number of bits, say m bits.
    - ⇨Bit rate of the digitized signal: m/T bps.

2.3.1 Bandwidth of Analog Signals

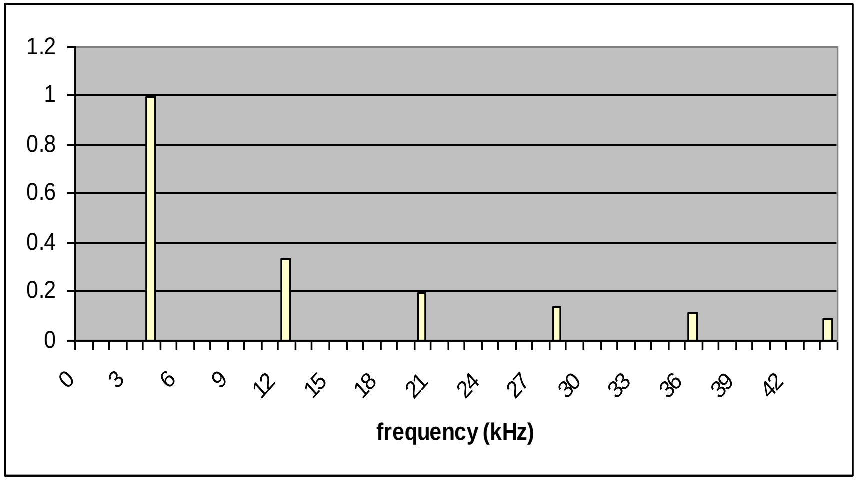
- Periodic signal: $x(t) = \sum a_k \cos(2\pi k f_0 t + \phi_k)$
  - Spectrum: the magnitude of the amplitudes of the sinusoidal components of a signal.
  - Bandwidth:
    - an indicator of how fast a signal varies with time;
    - a measure of the rate at which a signal varies with time;
    - the range of the frequencies contained in the signal;
    - Signals that vary quickly have a larger bandwidth than signals that vary slowly.

- Non-periodic signal:
  - Bandwidth: the range of frequencies at which the signal contains nonnegligible power. For peroidic signals, nonnegligible a_k.
    - 99 percent bandwidth: the frequency range that contains 99% of the power of the original signal
    - The appropriate choice of a signal bandwidth depends on the application.
      - ⇨Human-ear-detected signals: 20 Hz ~ 20 KHz.
      - ⇨Speech communication signals: 200 Hz ~ 3.5 KHz.

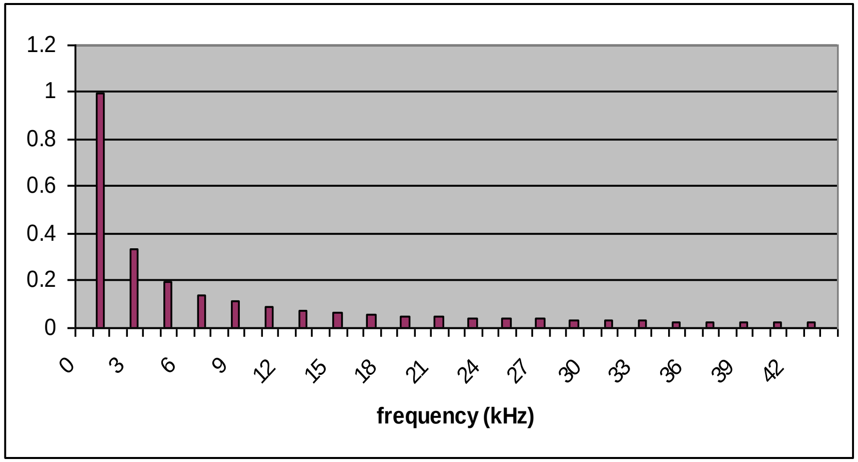
Spectrum & Bandwidth

- **Spectrum of a signal**: magnitude of amplitudes as a function of frequency.
- $x_1(t)$ varies faster in time and has more high frequency components than $x_2(t)$.
- Bandwidth W_s is defined as range of frequencies where a signal has non-negligible power, e.g. range of band that contains 99% of total signal power.

Spectrum of $x_1(t)$



Spectrum of $x_2(t)$



2.3.2 Sampling of an Analog Signal

- The sampling process replaces the continuous function of time by sequence of real-valued numbers: $x(t) \longrightarrow x(nT)$, where n is an integer and $1/T$ is the sampling rate.

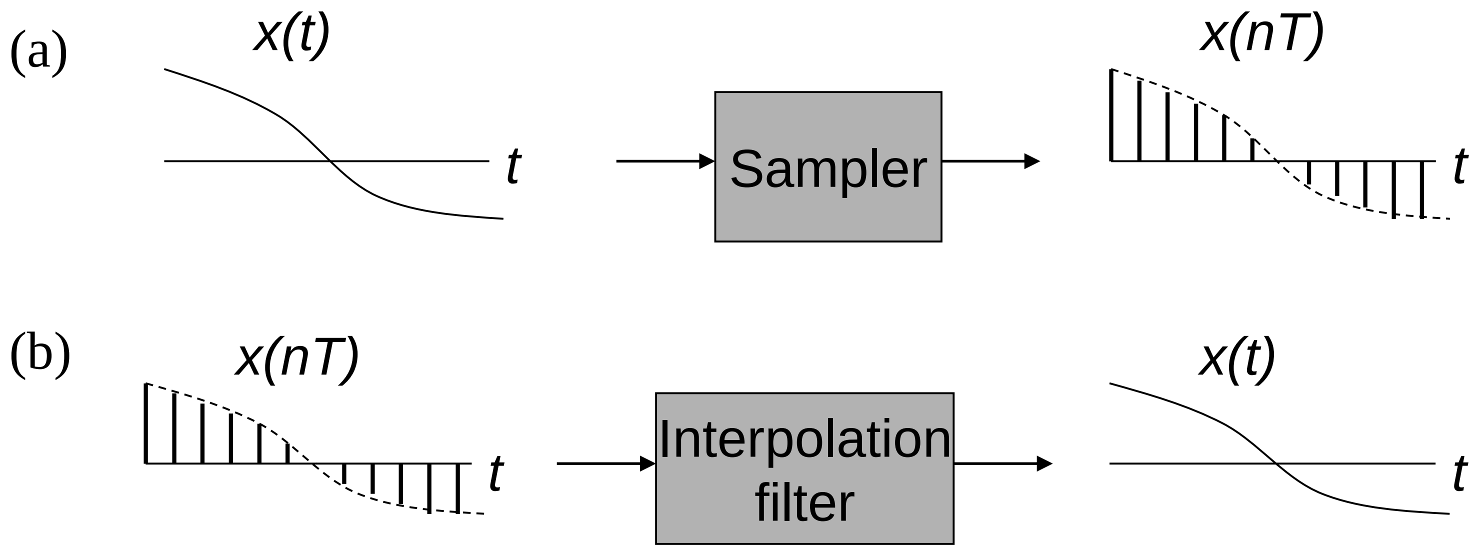


Fig. 2.10: (a) Sampling of signal $x(t)$; (b) recovery of original signal $x(t)$ by interpolation.

Nyquist Sampling Theorem

- **Question**: What is the sampling rate in relevant to the signal bandwidth in order to recover a good approximation of signal from the samples?
- **Answer**: Nyquist sampling theorem.
  - An anolog signal $x(t)$ with a bandwidth W Hz can reliably be recovered from its sample values $\{x(nT)\}$ if the sampling rate $1/T$ is **not smaller than** $2W$ samples/second.
  - **Nyquist sampling rate**: $2W$.
- The reconstrunction of $x(t)$ from $x(nT)$: interpolation filter.

$$x(t) = \sum_{n} x(nT) s(t - nT)$$

- Interpolation function: $s(t) = \dfrac{\sin(2\pi W t)}{2\pi W t}.$

2.3.3 Digital Transmission of Analog Signals

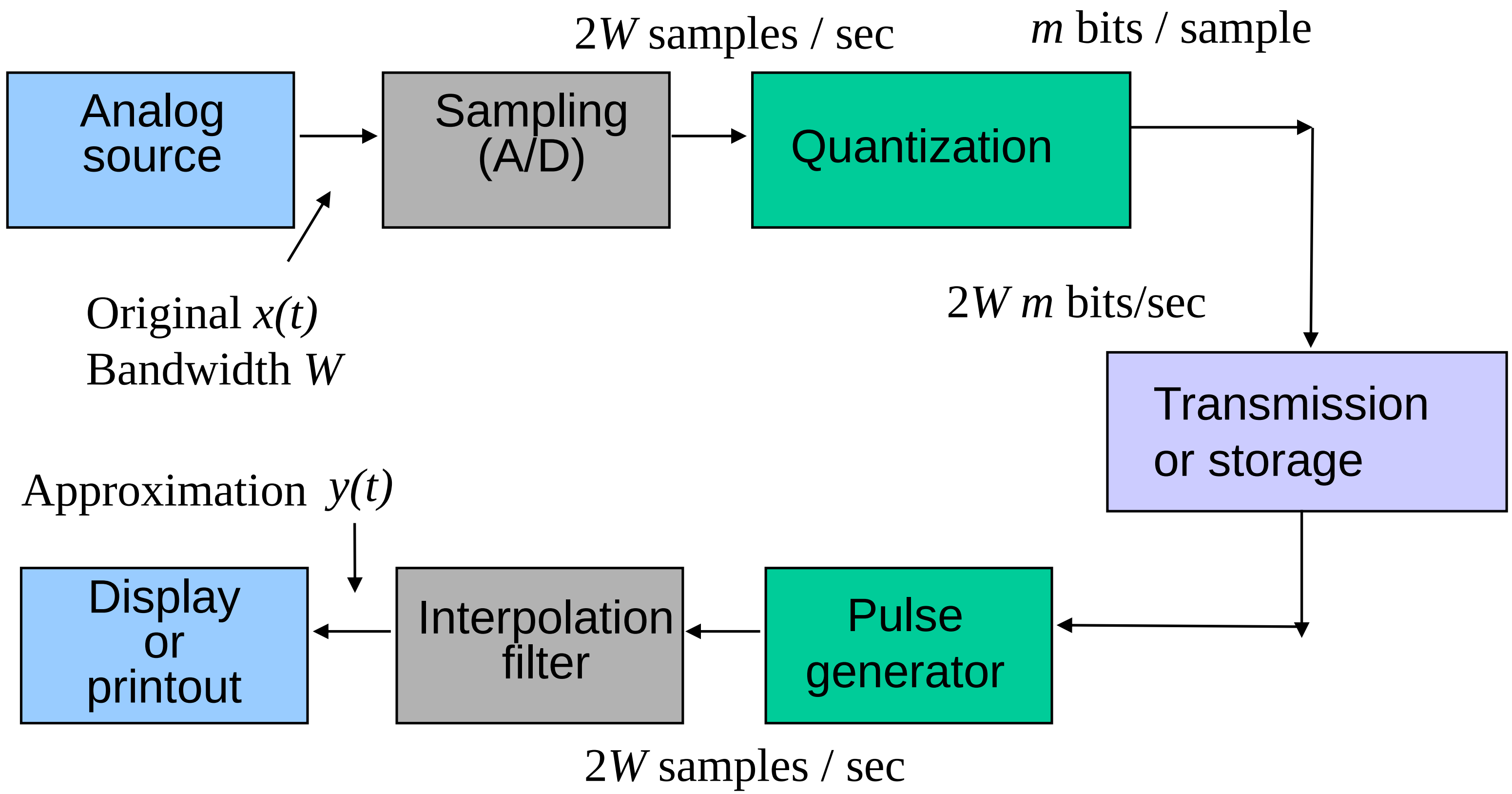
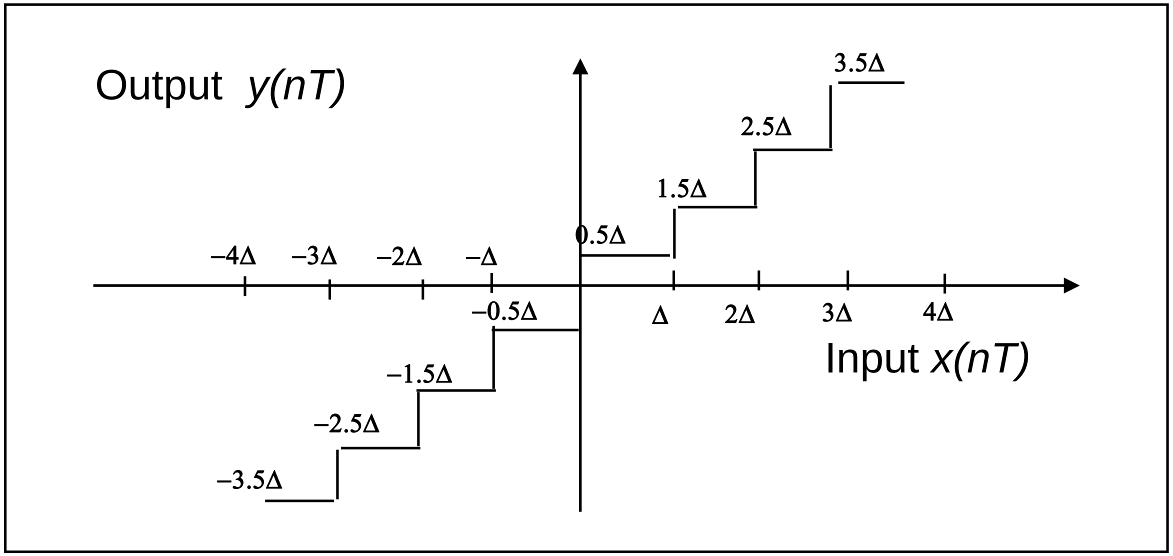


Fig. 2.11: Digital transmission of analog signals.

Quantizers

- Quantizer: approximates a sample value using m bits within a specified accuracy.
  - ⇨ Bit rate: $2Wm$ bits/second.
- A proper trade-off must be found between accuracy and the bit rate $2Wm$.
- Uniform quantizer: the range of signal amplitudes is covered by equally spaced approximation values.
  - $x(t)$ assumes the values in the range $[-V, V]$, which is devided into $M=2^m$ intervals of equal lengthΔ. Since $2V = M\Delta$, we have $\Delta = 2V/M = V/2^{m-1}$.
  - The approximation value $y(nT)$ is the midpoint of the interval where the input $x(nT)$ falls in. The output of the quantizer is simply the m bits that specify the interval.
- General quantizer: the intervals are not of the same length.

A Uniform Quantizer



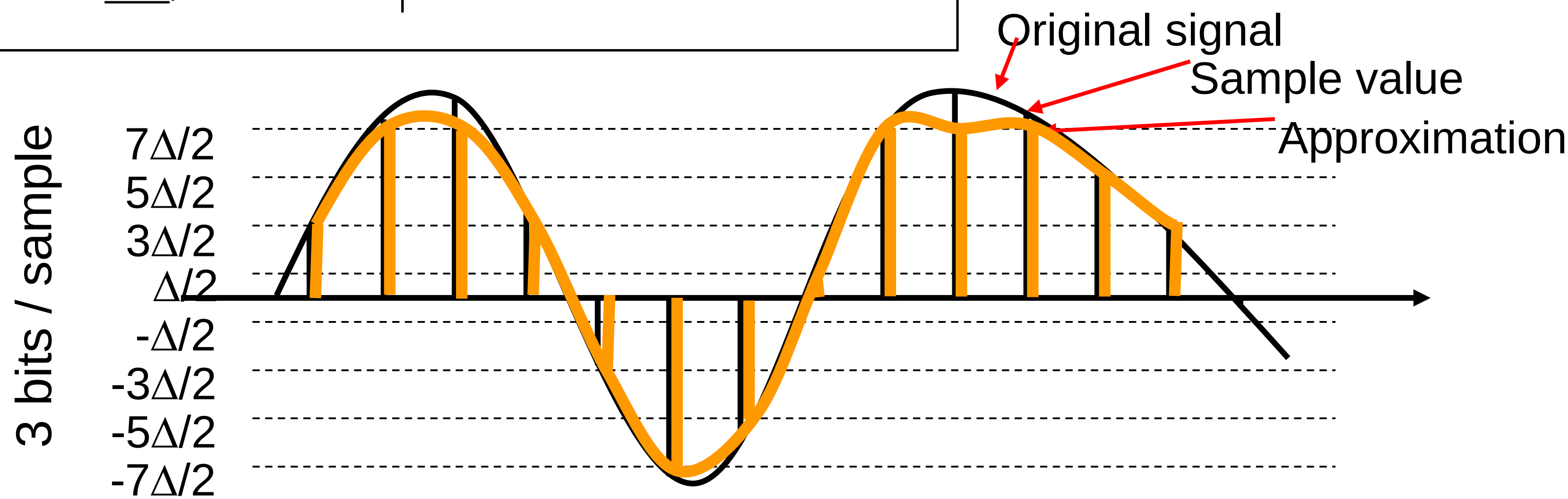


Fig. 2.12: A uniform quantizer.

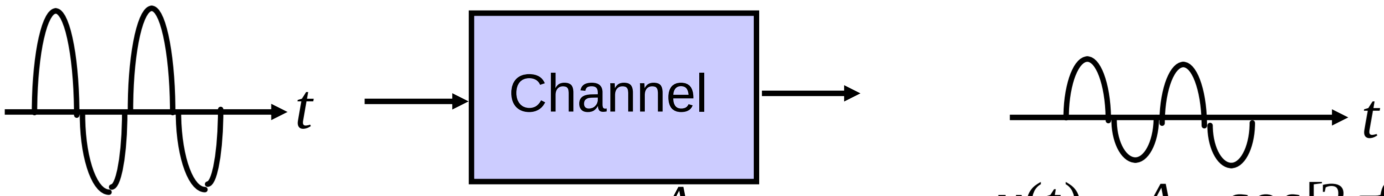
2.3.4 SNR Performance of Quantizers

- Quantizer error: $e(nT)=y(nT)-x(nT)$.
- Quantizer SNR: $\mathrm{SNR}=\dfrac{\text{average signal power}}{\text{average noise power}}=\dfrac{\sigma_x^2}{\sigma_e^2}$.
  - When $M=2^m$ is large, the error values $e(nT)$ are approximately uniformly distributed in the interval $(-\Delta/2,\Delta/2)$.
    - ⇨ The average noise power: $\sigma_e^2=\int_{-\frac{\Delta}{2}}^{\frac{\Delta}{2}} e^2 \frac{1}{\Delta}\mathrm{d}e=\dfrac{\Delta^2}{12}\overset{\Delta=\frac{2V}{M}}{=}\dfrac{V^2}{3M^2}=\dfrac{V^2}{3\cdot 2^{2m}}$.
  - $\mathrm{SNR}=3(\frac{M\sigma_x}{V})^2=3(\frac{2^m\sigma_x}{V})^2$.
  - $\mathrm{SNR(dB)}=10\log_{10}\mathrm{SNR}=6m+10\log_{10}\frac{3\sigma_x^2}{\mathrm{V}^2}\approx 6m-7.27\mathrm{dB}$ for $\frac{V}{\sigma_x}\approx 4$.

2.4 Characterization of Communication Channels

- A **communication channel** is a system consisting of a physical medium and associated electronic and/or optical equipments (e.g., amplifier and quantizer) that can be used for the transmission of information.
- A **physical medium** is an inherent part of a communications system.
  - Copper wires, radio medium, or optical fiber.
- Communications system includes **electronic or optical devices** that are part of the path followed by a signal.
  - Equalizers, amplifiers, signal conditioners.
- By **communication channel** we refer to the combined end-to-end physical medium and attached devices.
- Sometimes we use the term ***filter*** to refer to a channel especially in the context of a specific mathematical model for the channel.

2.4.1 Frequency Domain Characterization



$x(t) = A_{in} \cos 2\pi f t$

$A(f) = \dfrac{A_{out}}{A_{in}}$

$$y(t) = A_{out} \cos[2\pi f t + \varphi(f)]$$
$$= A_{out} \cos[2\pi f (t - \tau(f))]$$

Fig. 2.13: Channel characterization in frequency domain.

- **Amplitude-response function *A*(*f*)**: the ratio of the output amplitude A_{out} to the input amplitude A_{in} of the sinusoids at frequency f.
- **Phase shift**: a shift in the phase of the output signal relative to the input signal.
- The output $y(t)$ can be viewed as the input $x(t)$ attenuated by $A(f)$ and delayed by $\tau(f)$.

