# CHAPTER 2 THE PHYSICAL LAYER (物理层)

- **The Theoretical Basis for Data Communication**

- **Guided Transmission Media**
- **Wireless Transmission**

- **Digital Modulation and Multiplexing**
  - **OFDM**

- **The Public Switched Telephone Network (Stationary)**
- Communication Satellites (Celestial 天体的) *
- The Mobile Telephone System (Mobile) *
- Cable Television (Stationary)*

# THE THEORETICAL BASIS FOR DATA COMMUNICATION (数据通信的基本理论)

- Fourier analysis (傅立叶分析)
- Bandwidth-limited signals (有限带宽信号)
- Maximum data rate of a channel (信道的最大数据传送速率)

# Jean Baptiste Joseph Fourier (1768-1830)

- Had crazy idea (1807):
- **Any** periodic function can be rewritten as a weighted sum of Sines and Cosines of different frequencies.
- Don’t believe it?
  - Neither did Lagrange, Laplace, Poisson and other big wigs
  - Not translated into English until 1878!
- But it’s true!
  - called Fourier Series
  - Possibly **the greatest tool** used in Engineering

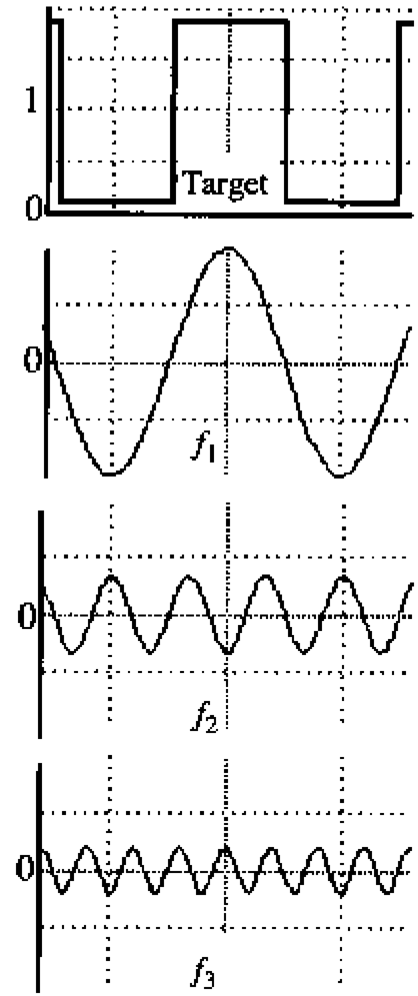

Credit: S. Narasimhan, CMU

# A Sum of Sinusoids

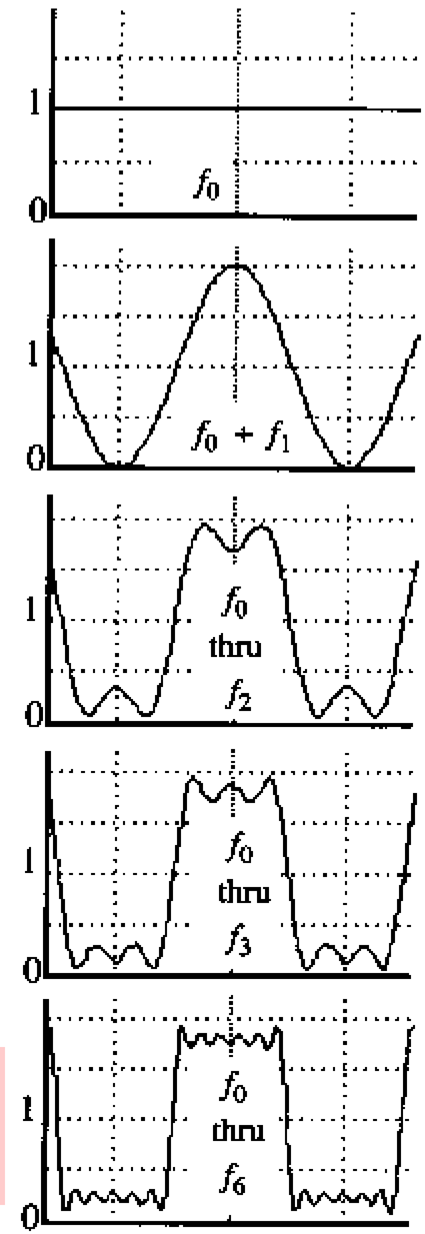
- Our building block:

$$A\sin(\omega x + \phi)$$

- Add enough of them to get any signal *f(x)* you want!
- How many degrees of freedom?
- What does each control?
- Which one encodes the coarse vs. fine structure of the signal?




f(target)=
$f_1 + f_2 + f_3 ... + f_n + ...$



# Fourier Transform

- We want to understand the frequency $\omega$ of our signal. So, let's reparametrize the signal by $\omega$ instead of $x$:

$$f(x) \longrightarrow \boxed{\text{Fourier Transform}} \longrightarrow F(\omega)$$

- For every $\omega$ from 0 to inf, $F(\omega)$ holds the amplitude $A$ and phase $\phi$ of the corresponding sine $A\sin(\omega x + \phi)$
  - How can $F$ hold both? Complex number trick!

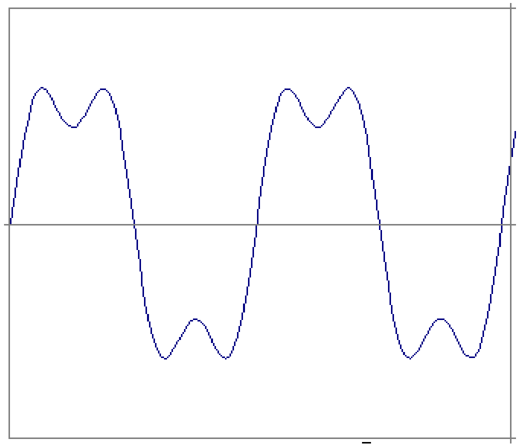
$$F(\omega) = R(\omega) + iI(\omega)$$

$$A = \pm\sqrt{R(\omega)^2 + I(\omega)^2} \qquad \phi = \tan^{-1}\frac{I(\omega)}{R(\omega)}$$

$$F(\omega) \longrightarrow \boxed{\text{Inverse Fourier Transform}} \longrightarrow f(x)$$

# Time and Frequency

- example : $g(t) = \sin(2pi\ f\ t) + (1/3)\sin(2pi\ (3f)\ t)$



# Time and Frequency

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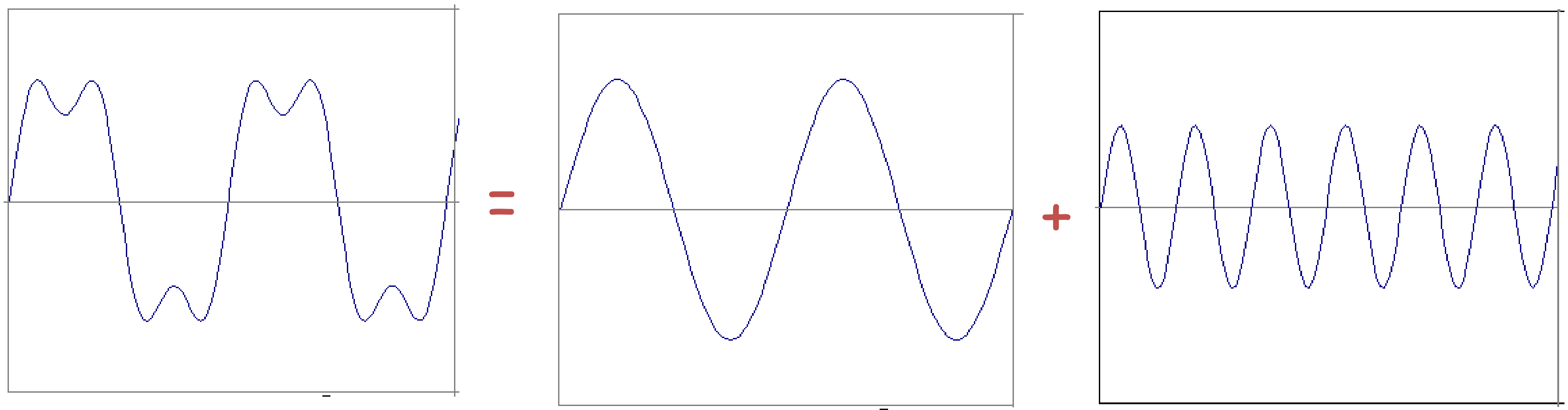

# Frequency Spectra

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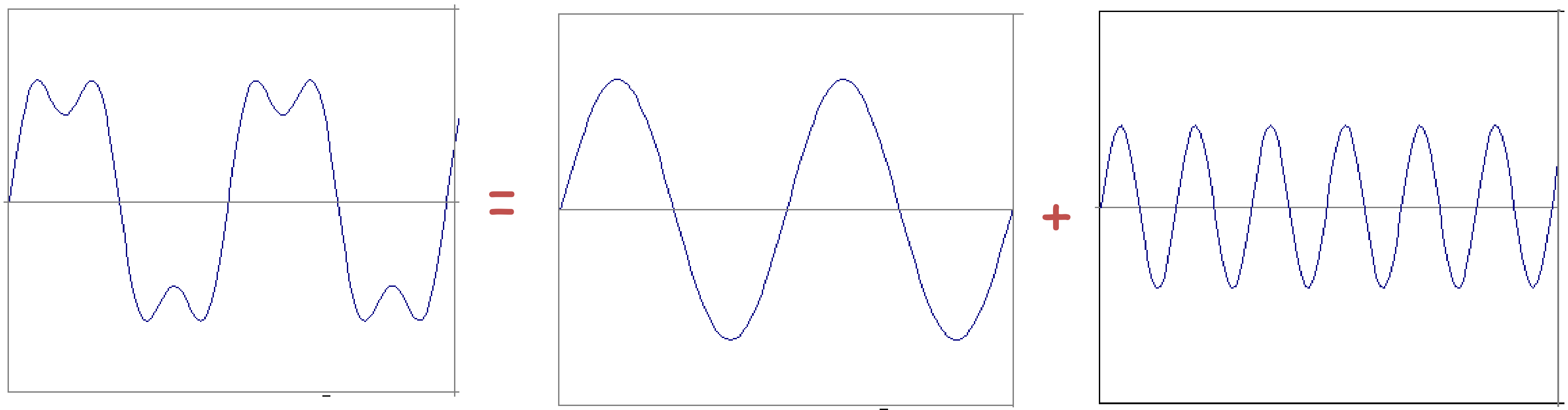
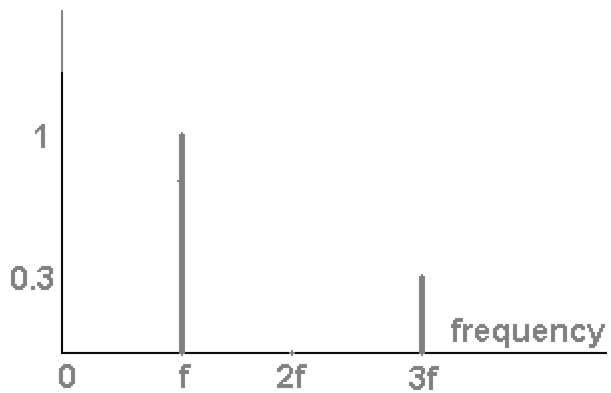
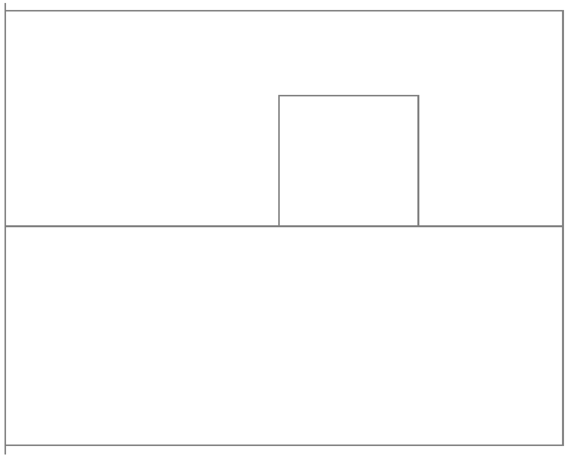


