Principles of Communications
(通信系统原理)
Undergraduate Course

Chapter 1: Introduction

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Chapter 1: Introduction
Contents

Chapter 1: Introduction
Contents

1. Historical Review of Communication Systems
2. Message, Information and Signal
3. Digital Communications
4. Communications Channel
5. Noise in Communications Channel
6. Summary

Historical Review of Communication Systems

Pre-industrial Wireless Communications Networks

1. Transmitting signals over line-of-sight (LoS) distances
2. Light signals, such as smoke, torch, flashing, flags, flares
3. Complex messages developed based on rudimentary signals
4. Relay systems

Historical Review of Communication Systems

Telegraph and Telephone Networks

- 1838: telegraph network invented by Samuel Morse
- 1895: Marconi, radio communications, 18 miles

  "In 1895, a few decades after the telephone was invented, Marconi demonstrated the first radio trans-mission from the Isle of Wight to a tugboat 18 miles away, and radio communications was born."
- Radio technology advanced rapidly to enable transmissions over larger distances with better quality, less power, and smaller, cheaper devices, thereby enabling public and private radio communications, television, and wireless networking
- Public and private communications:
  - Radio communications
  - Television, broadcasting
  - Wireless networks

Historical Review of Communication Systems

Pre-mobile-phone wireless/wired networks

- 1970’s: digital radio, bit streams, bit packets (packet radio)
- 1970’s: wired Ethernet technology (10Mbps)
- 1971: Hawwii University, ALOHANET
  - Star topology with seven campuses on four islands
  - Central computer used as a hub
  - Bidirectional radio transmission for any two computers
  - Packet data + Broadcast radio
- 1970’s to 1980’s: DARPA-supported military projects
  - Packet radio for tactical communications in the battlefield
  - Self-configure ability
  - Low datarate (a typical drawback)
- 1980’s to 1990’s: Commercial applications: Wireless data services
  - 20kbps, email, file transfer, Web browsing
  - Too low speed, expensive, and no killer applications
  - Disappear at the end of 1990’s

Historical Review of Communication Systems

Pre-mobile-phone wireless/wired networks

- 1985: FCC (Federal Communications Commission), Commercial wireless LAN
  - ISM (Industrial, Science and Medical) band
  - Pose no interference on primary ISM band user
  - Low power profile, inefficient signaling schemes, no standards
  - Low data rate and less coverage
- IEEE 802.11: local internet access methods in homes

Historical Review of Communication Systems

Cellular mobile phone networks (Analog)

- 1915: Wireless voice transmission from New York to San Francisco
- 1946: Public mobile telephone in 25 cities in USA
  - One base station covering whole city (543 users in NY)
- 1950s to 1960s: AT&T Bell Lab, cellular concept (1979)
  - the power of a transmitted signal falls off with distance
  - two users can operate on the same frequency at spatially separated locations with minimal interference between them
  - 1947 (spectrum allocated), 1960s (design finished), 1978 (field test), 1982 (FCC granted), 1983 (Chicago launch), 1984 (network saturated)
- Late 1980s: call for high capacity: digital cellular technologies

Historical Review of Communication Systems

Cellular mobile phone networks (Digital)

- Late 1980s: 2G: Digital wireless cellular network standards
  - GSM (TDMA)
  - CDMA
- Late 1990s: 3G standards
  - WCDMA
  - CDMA2000
  - TS-SCDMA
- Late 2000s: 4G standards
  - WiMAX
  - LTE-Advanced (FDD)
  - TD-LTE
- 2018: 5G standards NR

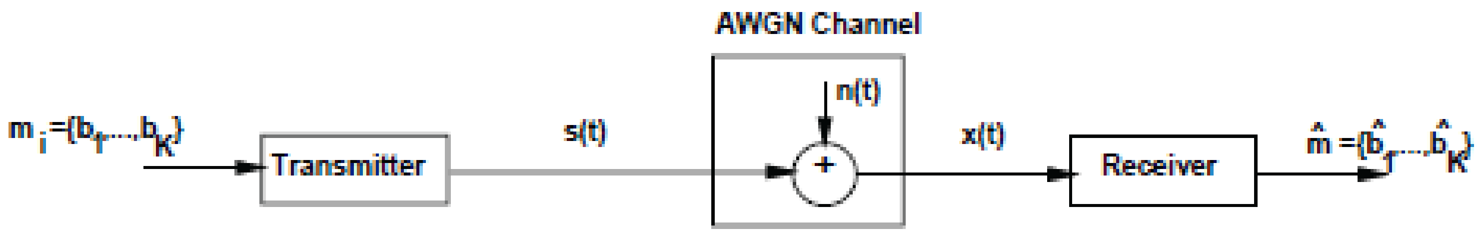
Historical Review of Communication Systems

Satellite Communication Systems

- Grouped by the heights of the orbits:
  - Low-earth-orbits (LEOs at roughly 2000km)
  - Medium-earth-orbits (MEOs at roughly 9000km)
  - Geosynchronous orbits(GEOs at roughly 40,000km)
- GEO satellite communication networks (Arthur C. Clarke)
  - Advantages: large coverage, LoS connection
  - Disadvantages: large delay, high power
- LEO satellite communication networks (1990s)
- Satellite broadcast systems (12GHz frequency band)

Historical Review of Communication Systems

Communications System Model



- Transmitter: converts message into a signal for transmission
- Channel: the physical medium (distortion, noise, interference…)
- Receiver: reconstructs the message

Message, Information and Signal

Basic Definitions

- Message (消息): speech, letters, figures, images…
- Signal (信号): the carrier of message
  - What transmitted in a communication system is signal
- Information (信息): effective content of message
  - Different types of messages may contain the same information

Chapter 1: Introduction

Contents

Message, Information and Signal

Information Contents

- "number of messages" ≠ information content

- Example
  - "Rainfall will be 1 mm tomorrow"
  - "Rainfall will be 1 m tomorrow"
  - "The sun will rise in the east tomorrow morning"

$$\boldsymbol{P(\mathrm{x}) < P(\mathrm{y}),\ I(\mathrm{x}) > I(\mathrm{y})}$$

- Information content $I = I\,[\,P(x)\,]$
- $P(x)$ – Occurrence probability

Message, Information and Signal

Information Contents

$$I = \log_a \frac{1}{P(x)} = -\log_a P(x)$$

- $a = 2$: the unit is bit
- $a = e$: the unit is nat

$P(x) < P(y)$, $I(x) > I(y)$

$P \to 1$， $I \to 0$

$P \to 0$， $I \to \infty$

$I[P(x)\, P(y) \ldots] = I(x) + I(y) + \ldots$

- For an equal probability binary symbol:

$$I = \log_2 [1/P(x)] = \log_2 [1/(1/2)] = 1 \text{ bit}$$

- For an equal probability M-ary symbol:

$$I = \log_2 [1/P(x)] = \log_2 [1/(1/M)] = \log_2 M \quad \text{bit}$$

– $M = 2^k$: $I = k$ bit

Chapter 1: Introduction
Contents

Digital Communications

Analog Signals and Digital Signals

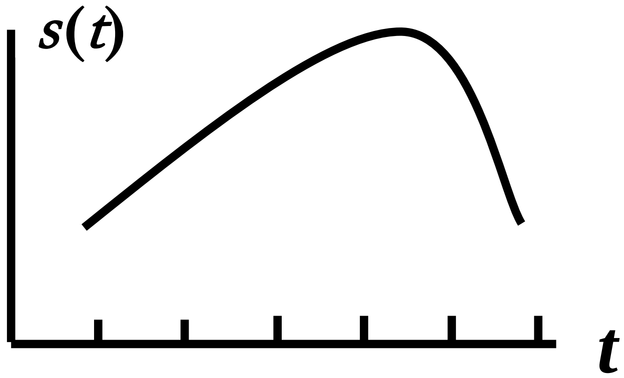
- Analog signal
  - Its voltage or current has continuous range of values
  - e.g., speech signal

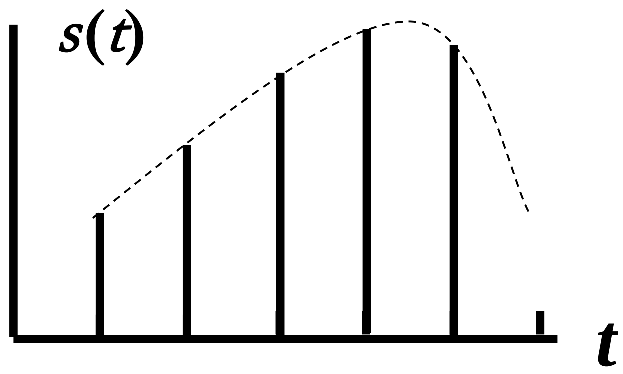
- Digital signal
  - Its voltage or current can only take finite number of discrete values
  - e.g., digital computer data signal