Frequency Domain Characterization

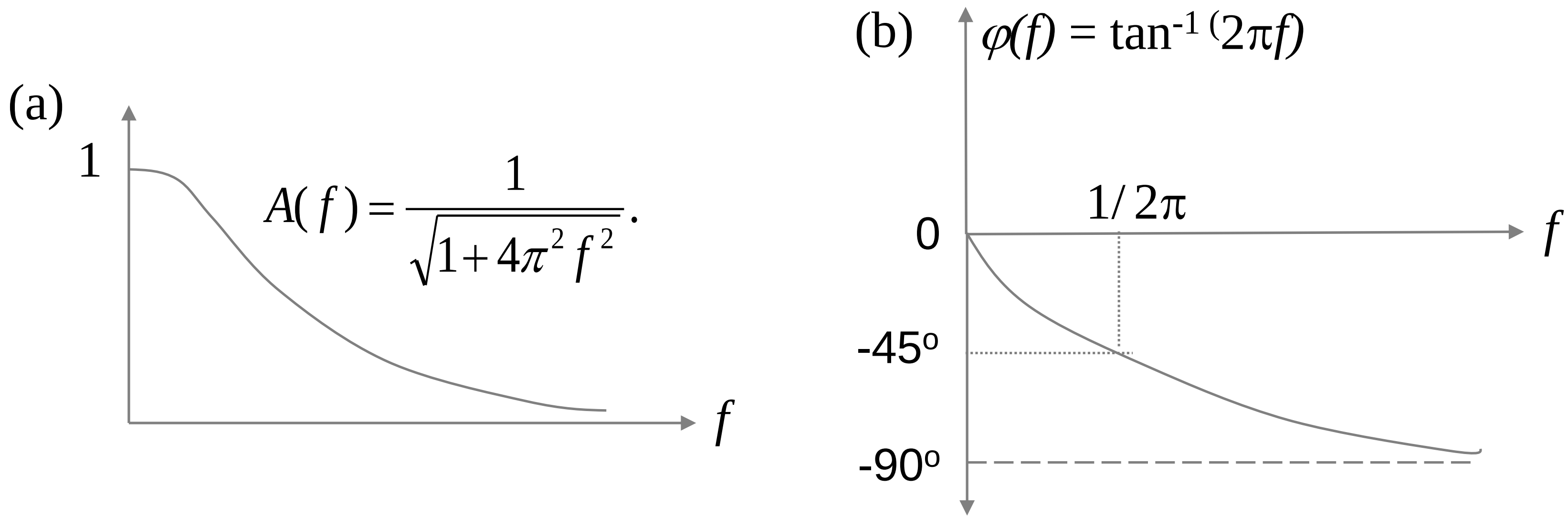


Fig. 2.14: (a) Amplitude-response function; (b) phase-shift function.

- The **amplitude-response function *A(f)*** can be viewed as specifying a window of frequencies that the channel will pass.
- **The bandwidth of a channel *W*** measures the window width of frequencies that are passed by the channel.
- **Attenuation** of a signal: the reduction or loss in signal power as it is transferred across a system.

$$\text{Attenuation (dB)} = 10\log_{10}\frac{P_{\text{in}}}{P_{\text{out}}} = 10\log_{10}\frac{A_{\text{in}}^2}{A_{\text{out}}^2} = 10\log_{10}\frac{1}{A^2(f)}.$$

Impact of Communication Channels on the Input Signal

- A periodic input signal: $x(t) = \sum a_k \cos(2\pi f_k t) = \sum a_k \cos(2\pi k f_0 t).$
- A channel: $A(f)$ and $\varphi(f)$
- Channel output: $y(t) = \sum a_k A(kf_0) \cos[2\pi k f_0 t + \varphi(kf_0)]$
  - The channel alters the relative weight of the frequency components, since $A(f)$ varies with f.
  - The shape of the output $y(t)$ generally differs from $x(t)$, since different frequency components are delayed differently.

2.4.2 Time Domain Characterization

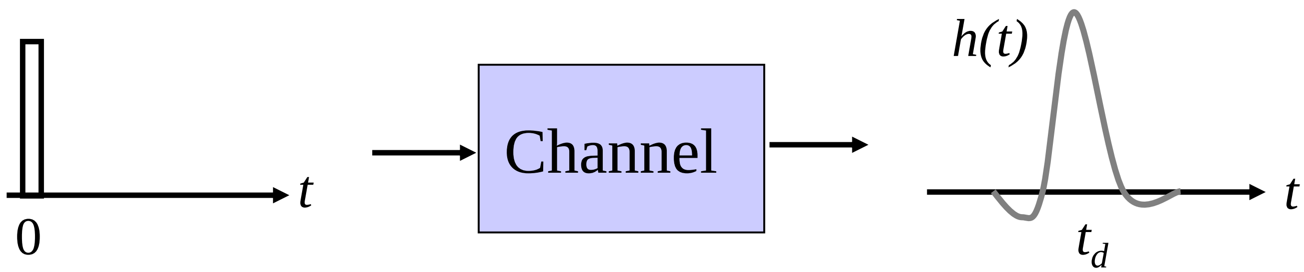


Fig. 2.15: Channel characterization –time domain.

- Time-domain characterization of a channel requires finding the impulse response *h(t)*.
- **Impulse response** $h(t)$: the observed channel output by applying a very narrow pulse to the channel input.
- Interested in system designs with *h(t)* that can be packed closely without interfering with each other.

Nyquist Pulse with Zero Intersymbol Interference

- For an idealized lowpass channel with bandwidth W, $A(f)$=1 and $\varphi(f) = -2\pi f t_d$ hold.
- The corresponding impulse response: $h(t)=s(t-t_d)$, where $s(t) = \dfrac{\sin(2\pi Wt)}{2\pi Wt}$.
    - $s(t)=1$ at $t=0$ and $s(t)$ has zero crossings at $t=kT=k/(2W)$, $k=1, 2, \ldots$
    - Pulses can be packed every T seconds with ***zero interference***.

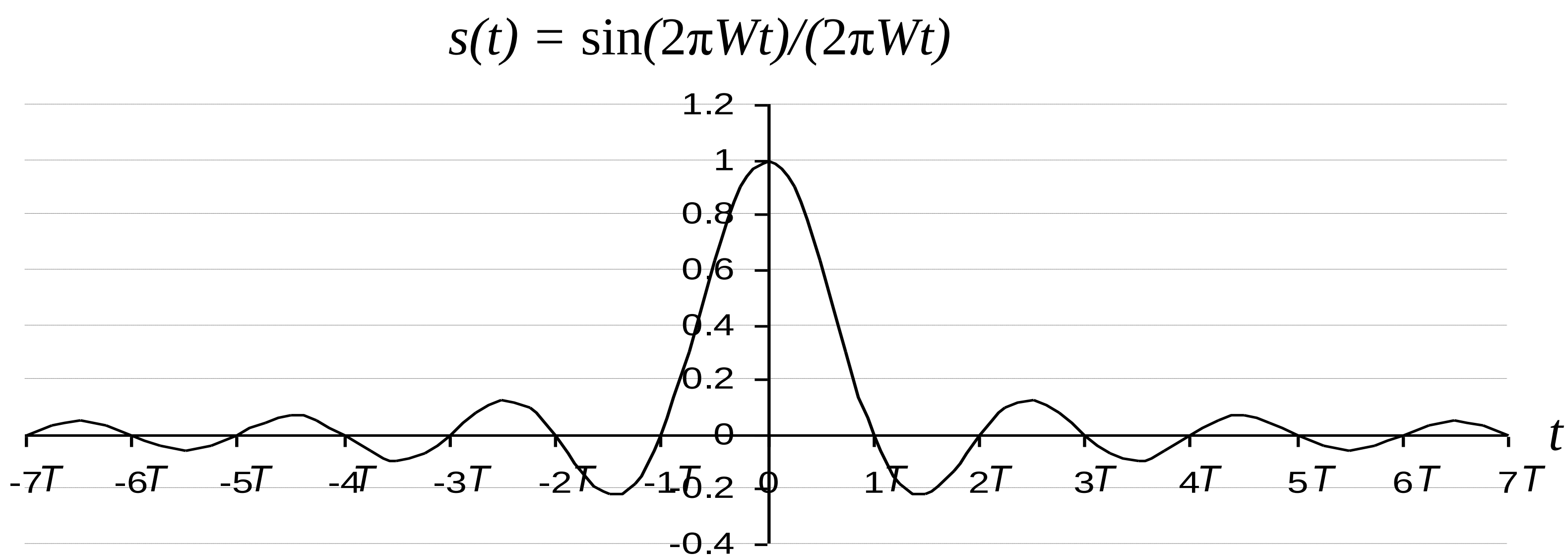


Fig. 2.16: Signaling pulse with zero intersymbol interference.

An Example of Composite Waveform

- Three Nyquist pulses shown separately: $s(t)$, $s(t-T)$, $-s(t-2T)$.
- Composite wave: $r(t)=s(t)+s(t-T)-s(t-2T)$.
- Samples at KT:
  - $r(0)=s(0)+s(-T)-s(-2T)=+1$;
    $r(T)=s(T)+s(0)-s(-T)=+1$;
    $r(2T)=s(2T)+s(T)-s(0)=-1$.

⇨ **Zero ISI at sampling times *kT*.**

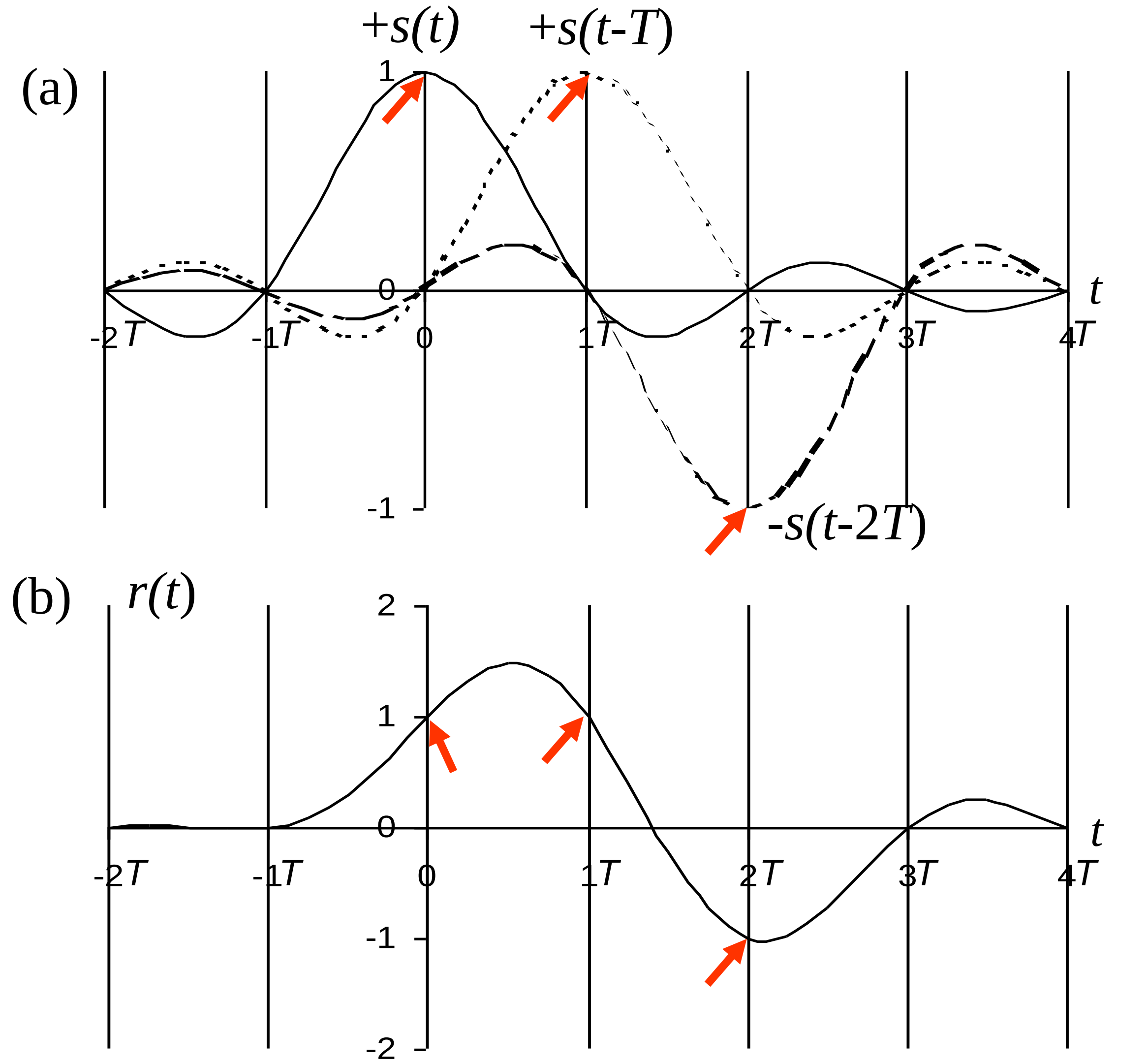


Fig. 2.17: (a) Three Nyquist pulses; (b) composite wave.

2.5 Fundamental Limits in Digital Transmission

- **Baseband transmission**: the transmission of digital information over a low-pass communication channel.

- Two parameters to measure the quality of a digital transmission system:
  - **Bit rate** (transmission speed or efficiency): number of bits/second.
  - **Bit error rate** (transmission reliability): the fraction of bits that are received in error.

  ⇨ These two parameters are determined by both the bandwidth of the communication channel and the SNR.

- Two questions:
  - How to address the problem of channel distortion?
  - How to maximize the pulse transmission rate?

2.5.1 The Nyquist Signaling Rate

- *p(t):* the basic pulse at the receiver after it has been sent over the combined transmitter filter, communication channel, and receiver filter.
- *r(t):* the waveform at the receiver in response to sequence of pulses.
  - $r(t) = \sum_k A_k p(t - kT)$, by assuming that the propagation delay is zero.
  - $r(0) = A_0 p(0) + \sum_{k \neq 0} A_k p(-kT)$
  - ⇨ The receiver must contend with *intersymbol interference* from all other transmitted pulses.

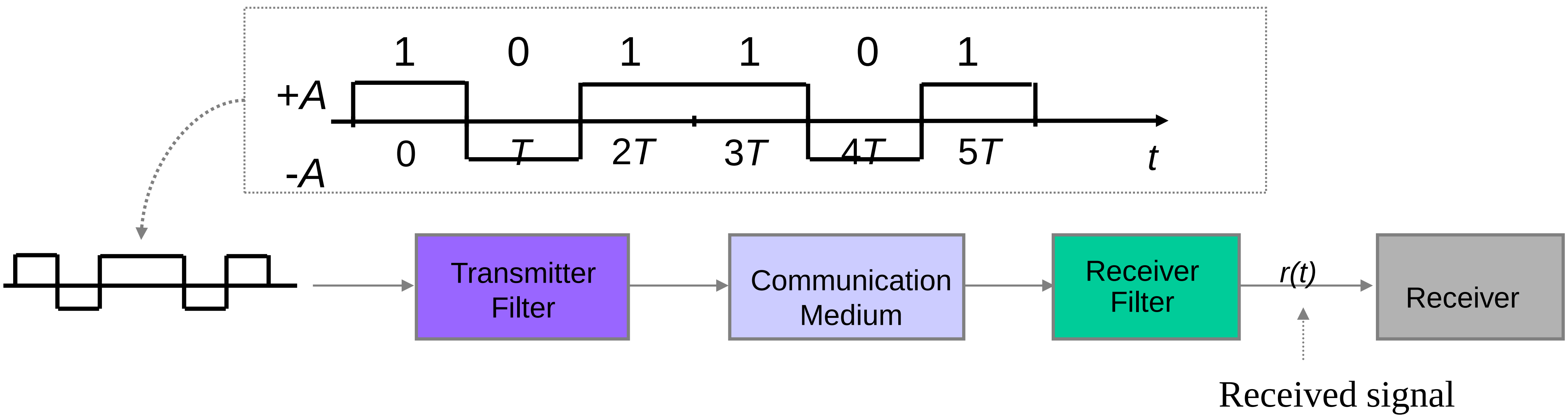
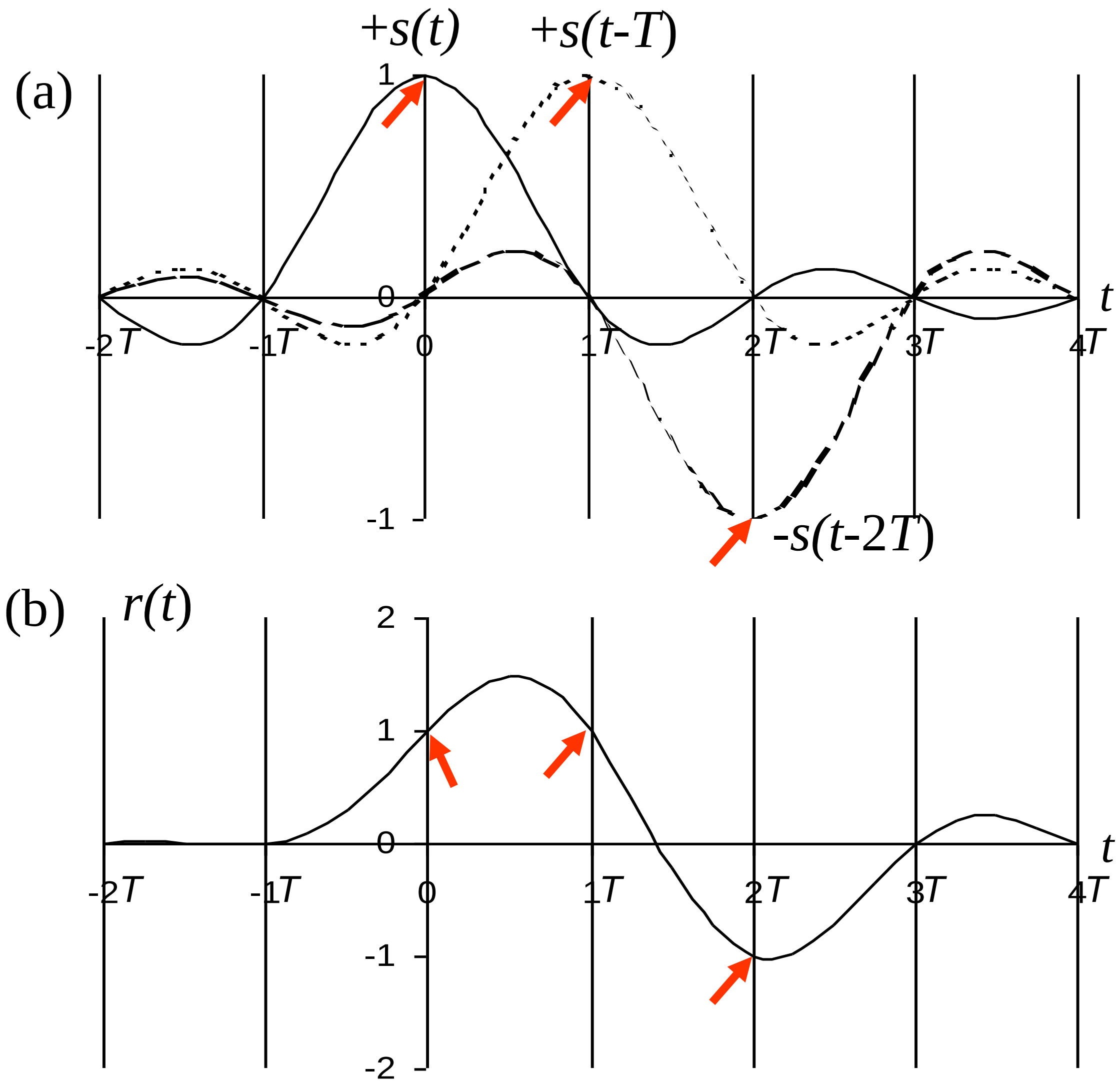


Fig. 2.18: Digital baseband signal and baseband transmission system.

Nyquist Pulses



- Nyquist pulses: provide zero intersymbol interference at the times $t=kT$ at the receiver.

Fig. 2.19: System response to binary input 110: (a) three separate pulses; (b) composite signal.