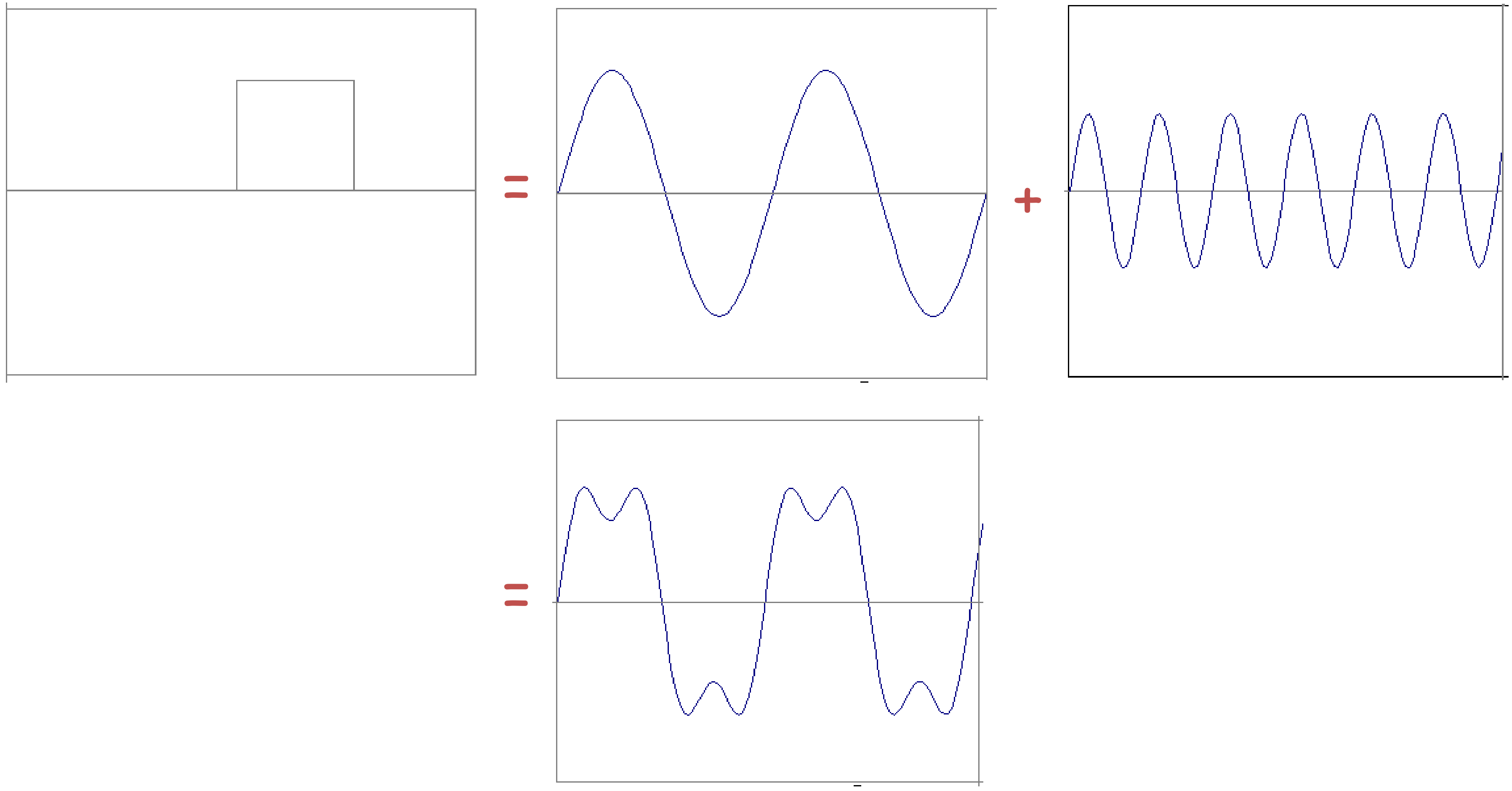


# Frequency Spectra

- Usually, frequency is more interesting than the phase



# Frequency Spectra



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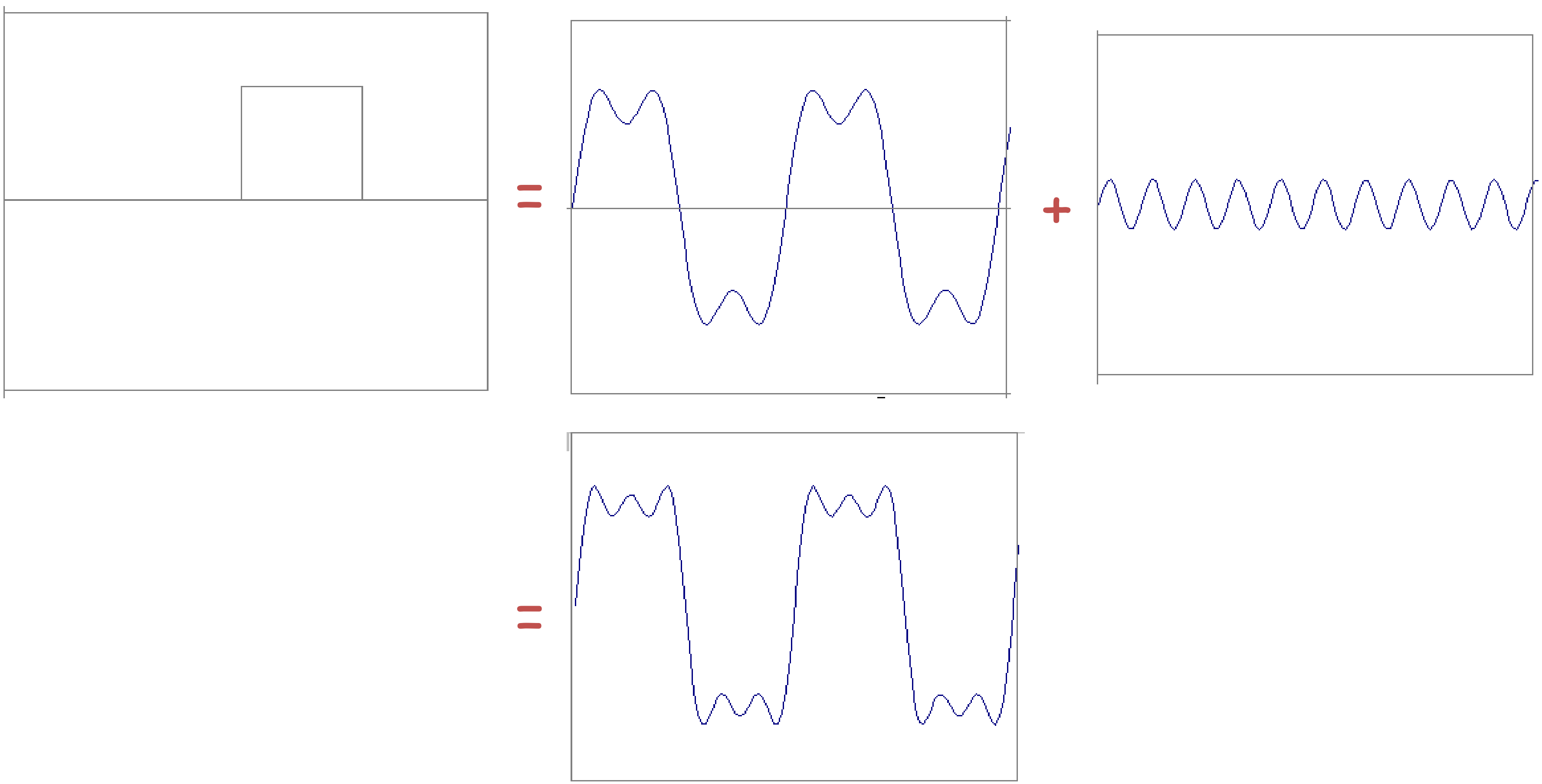

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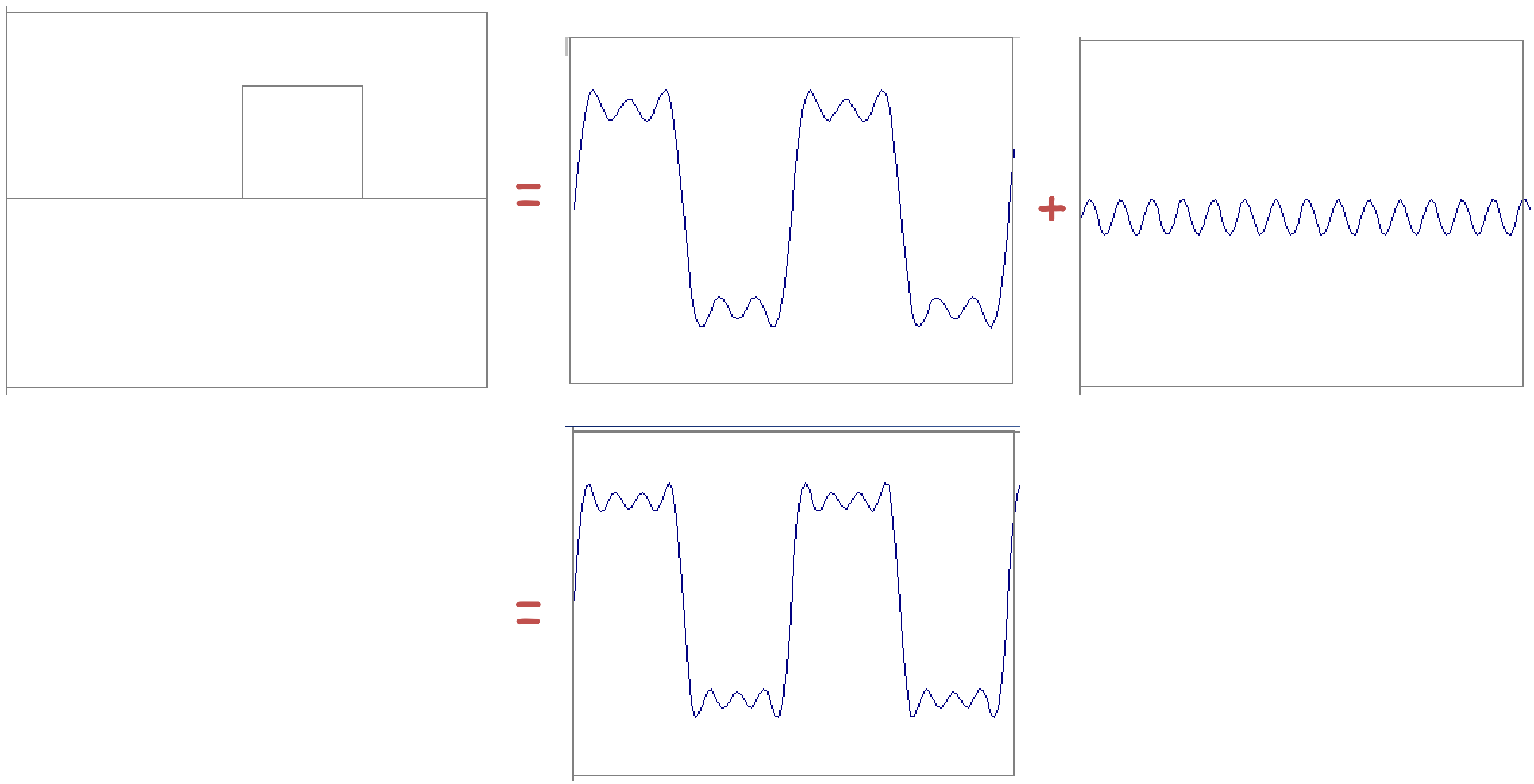

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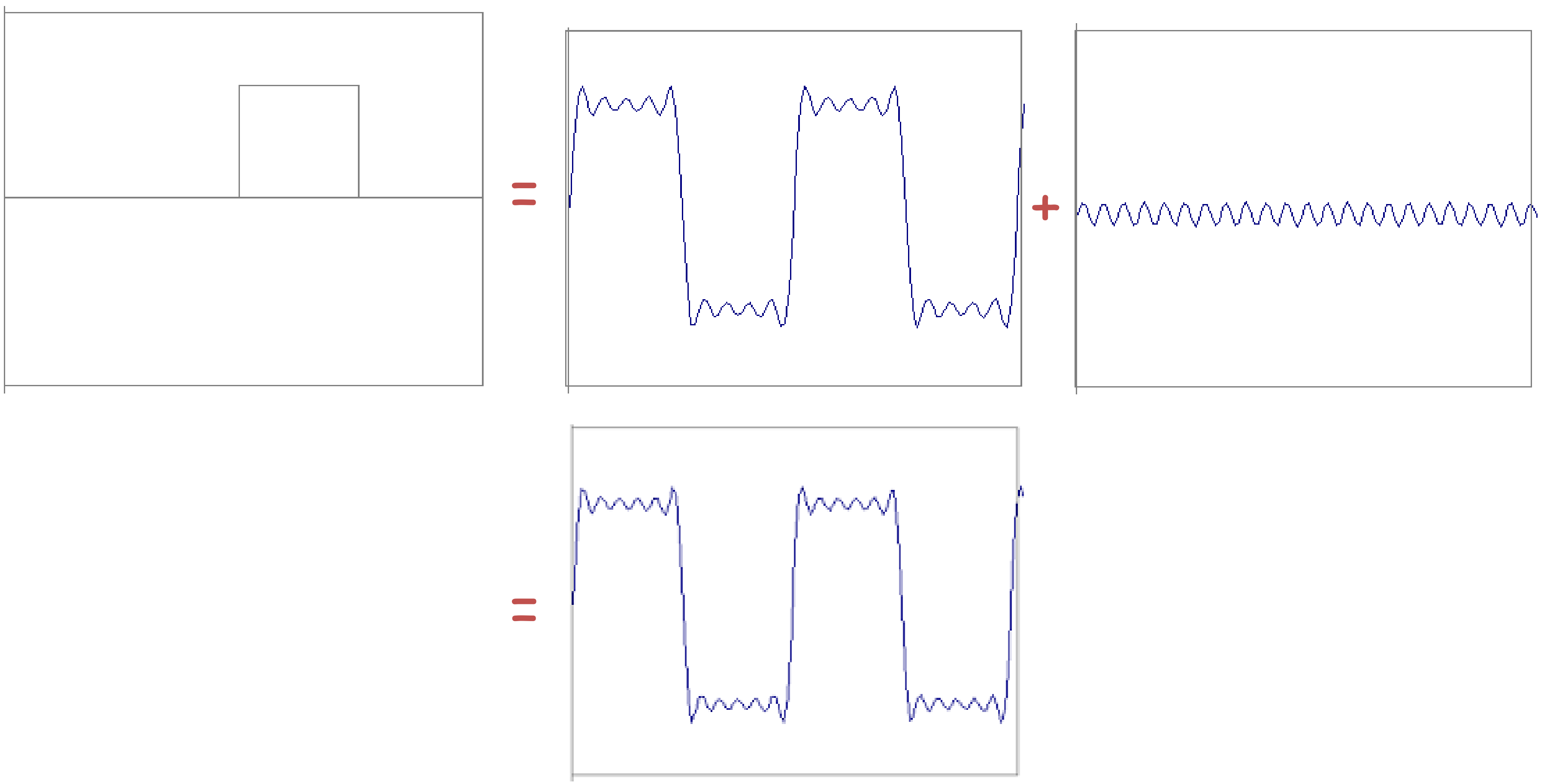