Digital Communications

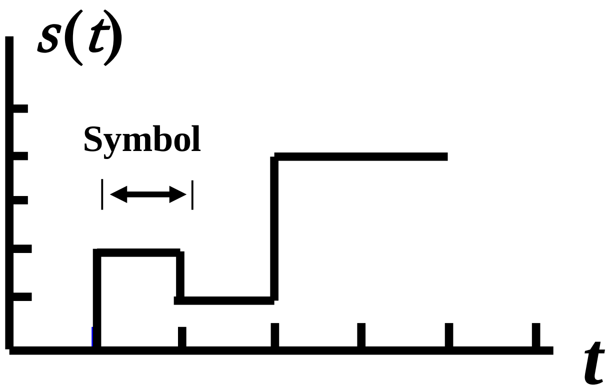
Analog Signals and Digital Signals

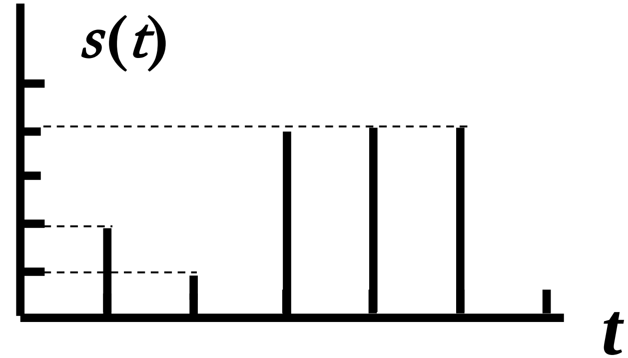
Analog signals





Digital signals





Digital Communications

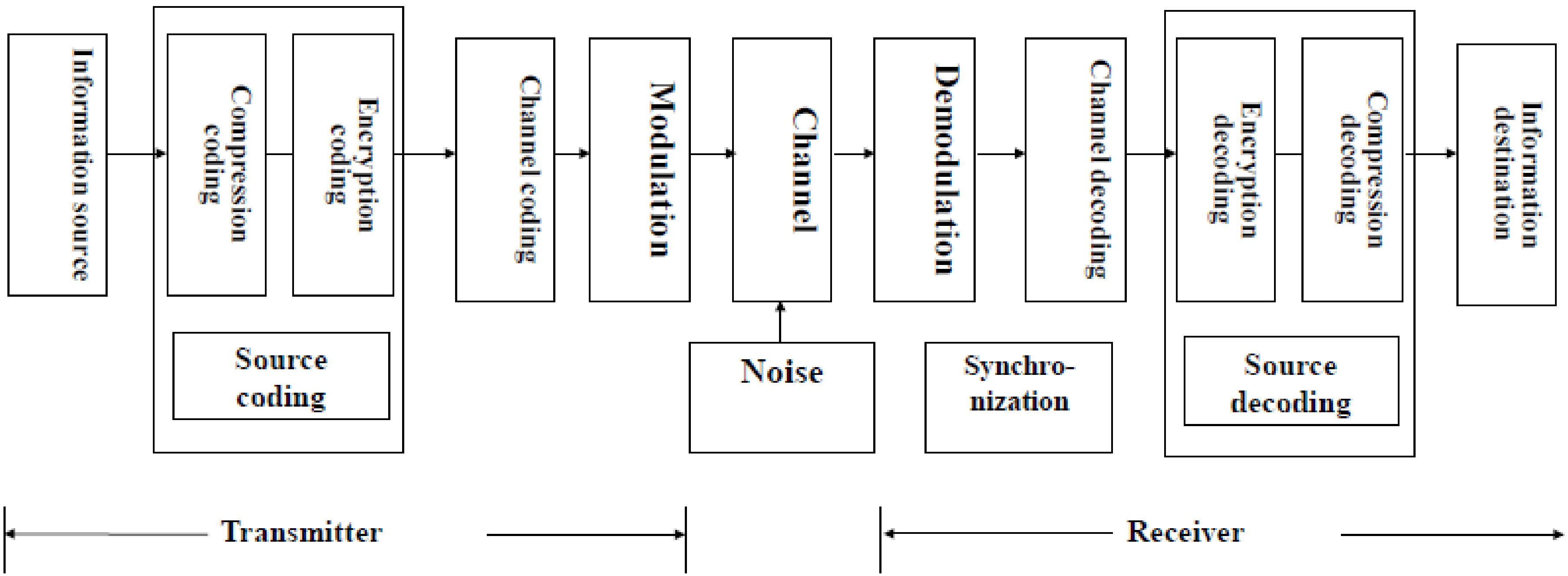
Communication systems

- Analog communication system
  - Requirement - high fidelity
  - Criterion - signal to noise ratio (S/N)
  - Basic issue - parameter estimation of continuous waveform

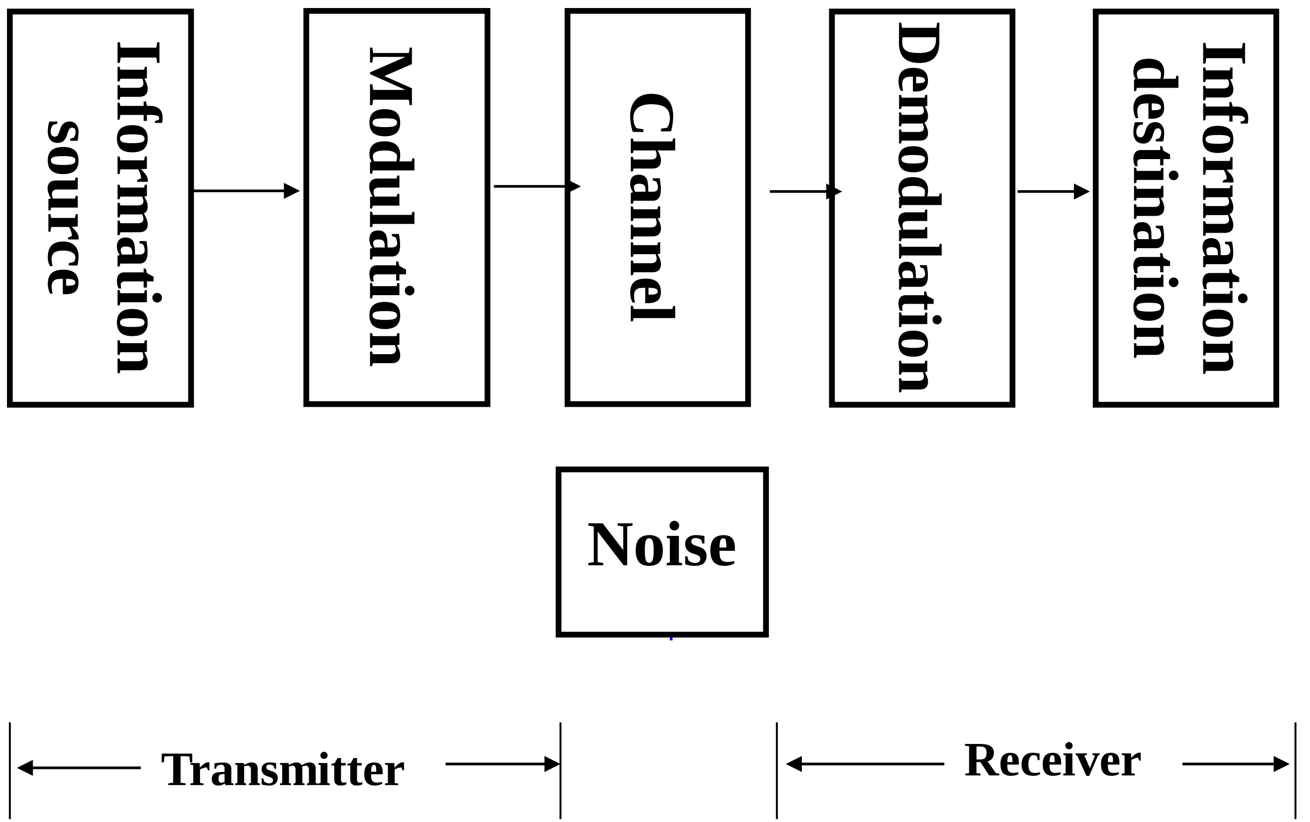
- Digital communication system
  - Requirement - correct decision
  - Criterion - error probability
  - Basic issue - statistical decision theory

Digital Communications

Digital Communication System Model



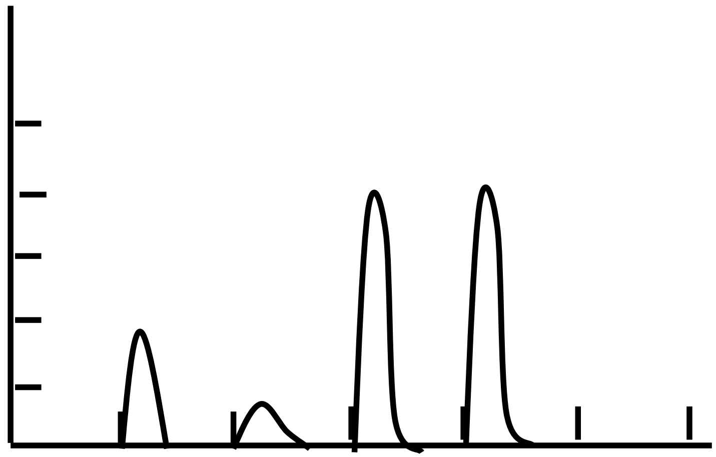
Digital Communications
Analog Communication System Model