Nyquist Signaling Rate

- **Nyquist signaling rate r_{max}**: the maximum signaling rate that is achievable through an ideal lowpass channel with zero intersymbol interference.
  - $r_{max}=2W$ pulses/second; W: channel bandwidth.
- With two signal levels, each pulse carries one bit of information.
  - Bit rate = $2W$ pulses/second * 1 bit/pulse = $2W$ bits/second.
- With $M = 2^m$ (m>1) signal levels, each pulse carries m bits.
  - Bit rate = $2W$ pulses/second * m bits/pulse = $2Wm$ bits/second.
  - Bit rate can be increased by increasing the number of levels 2^m.
  - The received signal $r(t)$ includes additive noise, which limits the number of levels that can be used reliably.

Channel Noise Limits Accuracy/Reliability

- Receiver makes decision based on transmitted pulse level plus noise.
- Error rate depends on relative value of noise amplitude and spacing between signal levels.
- Large (positive or negative) noise values can cause wrong decision.
- Noise level below impacts 8-level signaling more than 4-level signaling.

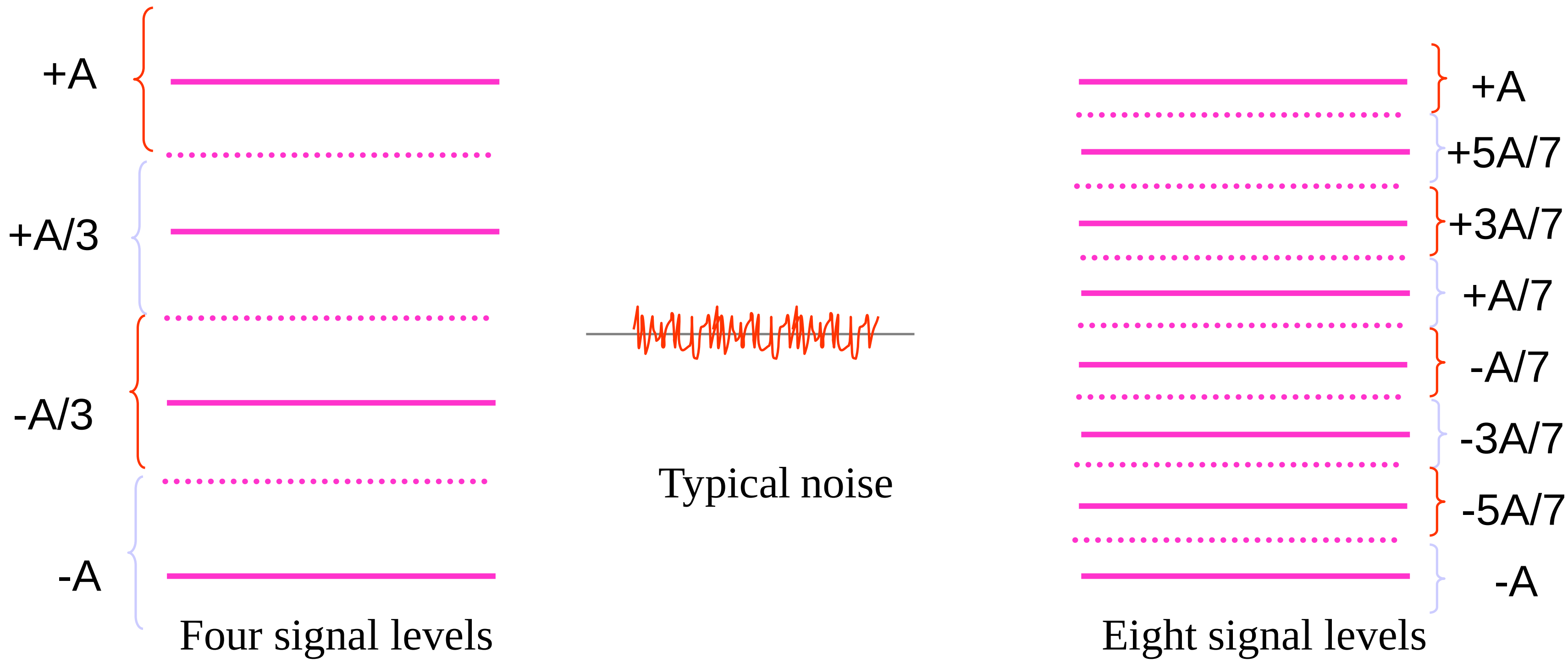


Fig. 2.20: Effect of noise on transmission errors as number of levels is increased.

Gaussian Noise Distribution

- Noise is characterized by the probability density function (PDF) of noise amplitudes.
- The PDF gives the relative frequency of occurrence of the noise amplitudes.
- Gaussian PDF (bell-shaped) is a good model for the noise amplitudes.

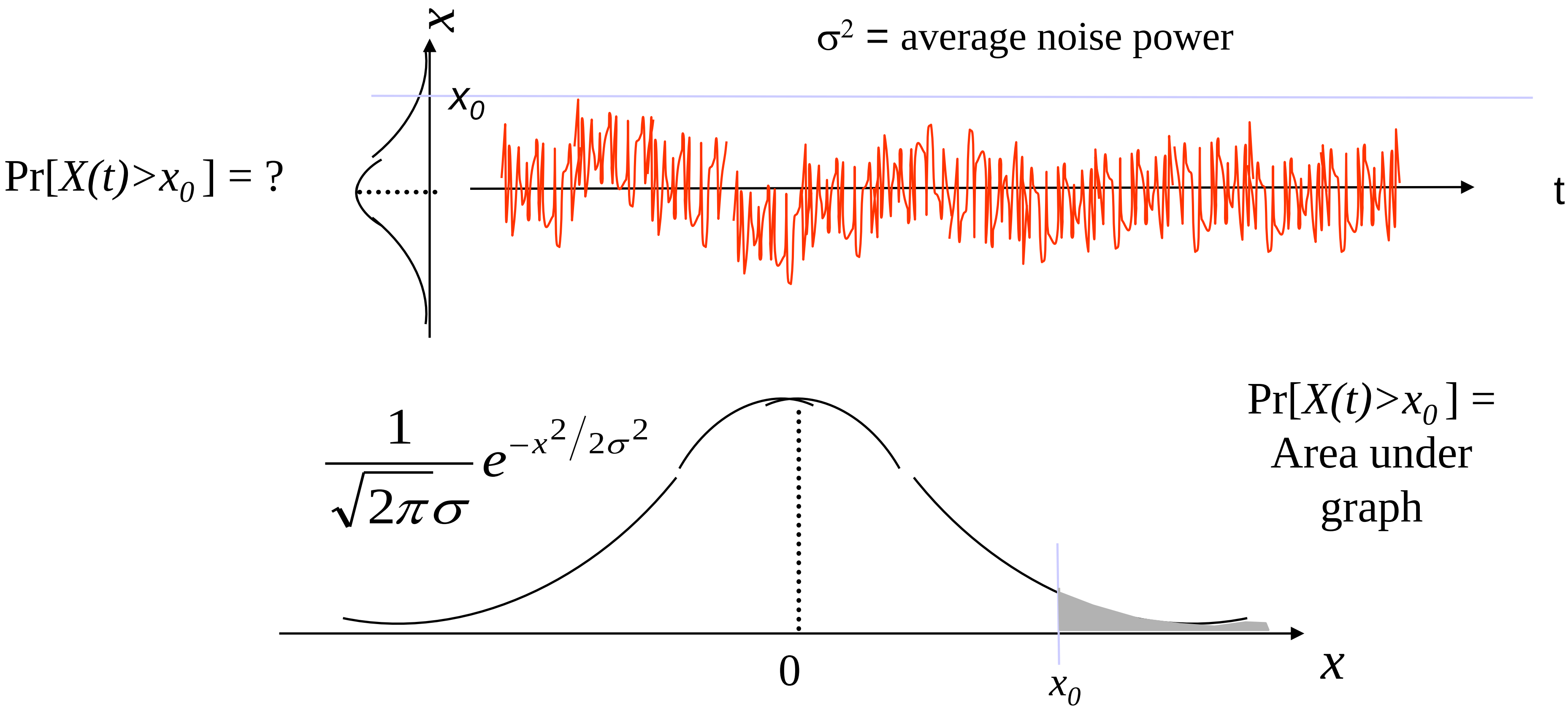


Fig. 2.21: Gaussian probability density function.

Probability of Error

- If we have maximum amplitudes $\pm A$ and M levels, the separation between adjacent levels is $\delta = 2A/(M-1)$.
- When an interior signal level is transmitted, an error occurs if the noise causes the received signal to be closer to one of the other signal levels, i.e., the noise amplitude is greater than $\delta/2$ or less than $-\delta/2$.
- The Probability of error for an interior signal level is given by:

$$P_e = \int_{-\infty}^{-\delta/2} \frac{1}{\sqrt{2\pi\sigma}} e^{-x^2/2\sigma^2} dx + \int_{\delta/2}^{\infty} \frac{1}{\sqrt{2\pi\sigma}} e^{-x^2/2\sigma^2} dx = 2Q\left(\frac{\delta}{2\sigma}\right)$$

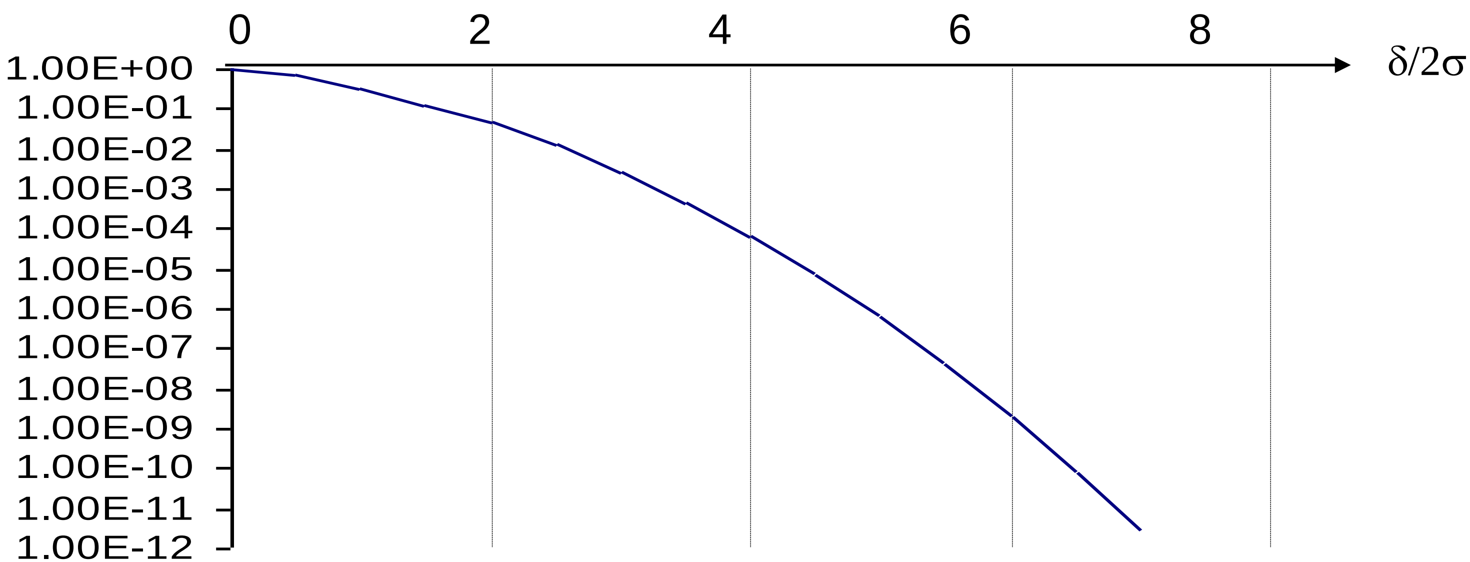


Fig. 2.22: Probability of error for an interior signal level.

2.5.2 The Shannon Channel Capacity

- The bit rate cannot be increased to arbitrarily high values by increasing the number of levels *M* without incurring significantly higher bit error rates.
- Presence of noise at receiver causes more frequent errors to occur as *M* is increased.
- **Shannon Channel Capacity**: the maximum reliable transmission rate over an ideal channel of bandwidth *W* Hz, with Gaussian distributed noise, and with a given SNR is
  - $C = W \log_2 (1 + \text{SNR})$ bits/second.
  - Reliable communication means bit error rate can be made arbitrarily small by sufficiently complex coding.
  - The bit error rate can be made arbitrarily small only if the transmission rate *R* is less than channel capacity *C*.

Example

- Consider a 3 kHz telephone channel with 8-level signaling. Compare the bit rate *R* to channel capacity *C* at 20 dB SNR.
  - The bit rate *R* of a 3KHz telephone channel with 8 level signaling:
    - R = 2*3000 pulses/second * 3 bits/pulse = 18 kbits/second.
  - From $10 \log_{10} \text{SNR} = 20$, we have SNR = 100.
  - Shannon Channel Capacity is then:
    - $C = 3000 \log_2 (1 + 100) = 19963$ bits/second.
  - $R<C$.

2.6 Properties of Media and Digital Transmission Systems

- The capacity of a channel to carry information reliably is determined by:
  - Amplitude-response function, phase-shift function, and bandwidth.
    - Dependence on distance.
  - Susceptibility of the medium to noise and interference from other sources.
    - Error rate and SNR.
- Propagation speed of signal:
  - Speed of light in a vacuum: $c = 3 \times 10^8$ meters/second.
  - Speed in a medium: $v = c/\sqrt{\varepsilon}$, where ε ($\varepsilon = 1$ in free space and $\varepsilon \geq 1$ otherwise) is the dielectric constant of the medium.
  - $v = 2.3 \times 10^8$ m/sec in copper wire; $v = 2.0 \times 10^8$ m/sec in optical fiber.

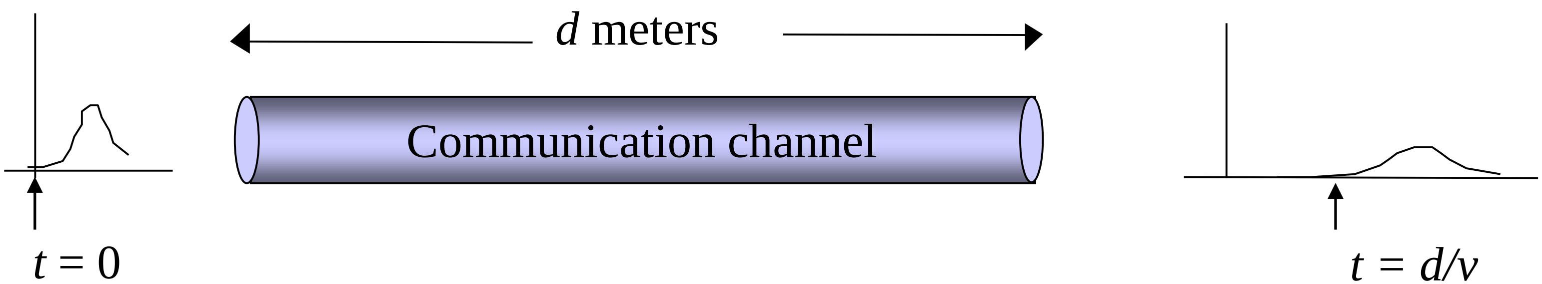


Fig. 2.23: Propagation delay of a pulse over the communication channel.

Communications Systems & Electromagnetic Spectrum

- Wavelength of the signal: $\lambda = v/f_0$ meters, with f_0 representing the carrier frequency.

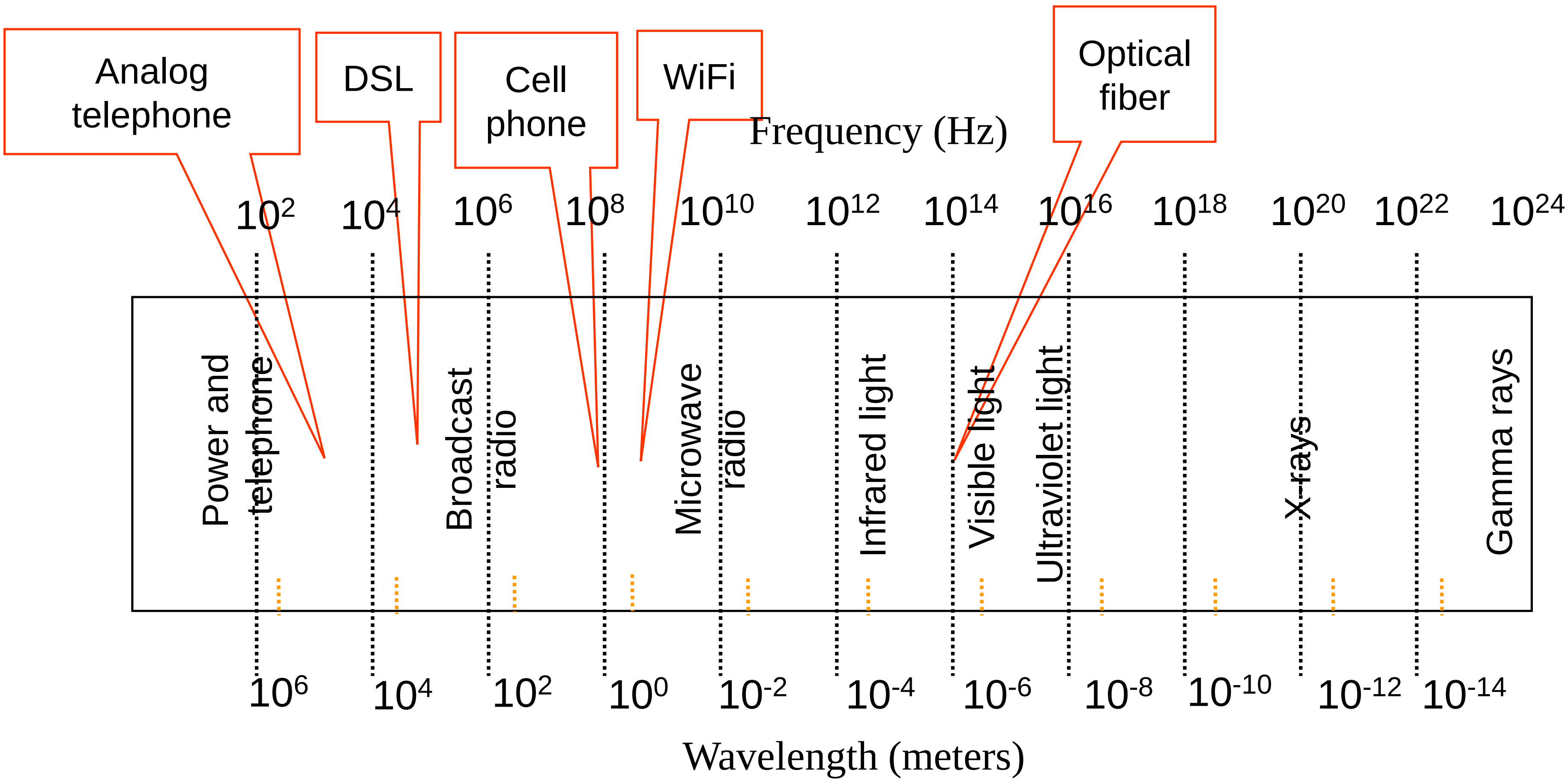


Fig. 2.24: Electromagnetic spectrum.

Wireless & Wired Media

- **Wireless Media (Unguided Media)**
  - Signal energy propagates in space, limited directionality.
  - Interference possible, so spectrum has to be regulated.
  - Limited bandwidth
  - Simple infrastructure (antennas & transmitters)⇨can therefore be deployed more quickly and at lower cost.
  - Wireless media leads to *continuous* network topologies.
  - Users can move.
- **Wired Media (Guided Media)**
  - Signal energy contained & guided within a solid medium.
  - Spectrum can be re-used in separate media (wires or cables), more scalable.
  - Extremely high bandwidth
  - Complex infrastructure (ducts, conduits, poles, right-of-way) ⇨ complicated, costly, and time-consuming.
  - Wired media leads to well-defined *discrete* network topologies.