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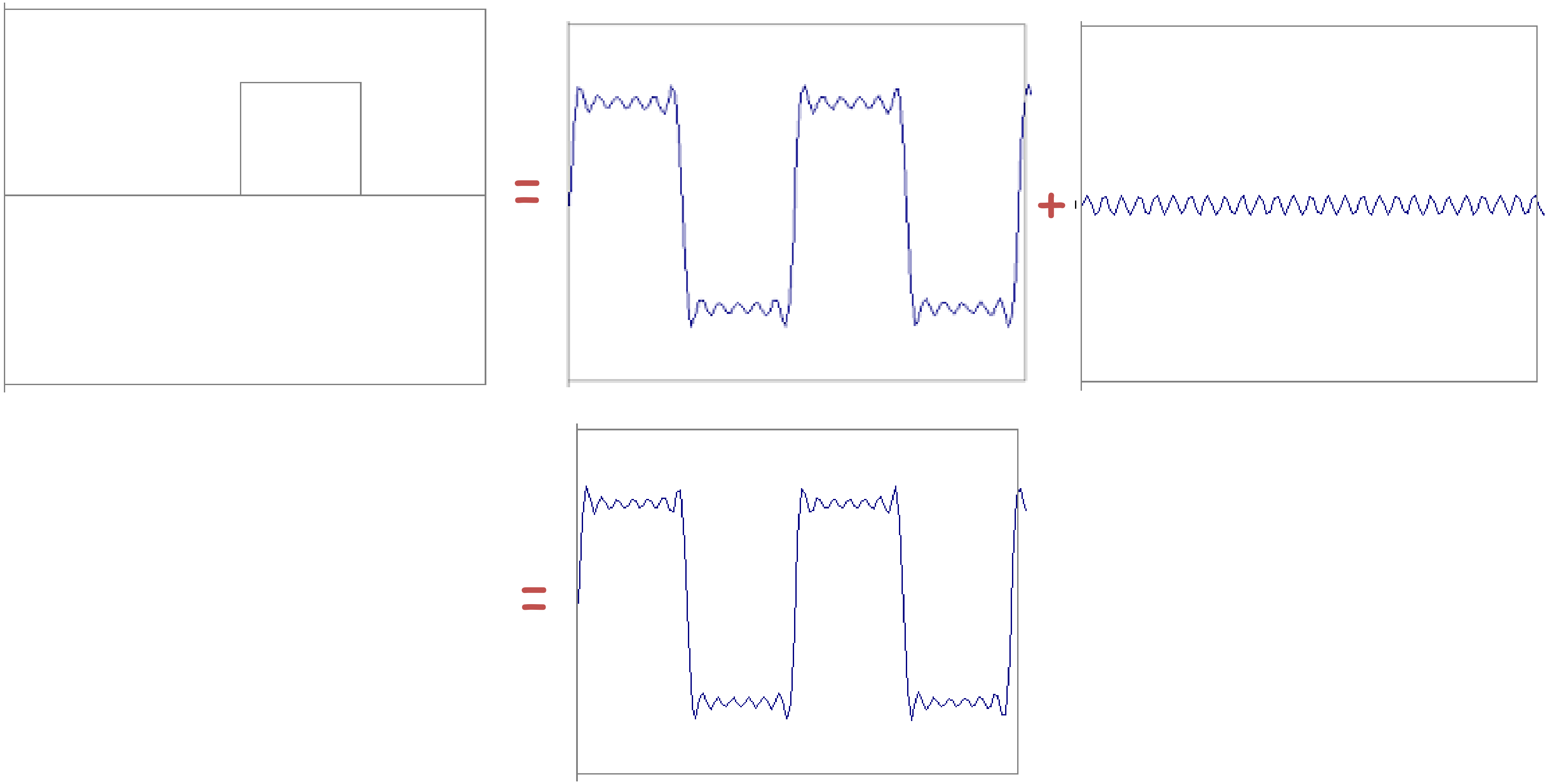

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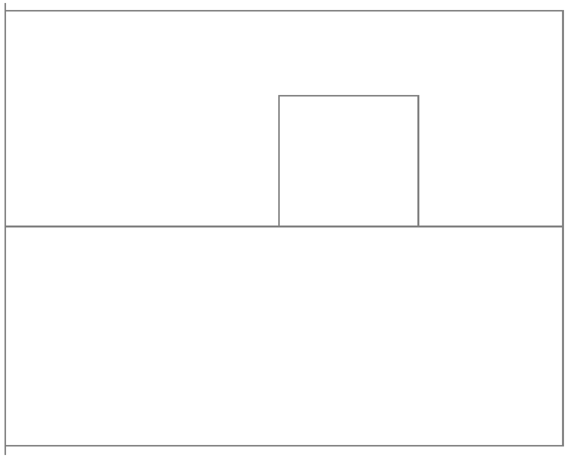
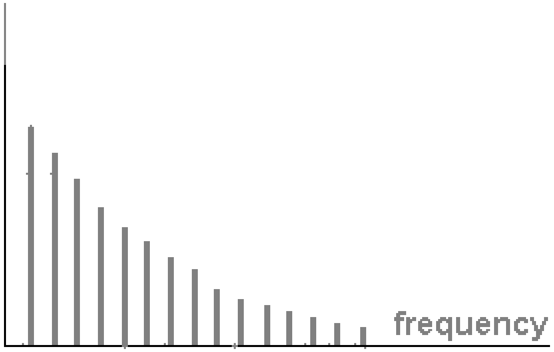


$$= \boxed{A\sum_{k=1}^{\infty}\frac{1}{k}\sin(2\pi kt)}$$



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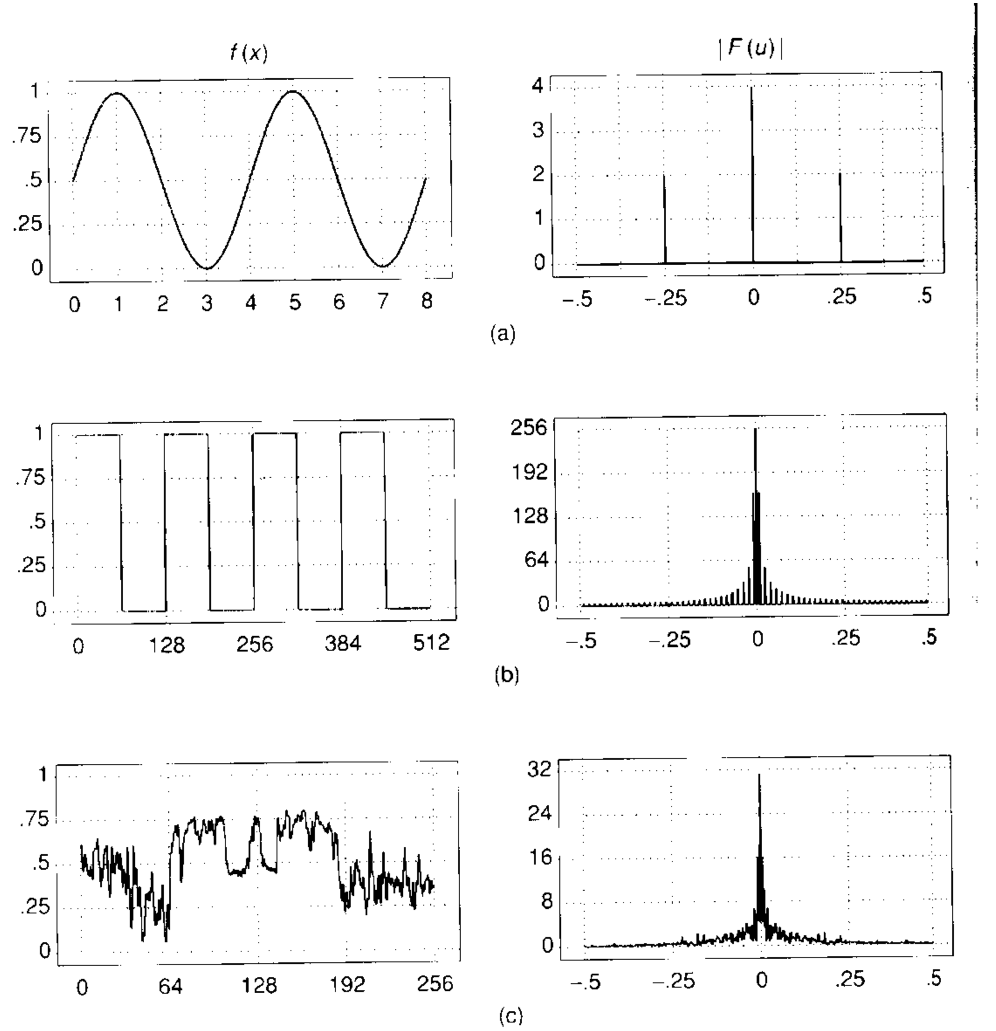

# The Theoretical Basis For Data Communication: Fourier Analysis

- We model the variation of voltage or current with mathematical function
- Any reasonably behaved periodic function g(t) with period T, can be constructed as the sum of a (possibly infinite) number of sines and cosines

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

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

- A data signal that has a finite duration (which all of them do) can be handled by just imagining that it repeats the entire pattern over and over forever.

# The Theoretical Basis For Data Communication

- Bandwidth-Limited Signals
  - Input → System (transmission, filtering) → output
  - Bandwidth (带宽) for systems
    - The range of frequencies transmitted without being strongly attenuated
    - The cutoff frequency is not really sharp, is defined as the frequency at which half the power gets through.
  - Any signal (bandwidth-limited or unlimited) (input)

    → system (filtering)

    → bandwidth-limited signal (output)

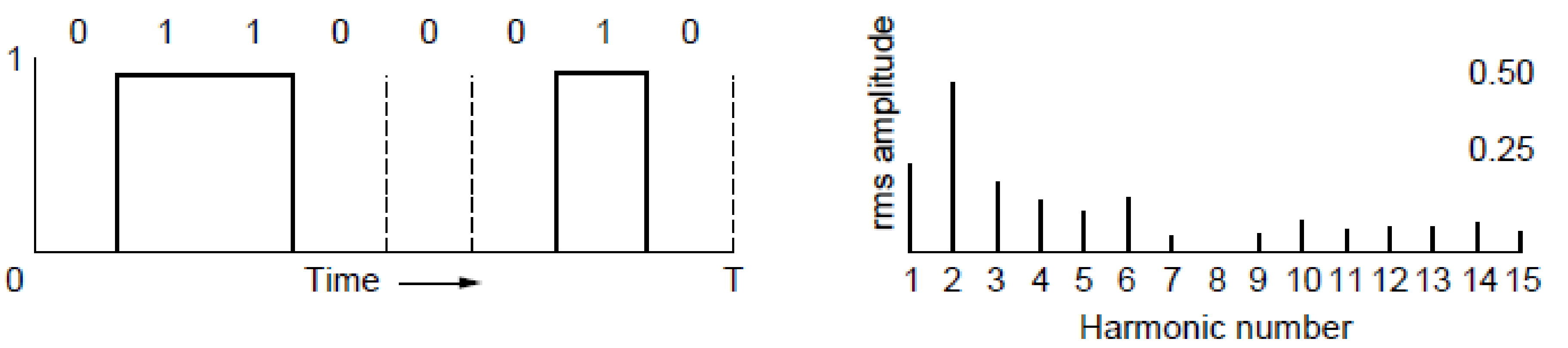
    (in time domain, convolution;

    In frequency domain, multiplication)

# The Theoretical Basis For Data Communication

- Bandwidth-Limited Signals
  - A binary signal and its root-mean-square Fourier amplitudes: rms = $(a_n^2 + b_n^2)^{1/2}$
  - These squares are proportional to the energy transmitted at the corresponding frequency

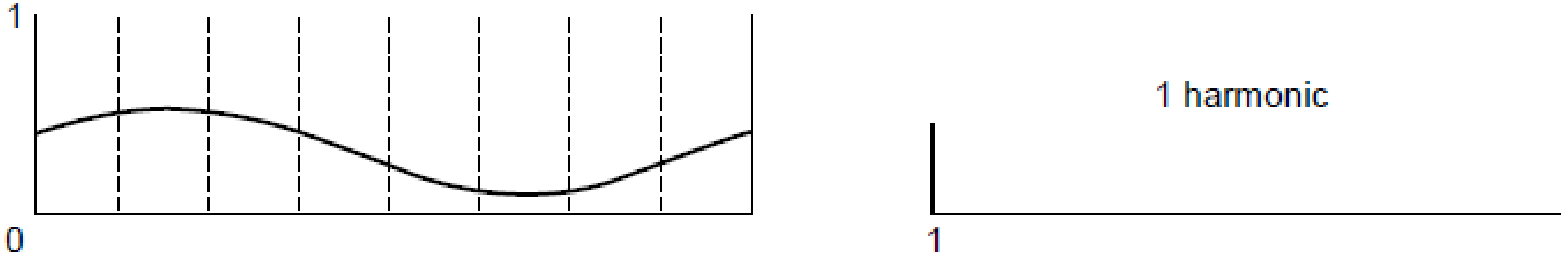
$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$




(a)

# The Theoretical Basis For Data Communication

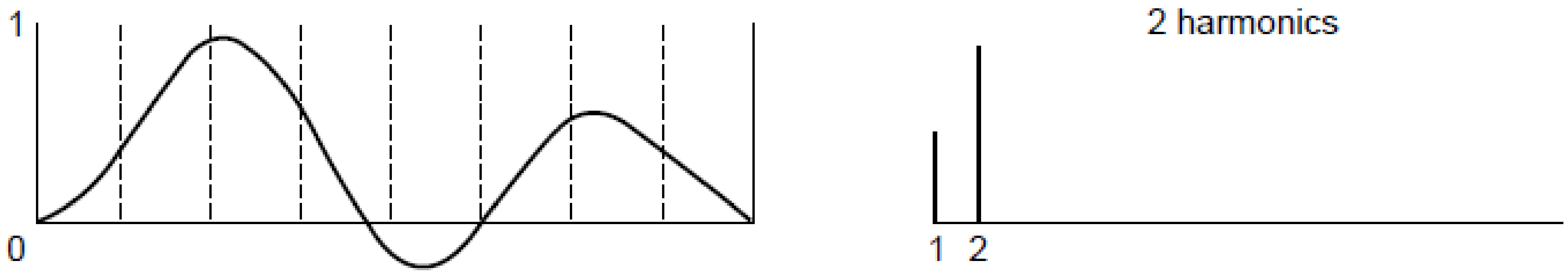
- Bandwidth-Limited Signals
  - Successive approximations to the original signal.




(b)

# The Theoretical Basis For Data Communication

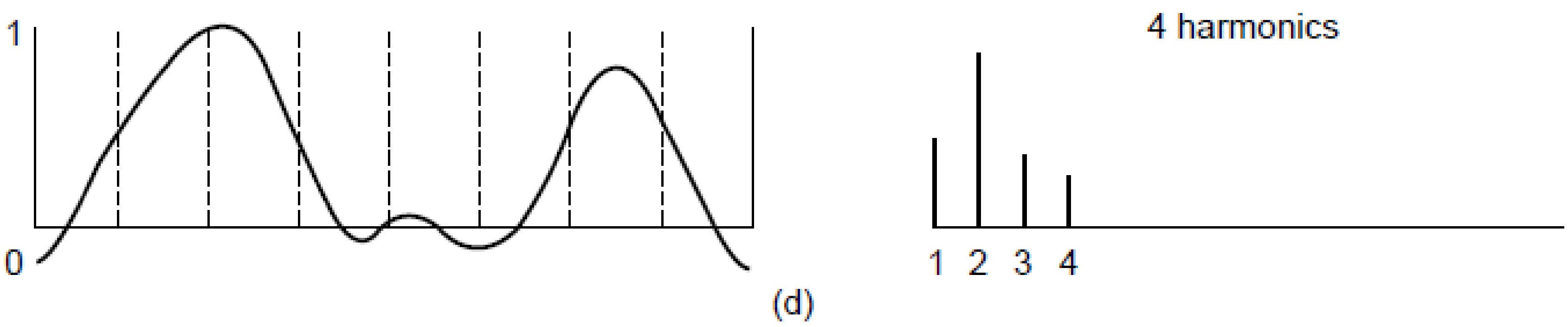
- Bandwidth-Limited Signals
  - Successive approximations to the original signal.




