Principles of Communications

Chapter I: Introduction

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教材与参考书目

- 张辉，曹丽娜，《现代通信原理与技术》，西安：西安电子科技大学出版社。
- 樊昌信,《Principles of Communications》（英文）, 北京：电子工业出版社，2010.7.
- 樊昌信，曹丽娜，《通信原理》（第六版），北京：国防工业出版社。
- John Proakis，《Digital Communications》(Sixth Edition).
- The slides used in this class can be downloaded from **web.xidian.edu.cn/ychwang**

Historical Review

Communication: Transmission and Exchange.

In this class, we focus on transmission technology.

- Origin of ancient communication: Beacon-fire
- Two modes of information communication
  - transferred by manpower or mechanical method, such as postal service;
  - transferred by electricity or optics, named telecommunication.
- Development of modern communication
  - (Land) Mobile communication: 3G/4G/5G;
  - Satellite communication;
  - Fiber communication;
  - ..., etc;

Message, information , and signal

- Message: speech, letters, figures, images etc...
- Information: effective content of message. "quantity of message" $\neq$ "information content".
- Signal: the carrier of message.

Measurement of Information

The information content I contained in a message should have the following attributes:

- I is a function of the occurrence probability $P(x)$ of the message, i.e., $I = I[P(x)]$.
- $P(x)$ is smaller, then I is larger.
- The information content contained in the message consisting of such independent events will equal to the sum of the information content of the message of each independent event, i.e., $I[P(x_1), \cdots, P(x_n)] = I[P(x_1)] + \cdots + P[(x_n)]$.

Definition of Information

Usually, we use the following definition of information

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

.

About parameter a

- If $a = 2$, the unit of I is bit;
- If $a = e$(natural logarithm, $e = 2.71828...$), the unit of I is nat;
- If $a = 10$, the unit of the I is hartley.

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Difference between analog/digital signals

- Analog: parameter is with analog information;
- Digital: parameter is with digital information;

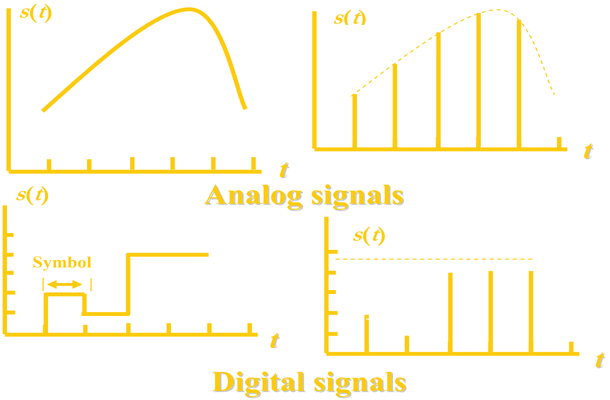

Figure: Comparison of analog signals and digital signals.

Advantages of digital communication

- Error correcting techniques can be used.
- Digital encryption can be used.
- Digital communication equipment:
  - Design and manufacture are easier.
  - Weight and size are smaller.
- Digital signal can be compressed by source coding to reduce redundancy.
- Output S/N increases with bandwidth according to exponential law.
- Correct decision may be achieved, suitable for relay system.
- Different kinds of analog and digital message can be integrated to transmit.
- Finite number of possible values of signals.
- ...

Digital Communication Model

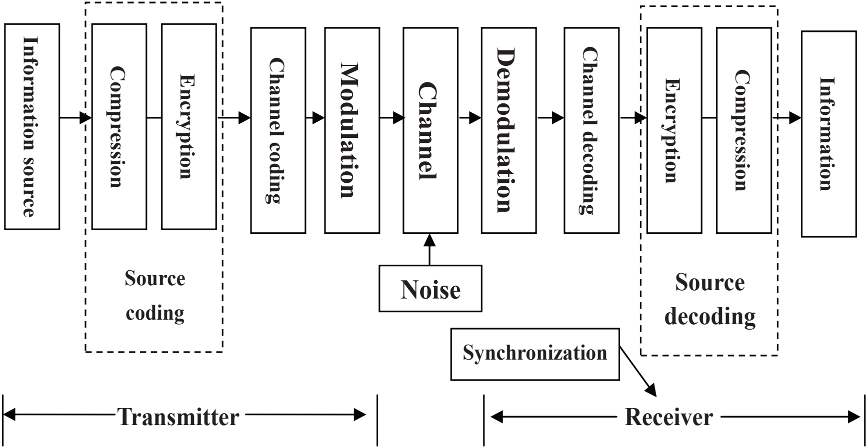

Figure: Digital communication system model.