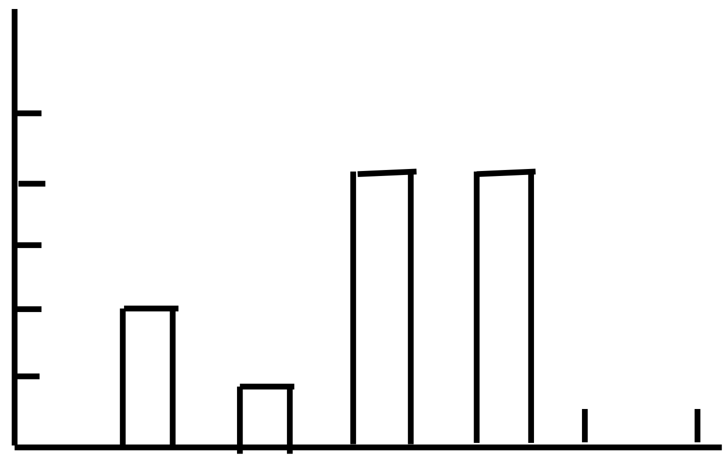
Digital Communications

Advantages of Digital Communications

- Finite number of possible values of a signal: Correct decision may be achieved even with distortion



(a) Waveform of distorted digital signal



(b) Waveforms of digital signal after shaping

Digital Communications

Advantages of Digital Communications

- Correct decision may be achieved even with distortion.
- Error correcting techniques can be used.
- Digital encryption can be used
- Digital signal can be compressed by source coding to reduce redundancy
- Different kinds of analog & digital message can be integrated to transmit
- Digital communication equipment:
  - Design and manufacture are easier
  - Weight & volume are smaller
- Output S/N increases with bandwidth according to exponential law

Digital Communications

Specifications of digital communication systems

- Performance figures of merit: efficiency & reliability (rate ~ accuracy)
  - A tradeoff between efficiency & reliability
- Transmission rate
  - Symbol rate: $R_B = \dfrac{1}{T}\ \mathrm{Bd}$
  - Information rate: R_b — bit/s (bps)
  - For M-ary system： $R_b = R_B \log_2 M$
  - Utilization factor of frequency band: spectral efficiency $\dfrac{R_b}{B}\ \mathrm{bit/s/Hz}$
  - Utilization factor of energy: energy efficiency $\dfrac{R_b}{P}\ \mathrm{bit/J}$

Digital Communications

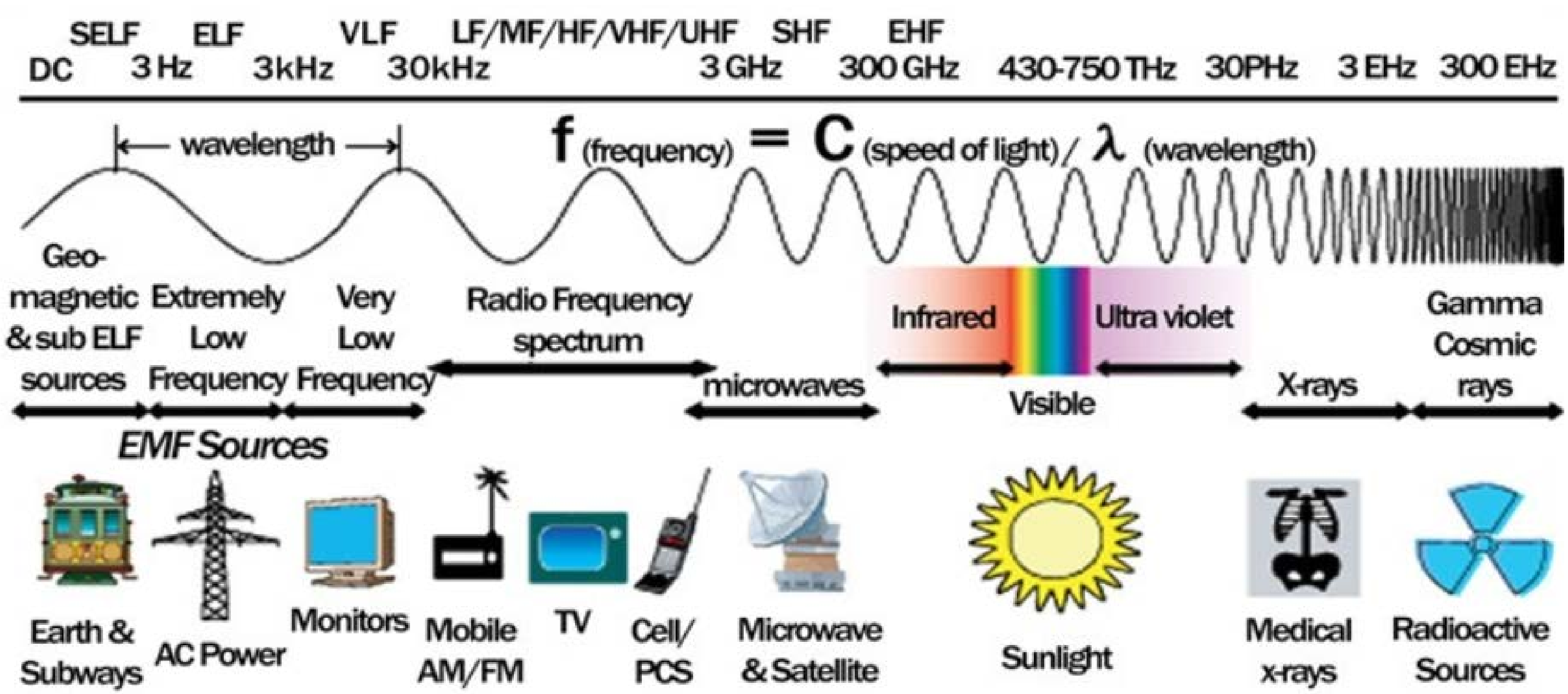
Error Probability

- Symbol error probability $P_e = \dfrac{\text{number of received symbols in error}}{\text{number of transmitted symbols}}$
- Bit error probability $P_b = \dfrac{\text{number of received bits in error}}{\text{number of transmitted bits}}$
- Word error probability $P_w = \dfrac{\text{number of received words in error}}{\text{number of transmitted words}}$
- For binary system
  - $P_e = P_b$
  - $P_w = 1 - (1 - P_e)^k$, if a word consists of k bits

Chapter 1: Introduction
Contents

Communications Channel
Wireless Channel

- Dimension of antenna >= 0.1*wavelength
- Division of frequency band (wavelength)



Communications Channel

Division of the Spectrum

Frequency band (KHz)	Name	Typical application
3 – 30 (VLF)	Very low frequency	Long-distance navigation Underwater comm. Sonar
30 – 300 (LF)	Low frequency	Navigation, underwater comm. radio beaconing
300 – 3000 (MF)	Medium frequency	Broadcasting maritime comm. direction-finding, distress calling, coast guard

Note: KHz = 10^3 Hz

Communications Channel

Division of the Spectrum

Frequency band (MHz)	Name	Typical application
3 – 30 (HF)	High frequency	Long-distance broadcasting, telegraph, telephone, fax, search and lifesaving, communications between aircrafts & ships, and between ship & coast, amateur radio
30 – 300 (VHF)	Very high frequency	TV, FM broadcasting, land traffic, air traffic, control, taxi, police, navigation, aircraft communications
300 – 3000 (UHF)	Ultra high frequency	TV, cellular phone network, microwave link, radio sounding, navigation, satellite communication, GPS, surveillance radar, altimeter radio

Note: MHz = 10^6 Hz

Communications Channel

Division of the Spectrum

Frequency band (GHz)	Name	Typical application
3 – 30 (SHF)	Super high frequency	Satellite comm., radio altimeter, microwave link, aircraft radar, meteorological radar, public land vehicle communication
30 – 300 (EHF)	Extremely high frequency	Radar landing system, satellite comm., vehicle comm., railway traffic
300 – 3000	Submillimeter wave （0.1 – 1 mm）	Experiment not designated