Attenuation

- Attenuation varies with media.
  - Dependence on distance is of central importance.
- Wired media has an exponential dependence on the distance.
  - The attenuation at d meters is proportional to 10^{kd}, where k depends on the specific frequency.
  - Attenuation in dB = kd; increases **linearly** with the distance d.
- Wireless media has a logarithmic dependence on the distance.
  - The attenuation at d meters is proportional to d^n, where n is path loss exponent.
  - Attenuation in dB = $n \log_{10} d$; increases **logarithmically** with the distance d; $n=2$ in free space.
  - Signal level can be maintained for much longer distances than in wired systems.

2.6.1 Guided Transmission Media

- Magnetic Media
- Twisted Pair
- Coaxial Cable
- Fiber Optics

Magnetic Media

- Write data onto magnetic tape or removable media (e.g., recordable DVDs), physically transport the tape or disks to the destination machine, and read them back in again.
- High bandwidth and most cost effective, but long delay.
- Example: An industry standard Ultrium tape can carry 200 gigabytes.
  - A box of 60*60*60 cm^3 can hold about 1000 tapes, which corresponds to $2*10^5$ gigabytes or $1.6*10^6$ gigabits.
  - Sending such a box can be done anywhere in the USA within 24 hours.
  - The effective bandwidth: $1.6*10^{15}$ bits/86400 seconds=18.5 Gbps.

⇨ Never underestimate the bandwidth of a station wagon full of tapes hurtling down the high way.

Twisted Pair

- Two insulated copper wires, twisted in a helical form, like a DNA string.
- Twisting is done because two parallel wires constitute a fine antenna. The waves from different twists cancel out, so the wire radiates less effectively.
- The bandwidth depends on the thickness of the wire and the distance traveled.
- Application: telephone system.
- Further distinguish between shielded (STP) and unshielded (UTP) versions. The shielded ones are primarily used only with IBM installations.
- Compared with Category 3 UTP, Category 5 UTP has more twists per centimeter, resulting in less crosstalk and a better quality signal over longer distances.

Fig. 2.25: (a) Category 3 UTP. (b) Category 5 UTP.

Coaxial Cable

- Better shielding than twisted paris, so it can span longer distances at higher speeds.
- Good combination of high bandwidth and excellent noise immunity.
- The bandwidth depends on the cable quality, length, and SNR of the data signal.
- Application: Cable TV and MANs; Used to be widely used in telephone systems for long-distance lines but have now largely been replaced by fiber optics over long-haul routes.

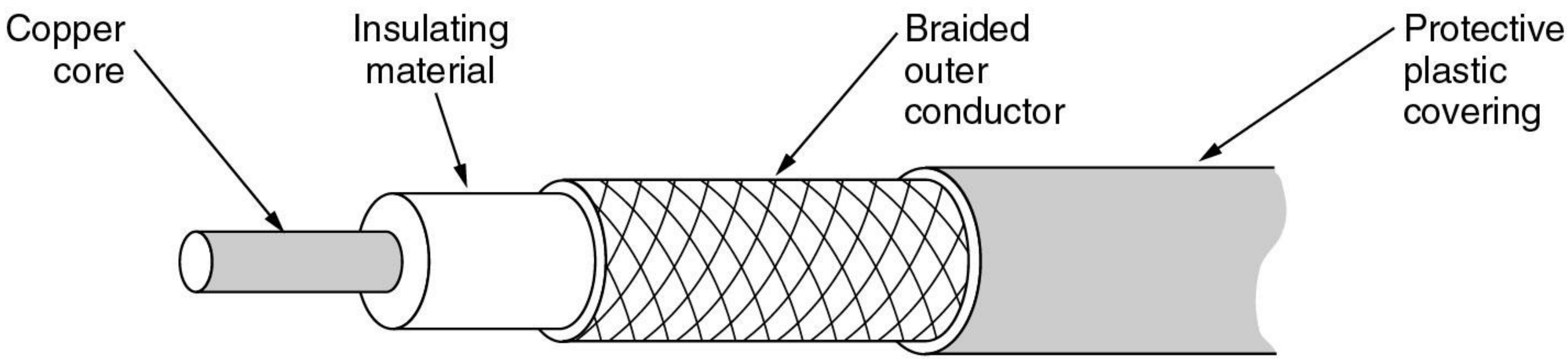


Fig. 2.26: A coaxial cable.

Fiber Optics

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

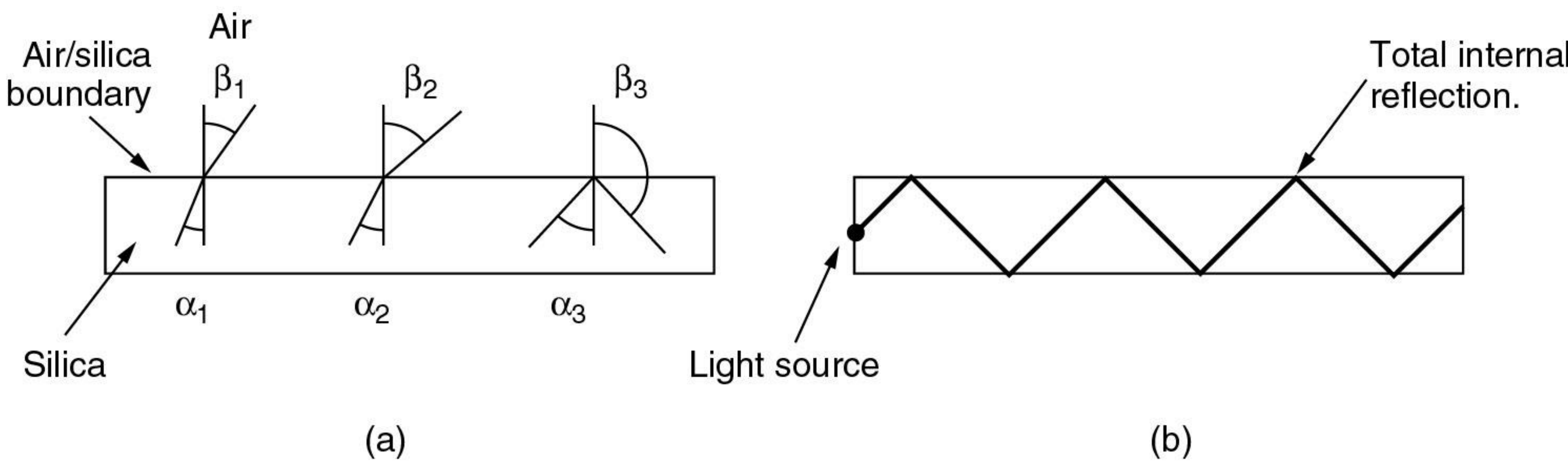


Fig. 2.27: (a) Three examples of a light ray from inside a silica fiber impinging on the air/silica boundary at different angles. (b) Light trapped by total internal reflection.

Transmission of Light Through Fiber

- Optical fibers are made of glass, which, in turn, is made from sand.
- Attenuation is extremely small in optical fiber. This means that they can be used for long distances. In addition, the bandwidth is enormous.

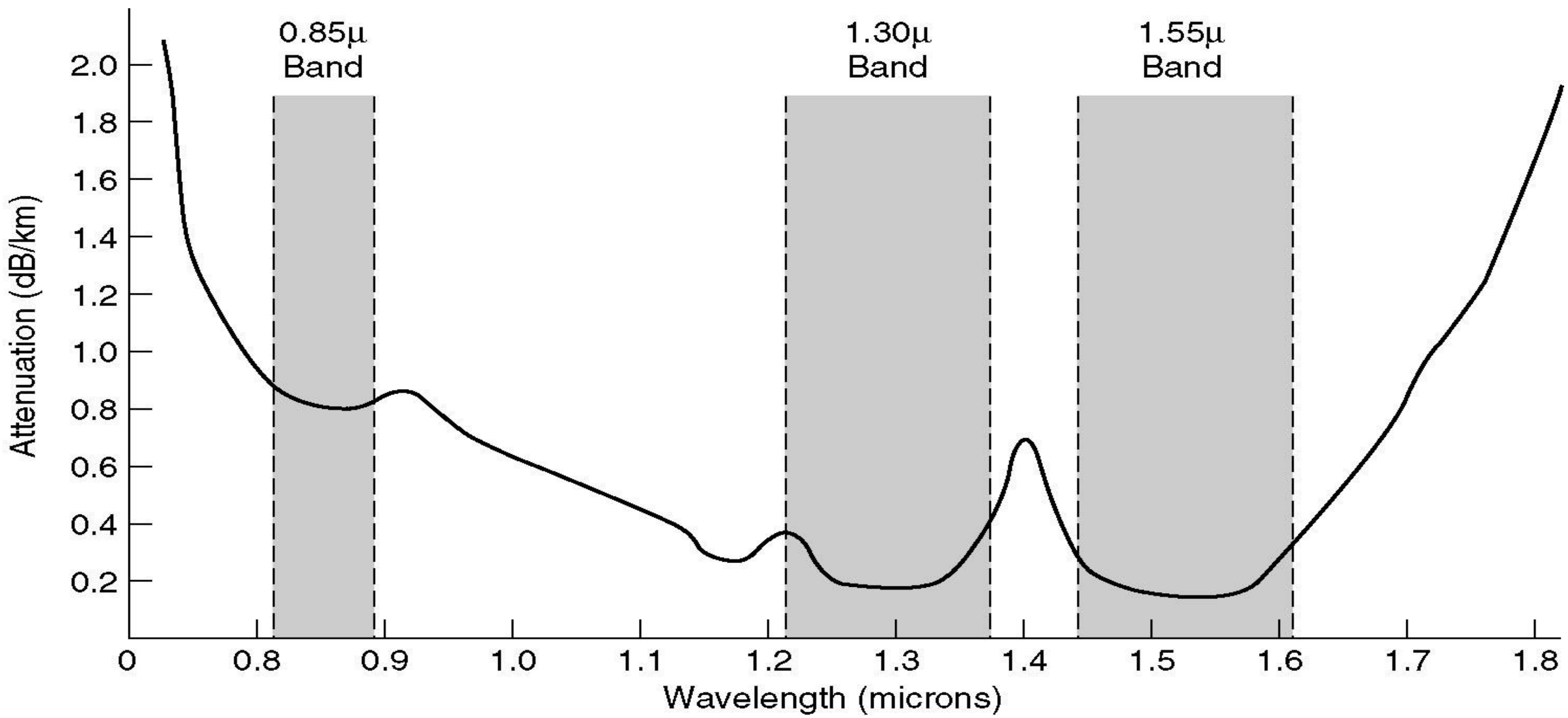


Fig. 2.28: Attenuation of light through fiber in the infrared region.

Fiber Cables (1/2)

- Similar to coaxial cables, except without the braid.
- **Glass core**: through which the light propagates.
- **Glass cladding**: with a lower refraction index than the core, to keep all the light in the core.
- **Plastic jacket**: protect the cladding.

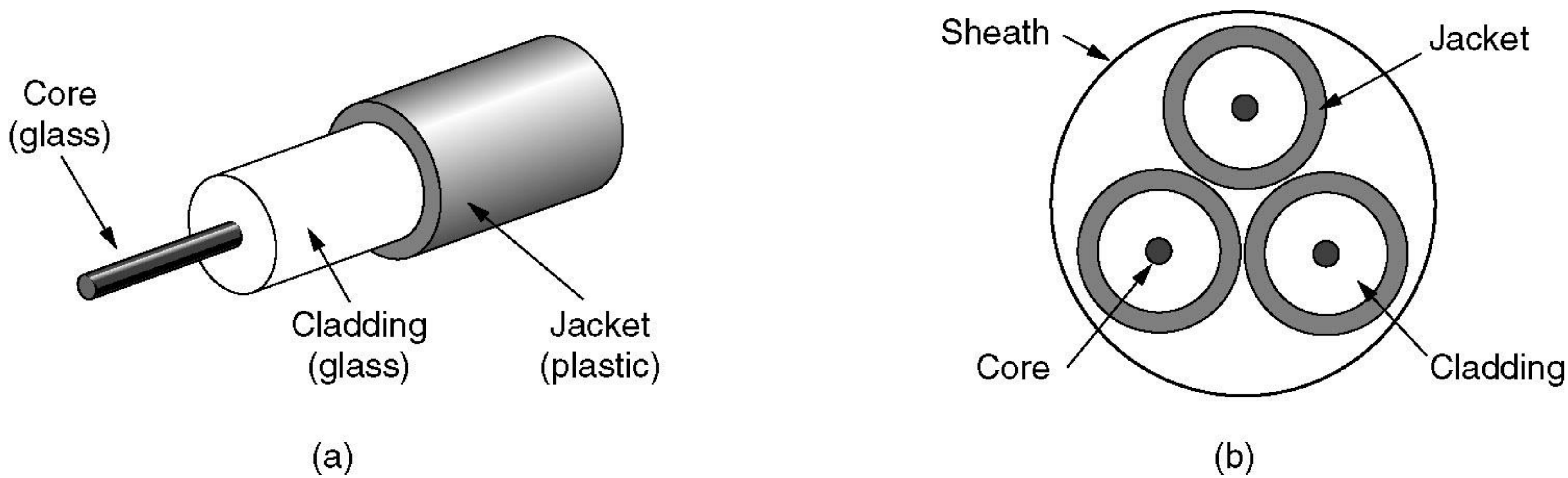


Fig. 2.29: (a) Side view of a single fiber. (b) End view of a sheath with three fibers.

Fiber Cables (2/2)

- Two kinds of light sources: LEDs (Light Emitting Diodes) and semiconductor lasers.

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

Fig. 2.30: A comparison of semiconductor diodes and LEDs as light sources.

Fiber Optic Networks

- Fiber optics can be used for LANs as well as for long-haul transmission.
- **Passive interface:** consists of two taps (LED or laser diode transmitter and photodiode receiver) fused onto the main fiber.
- **Active interface:** an electrical (or purely optical) regenerator connected to two fiber segments and the computer. If an active repeater fails, the ring is broken and the network goes down.

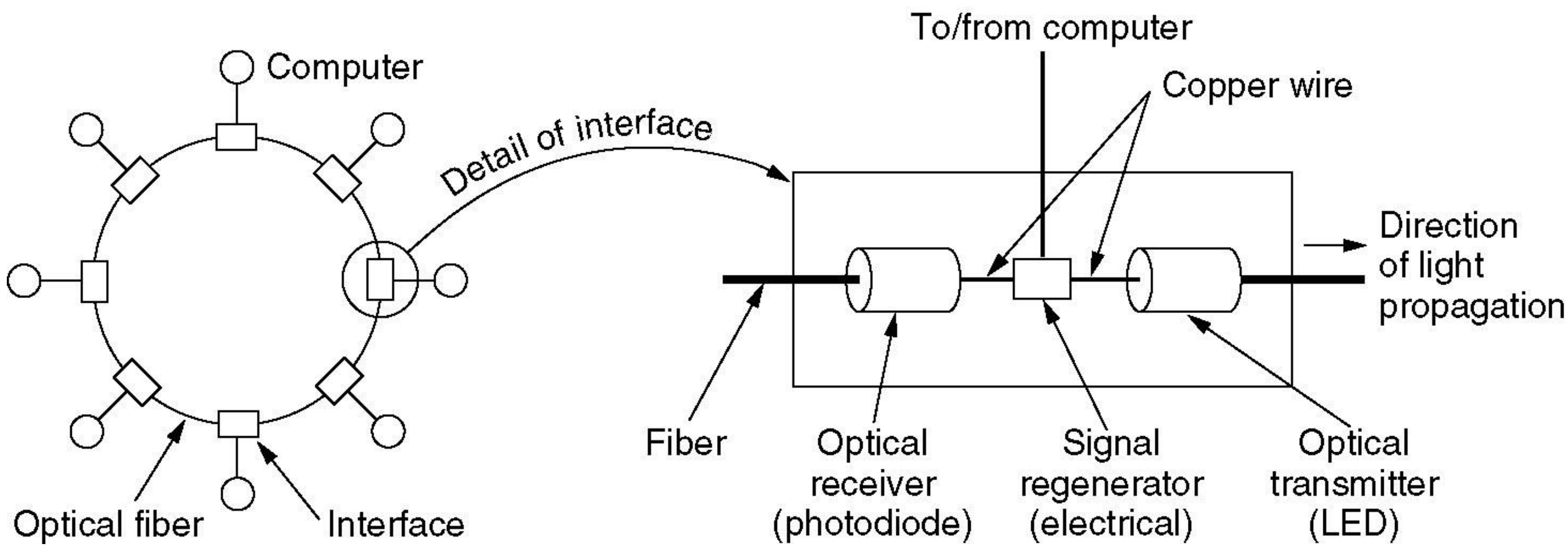


Fig. 2.31: A fiber optic ring with active repeaters.

Fiber Optics vs. Copper Wire

- **Advantages** over copper wire:
  - Much higher bandwidth.
  - Lower attenuation; repeaters needed only about every 50 km versus about every 5 km for copper.
  - No external influence from power surges, electromagnetic interference, power failures, or corrosive chemicals.
  - Thin and lightweight.
  - Excellent security since fibers do not leak light and are quite difficult to tap.
- **Disadvantages:**
  - Less familiar technology.
  - Can be damaged easily by being bent too much.
  - Inherently unidirectional.
  - Fiber interfaces cost more than electrical interfaces.

2.6.2 Wireless Transmission

- 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).
- Wireless transmission is also convenient when wiring is needed where it can't be done, or is not really worth the trouble (jungles, islands, mountains).
- Wireless transmissions travel at the speed of light (c), uses a frequency (f) which has a wavelength (λ): $c = \lambda f$.

The Electromagnetic Spectrum (1/2)

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

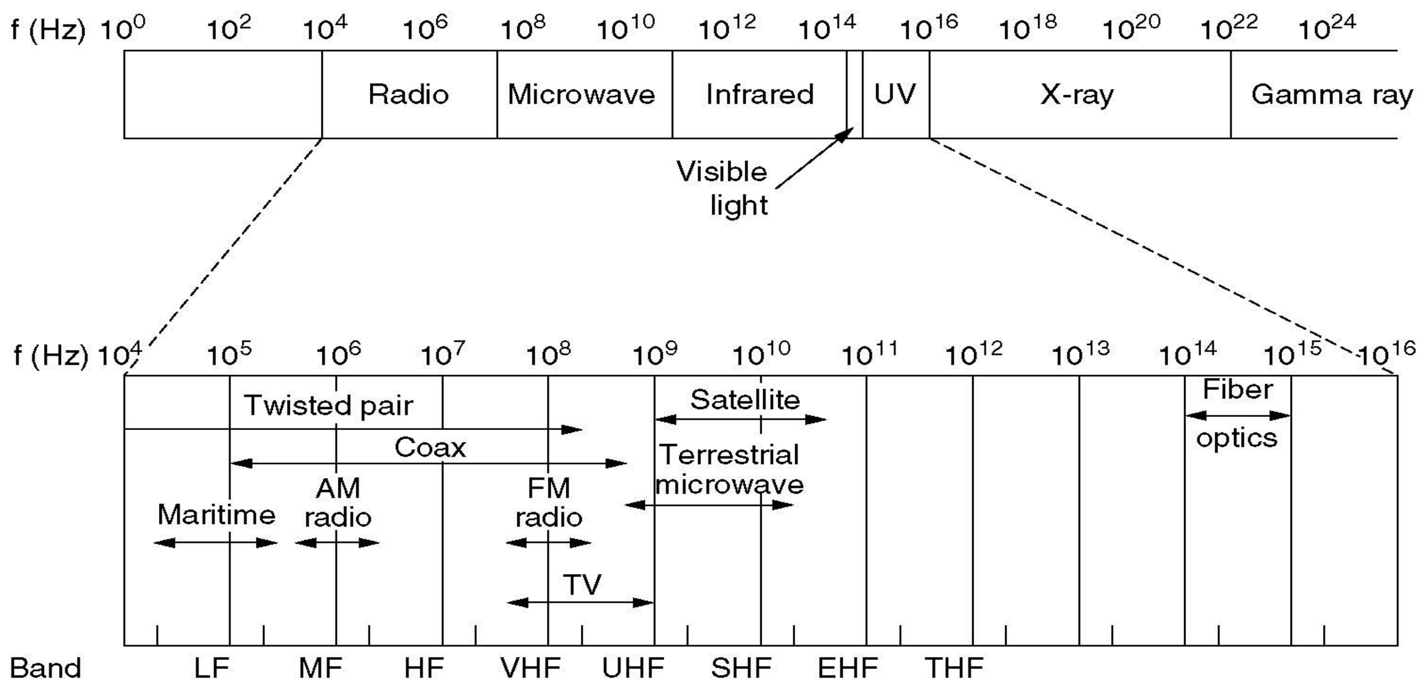


Fig. 2.32: The electromagnetic spectrum and its uses for communication.