Functions of the Units

- Source coding and decoding: Compression (PCM and ΔM, in chapter 4) and Encryption.
- Channel coding: error control coding: convolutional coding, turbo coding, LDPC coding.
- Modulation: ASK, PSK, FSK, APK (in chapter 6).
- Channel: fading channel, additional white gaussian noise (AWGN).
- Synchronization: carrier sync, bit sync, group sync. (in chapter 7)

Efficiency and Reliability of Digital Communication System

Efficiency measures

- Transmission Rate
  - Symbol rate (R_B): The number of symbols transmitted in unit time (s). Baud, symbols/s.
  - Information rate (R_b): The number of bits transmitted in unit time (s). bit/s.
  - For a M-ary system, $R_b = \log_2 M \cdot R_B$.
  - For a discrete information resource, each entry is with probability $P(x_i)$ and independent. Its entropy (average information content per symbol) is

$$H(x) = -\sum_{i=1}^{n} P(x_i) \log_2 P(x_i).$$

    Then, we have $R_b = HR_B$
- The utilization factor of frequency band: $\eta = \frac{R_B}{B}$ or $\eta = \frac{R_b}{B}$. Baud/Hz, bit/s/Hz.

Efficiency and Reliability of Digital Communication System

Reliability measures: Error Probability

- Symbol error probability P_e (Two definitions)
  - obtain in practice (simulation):

$$P_e = \frac{\text{the number of the received symbols in error}}{\text{the total number of the transmitted symbols}}$$

.

  - obtain in theory (analytic expression): the error probability of transmitted symbol through the channel.
- Bit error probability P_b.
- Relation between P_e and P_b: $P_e \geq P_b$. If Gray code is applied to M-ary symbol, we have

$$P_b \approx \frac{P_e}{\log_2 M}$$

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Wireless Channel

The transmission of signals is transmitted/received by the propagation of electromagnetic waves in space.

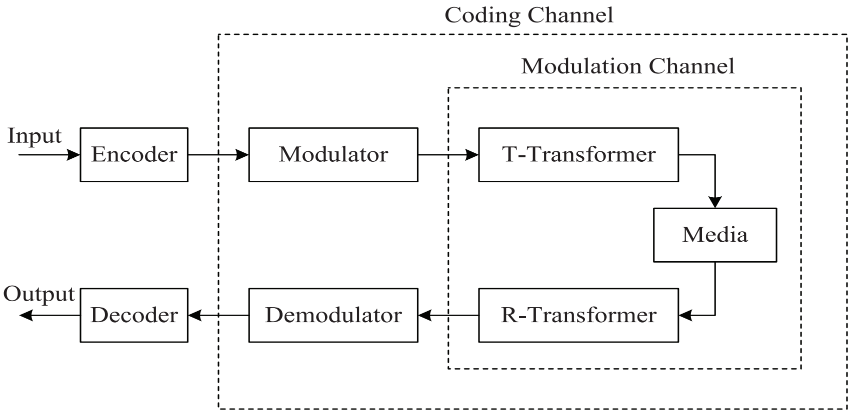
- Division of frequency band.
- Ground wave propagation: frequency $\leq$ 2MHz. diffraction ability.
- Sky wave propagation
  - reflected by the ionosphere: frequency $2 \sim 30MHz$.
  - short distance line-of-sight: ground relay $\leq 50km$.
  - long distance line-of-sight: satellite communication, stratosphere communication (HAPS: high altitude platform station, $3 \sim 22km$).
  - Scattering: Troposphere scattering/Meteor-tail scattering.
  - Besides, Cellular communications.