Note: GHz = 10^9 Hz, mm = 10^{-3} m

Communications Channel

Division of the Spectrum

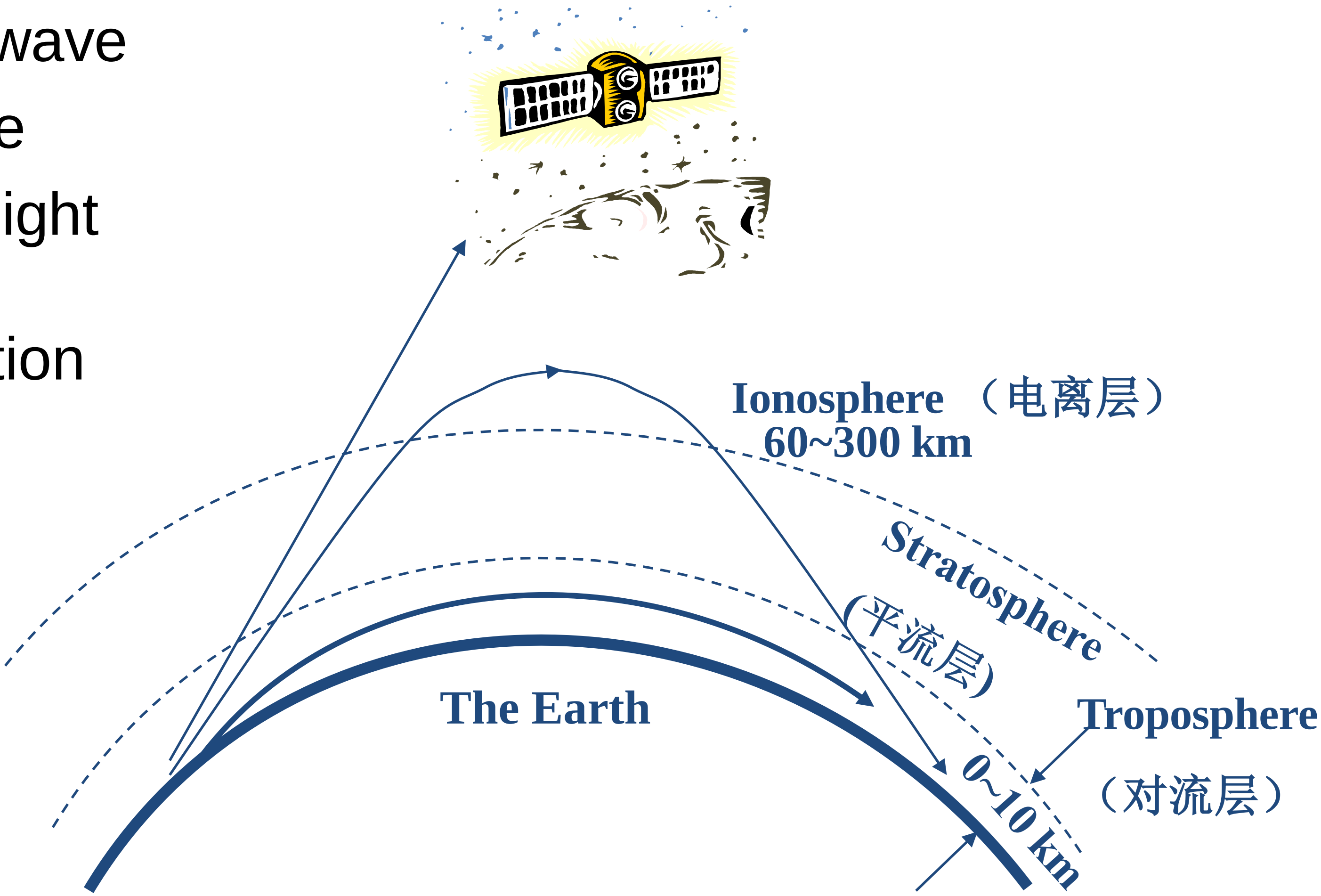
Frequency band (THz)	Name	Typical application
43 – 430	Infrared (7 – 0.7 μm)	Optical communication
430 – 750	Visible light (0.7 – 0.4 μm)	Optical communication
750 – 3000	Ultraviolet (0.4 – 0.1 μm)	Optical communication

Note: THz = 10^{12} Hz, μm = 10^{-6} m

Communications Channel

EM Wave Propagation

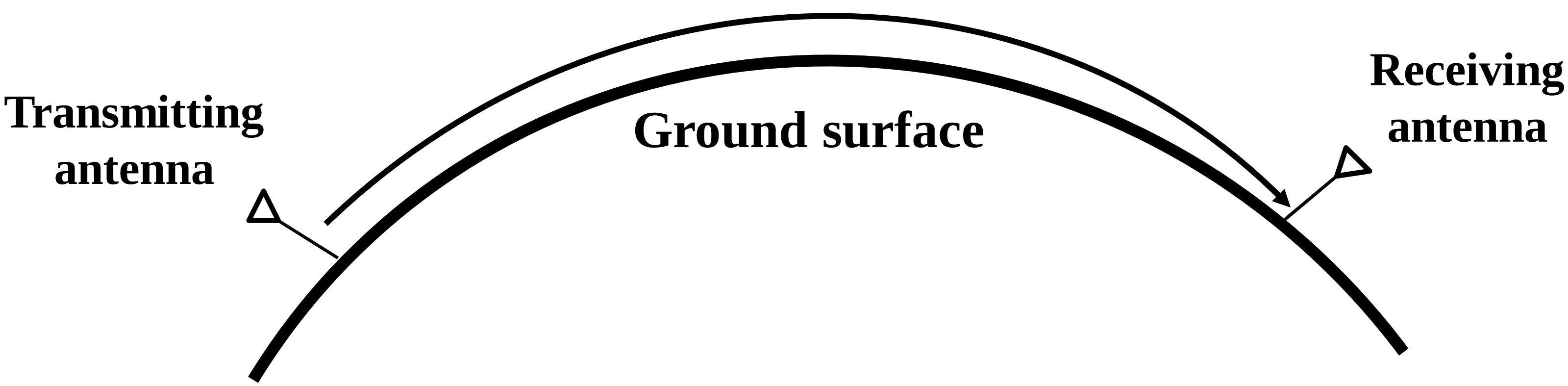
- Ground-wave
- Sky-wave
- Line-of-sight (LoS) propagation



Communications Channel

Ground Wave

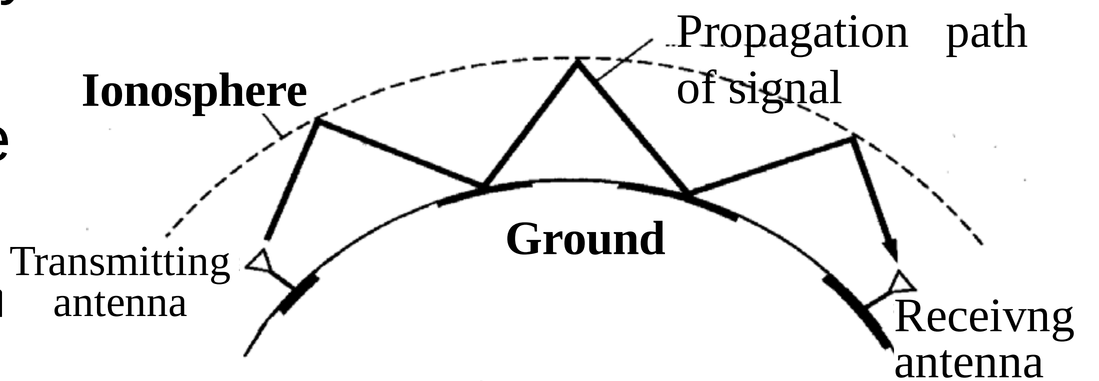
- Frequency: below 2MHz
- Property: diffraction
- Propagation distance: hundreds to thousands of km
- Applications: AM radio



Communications Channel

Sky Wave

- Frequency：2 ～ 30 MHz
- Property: reflection by ionosphere
- Propagation distance
  - One hop : <4000 km
  - Multi-hop: >10000 km
- Applications: long distance communications



Communications Channel

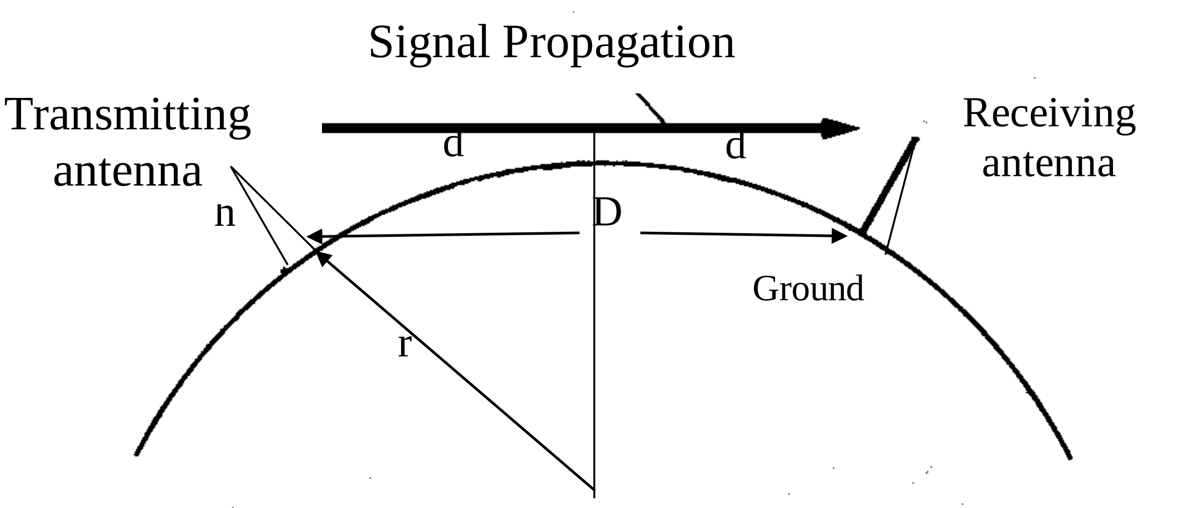
Line-of–sight (LoS) propagation

- Frequency: > 30 MHz
- Properties: penetrates the ionosphere, LoS transmission
- Propagation distance:

$$\boldsymbol{d^2 + r^2 = (h+r)^2}$$

$$\boldsymbol{h \approx D^2/50\ \text{(m)},\ D\ \text{in km}}$$

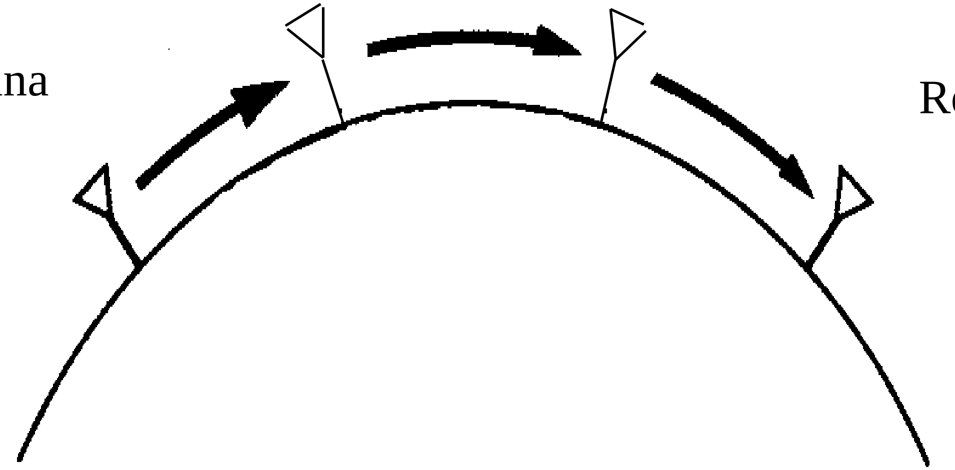
- Application: satelite communication, mmWave...



Communications Channel

Radio Relay

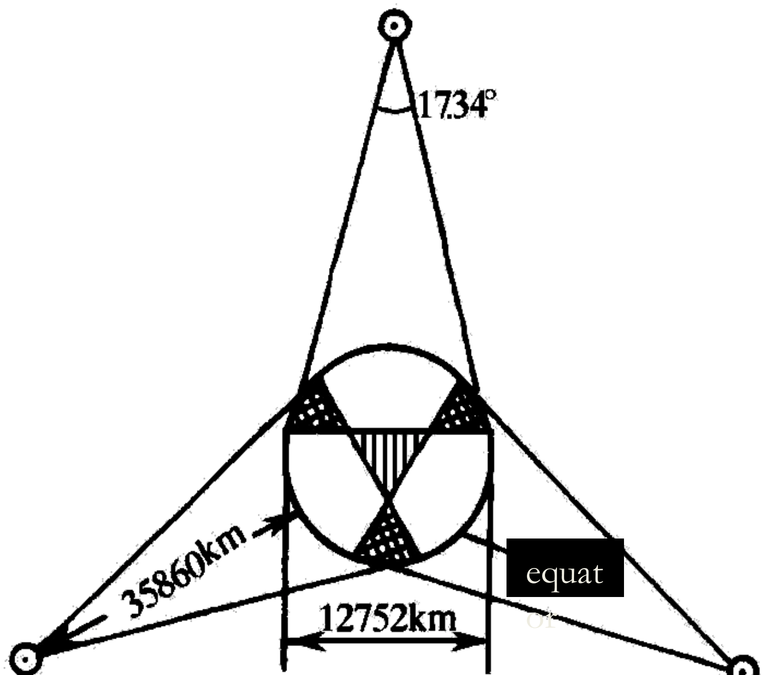
Transmitting antenna



Receiving antenna

Communications Channel

Geostationary Satellite



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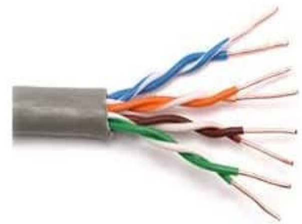
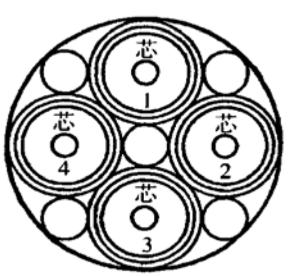
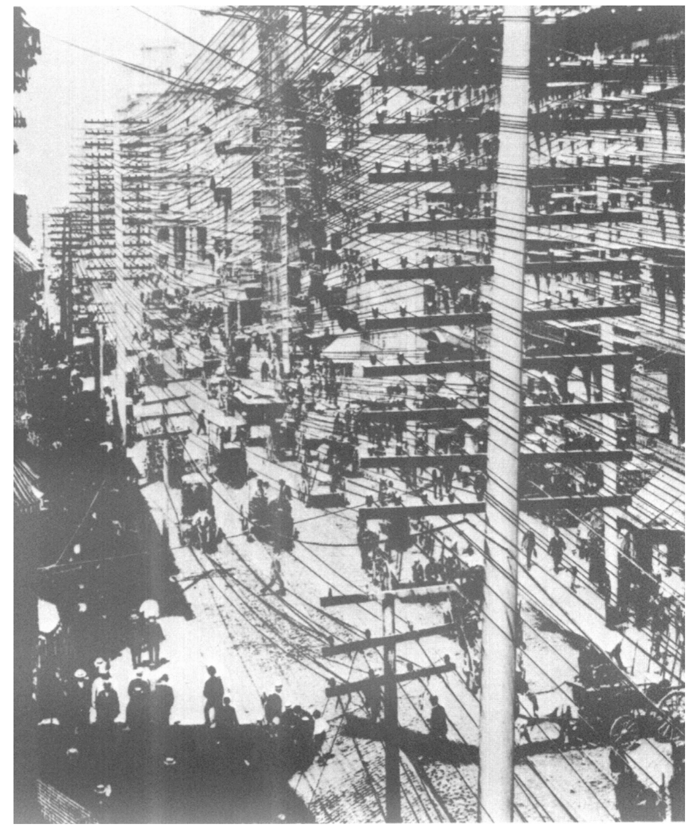
Communications Channel
Wired Channel

- Open wires
- Symmetrical cables
- Coaxial cables





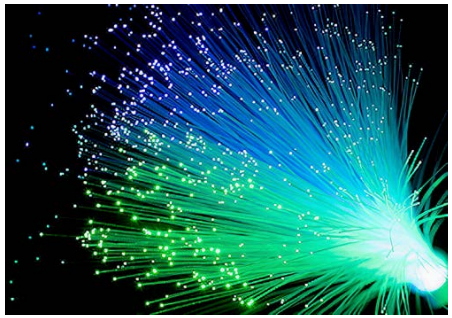
Communications Channel

General electrical characteristics of wired channels

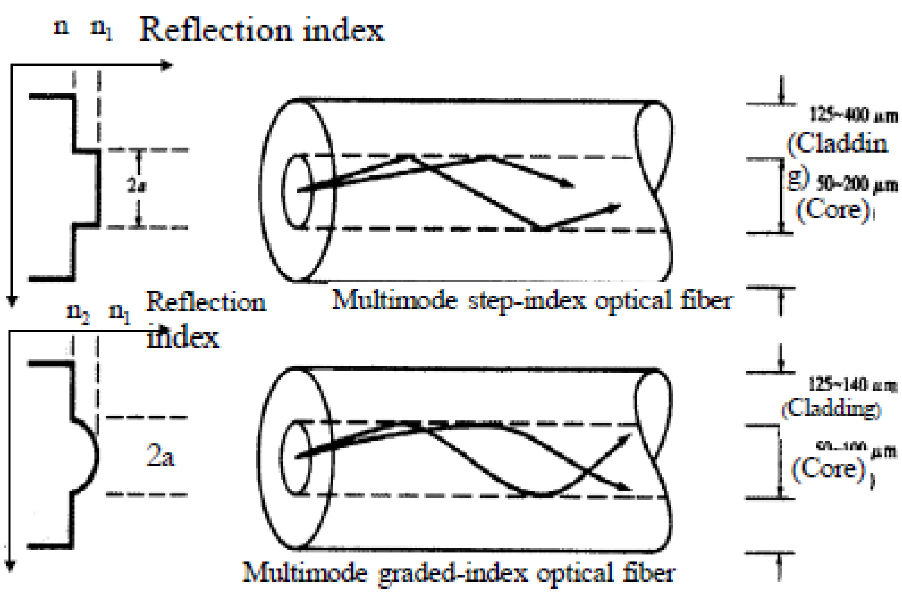
Kinds of channel	Communication capacity (channels)	Frequency range (kHz)	Transmission distance (km)
Open wire	1+3	03.~27	300
Open wire	1+3+12	0.3~150	120
Symmetrical cable	24	12~108	35
Symmetrical cable	60	12~252	12~18
Small coaxial cable	300	60~1300	8
Small coaxial cable	960	60~4100	4
Medium coaxial cable	1800	300~9,000	6
Medium coaxial cable	2700	300~12,000	4.5
Medium coaxial cable	10800	300~60,000	1.5