(c)

# The Theoretical Basis For Data Communication

- Bandwidth-Limited Signals
  - Successive approximations to the original signal.



# The Theoretical Basis For Data Communication

- Bandwidth-Limited Signals
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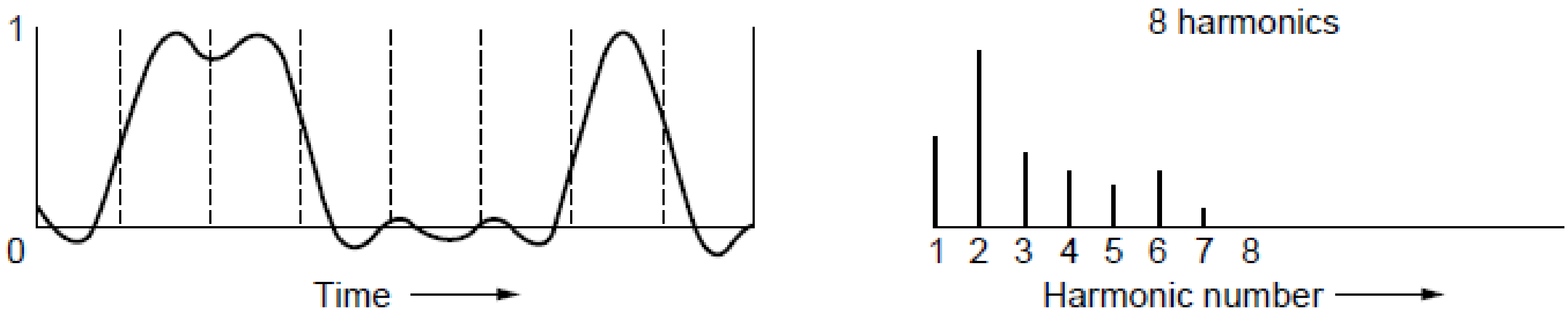



(e)

# The Theoretical Basis For Data Communication

- Bandwidth-limited signals
  - Given a bit rate *b* bits/sec,
    - → the time to send *1* bit is *1/b*,
    - → the time required to send *8* bits is *8/b* sec,
    - → the frequency of the 1st harmonic (一次谐波) is *b/8*.
  - An ordinary telephone line (often called as a voice-grade line (话音级线路)) has an *artificially* introduced cutoff frequency near *3000Hz*. This restriction means that the number of the highest harmonic passed through is *3000/(b/8)* or *24000/b*.

# The Theoretical Basis For Data Communication

- Bandwidth-Limited Signals: Relation between data rate and harmonics for the voice-grade line (*3000Hz*)

| 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 |

**Conclusion: the data rate is limited by the bandwidth of transmission system or media.**

# The Theoretical Basis For Data Communication

- The maximum data rate of a channel
  - In 1924, Henry Nyquist derived an equation expressing the maximum data rate for a finite bandwidth *noiseless* channel:
    Max data rate = $2H \log_2 V$ bits/sec, or
    **Max symbol rate = 2H**
    where H is the bandwith, V is the discrete levels
  - If we use B to denote the data rate (bits/s), and S to denote the symbol rate (symbol/s),
    $B \le 2H \log_2 V$
    **$S \le 2H$**

# Symbol rate vs. Data rate

- Symbol rate == baud rate
- Usually, **data rate = symbol rate * bits per symbol**
- **Ex 1**: we use 8 discrete voltage levels to represent bits
  ➔ 1 symbol represent 3 bits ➔ data rate = 3 * symbol rate
- **Ex 2**: we use 1-0 (high-to-low) transition to represent 1 and 0-1 (low-to-high) transition to represent 0, i.e. Manchester encoding
  ➔ 2 symbols represent 1 bit ➔ data rate = ½ * symbol rate
- The modulation technique determines the number of bits/symbol.

# The Theoretical Basis For Data Communication

- The max data rate of a channel
  - In 1943, Claude Shannon extend it to channel *with random noise*
    **Max data rate = H $\log_2$ (1+S/N) bits/sec**
    where S/N is the signal to noise ratio
  - If we use B to denote the data rate (bits/s)
    **B <= H $\log_2$ (1+S/N)**
  - SNR: typically measured in dB, decibel
    **dB = $10\log_{10}$ S/N**
    **Ex**: S/N=10 → 10dB, S/N=100 → 20dB, ...

# GUIDED TRANSMISSION MEDIA (有线数据传输)

- Magnetic media (磁介质)
- Twisted pair (双绞线)
- Coaxial cable (同轴电缆)
- Power Lines (电力线)
- Fiber optics (光纤)

# Guided Transmission Media: Magnetic media

- One of the most common ways to transport data from one computer to another is
  - To write them onto magnetic tape or removable media,
  - To transport the tape or disks to the destination machine, and
  - To read them back in again.
- Bandwidth:

  800GB/tape * 1000 tapes/box / (24*60*60s) = 70+Gbps
- Cost:

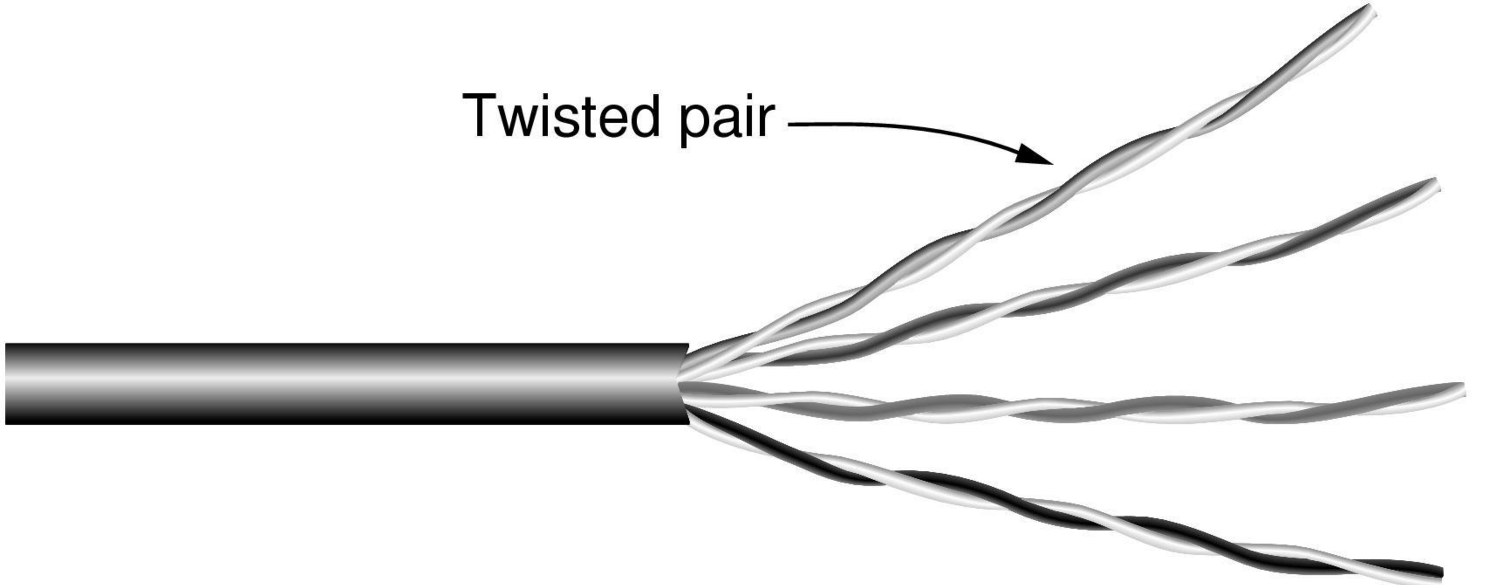
  (800GB/tape * 1000 tapes/box) / 5000$ = 160GB/$
- Conclusion:

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

- Why computer network?

# Guided Transmission Media: Twisted pair

- A twisted pair consists of two insulated copper wires, typically about 1 mm thick. The wires are twisted together in a helical form, just like a DNA molecule.
- Twisted pairs can run several kilometers without amplification, but for longer distances, repeaters are needed.



# Guided Transmission Media: Twisted pair

(a) Category 3 UTP.

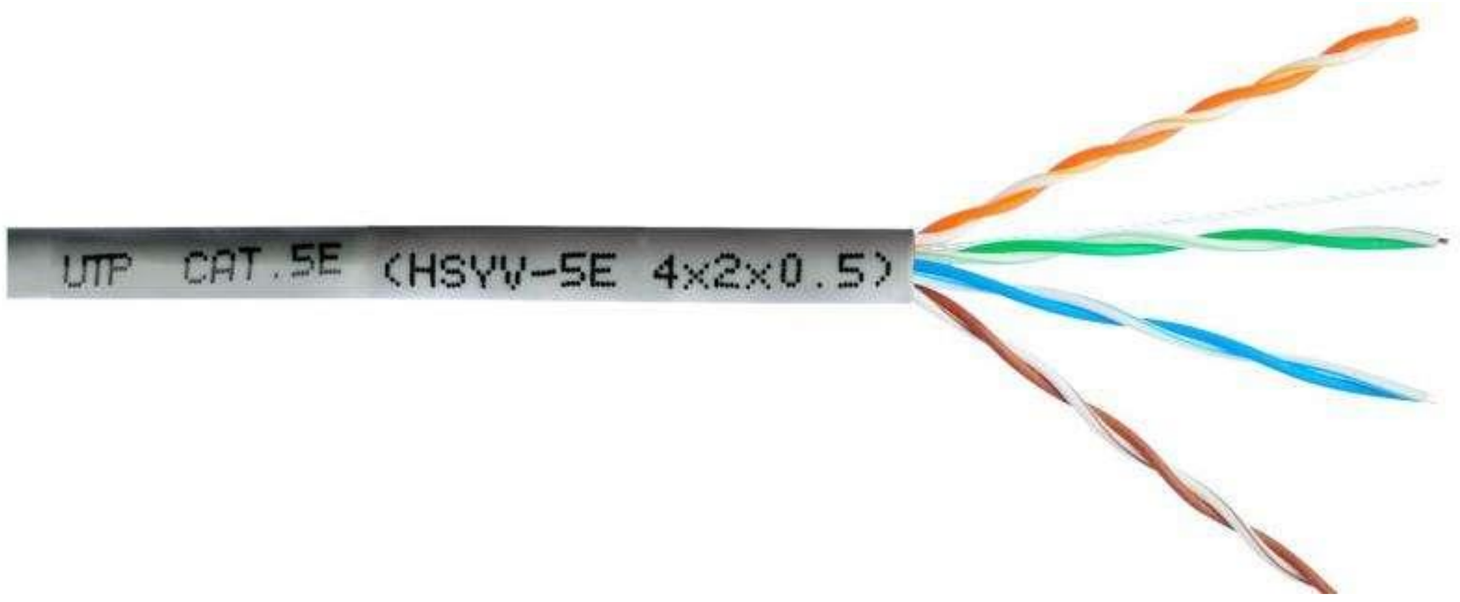
(b) Category 5 UTP.

(a)

(b)

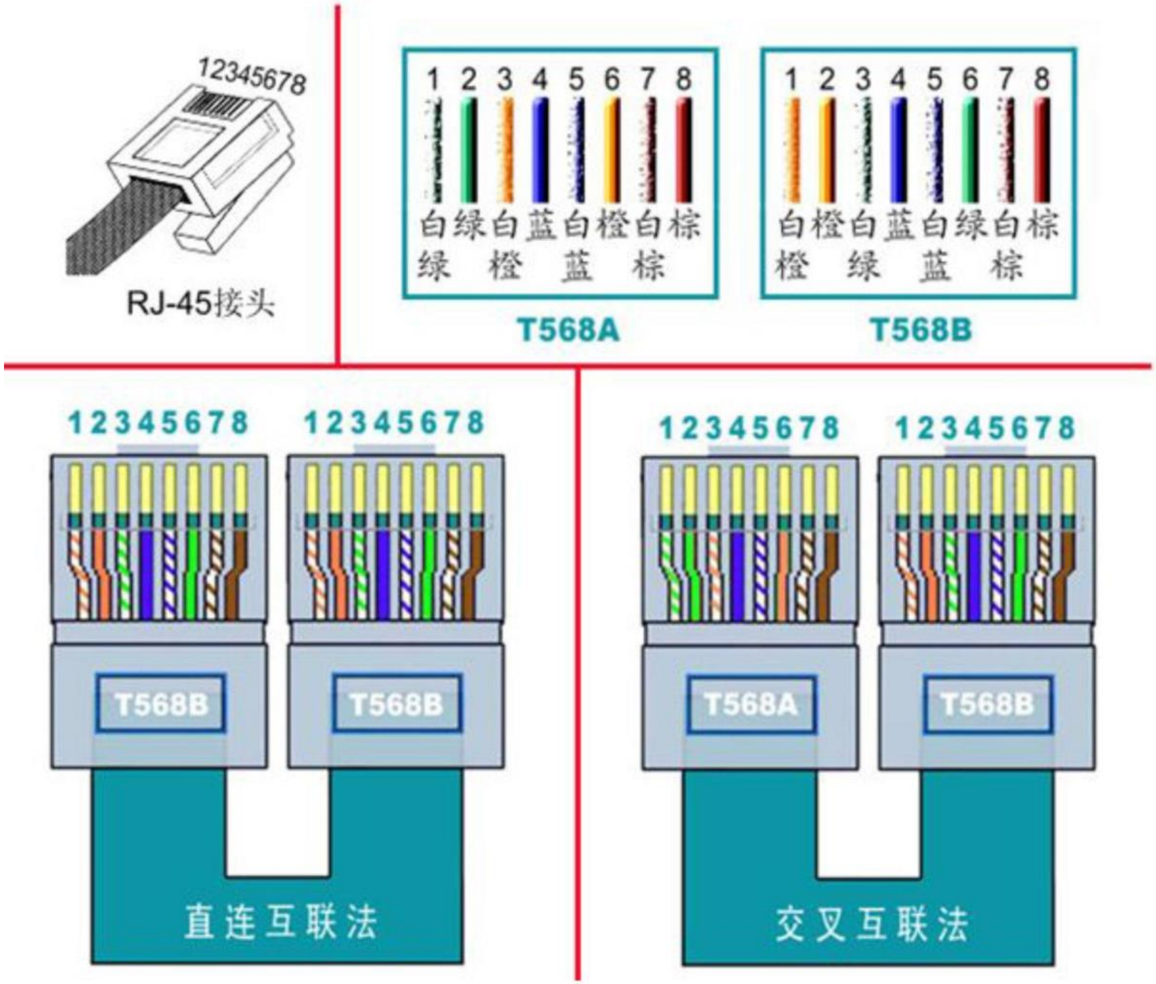
# Guided Transmission Media: Twisted pair