The Electromagnetic Spectrum (2/2)

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

⇨ The wider the wavelength band $\Delta\lambda$, and the shorter the wavelength λ, the higher the bandwidth Δf.

  - Example: Fiber optics often work at λ=1.3*10^{-6} with $\Delta\lambda$=0.17* 10^{-6} leading to 30 THz bandwidth!

- **Frequency hopping spread spectrum:** uses a wide band, but lets the transmitter hop from frequency to frequency (hundreds of times per second). Good for avoiding continuous interference and reducing the effect of reflected signals.
  - Applications: IEEE 802.11 and Bluetooth.
- **Direct sequence spread spectrum:** Simply spreads the signal over a wide fequency band. Good spectral efficiency and noise immunity.
  - Applications: 2nd and 3rd generation cellular mobile communication systems.

Frequency hopping spread spectrum

Hedy Lamarr (1914-2000)

Patented Aug. 11, 1942 2,292,387

UNITED STATES PATENT OFFICE

2,292,387

SECRET COMMUNICATION SYSTEM

Hedy Kiesler Markey, Los Angeles, and George Antheil, Manhattan Beach, Calif.

Application June 10, 1941, Serial No. 397,412

6 Claims. (Cl. 250—2)

This invention relates broadly to secret communication systems involving the use of carrier waves of different frequencies, and is especially useful in the remote control of dirigible craft, such as torpedoes.

An object of the invention is to provide a method of secret communication which is relatively simple and reliable in operation, but at the same time is difficult to discover or decipher.

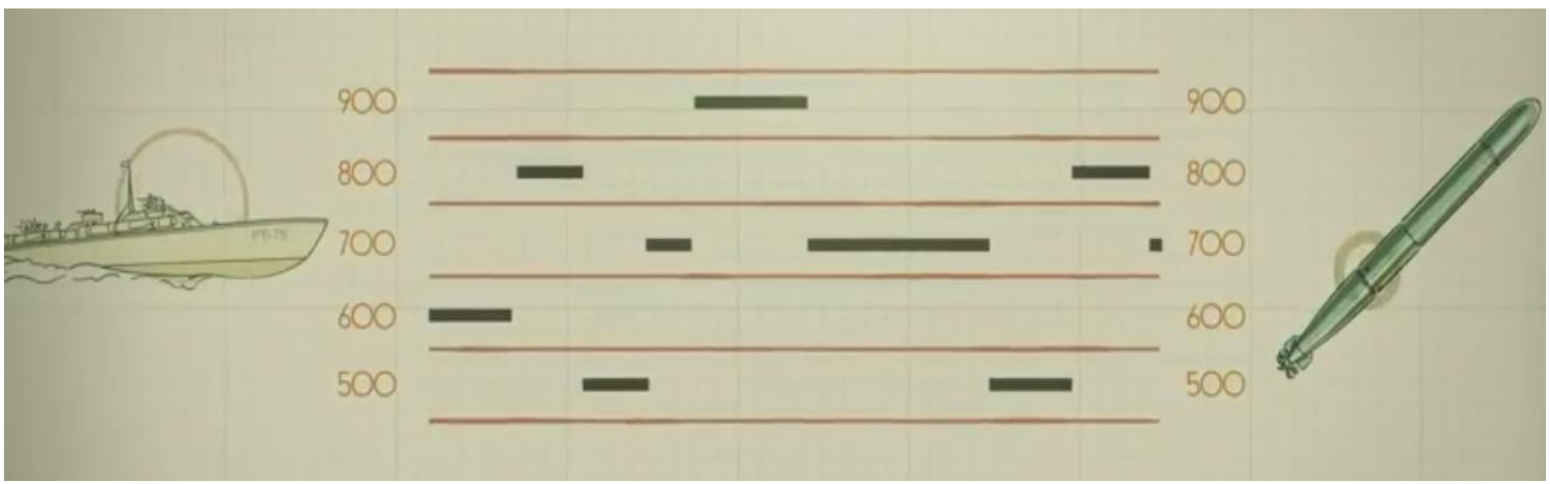
Briefly, our system as adapted for radio control

Fig. 2 is a schematic diagram of the apparatus at a receiving station;

Fig. 3 is a schematic diagram illustrating a starting circuit for starting the motors at the transmitting and receiving stations simultaneously;

Fig. 4 is a plan view of a section of a record strip that may be employed;

Fig. 5 is a detail cross section through a record-responsive switching mechanism employed in



Radio Transmission (1/2)

- **Radio signals:** Antenna transmits sinusoidal signal ("carrier") that radiates in air/space.
- Radio waves are easy to generate, can travel long distances, and can penetrate buildings easily.
- The properties of radio waves are frequency dependent:
  - Low frequencies: pass through obstacles well; power falls off sharply
  - High frequencies: travel in straight lines and bounce off obstacles; absorbed by rain.
- Multipath propagation causes fading.
- Interference from other users, motors, and other electrical equipments.
- Spectrum regulated by national & international regulatory organizations.

Radio Transmission (2/2)

- VLF, LF, and MF bands: Radio waves pass through buildings easily; low bandwidth.
- HF band: Ground waves are absorbed by the earth; refracted by the ionosphere and sent back to earth.

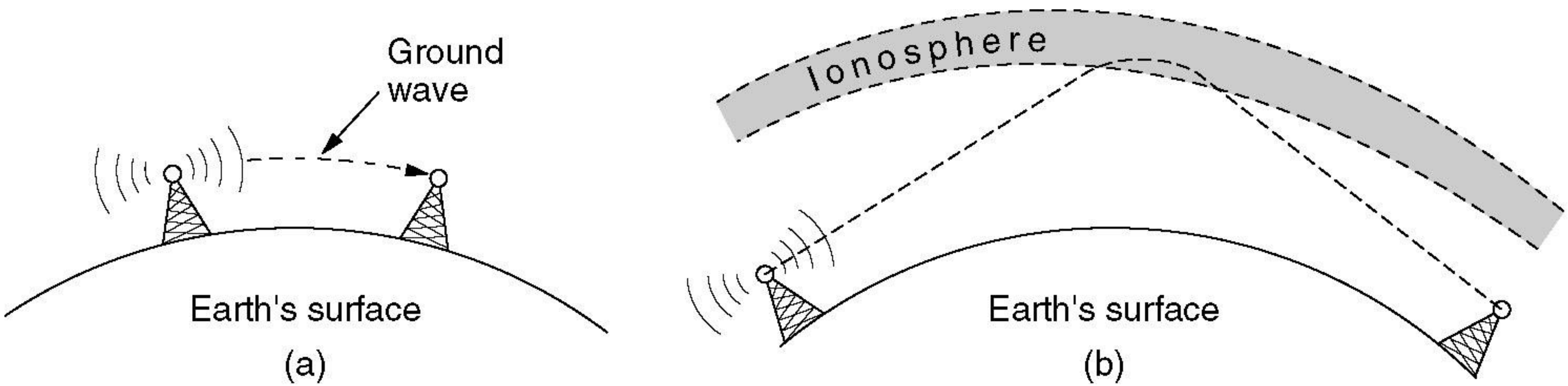


Fig. 2.33: (a) In the VLF, LF, and MF bands, radio waves follow the curvature of the earth. (b) In the HF band, they bounce off the ionosphere.

Politics of the Electromagnetic Spectrum

- ISM (industrial, scientific, medical) bands: unlicensed usage.
  - Let everyone transmit at will but regulate the power used so that stations have such a short range they do not interfere with each other.
  - All devices in the ISM bands use spread spectrum techniques in order to minimize interference.

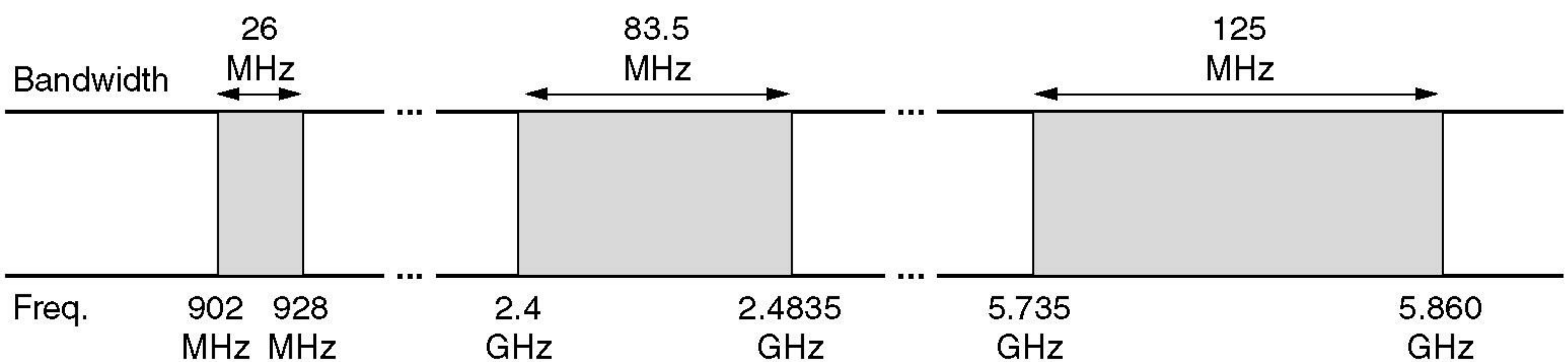


Fig. 2.34: The ISM bands in the United States.

Lightwave Transmission

- Connect LANs in two buildings via lasers mounted on their rooftops.
- High bandwidth, very low cost, easy to install.

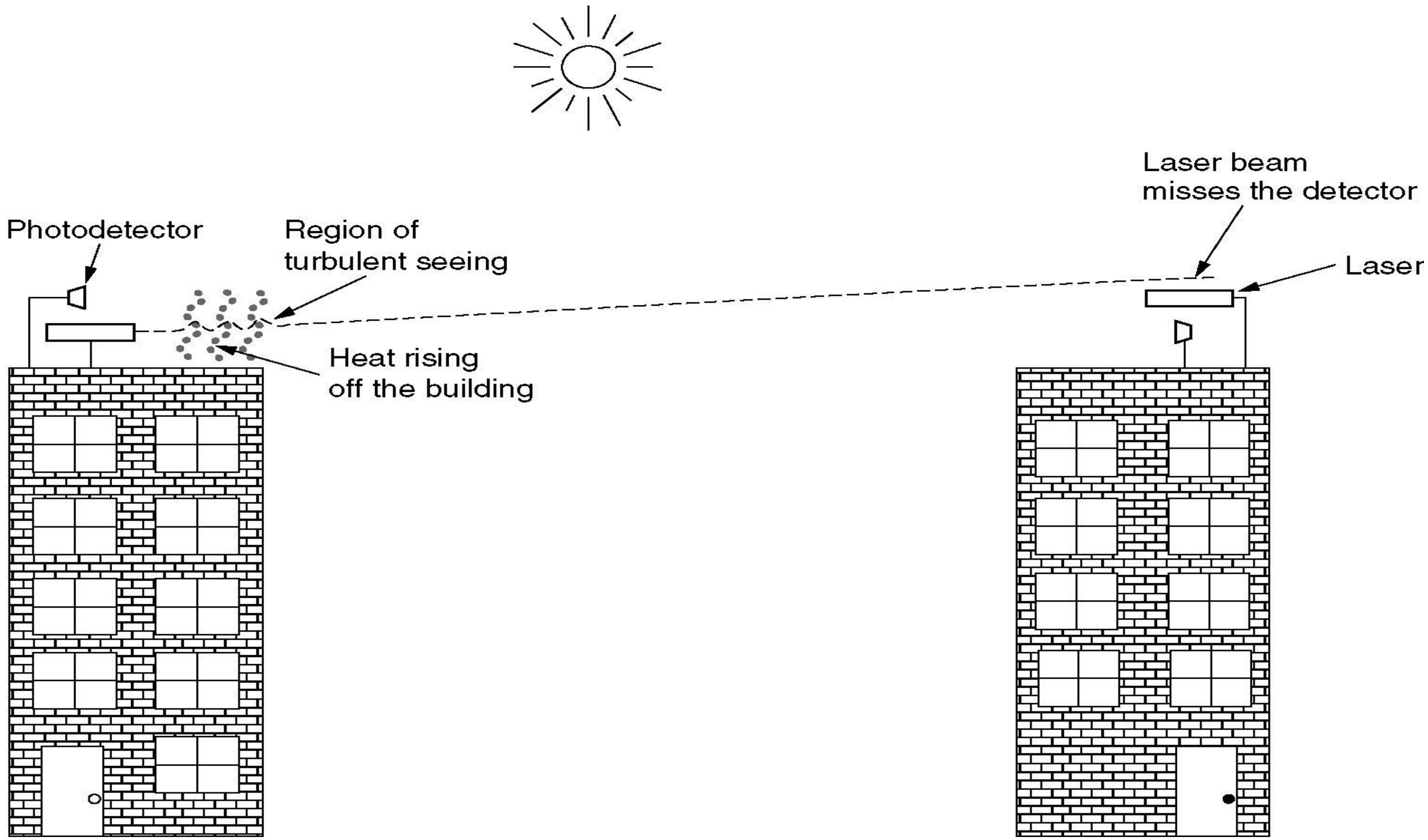


Fig. 2.35: Convection currents can interfere with laser communication systems.
A bidirectional system with two lasers is pictured here.

2.6.3 Communication Satellites

- Satellites are attractive because they provide a relatively simple model of communication: one signal up can be broadcast to many receivers downwards⇨bent pipe.
- Issues in determining where to place it:
  - **Orbital period**: The higher the satellite, the longer the period. Altitude of 35,800 km: 24 hours; Altitude of 384,000 km: one month.
  - **Van Allen belts/layers**: Avoid layers around the earth consisting of highly-charged particles that would destroy a satellite. These factors lead to three regions in which satellites can be placed safely, resulting in three types of satellites.

Three Types of Satellites

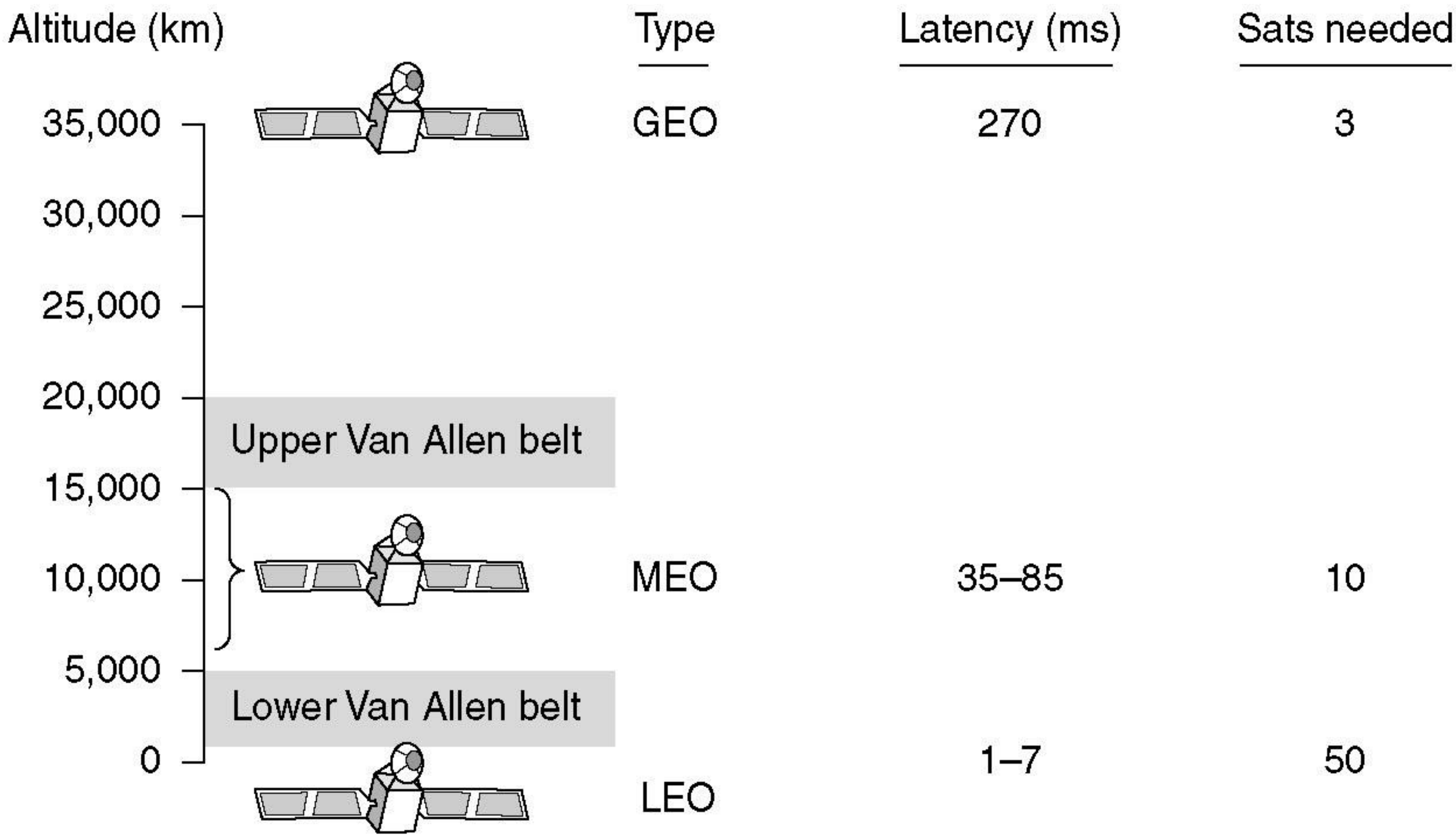


Fig. 2.36: Communication satellites and some of their properties, including altitude above the earth, round-trip delay time and number of satellites needed for global coverage.

Geostationary Earth Orbit (GEO) Satellites

- **Feature:** GEO satellites are placed at 35,800 km in a circular equatorial orbit above the earth where their rotational speed is the same as that of earth. The effect is that they appear to remain motionless in the sky. No need for tracking!
- **Very Small Aperture Terminals (VSATs):** simple systems that output (uplink) 1 Watt at 19.2 kbps but can download (downlink) 512 kbps or more. To allow the VSATs to communicate with each other, hubs (special ground stations) are used.

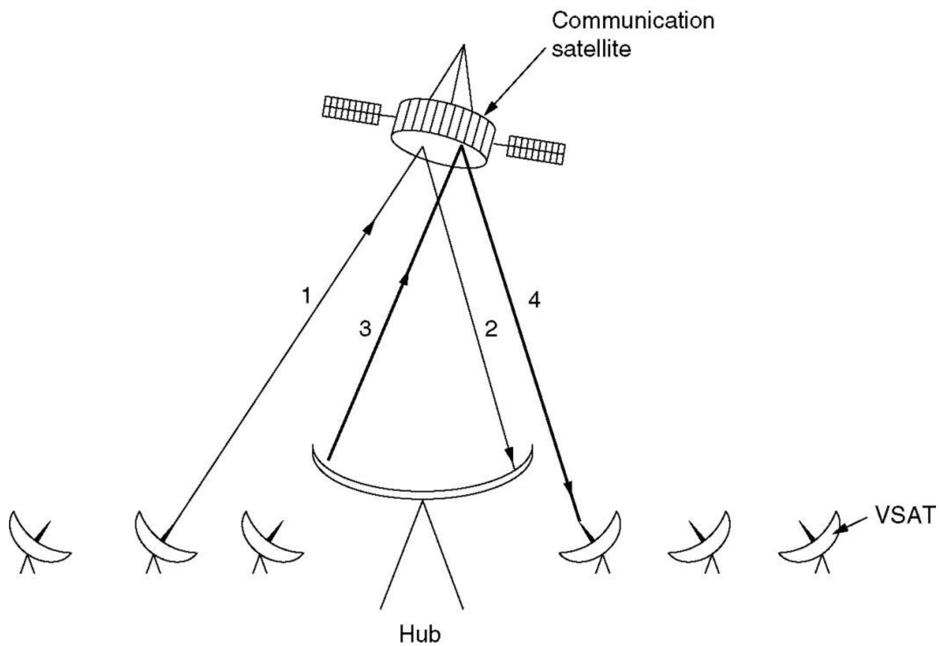


Fig. 2.37: VSATs using a hub.