Communications Channel

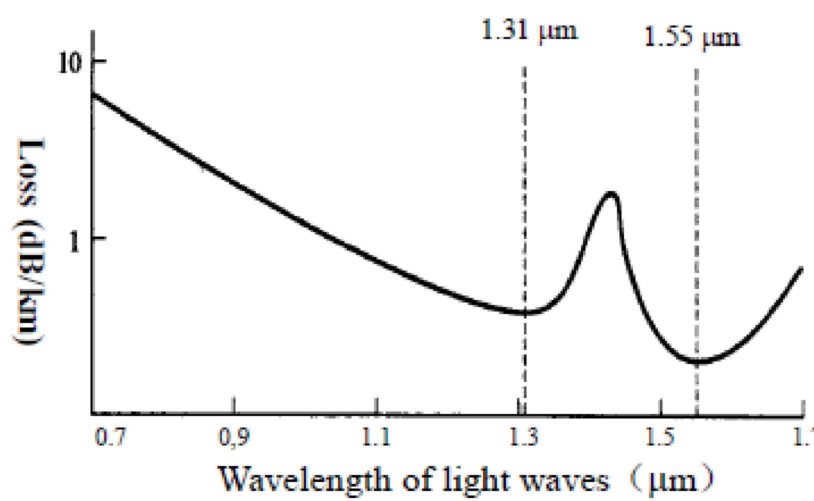
Optical Fiber



- **Structure**

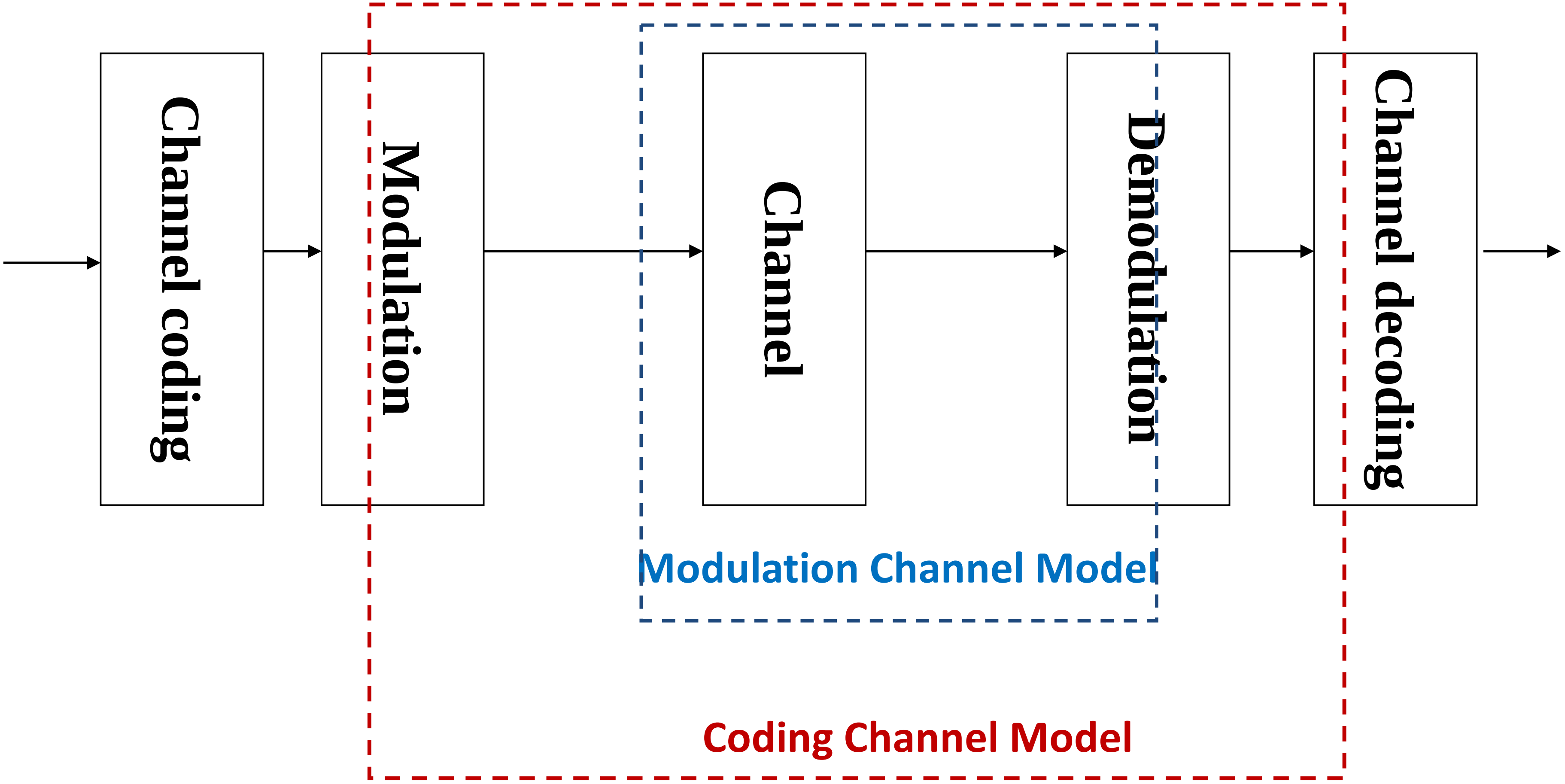


- **Transmission loss**



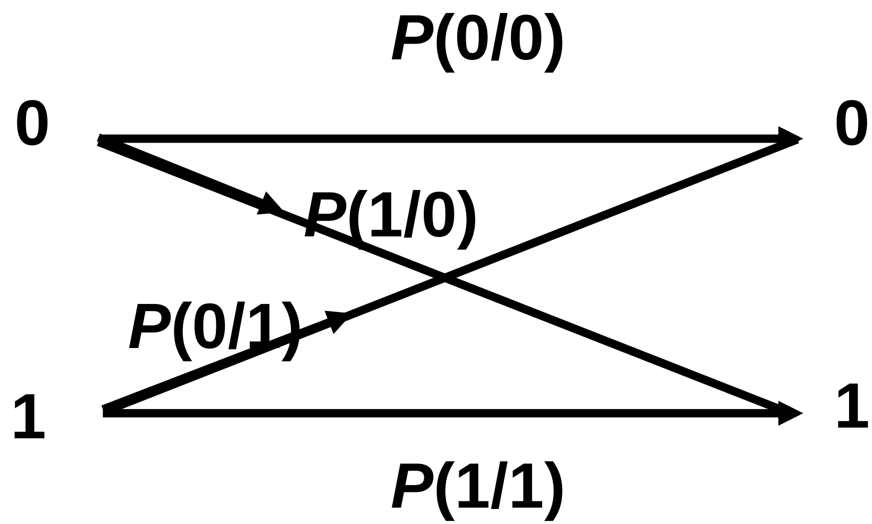
Communications Channel

Channel Models



Communications Channel

Binary Coding Channel Model

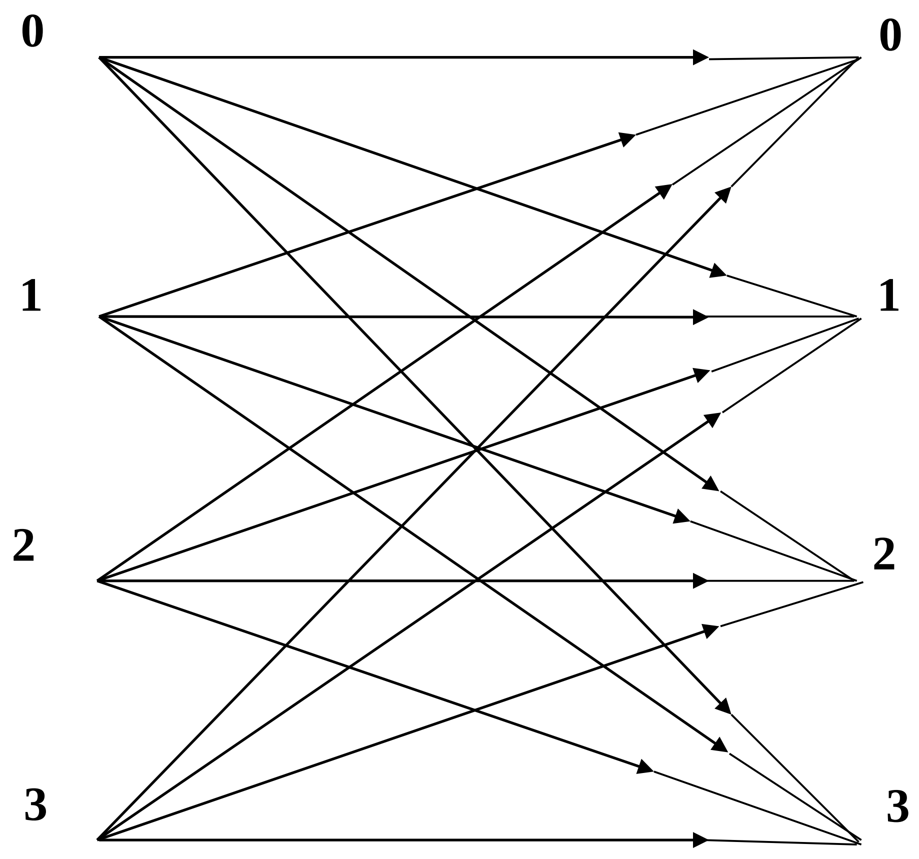


- $P(0/0)$, $P(1/1)$ - correct transfer probabilities
- $P(0/1)$, $P(1/0)$ - error transfer probabilities
- $P(0/0) = 1 - P(1/0)$
- $P(1/1) = 1 - P(0/1)$