- Twisted pairs: analog or digital signals.
- Full-Duplex, Half-Duplex, Simplex
- Types
  - Category 5 (100Mbps, 1Gbps)
  - Category 6 (10Gbps)
  - Category 7 (Shielded Twisted Pair)



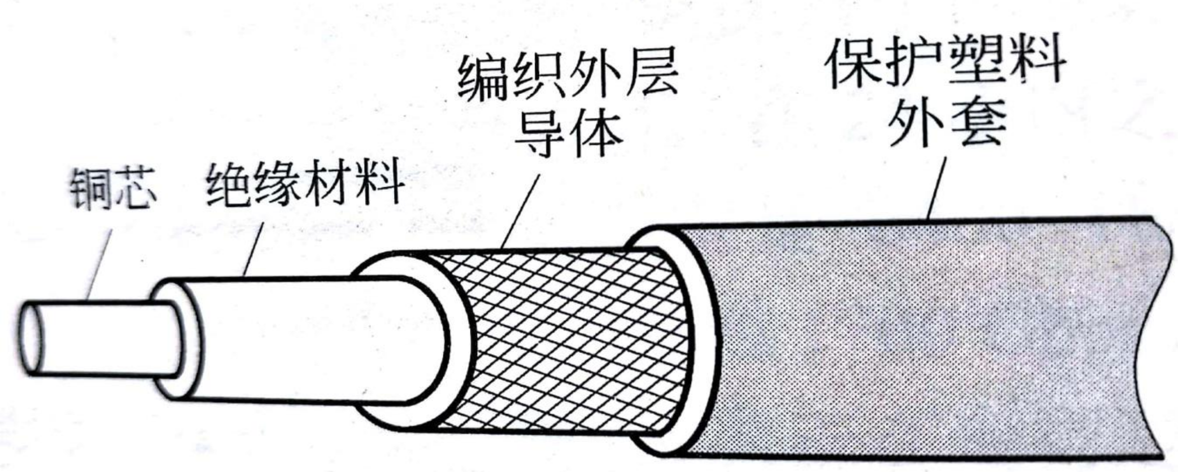
# Guided Transmission Media: Twisted pair

- Category 5 (100Mbps, 1Gbps)



# Guided Transmission Media: Coaxial cable

- A coaxial cable consists of
  - a stiff copper wire as the core,
  - surrounded by an insulating material.
  - The insulator is encased by a cylindrical conductor, often as a closely-woven breaded mesh.
  - The outer conductor is covered in a protective plastic sheath.



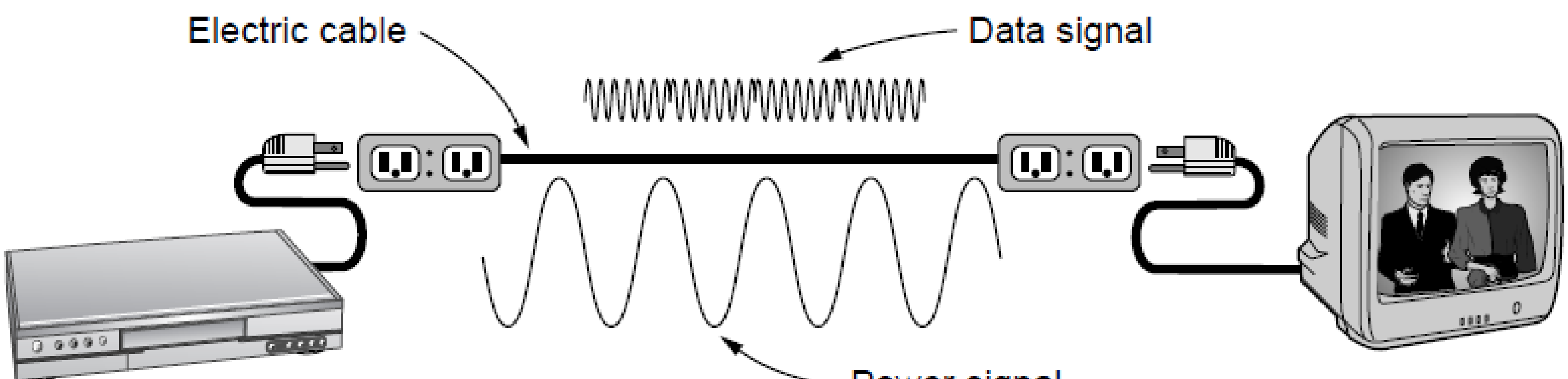

- Two types:  50-ohm (digital), 75-ohm (analog and digital)
- High bandwidth and excellent noise immunity
- Used to be widely used for long-distance lines.

# Guided Transmission Media: Power Lines

- Power lines have been used by electricity companies for low-rate communication such as remote metering for many years, as well in the home to control devices.
- In recent years, there has been renewed interest in high-rate communication over these lines, both inside the home as a LAN and outside the home for broadband Internet access.

# Guided Transmission Media: Power Lines

- Now, many products use various proprietary standards for power-line networking, so international standards are actively under development.



# Guided Transmission Media: Fiber optics

- In the race between computing and communication, communication won
  - Original IBM PC at 4.77 MHz in 1981 → four-core CPU at 3GHz ➔ (16 per decade) and physical limits
  - 45Mbps (T3 line) → 100Gbps (optical communication) ➔ 16 per decade and error rate almost zero and almost no limits
- The new conventional wisdom should be that:

  ***all computers are hopeless slow and***

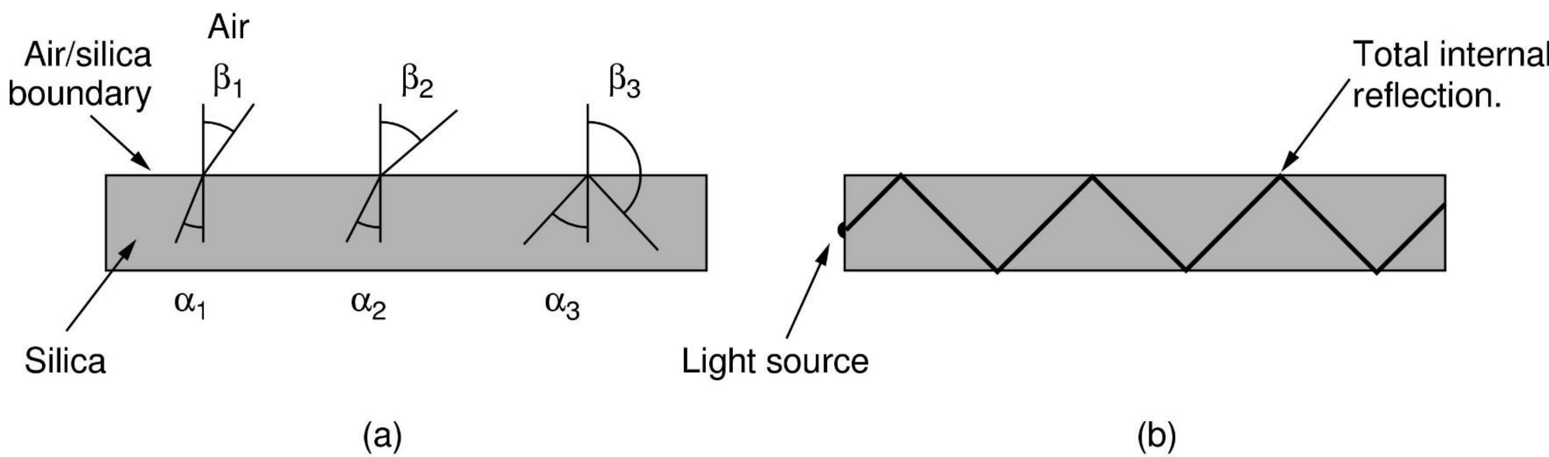
  ***networks should try to avoid computation at all costs,***

  ***no matter how much bandwidth that wastes.***
- An optical transmission system: the light source → the transmission medium → the detector.

# Guided Transmission Media: Fiber optics

(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 (反射) (no refraction (折射) ).



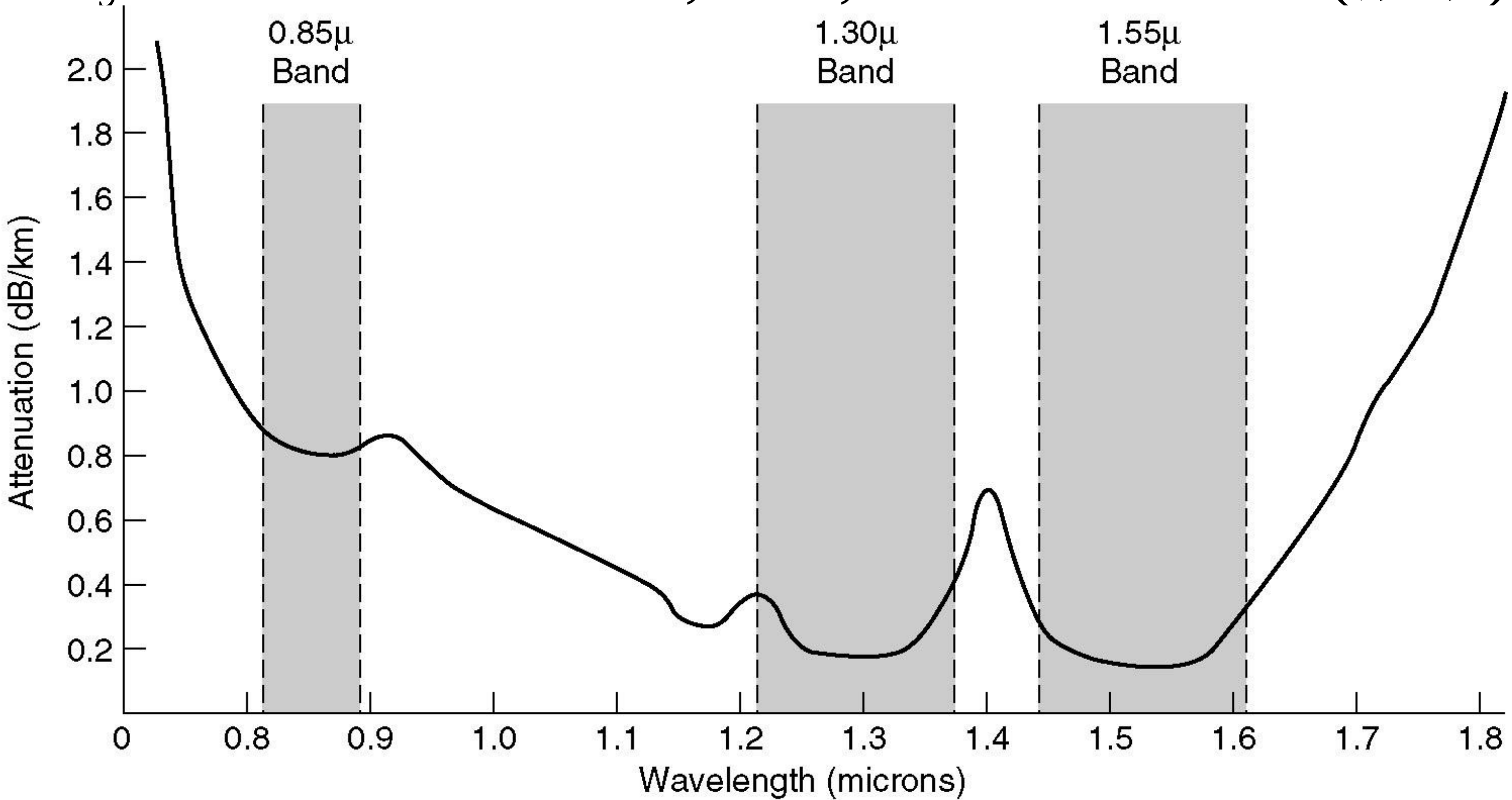

- Two types of fiber optics

  Multimode (多模): many different rays

  Unimode (单模): single rays, longer distance

# Guided Transmission Media: Fiber optics

- Transmission of light through fiber
  - Attenuation (衰減) of light through fiber in the infrared region.
  - Three wavelength bands are used for optical communication. They are centered at 0.85, 1.30, and 1.55 micros (微米).

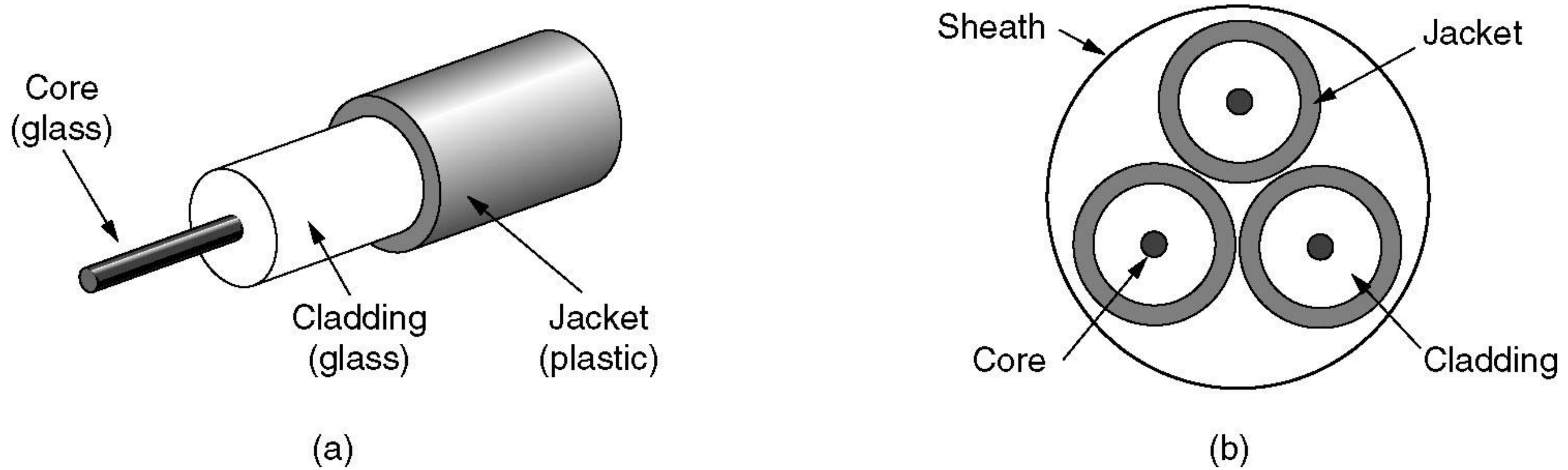


# Guided Transmission Media: Fiber optics

- Fiber cables
  - Fiber optic cables are similar to coax, except without the braid.