Medium-Earth Orbit (MEO) Satellites

- Between the two Van Allen belts.
- It takes about 6 hours for MEO satellites to circle the earth. They must be tracked as they move through the sky.
- Since the MEOs are lower than the GEOs, they have a smaller footprint (covering the earth's surface) on the ground and require less powerful transmitters to reach them.
- They are not currently used for telecommunications.
- **Example:** The global Positioning System (GPS) orbit at 18,000 km.

Low-Earth Orbit (LEO) Satellites (1/2)

- **Features**: close to the earth; low transmit power needed; rapid motion; large numbers necessary for a complete system; small round-trip delay.
- Iridium satellites: 66 (6*11) satellites positioned at an altitude of 750 km, each having a maximum of 48 cells (i.e., spot beams), totaling 1628 cells.
- This approach is virtually the same as that of cellular radio, except that the cells are moving instead of the subjects.

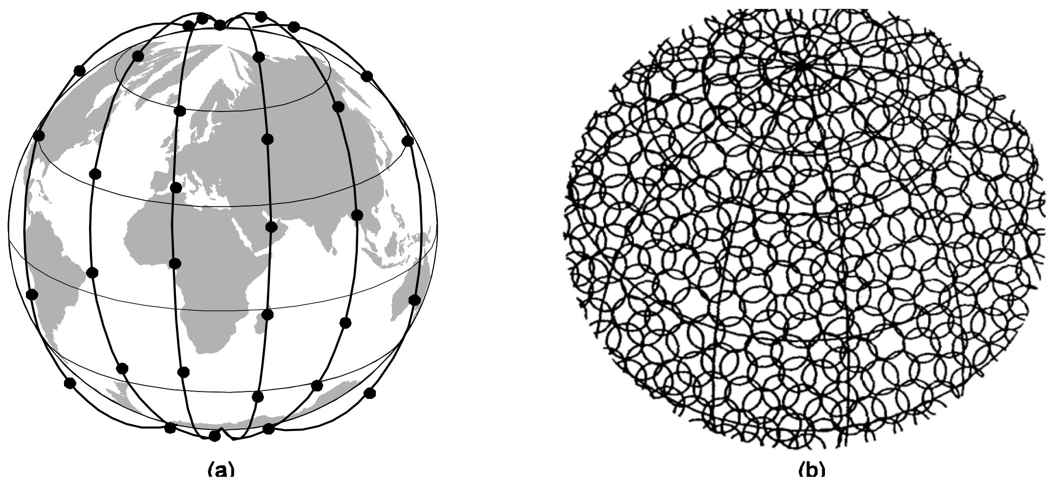


Fig. 2.38: (a) The Iridium satellites from six necklaces around the earth; (b) 1628 moving cells cover the earth.

Low-Earth Orbit (LEO) Satellites (2/2)

- **Iridium:** Communication takes place in space, with one satellite relaying data to the next one. Requires sophisticated switching equipment in the satellites.
- **Globalstar**: 48 satellites. 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. This schemem avoids much of the complexity for (managing) inter-satellite communication.

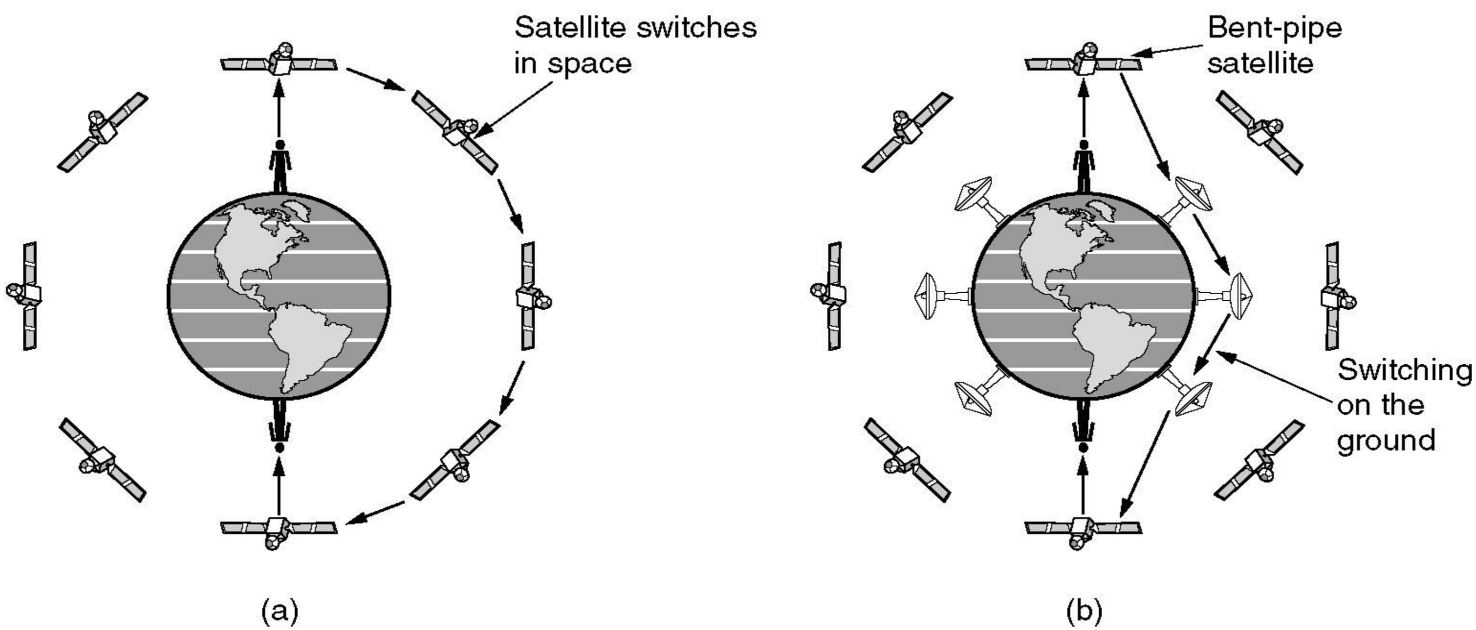


Fig. 2.39: (a) Relaying in space. (b) Relaying on the ground.

Satellites vs. Fiber

- **Bandwidth:** A single fiber has more potential bandwidth but not everyone has access to all the availble bandwidth. With satellites, it is practical for a single user to get high bandwidth.
- **Mobile communication:** Satellite links are of potential use. Although cellular radio+fiber may do just fine for most users, but probably not for those airborne or at sea.
- **Broadcasting:** It is much cheaper to use a satellite system.
- **Communication in hostile terrain:** Cheaper to use satellites!
- **Right of way:** Satellites can be used to cover areas where obtaining the right of way for laying fiber is difficult or unduly expensive.
- **Military communication systems**: Satellites win easily.

Telstar

- Telstar is the name of various communications satellites. The first two Telstar satellites were experimental and nearly identical. Telstar 1 launched on top of a Thor-Delta rocket on *July 10, 1962*. It successfully relayed through space the first television pictures, telephone calls, and telegraph images, and provided the first live transatlantic television feed. Telstar 2 launched May 7, 1963. Telstar 1 and 2—though no longer functional—still orbit the Earth.

Manufacturer	Bell Labs
Launch mass	171 kilograms
Regime	Medium Earth orbit

(https://en.wikipedia.org/wiki/Telstar)

2.7 The Public Switched Telephone Network

- When there are many computers or the cables have to pass through a public road or other public right of way, the network designers must rely on the existing telecommunication facilities, such as the PSTN.

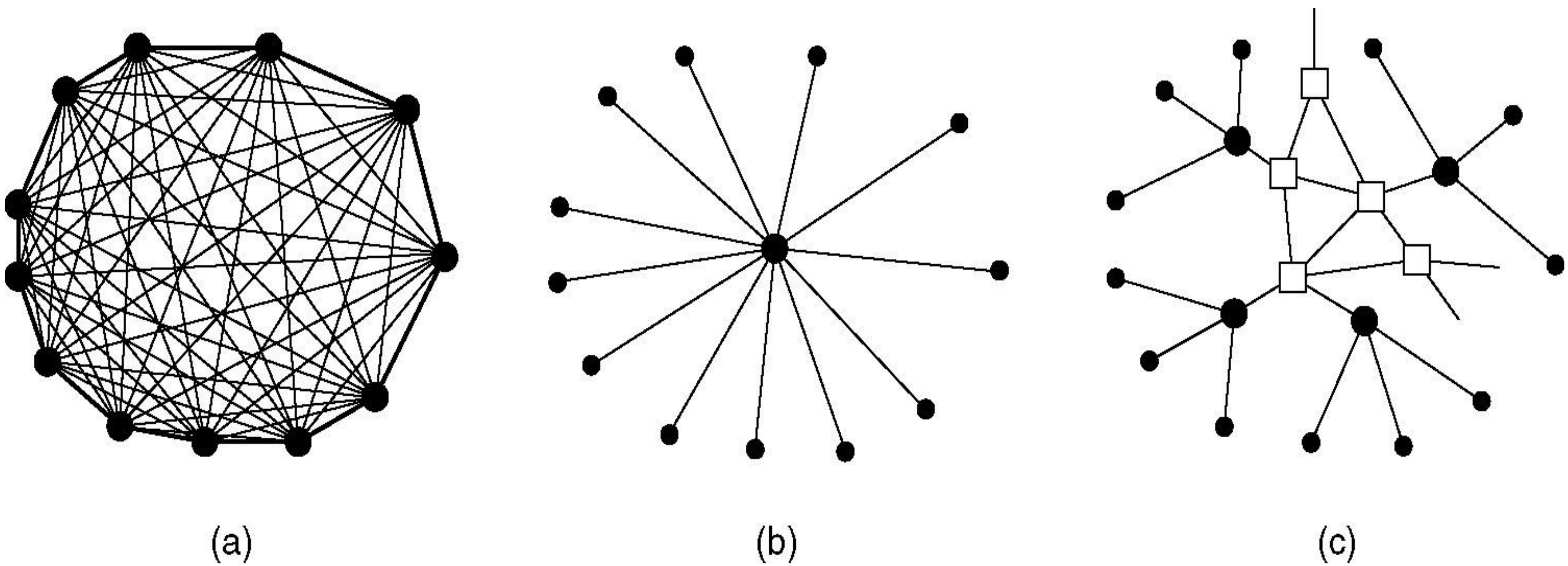


Fig. 2.40: Structure of the telephone system. (a) Fully-interconnected network. (b) Centralized switch. (c) Two-level hierarchy.

An Example of a Medium-Distance Connection

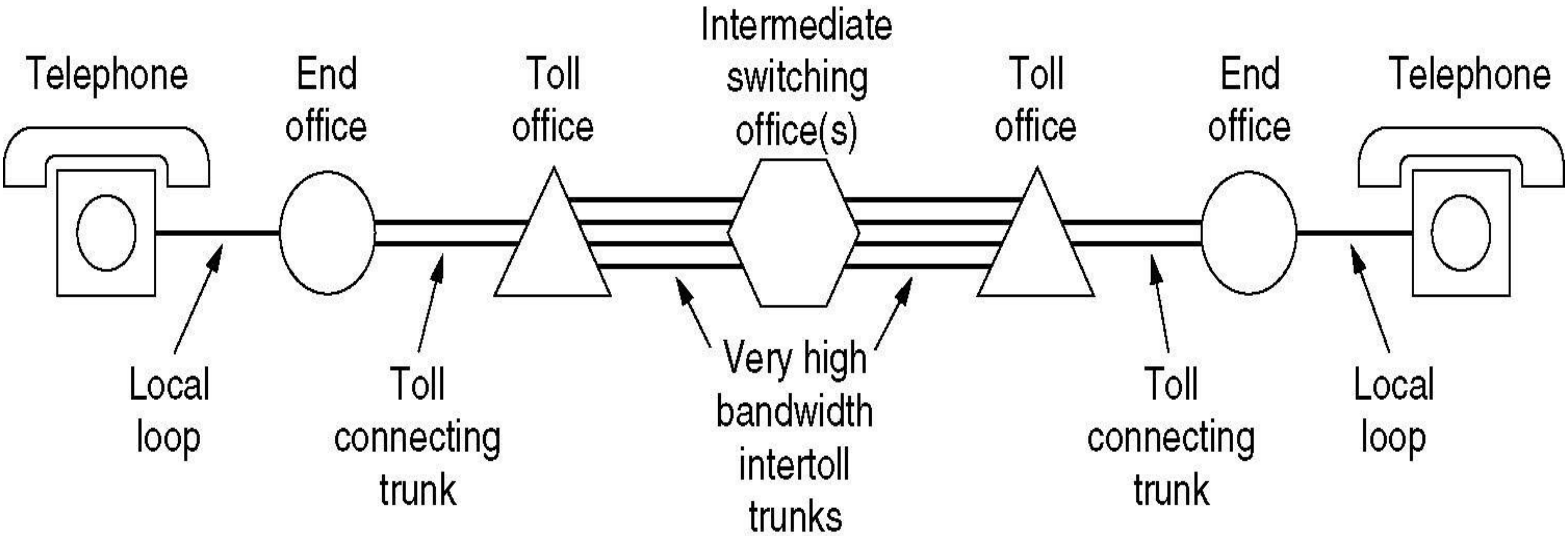


Fig. 2.41: A typical circuit route for a medium-distance call.

Three Major Components of the Telephone System

- **Local loops**: analog twisted pairs between each subscriber's telephone and the end office.
  - Weakest link in the system. Provide everyone access to the whole system.
- **Trunks**: digital fiber optics connecting the switching offices.
  - Multiplexing: how to collect multiple calls together and send them out over the same fiber.
- **Switching offices**: where calls are moved from one trunk to another.
  - Switching

The Local Loop

- The local loop is also frequently referred to as the ”last mile”.
- Digital data must first be converted to analog form for transmission over the local loop by a modem.

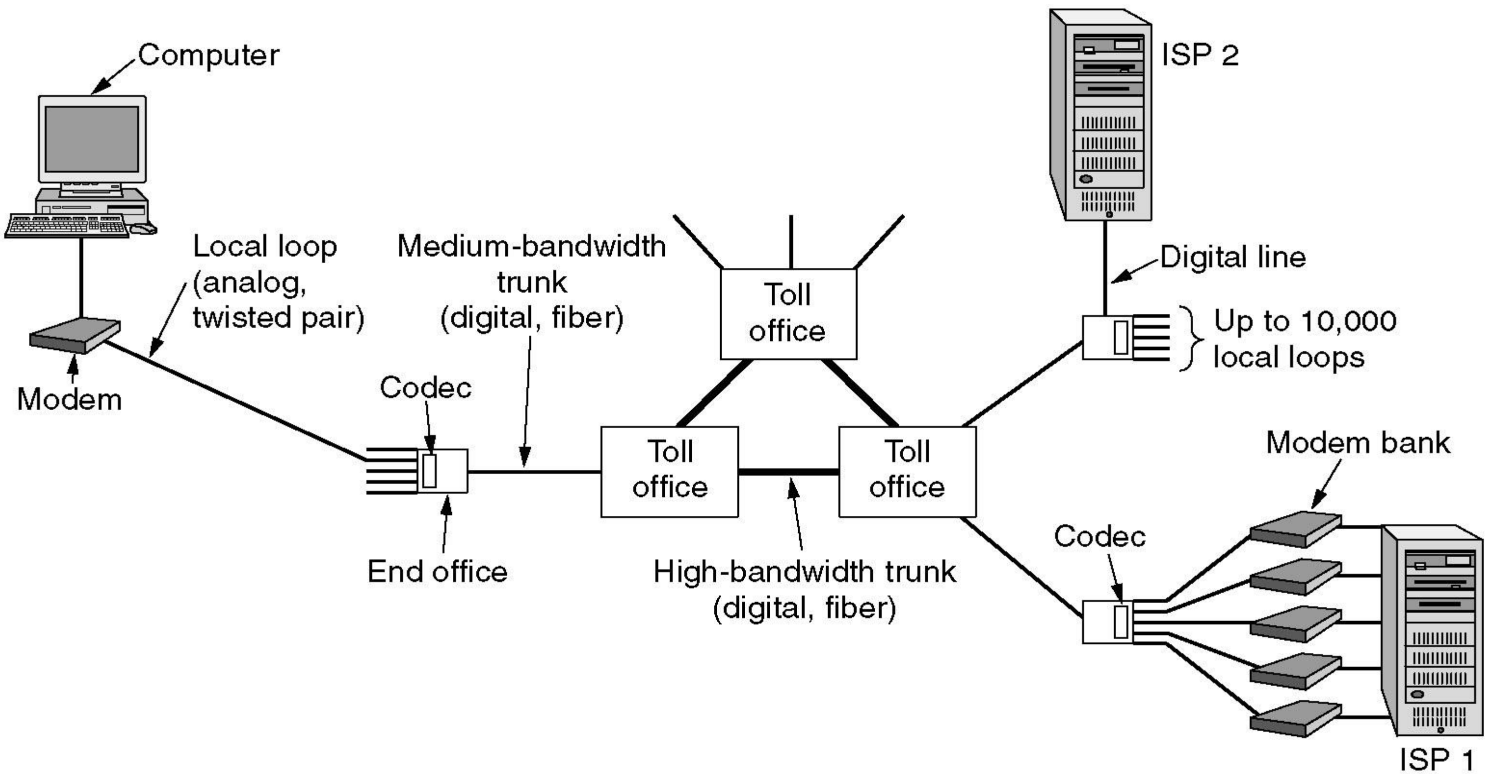


Fig. 2.42: The use of both analog and digital transmissions for a computer to computer call. Conversion is done by the modems and codecs.

Modem

- Attenuation and delay distortion are frequency dependent, which makes undesirable to have a wide range of frequencies in the signal. The square waves used in digital signals have a wide frequency spectrum. ⇨Apply modulation techniques.
- Modem (modulator-demodulator): a device that accepts a serial stream of bits as input and produces a carrier modulated by one of the following methods (or vice versa).
    - Amplitude modulation: Two different amplitudes are used to represent 0 and 1.
    - Frequency modulation (frequency shift keying): Use two different frequencies to encode your bits.
    - Phase modulation: Change the phase of the wave (eg. sine and cosine) to do signal encoding.