Communications Channel

4-ary Coding Channel Model

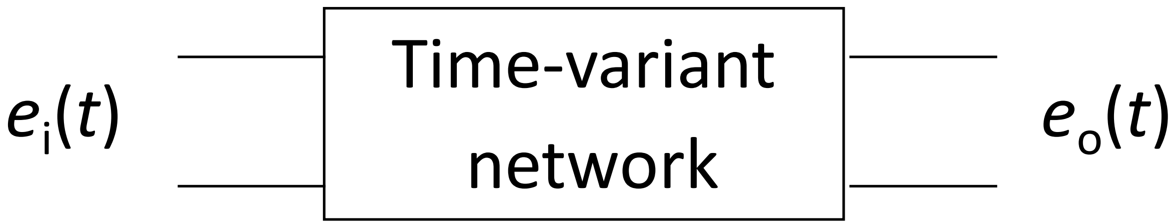
Transmitting end

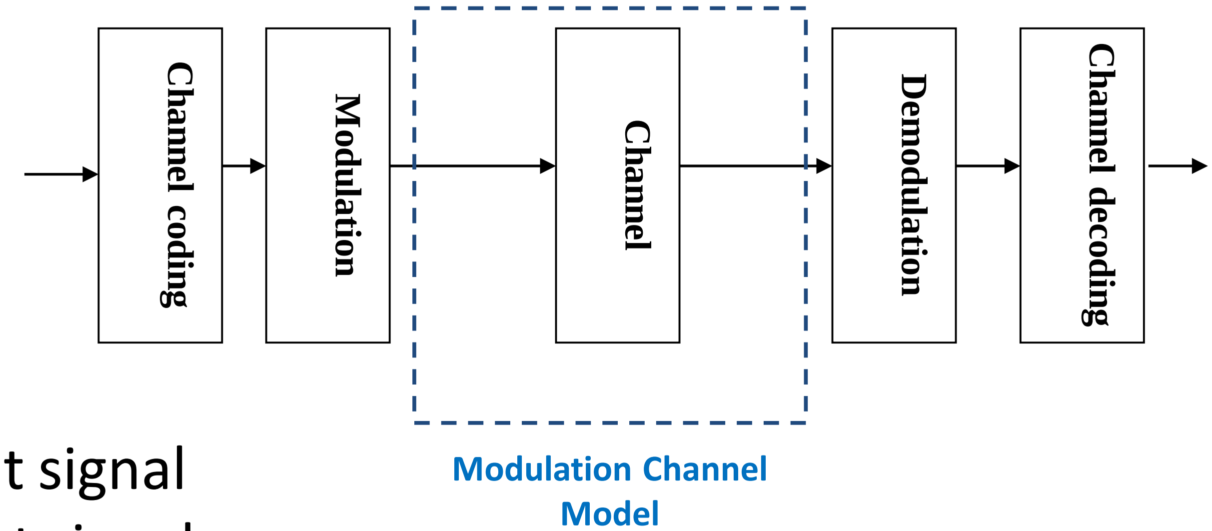


Receiving end

Communications Channel

Modulation Channel Model





- $e_o(t) = f\,[e_i(t)] + n(t)$

- where $e_i(t)$ — input signal
- $e_o(t)$ — output signal
- $n(t)$ — additive noise
- $f\,[e_i(t)\,]$ — function relating input and output signals

Communications Channel

Modulation Channel Model

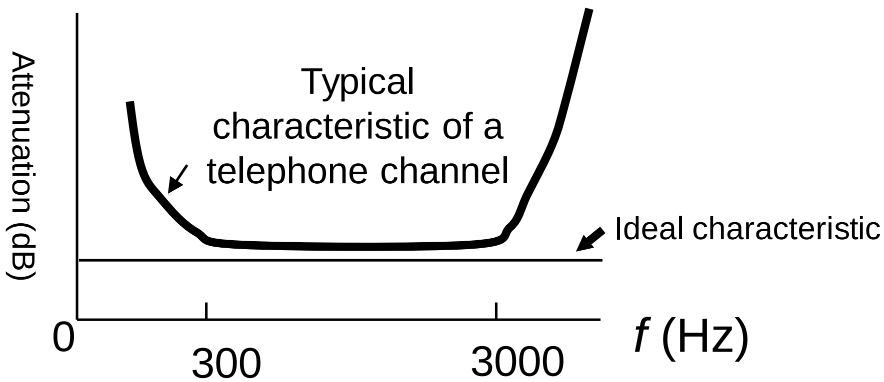
- Assume $f\,[e_i(t)\,]$ can be expressed as $k(t)\,e_i(t)$

$$e_o(t) = k(t)\,e_i(t) + n(t)$$

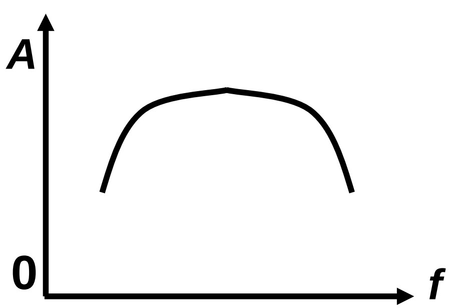
- $k(t)$
  - multiplicative interference
  - a complicated function which reflects the characteristics of the channel
- k(t) = const.: a constant parameter channel, e.g., coaxial cable
- k(t) $\neq$ const.: a random parameter channel, e.g., mobile communication channel

Communications Channel
Constant Parameter Channel

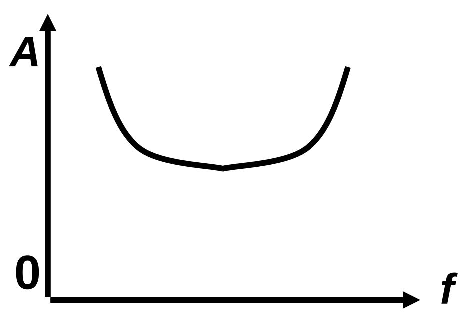
- Constant parameter channel ~ Time-invariant linear network
  - Amplitude ~ frequency characteristics



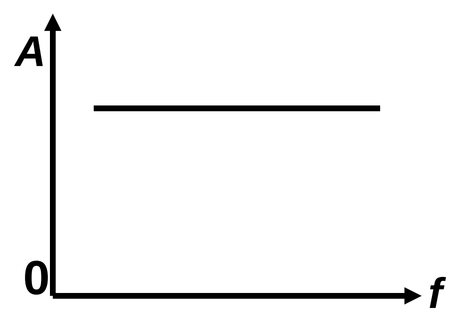
  - Compensation of frequency distortion



(a) Channel characteristic with frequency distortion



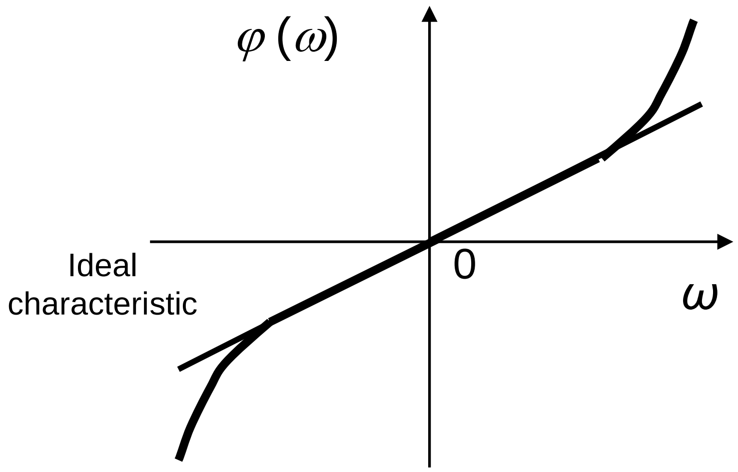
(b) Charact. of linear compensation network



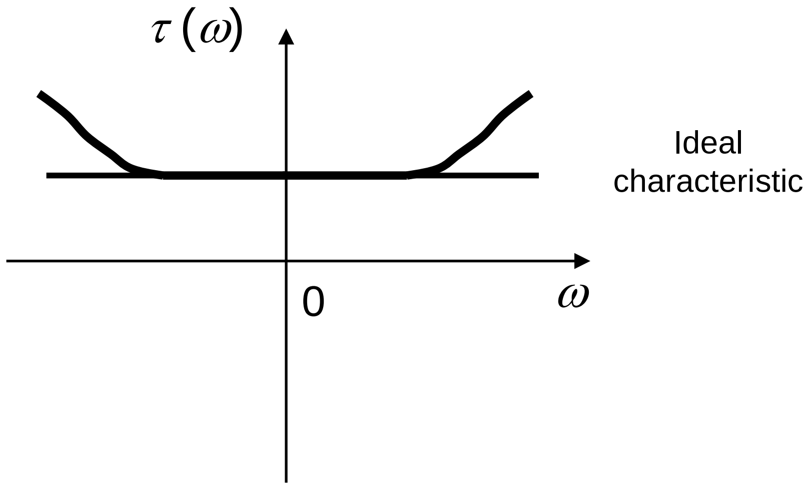
(c) Channel characteristic after compensation