Wired Channel

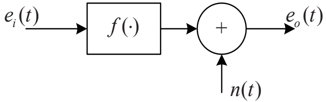
- open wires: rarely used now.
- symmetrical cables: telephone.
- coaxial cables: CATV.
- fiber, invented by Chinese (高昆Nobel Prize laureate, also named "Father of Fiber Communications"). Transmission loss is about 0.2dB/km. Transmission rate: could be more than 100Gbit/s.

Channel Models

There are different definitions of channels for the discussion of communication system performance.



Modulation Channel



The relationship between the input $e_i(t)$ and the output $e_o(t)$ can be expressed as

$$e_o(t) = f[e_i(t)] + n(t).$$

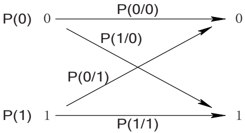
Normally, $f[e_i(t)]$ can be expressed as the convolution of unit impulse response and input signal, i.e.,

$$e_o(t) = e_i(t) * c(t,\tau) + n(t)$$

According to the characteristics of the $c(t,\tau) \leftrightarrow C(\omega)$ in the range of signal frequency band, we have

- $C(\omega)$ is constant, i.e, $e_o(t) = ce_i(t) + n(t)$.
- $C(\omega)$ is time-invariant, i.e., $e_o(t) = e_i(t) * c(t) + n(t)$.
- $C(\omega)$ is time-variant, i.e., $e_o(t) = e_i(t) * c(t,\tau) + n(t)$.
- examples in the practice.

Coding Channel



- Coding channel is digital channel or discrete channel. Its inputs and outputs are discrete/digital signals. The influence on the signal is to change input digital sequences into another kind of output digital sequences. Due to channel noise or other factors,it will cause output errors. Therefore the relationship between input, output digital sequences can be represented by a group of transition probability.
- $P(0)$ and $P(1)$ are the prior probability of sending "0" and "1"; $P(0/0)$ and $P(1/1)$ are correct transition probability; $P(1/0)$ and $P(0/1)$ are error transition probability.
- The bit error rate (BER) is $P_b = P(0)P(1/0) + P(1)P(0/1)$.

Constant Parameter Channel

- The influence that constant parameter channel on signals is sure or changed extremely slow. The amplitude-frequency characteristic and phase-frequency characteristic are used to describe the influence. $H(\omega) = |H(\omega)|e^{-j\varphi(\omega)}$.
- Ideal constant parameter channel characteristic:
  - $|H(\omega)| = K$;
  - $\varphi(\omega) = \omega\tau$. Or $\frac{\partial\varphi(\omega)}{\partial\omega} = \tau$.
  - What do they mean? Pictures? Impulse response $h(t)$=?
- Amplitude frequency distortion: attenuation, for different frequency components, are different.
- Phase frequency distortion: delay, for different frequency components, are different.

Random Parameter Channel

- the transmission attenuation varies with time;
- transmission delay varies with time;
- multipath effect.

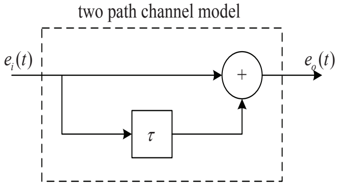
Assuming that the transmitting signal be $A \cos \omega_0 t$, and let it propagate to the receiver over n paths, the received signal

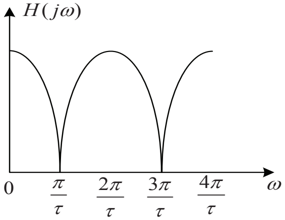
$$R(t) = \sum_{i=1}^{n} r_i(t) \cos \omega_0 [t - \tau_i(t)] = \sum_{i=1}^{n} r_i(t) \cos \omega_0 t + \varphi_i(t).$$

Let $X_c(t) = \sum_{i=1}^{n} r_i(t) \cos \varphi_i(t)$ and $X_s(t) = \sum_{i=1}^{n} r_i(t) \sin \varphi_i(t)$, we obtain $R(t) = X_c(t) \cos \omega_0 t - X_s \sin \omega_0 t = V(t) \cos[\omega_0 t + \varphi_i(t)]$.

- What are the characteristics of the current $R(t)$?