    (a) Side view of a single fiber.

    (b) End view of a sheath with three fibers.



# Guided Transmission Media: Fiber optics

- Fiber cables
  - Deployment
    - Laid in the ground within a meter of the surface
    - Buried in trenches near the shore
    - Lie on the bottom in deep water
  - Connection
    - Fiber sockets
    - Spliced mechanically
    - Fusion splice
  - Detection
    - Photodiode (光电二极管). The response time is 1ns, which limits data rates to about 1Gbps.

# Guided Transmission Media: Fiber optics

- Fiber cables
  - Light sources
    - LED: 发光二极管
    - Semiconductor laser: 半导体激光

| 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 |

# Guided Transmission Media: Fiber optics

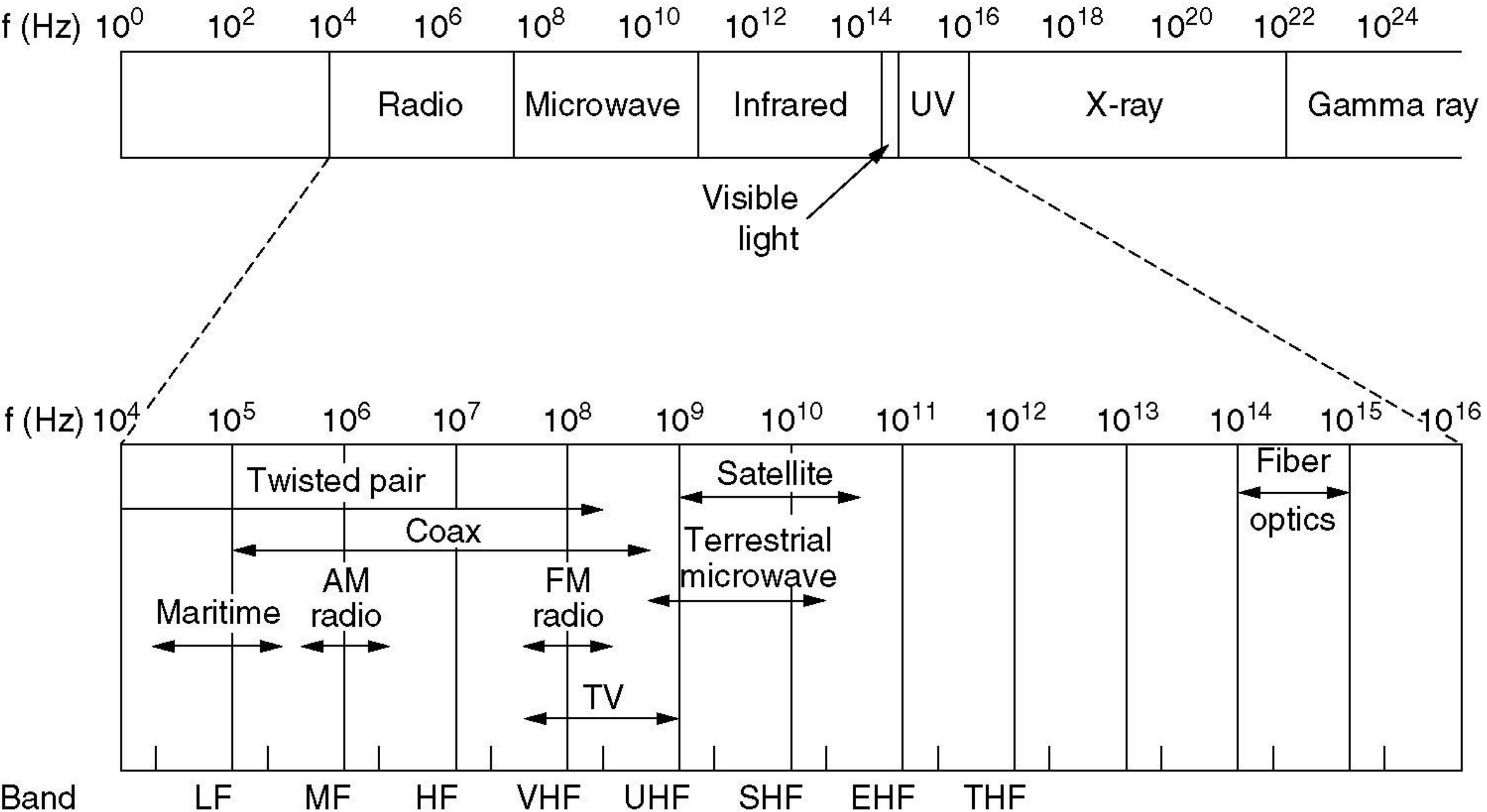
- Comparison of fiber optics and copper wire
  - Advantages
    - Higher bandwidths and Low attenuation.
    - Not being affected by power surges, electromagnetic interference, or power failures.
    - Not affected by corrosive chemicals in the air.
    - Thin and lightweight.
    - Fibers do not leak light and quite difficult to tap.
  - Disadvantages
    - Less familiar technology.
    - Fiber interfaces more expensive.
  - Conclusion: **For new routes (longer ones), fiber wins!**

# WIRELESS TRANSMISSION
# (无线传输)

- The electromagnetic spectrum (电磁波谱)
- Radio transmission (无线电传输)
- Microwave transmission (微波传输)
- Infrared and millimeter waves (红外线和毫米波)
- Lightwave transmission (光波传输)

# Wireless Transmission: The Electromagnetic Spectrum

The electromagnetic spectrum and its uses for communication.

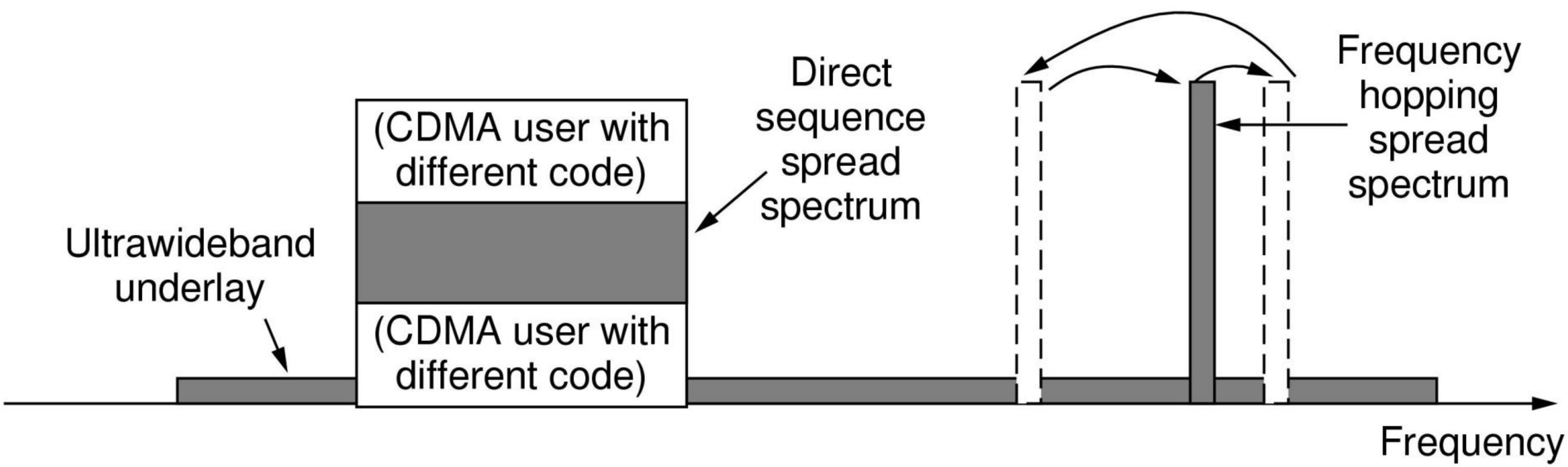


# Wireless Transmission: The Electromagnetic Spectrum

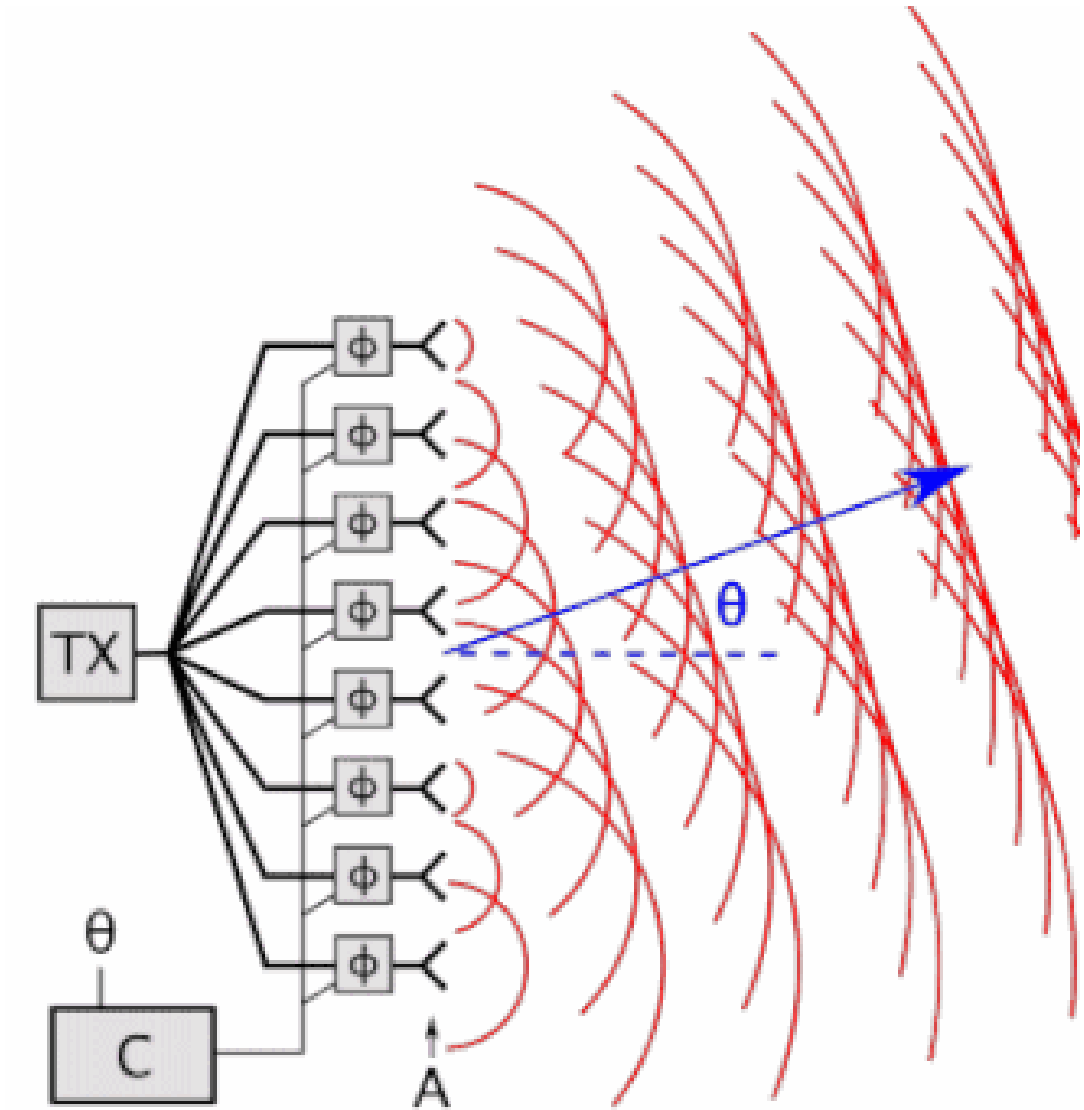
- LF(Low), MF(Medium), HF(High), VHF(Very), UHF(Ultra), SHF(Super), EHT(Extremely), THF(Tremendously), (IHF(Incredibly), AHF(Astonishingly), PHF(Prodigiously))
- The wider the band, the higher the data rate.
- To prevent total chaos, there are national and international agreements about who gets to use which frequencies.
- Most transmissions use a *narrow frequency band*. (GSM)

# Wireless Transmission: The Electromagnetic Spectrum

- Some spread its frequency over a *wide frequency band* (spread spectrum, 扩频).
  - Frequency hopping spread spectrum (military, 802.11, Bluetooth)
  - Direct sequence spread spectrum (3G mobile phones)
  - UWB (UltraWideBand)



# Wireless Transmission & Radar



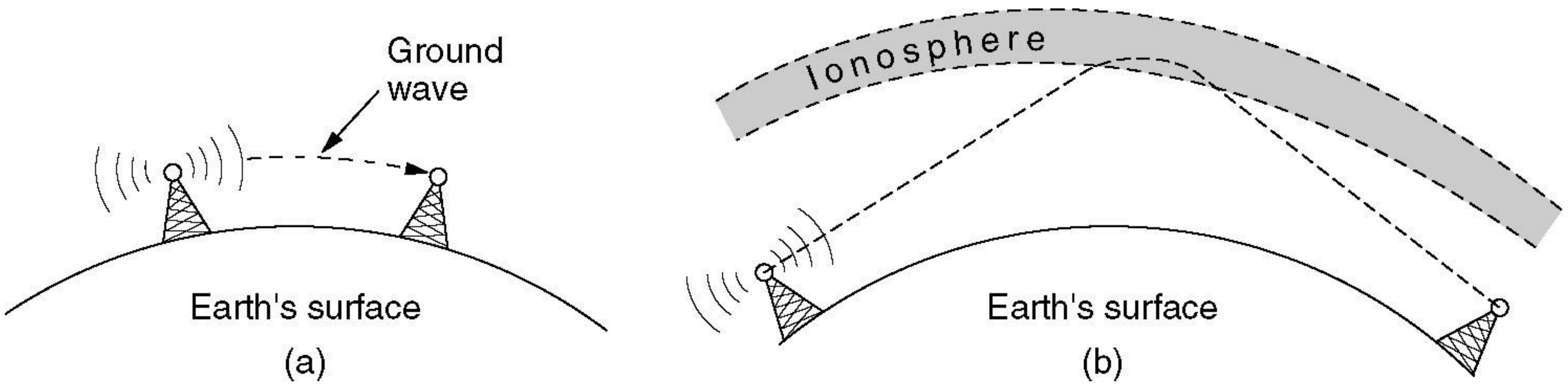

# Wireless Transmission: Radio transmission

- Radio waves are easy to generate, can travel long distances, and can penetrate buildings easily, so they are widely used for communication
- Radio waves also 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.
- Due to radio’s ability to travel long distances, interference between users is a problem. For this reason, all governments tightly license the use of radio transmitters.