Communications Channel

Phase/Frequency Characteristics



phase --- $\varphi\ (\omega) = k\ \omega$



group delay --- $\tau\ (\omega) = d\varphi(\omega)/d\omega = k$

- Influence of distortion: waveform distortion, inter-symbol interference
- Linear distortion including frequency distortion & phase distortion can be corrected by linear compensation network
- Nonlinear distortion: nonlinear amplitude characteristic, frequency deviation, phase jittering, …

Communications Channel
Random Parameter Channel

- Random parameter channel: Time-variant network
  - Common characteristics
    - Attenuation: varying with time
    - Transmission delay: varying with time
    - Multi-path propagation: fast fading
  - Characteristics of received signal
    - Let transmitting signal be $A\cos\omega_0 t$, after transmission through n paths, the received signal R(t) can be expressed as

$$R(t) = \sum_{i=1}^{n} r_i(t)\cos\omega_0[t-\tau_i(t)] = \sum_{i=1}^{n} r_i(t)\cos[\omega_0 t + \phi_i(t)]$$

r_i (t) — amplitude of received signal passing over *i*-th path
τ_i (t) — delay of the received signal passing over *i*-th path
φ_i (t) = $-\omega_0 \tau_i$ (t)

Communications Channel

Random Parameter Channel

$$R(t) = \sum_{i=1}^{n} r_i(t)\cos\omega_0[t-\tau_i(t)] = \sum_{i=1}^{n} r_i(t)\cos[\omega_0 t + \phi_i(t)]$$

$$R(t) = \underbrace{\sum_{i=1}^{n} r_i(t)\cos\phi_i(t)}_{X_c(t)}\cos\omega_0 t - \underbrace{\sum_{i=1}^{n} r_i(t)\sin\phi_i(t)}_{X_s(t)}\sin\omega_0 t$$

$$R(t) = X_c(t)\cos\omega_0 t - X_s(t)\sin\omega_0 t = V(t)\cos[\omega_0 t + \phi(t)]$$

$V(t) = \sqrt{X_c^{\,2}(t) + X_s^{\,2}(t)}$ – envelope of the received signal *R*(*t*)

$\phi(t) = \arctan\dfrac{X_s(t)}{X_c(t)}$ – phase of the received signal *R*(*t*)

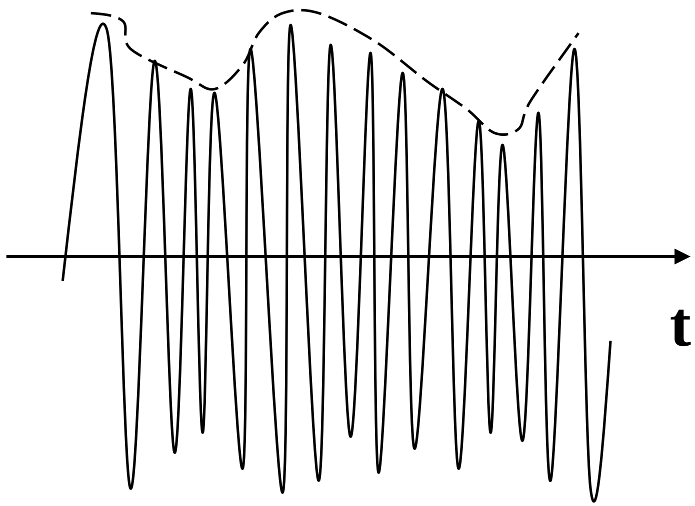
- $r_i(t)$ and $\varphi_i(t)$ are slowly varied compared to $\cos\omega_0 t$

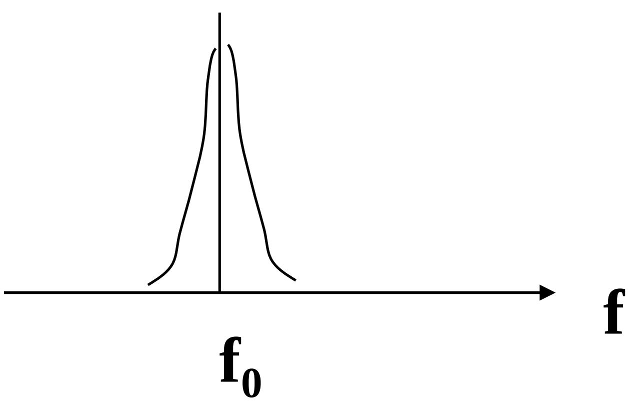
Communications Channel

Random Parameter Channel

$$R(t) = V(t)\cos[\omega_0 t + \phi(t)]$$

- After transmission, the transmitting signal $A \cos \omega_0 t$
  - Amplitude A becomes slowly varied amplitude $V(t)$
  - Phase 0 becomes slowly varied phase $\varphi(t)$
  - Spectrum becomes narrowband spectrum from single frequency

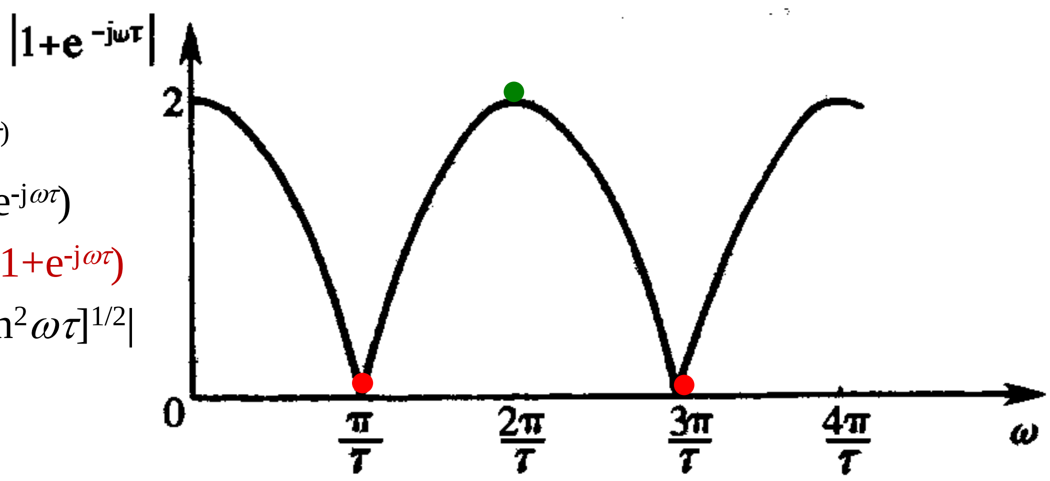




Communications Channel
Random Parameter Channel

- Suppose there are only two paths with identical attenuation and different delays
- Transmitting signal is f(t), received signals are $af(t - \tau_0)$ and $af(t - \tau_0 - \tau)$； spectrum of transmitting signal is $F(\omega)$

$$f(t) \Leftrightarrow F(\omega)$$
$$af(t - \tau_0) \Leftrightarrow a F(\omega)\, e^{-j\omega\tau_0}$$
$$af(t - \tau_0 - \tau) \Leftrightarrow a F(\omega)\, e^{-j\omega(\tau_0 + \tau)}$$
$$af(t - \tau_0) + af(t - \tau_0 - \tau) \Leftrightarrow a F(\omega)\, e^{-j\omega\tau_0} (1+e^{-j\omega\tau})$$
$$\therefore H(\omega) = a F(\omega)\, e^{-j\omega\tau_0} (1+e^{-j\omega\tau})/F(\omega) = ae^{-j\omega\tau_0} (1+e^{-j\omega\tau})$$
$$|1+e^{-j\omega\tau}| = |1+\cos\omega\tau - j\sin\omega\tau| = |[(1+\cos\omega\tau)^2+\sin^2\omega\tau]^{1/2}|$$
$$=2|\cos(\omega\tau/2)|$$



Chapter 1: Introduction

Contents

Noise in Channel
Definition and Classification

- Classified according to origin:
  - Man-made noise: electric sparks, …
  - Natural noise: lightning, atmosphere noise, thermal noise,...
- Classified according to characteristics:
  - Impulse noise
  - Narrowband noise
  - Fluctuation noise
- Main noise involved in communication systems:
  - White noise – thermal noise is a kind of typical white noise

Chapter 1: Introduction
Contents

1. Historical Review of Communication Systems
2. Message, Information and Signal
3. Digital Communications
4. Communications Channel
5. Noise in Communications Channel
6. Summary

Summary

- Messages, information and signals
  - Information contents
- Digital & analog communications
  - Digital & analog signals, system models, …
  - Performance figures of merit: Efficiency (rate) & reliability (accuracy)
- Channels
  - Wireless channel, wired channel
  - Modulation channel, coding channel
  - Constant & random parameter channels (modulation channel)
  - Noise

Principles of Communications (通信系统原理)

Undergraduate Course

Chapter 1: Introduction

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