Random Parameter Channel





Two path channel-Selective frequency fading channel

- Impulse response, $h(t) = \delta(t) + \delta(t - \tau)$;
- Transfer function, $H(j\omega) = 1 + e^{-j\omega\tau}$;
- Some frequency (fading to zero): π/τ, $3\pi/\tau \cdots$;
- To avoid fading, transmitted signal should locate between the two zero points;
- Coherent bandwidth: $\Delta f = 1/\tau$. Pulse width $3\tau < T_s < 5\tau$.
- How about multi-path?

Noise

Noise always exists in communication systems. Since such noise is superimposed on the signal, it is called additive noise.

Category

- According to the sources: man-made noise and natural noise.
- According to the characteristics: temporal/frequency
  - impulse noise:
  - Narrow band noise:
  - Fluctuation noise: thermal noise power

$$P = 4kTB,$$

    where $k = 1.38 \times 10^{-23}$ is called the Boltzmann constant, T is the thermodynamic temperature (^{o}K);
  - In the communication system, the noise is usually additive white gaussian noise.

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Channel Capacity

Definition

- Channel capacity is the tightest upper bound on the rate of information that can be reliably transmitted over a communications channel.
- We define two kinds of generalized channel models： modulation model and coding channel.
  - Modulation channel is continuous, which should be characterized by channel capacity of continuous channel；
  - Code channel is discrete， which is characterized by channel capacity of discrete channel.
- Here we only study the former.

Shannon Formula

- For some continuous channel, frequency bandwidth is $B(Hz)$, input signal is $x(t)$， the noise $n(t)$ is Gaussian and white, and the output is

$$y(t) = x(t) + n(t)$$

- Power of input signal is S, power of channel noise is N， mean and variance of $n(t)$ is zero and σ_n^2， respectively, and power spectrum density is n_0. Channel capacity is characterized by

$$C = B\log_2\left(1 + \frac{S}{N}\right)(b/s) \qquad N = n_0 B$$

- The above is **Shannon formula**.
- It gives the maximum transmission rate under the given parameters.
- 只要传输速率小于等于信道容量，则总可以找到一种信道编码方式，实现无差错传输；若传输速率大于信道容量，则不可能实现无差错传输。

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Some results from Shannon formula

- Channel capacity C is increased while increasing signal power S.
$$\lim_{S\to\infty} C = \lim_{S\to\infty} B\log_2\left(1+\frac{S}{n_0 B}\right)\to\infty$$
- Channel capacity C is increased while reducing noise power.
$$\lim_{N\to 0} C = \lim_{N\to 0} B\log_2\left(1+\frac{S}{N}\right)\to\infty$$
- Channel capacity C is increased while increasing signal bandwidth.
$$\lim_{B\to C} = \lim_{B\to\infty} B\log_2\left(1+\frac{S}{n_0 B}\right)\approx 1.44\frac{S}{n_0}$$
- Shannon formula only gives the upper bound of information transmission rate. But don't show how to realization.

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Applications

- For the desired channel capacity C， B and S/N have different choice。
- If increasing channel frequency bandwidth, we can use smaller signal-to-noise ratio S/N, and vice versa.
- If signal-to-noise ratio S/N is fixed, increasing B can reduce transmission time.
- If channel capacity C is fixed, we can use ($B1$, $S1/N1$) and ($B2$,$S2/N2$), i.e.,

$$B_1 \log_2 \left(1 + \frac{S_1}{N_1}\right) = B_2 \log_2 \left(1 + \frac{S_2}{N_2}\right)$$

- This gives great freedom for designing system.

Example

A picture consists of 2.25×10^6 pixels. Each pixel is expressed by 16 levels and each level is with equal possibility. Assume the channel $B = 3KHz$, $S/N = 30dB$. Determine minimum time of transmitting the picture.

- Information in each pixel

$$I_i = \log_2 \frac{1}{P(N_i)} = \log_2 16 = 4bit$$

- Information of the whole picture

$$I_{total} = 2.25 \times 10^6 \times I_i = 9 \times 10^6 bit/s$$

- Channel capacity

$$C = B \log_2 \left(1 + \frac{S}{N}\right) = 3 \times 10^3 \times \log_2(1 + 10^3) \approx 3 \times 10^4 bit/s$$

- Minimum time

$$t_{min} = \frac{I_{total}}{C} = 300s$$

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