# Wireless Transmission: Radio transmission

(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 (电离层).



# Wireless Transmission: Microwave transmission

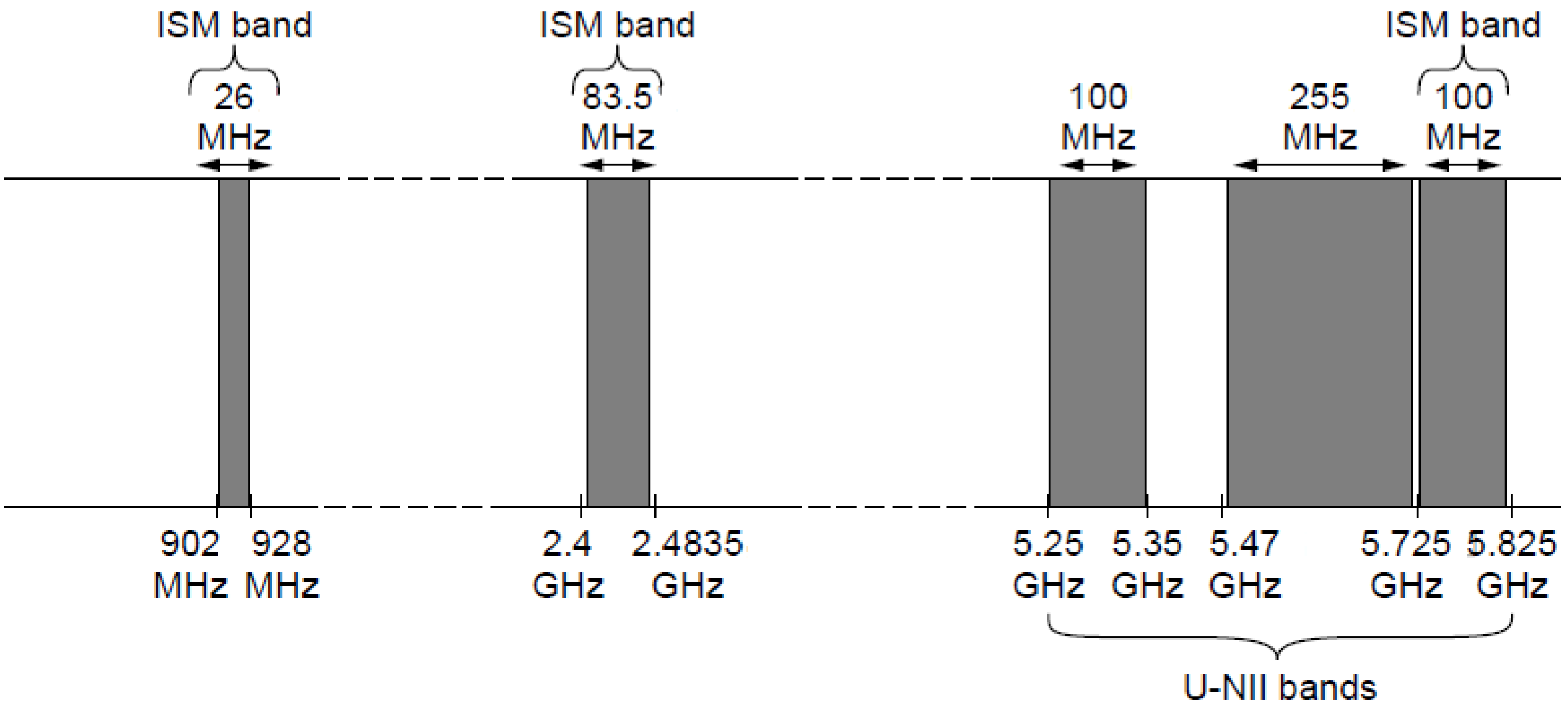
- Above 100MHz, the waves travel in straight lines and can therefore be narrowly focused.
- The higher the transmission towers are, the further apart they can be. For 100-m high towers, repeaters can be spaced 80km apart.
- Microwave can cause *multipath fading* or be *absorbed by rain*.
- Microwave communication is so widely used for long-distance telephone communication, cellular telephones, television distribution, and other uses, that a severe shortage of spectrum has developed.
- Microwave has some advantages over fiber: no right of way problem, being inexpensive.

# Wireless Transmission: Microwave transmission

- Who allocates frequencies?
  - ITU: recommendation
  - 无线电管理委员会 (CN)
  - FCC (Federal Communication Commission) (US)
- Who gets frequencies?
  - Auctioning off the bandwidth to the highest bidder

# Wireless Transmission: Microwave transmission

- Free frequencies:
  - The location of the **ISM** (Industrial, Scientific, Medical) band varies from country to country.
  - ISM and U-NII (Unlicensed National Information Infrastructure) bands used in the United States by wireless devices.



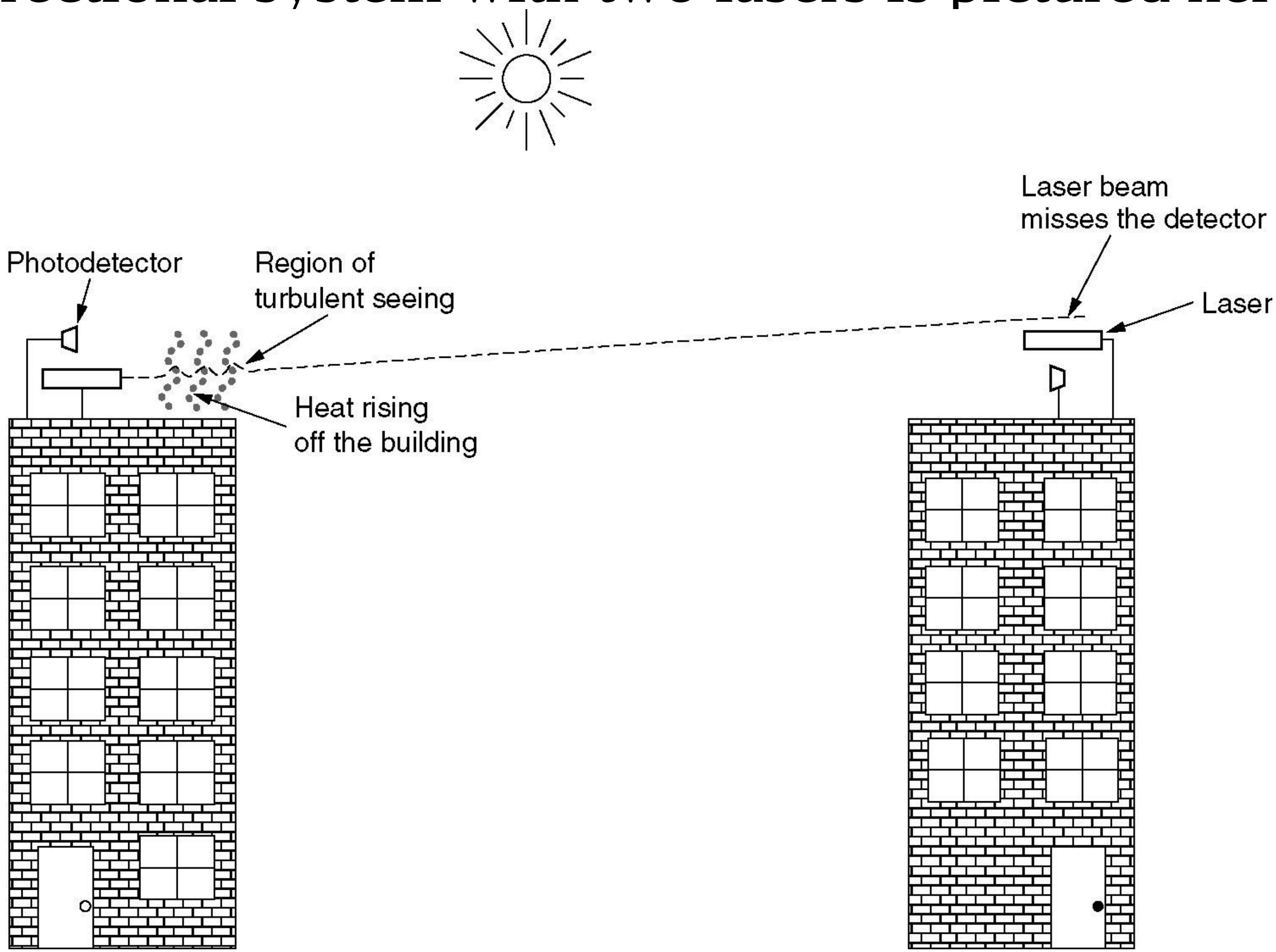
# Wireless Transmission: Infrared and millimeter waves

- Infrared and millimeter waves can not pass through solid objects.
- Infrared can be used for indoor wireless LANs, remote controllers.
- Infrared can not be used outdoors for the sun shines as brightly in the infrared as in the visible spectrum.
- Advantages
  - The infrared controller cannot control the TV of your neighbor.
  - More secure.

# Wireless Transmission: Lightwave transmission

Convection currents (气流) can interfere with laser comm systems.

A bidirectional system with two lasers is pictured here.



# DIGITAL MODULATION AND MULTIPLEXING

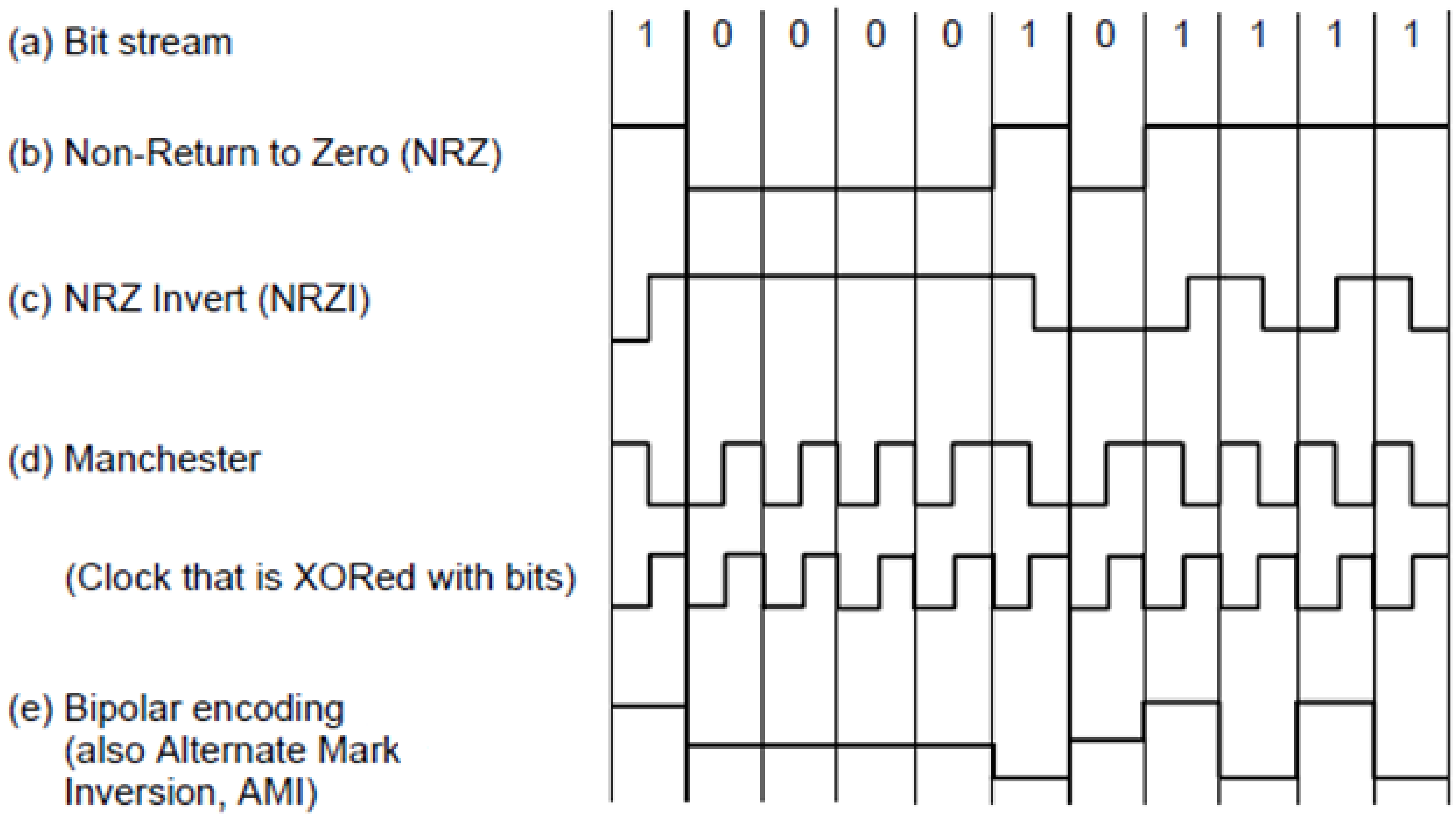
- Baseband Transmission (基带传输)
  - signal occupies frequencies from zero up to a maximum
- Passband Transmission (通带传输)
  - signal occupies a band of frequencies around the frequency of the carrier signal
- Frequency Division Multiplexing (频分复用)
- Time Division Multiplexing (时分复用)
- Code Division Multiplexing (码分复用)

# Digital Modulation and Multiplexing

- To send digital information we must devise analog signals to represent bits.
- The process of converting between bits and signals that represent them is called **Digital Modulation (数字调制).**

- Channels are often shared by multiple signals.
- This kind of sharing is called **Multiplexing (复用)**

# Digital Modulation and Multiplexing:
## Baseband Transmission



# Digital Modulation and Multiplexing: Baseband Transmission

- Clock Recovery
  - Accurate clock: For all schemes that encode bits into symbols, the receiver must know when one symbol ends and the next symbol begins to correctly decode the bits.
  - NRZ (Non-Return-to-Zero,不归零制): the symbols are simply voltage levels.
    - Problem: a long run of 0s or 1s leaves the signal unchanged. After a while it is hard to tell the bits apart, as 15 zeros look much like 16 zeros unless you have a very accurate clock.