Three Modulation Methods

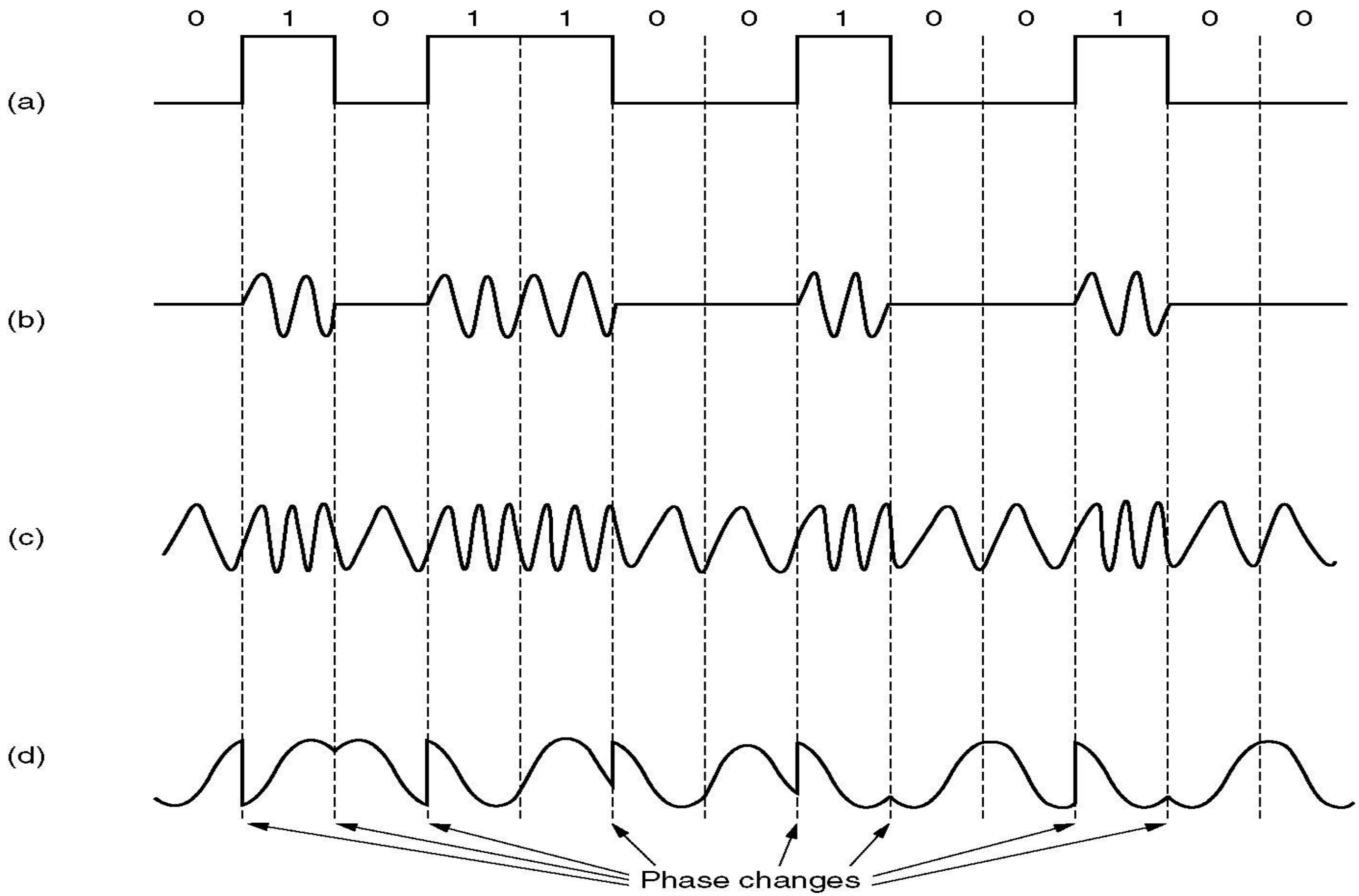


Fig. 2.43: (a) A binary signal. (b) Amplitude modulation. (c) Frequency modulation. (d) Phase modulation.

Constellation Diagrams

- The legal combinations of amplitude and phase are called constellation disgrams.
- The **baud rate** (sampling rate): the number of samples/sec; the same as **symbol rate**.
- The modulation technique determines the number of bits/symbol.
- The **bit rate**=the number of symbols/sec * the number of bits/symbol.

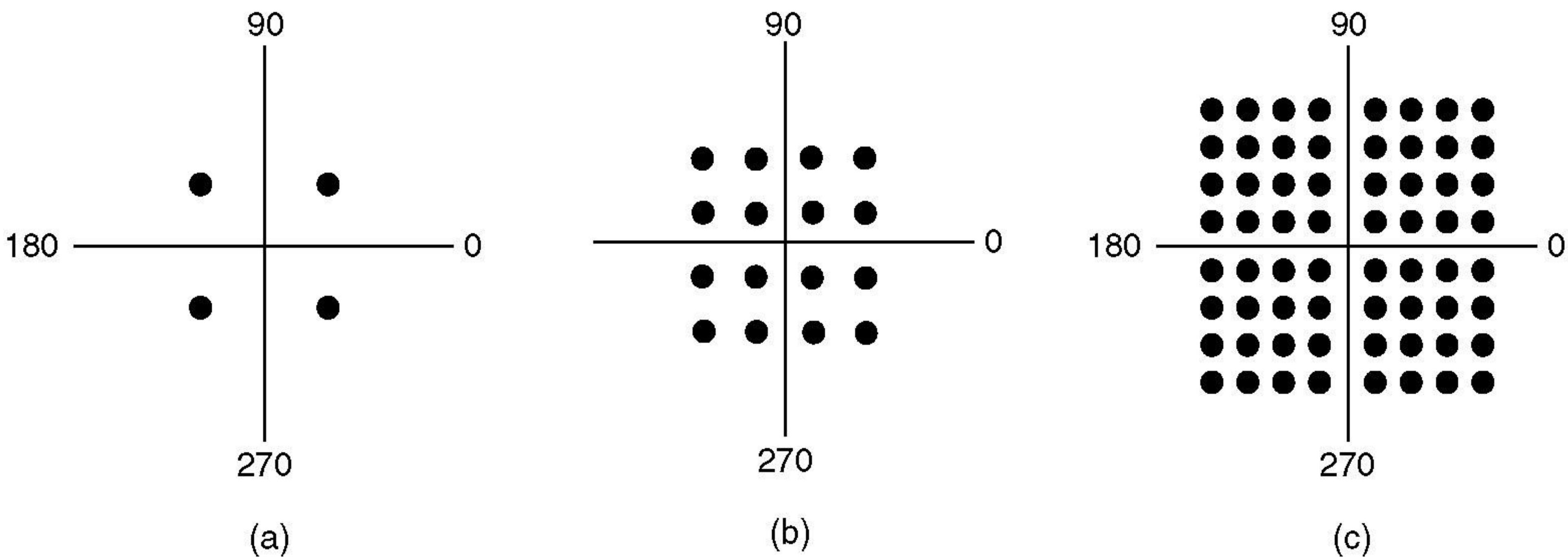


Fig. 2.44: (a) QPSK; (b) QAM-16; (c) QAM-64.

Traffic Directions

- **Full duplex:** a connection that allows traffic in both directions simultaneously (by using different frequencies for different directions).
- **Half duplex:** a connection that allows traffic either way, but only one way at a time.
- **Simplex:** a connection that allows traffic only one way.

Trunks and Multiplexing

- It costs essentially the same to install and maintain a high-bandwidth trunk as a low-bandwidth trunk between two switching offices.

- Telephone companies have developed elaborate schemes for **multiplexing** many conversations over a single physical **trunk**.

- **Multiplexing:** carry many conversations over a single physical trunk.

  - **Frequency division multiplexing (FDM):** The frequency spectrum is divided into non-overlapping frequency bands, with each user having exclusive possession of some band.

  - **Time division multiplexing (TDM):** The users take turns, each one periodically getting the entire bandwidth for a little burst of time.

Switching

- From a telephone engineer's view, the phone system is divided into two parts:
  - Outside plant: the local loops and trunks, physically outside the switching offices.
  - Inside plant: the switches which are inside the switching offices.
- **Circuit switching:** Making a true physical connection from sender to receiver. This is what happens in traditional telephone systems. Once a call has been set up, a dedicated path between both ends exists and will continue to exist until the call is finished.
- **Message switching**: Store-and-forward switching – a message is completely received at a router, stored, and then put into an outgoing queue for further routing. Not used any more!
- **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. No dedicated path needs to be set up in advance.

⇨ Computer networks are usually packet switched, occasionally circuit switched, but never message switched.

Circuit Switching vs. Packet Switching

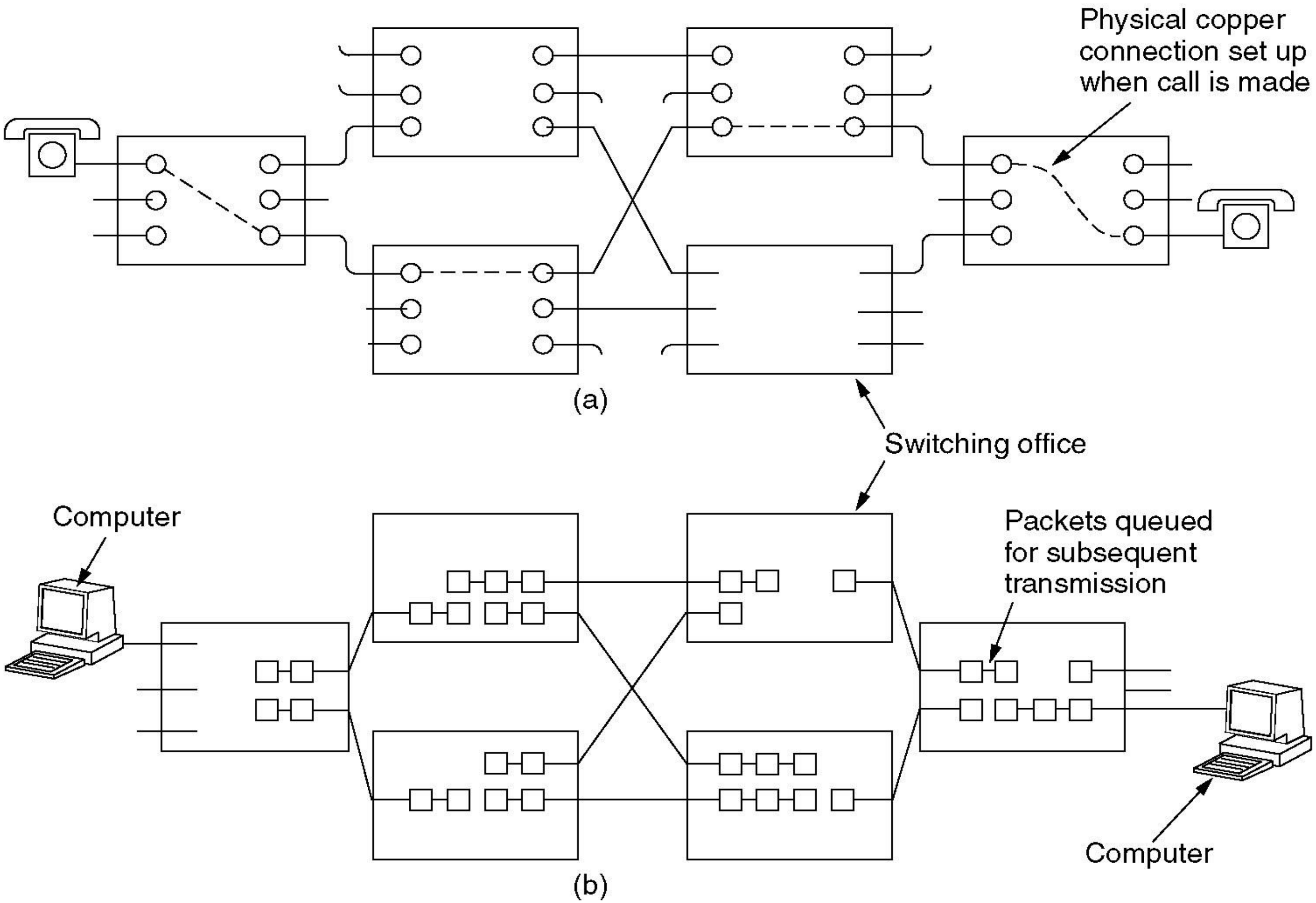


Fig. 2.45: (a) Circuit switching; (b) Packet switching.

Circuit Switching, Message Switching, Packet Switching

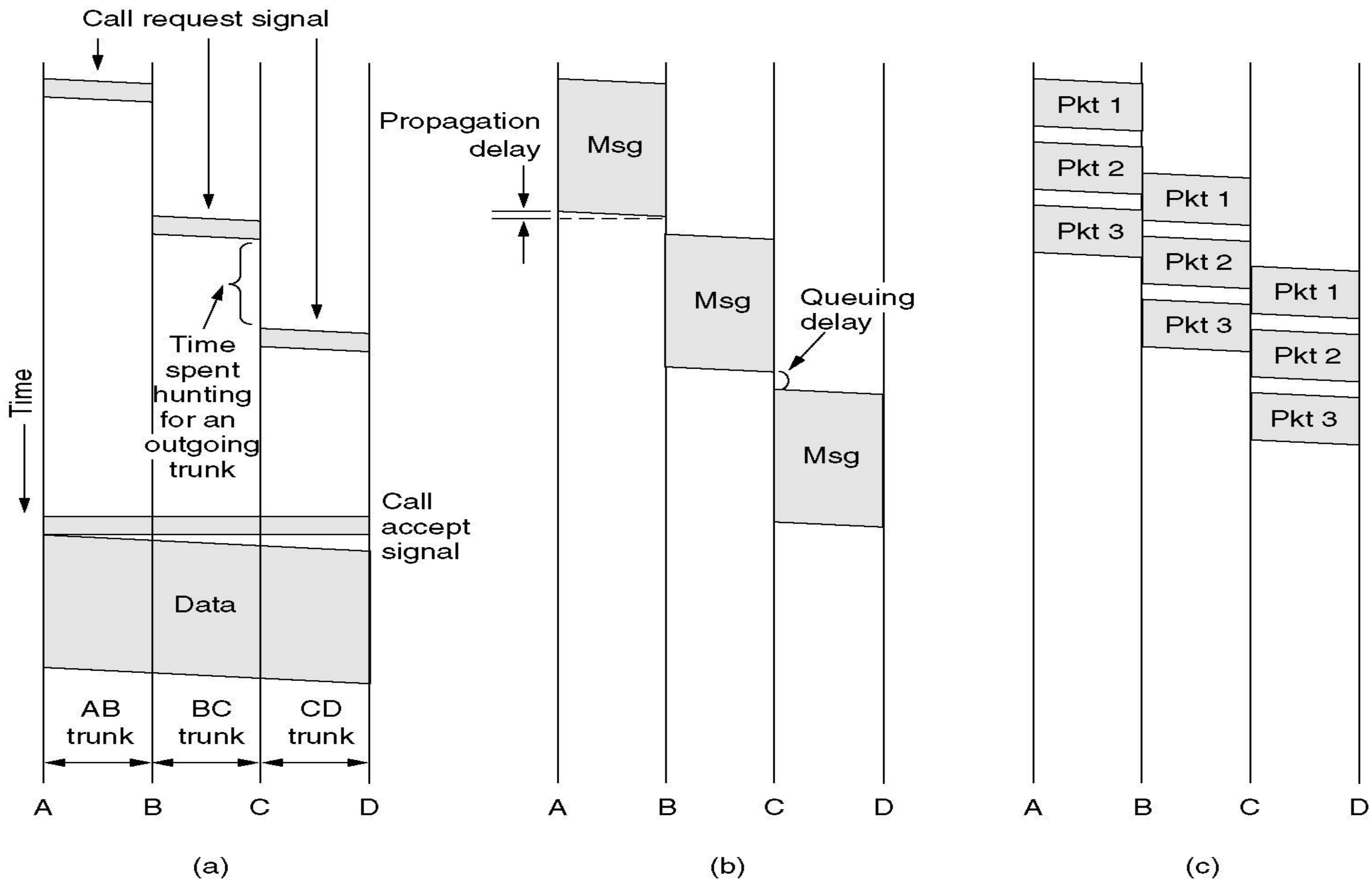


Fig. 2. 46: Timing of events in (a) circuit switching, (b) message switching, (c) Packet switching.

Circuit-Switched Networks vs. Packet-Switched Networks

Item	Circuit-switched	Packet-switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
Is a switch crash fatal	Yes	No
Bandwidth available	Fixed	Dynamic
When can congestion occur	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

2.8 The Mobile Telephone System

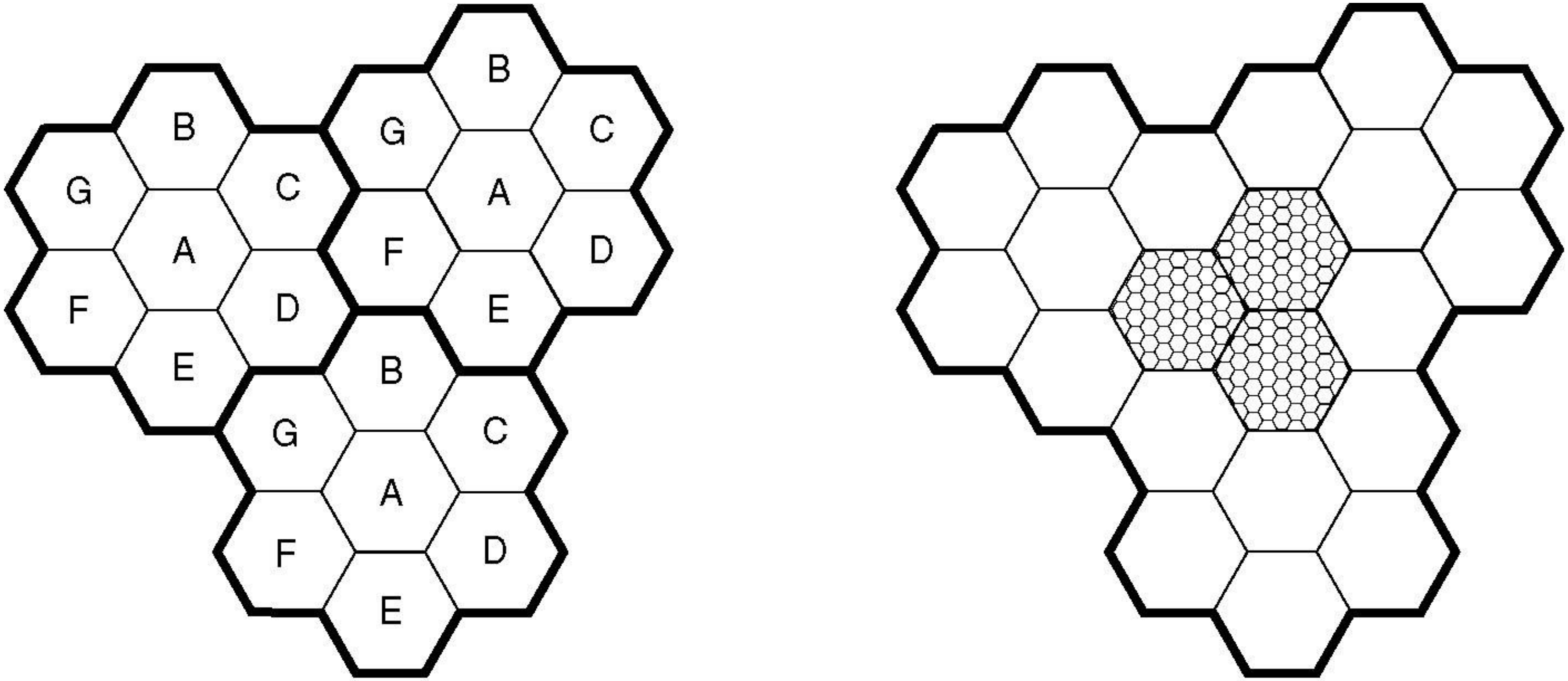
- Three distinct generations, with different technologies:
  - First-generation mobile phones: analog voice
    - Frequency division multiple access (FDMA)
  - Second-generation mobile phones: digital voice
    - F/TDMA or F/CDMA
  - Third-generation mobile phones: digital voice and data (Internet, e-mail, etc.)
    - CDMA or T/S/CDMA

2.8.1 First-Generation Mobile Phones: Analog Voice

- Advanced Mobile Phone System (AMPS)
  - First installed in the USA in 1982; Called TACS (total access communicaiton system) in Europe and MCS-L1 (mobile control station-version 1) in Japan.
- **Cells:** Divide a geographic region into small cells, each having their own frequency range. No two adjacent cells have the same frequency.
  - At the center of each cell is a base station (with highly-located antenna).
  - Some base stations are connected to a Mobile Switching Center (MSC).
  - The cellular design increases the system capacity thanks to the frequency reuse.
  - Smaller cells⇨less power⇨smaller and cheaper transmitters and handsets.
- **Handoff:** When a mobile moves from a cell to another, the current BS then transfers ownership to another. A new channel will be assigned to the mobile. Channel assignment is done by the MSC. BSs are radio relays.

Frequency Resue

- Adjacent cells do not use the same frequency for good separation and low interference.
- The overloaded cells are split into smaller microcells to permit more frequency resue.



(a) (b)

Fig. 2.47: (a) Frequencies are not reused in adjacent cells. (b) To add more users, smaller cells can be used.

Channel Categories

- The AMPS uses 832 full-duplex channels.
  - 832 simplex uplink channels (mobile to base) from 824 to 849 MHz.
  - 832 simplex downlink channels (base to mobile) from 869 to 894 MHz.
  - Each of these simplex channels is 30 kHz wide.
- The 832 channels are divided into four categories:
  - Control (base to mobile) to manage the system.
  - Paging (base to mobile) to alert users to calls for them.
  - Access (bidirectional) for call setup and channel assignment.
  - Data (bidirectional) for voice, fax, or data.

2.8.2 Second-Generation Mobile Phones: Digital Voice

- Four systems in use: D-AMPS, GSM, CDMA, and PDC.
- D-AMPS: co-exist with AMPS; an additional new frequency band: 1850-1910 MHz (upstream), 1930-1990 MHz (downstream).
  - Each frequency pair supports 25 frames/sec of 40 msec each; Each frame is divided into 6 time slots of 6.67 msec each.

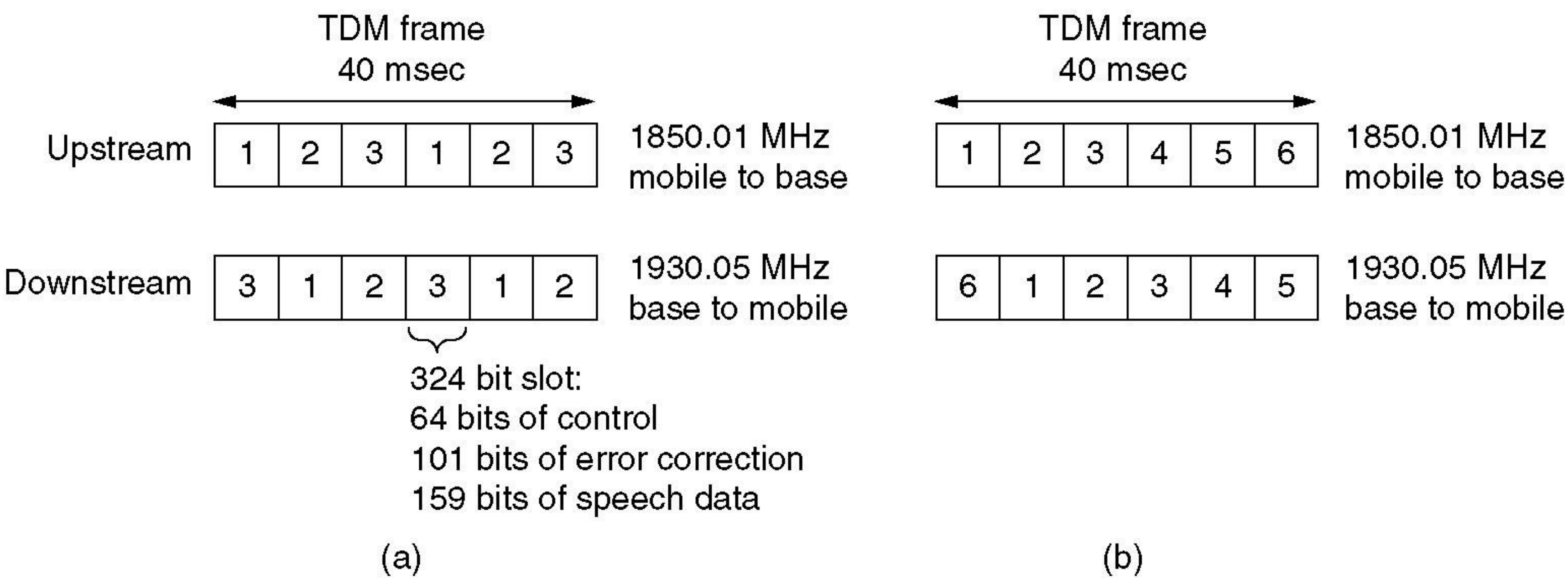


Fig. 2.48: (a) A D-AMPS channel with three users. (b) A D-AMPS channel with six users.

GSM-The Global System for Mobile Communications

- 200 kHz for each channel bandwidth; 124 pairs of simplex channels; Each channel supports 8 separate connections (8 time slots) using TDM.

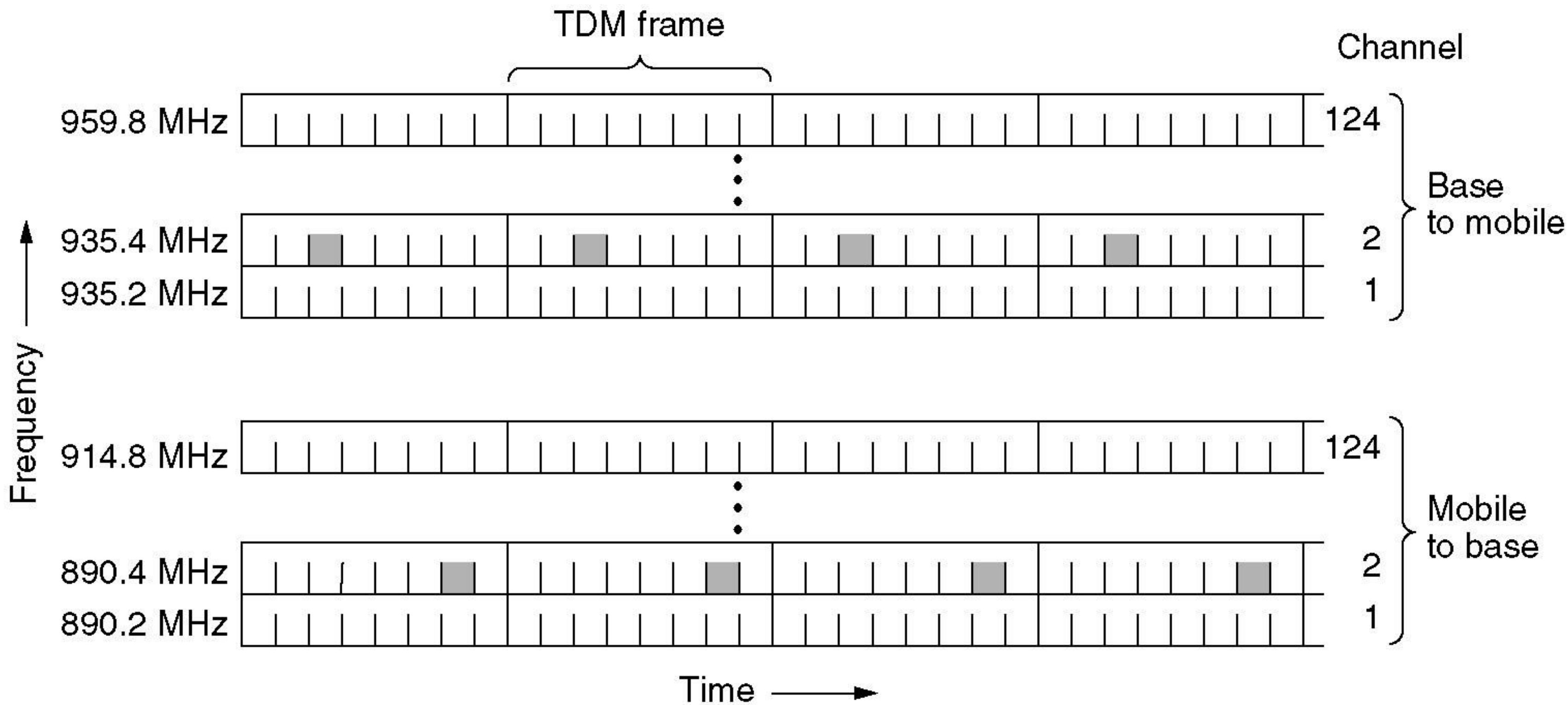


Fig. 2.49: GSM uses 124 frequency channels, each of which uses an eight-slot TDM system

Framing Structure of GSM

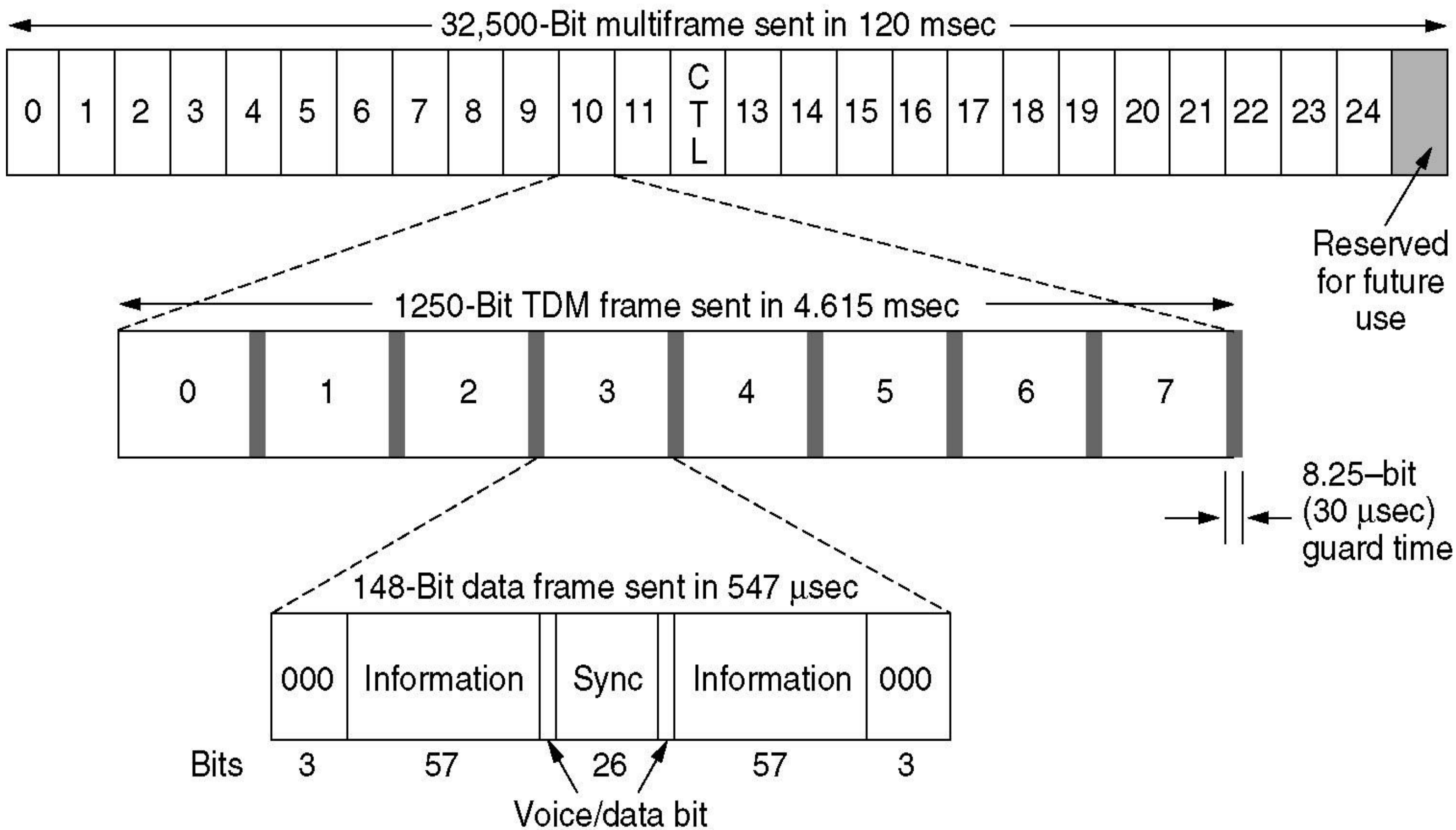


Fig. 2.50: A portion of the GSM framing structure.

CDMA-Code Division Multiple Access

- Allows each station to transmit over the entire frequency spectrum all the time.
- Multiple simultaneous transmissions are separated using coding theory.
- The key to CDMA is to be able to extract the desired signal while rejecting everything else as random noise.
- Principle:
  - Each bit time is subdivided into *m* short intervals called **chips**.
  - Each station is assigned a unique m-bit code called a **chip sequence**.
  - Make sure that all chip sequences are pairwise orthogonal (normalized inner product is 0).
  - During each bit time, each station can transmit a 1 (chip sequence) or 0 (negative chip sequence) or nothing.
  - When two or more stations transmit simultaneously, their **bipolar signals** (0 as -1; 1 as +1) add linearly.
  - To recover the bit stream of an individual station, the receiver must know that station's chip sequence in advance. It does the recovery by computing the normalized inner product of the received chip sequence (the linear sum of all the stations that transmitted) and the chip sequence of the station whose bit stream it is trying to recover.

CDMA Example

A: 0 0 0 1 1 0 1 1
B: 0 0 1 0 1 1 1 0
C: 0 1 0 1 1 1 0 0
D: 0 1 0 0 0 0 1 0

(a)

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)

(b)

Six examples:

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

Fig. 2.51: (a) Binary chip sequences for four stations. (b) Bipolar chip sequences. (c) Six examples of transmissions. (d) Recovery of station C’s signal.

2.8.3 Third-Generation Mobile Phones: Digital Voice and Data

- Basic services an IMT-2000 network is supposed to provide:
  - High-quality voice transmission.
  - Messaging (e-mail, fax, SMS, chat, etc.).
  - Multimedia (music, videos, films, TV, etc.).
  - Internet access (web surfing, including pages with audio and video).
- Three Standards:
  - W-CDMA (wideband CDMA): Europe, also called UMTS (universal mobile telecommunications system)
  - CDMA2000: USA
  - TD-SCDMA: China
- 2.5G: EDGE (Enhanced Data Rates for GSM Evolution) and GPRS (General Packet Radio Service).
- Beyond 3G or 4G: high bandwidth, ubiquity, high QoS for multimedia, etc.

2.9 Cable Television

- Evolution: Community Antenna Television→HFC (Hybrid Fiber Coax).
- HFC system (Internet over cable): a system with fiber for the long-haul runs and coaxial cable to the houses; head-end (amplifier), switch, fiber, fiber node (optical-electronic converter), coaxial cable.

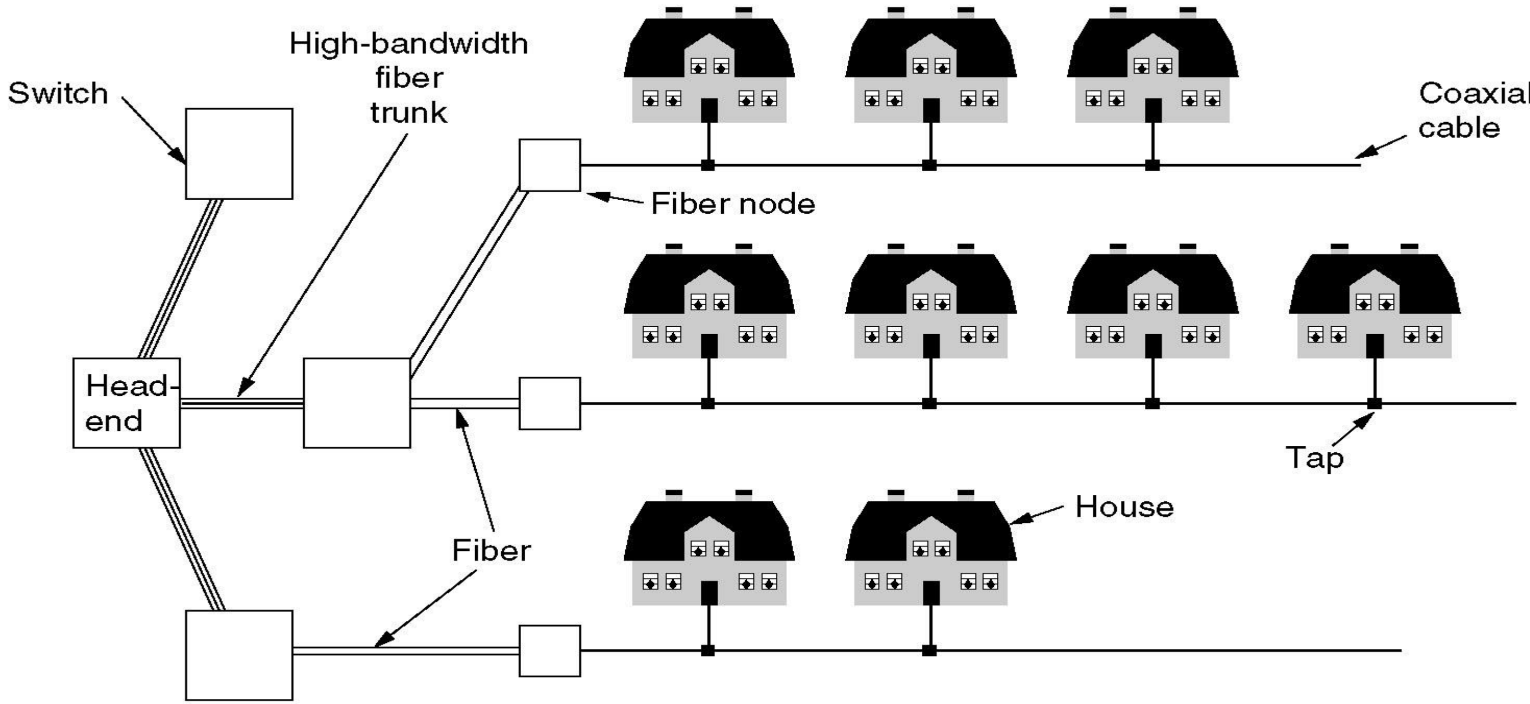


Fig. 2.52: HFC cable television system.

Internet over Cable vs. Internet over Telephone

- HFC system: Coax has much higher bandwidth than twisted pairs, but a single cable is shared by many houses.
  - For TV broadcasting, no matter of the users. For Internet access, the number of users matters a lot. The more users, the more competition for bandwidth.
- Fixed telephone system: every house has its own private local loop.

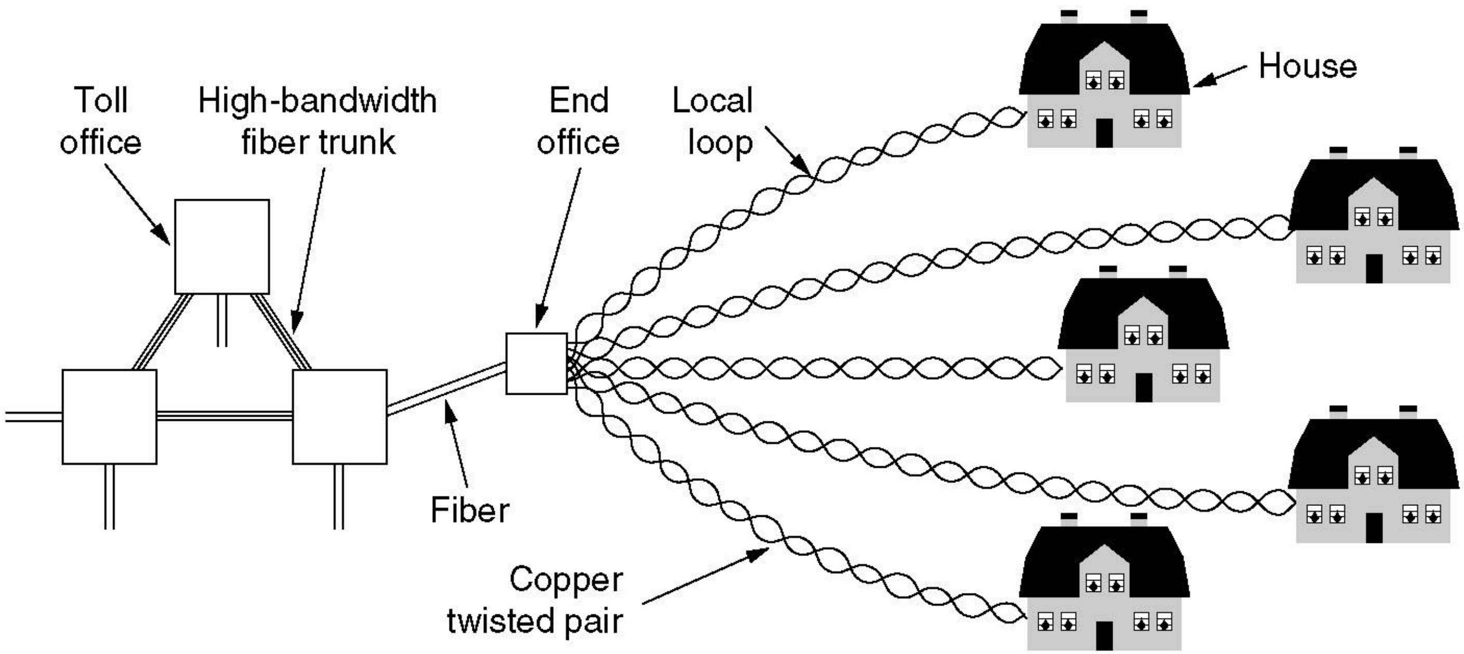


Fig. 2.53: The fixed telephone system.