# Digital Modulation and Multiplexing: Baseband Transmission

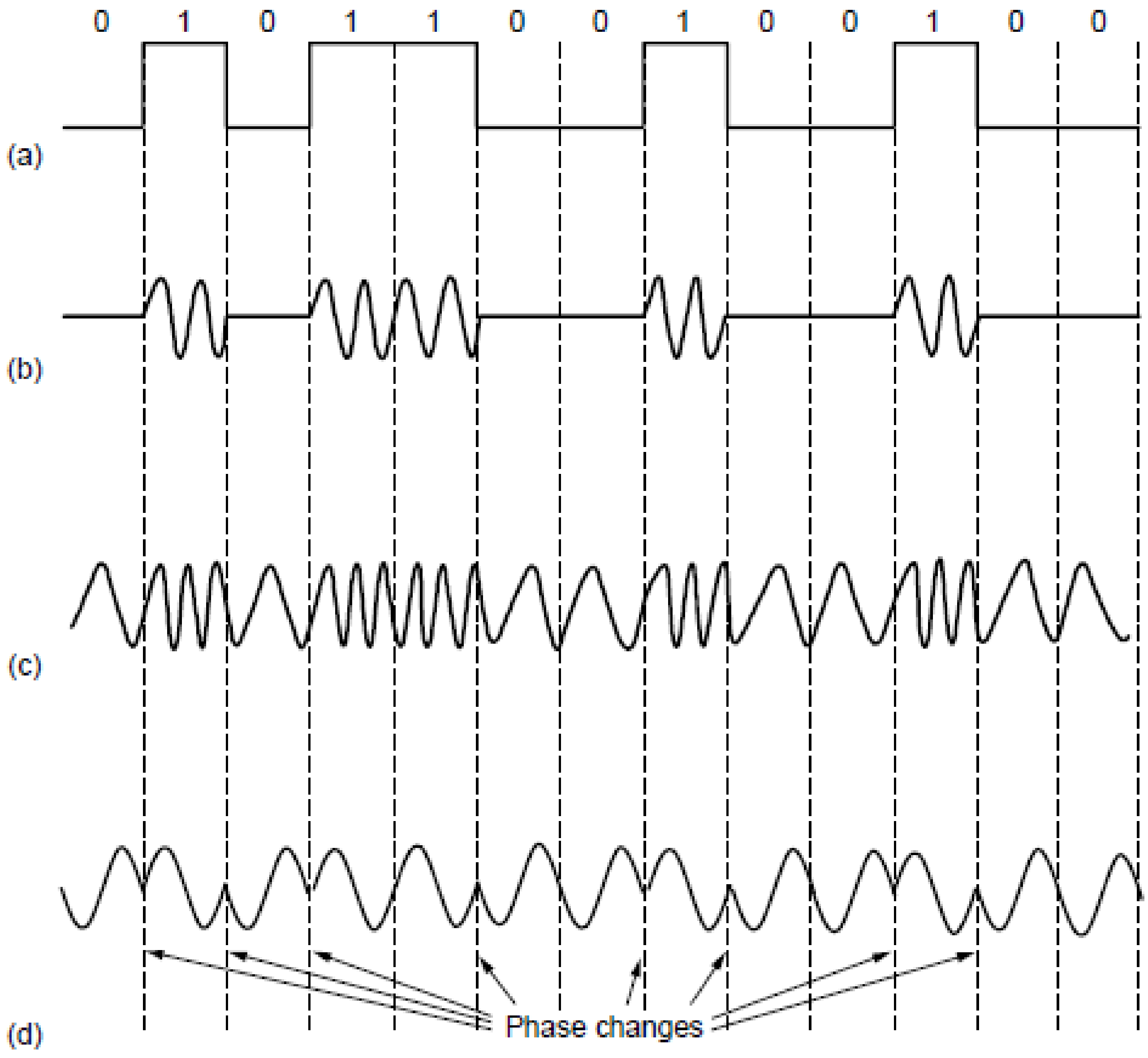
- Clock Recovery
  - One strategy is to send a separate clock signal to the receiver.
  - A clever trick is to mix the clock signal with the data signal by XORing them together so that no extra line is needed. → Manchester Encoding
  - As a step in the right direction, we can simplify the situation by encoding a 1 as a transition and a 0 as no transition, or vice versa. → NRZI (Non-Return-to-Zero Inverted,不归零倒相制) (Used in USB)
    - Problem: long runs of 0s? → 4B/5B

# Digital Modulation and Multiplexing: Baseband Transmission

- Clock Recovery
  - 4B/5B: The five bit patterns are chosen so that there will never be a run of more than three consecutive 0s.

| 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 |

# Digital Modulation and Multiplexing: Passband Transmission (振幅、频率、相位)



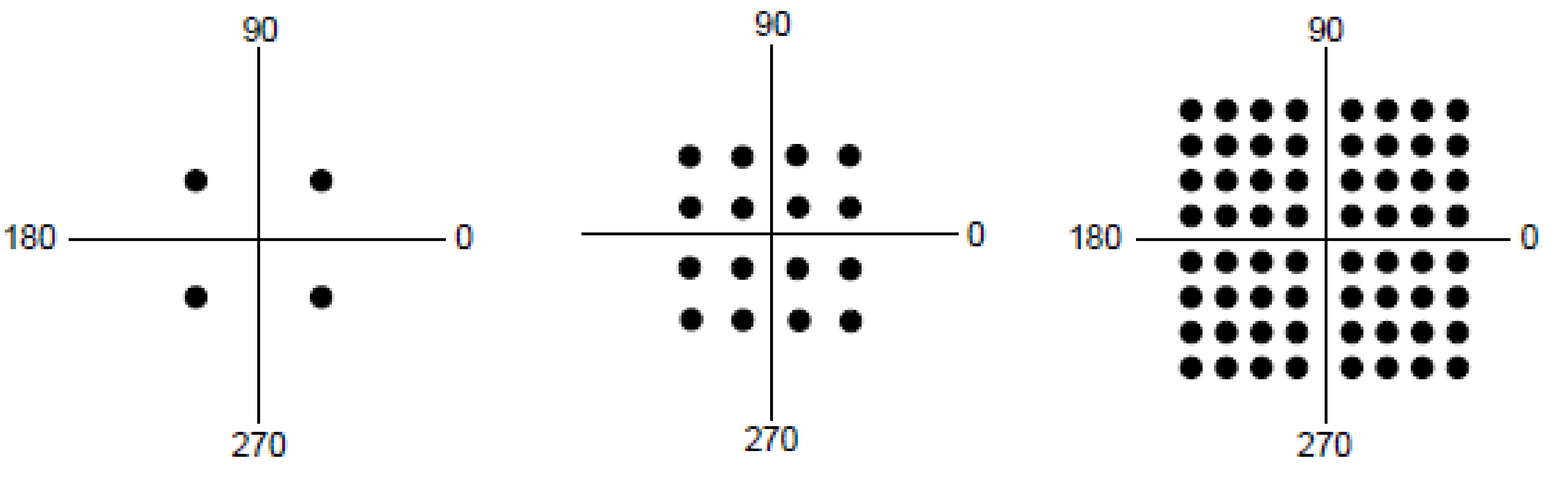
# Digital Modulation and Multiplexing: Passband Transmission

Constellation diagrams (星座图)

(a) QPSK. (Quadrature Phase Shift Keying)

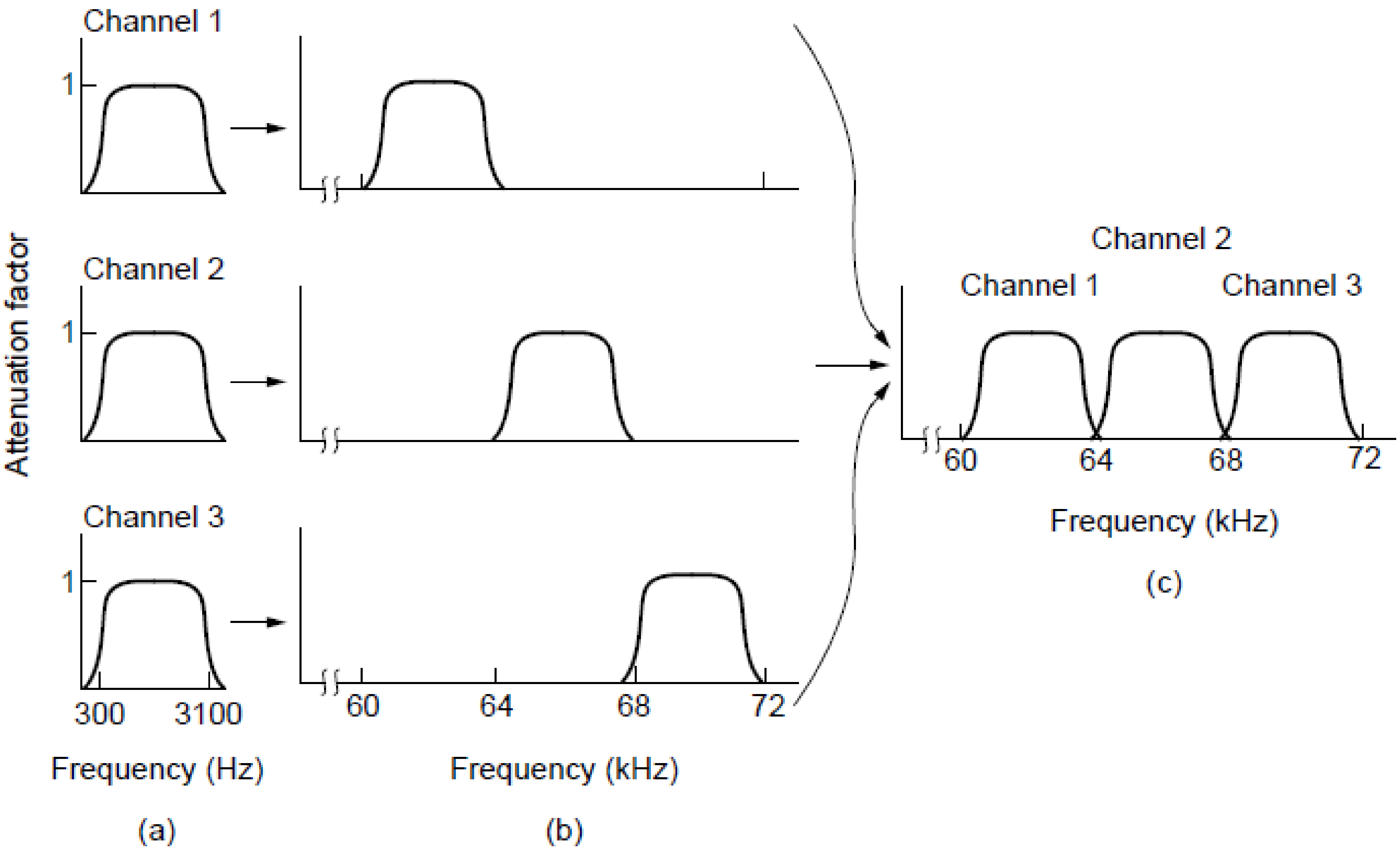
(b) QAM-16. (Quadrature Amplitude Modulation)

(c) QAM-64.

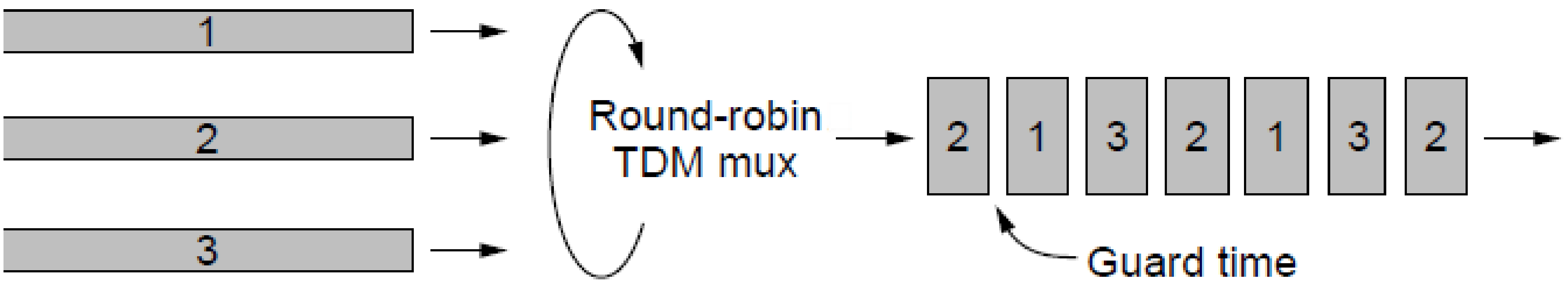



(a) (b) (c)

# Digital Modulation and Multiplexing:
## Frequency Division Multiplexing



# Digital Modulation and Multiplexing:
## Time Division Multiplexing



# Digital Modulation and Multiplexing: Code Division Multiplexing

- Each station is assigned a chip sequence
- The chip sequences are **orthogonal**
- Station transmits bit 1 represented by its chip sequence, and bit 0 represented by the inverse of its chip sequence
- The transmissions are synchronized
- The channel is additive

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

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

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

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

# Digital Modulation and Multiplexing:
## Code Division Multiplexing

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

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

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

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

(a)

(a) Chip sequences for four stations.

(c) Six examples of transmissions.

(d) Recovery of station C's

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

(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)