Principles of Communications

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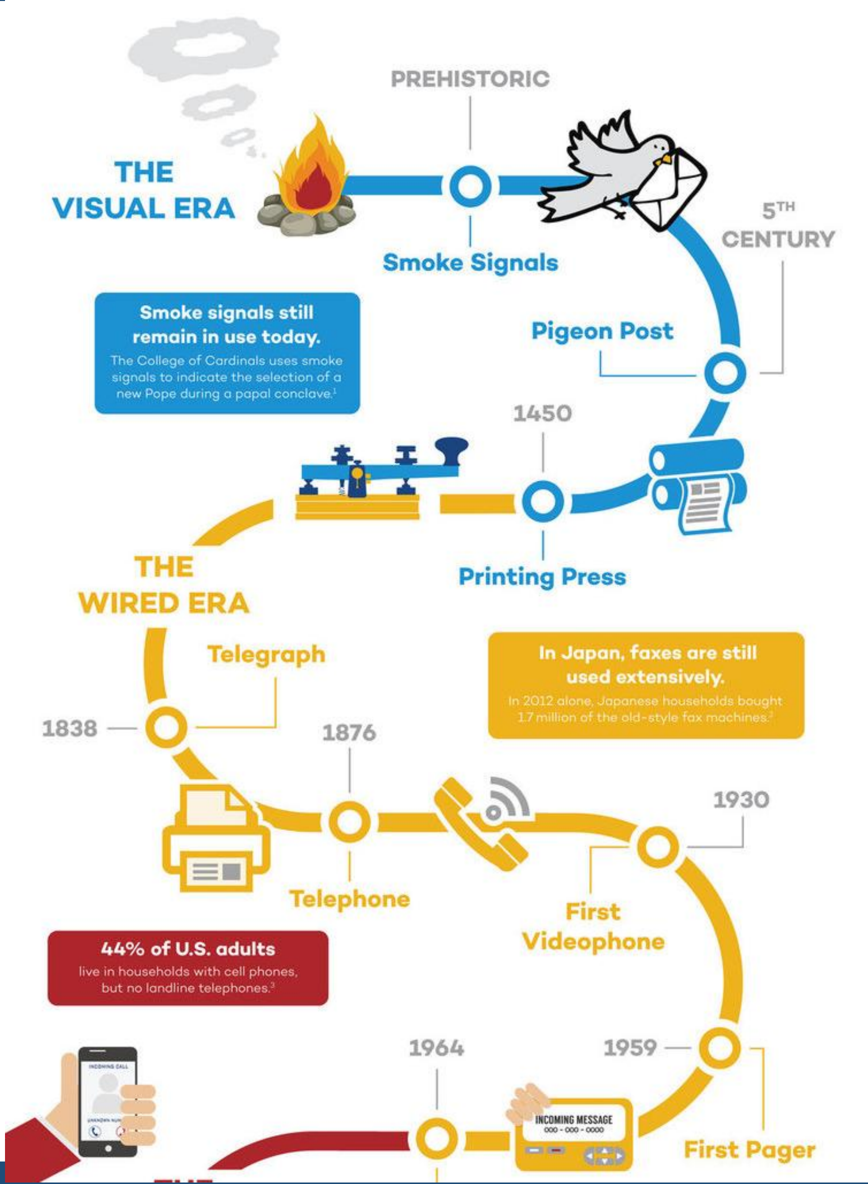
Content

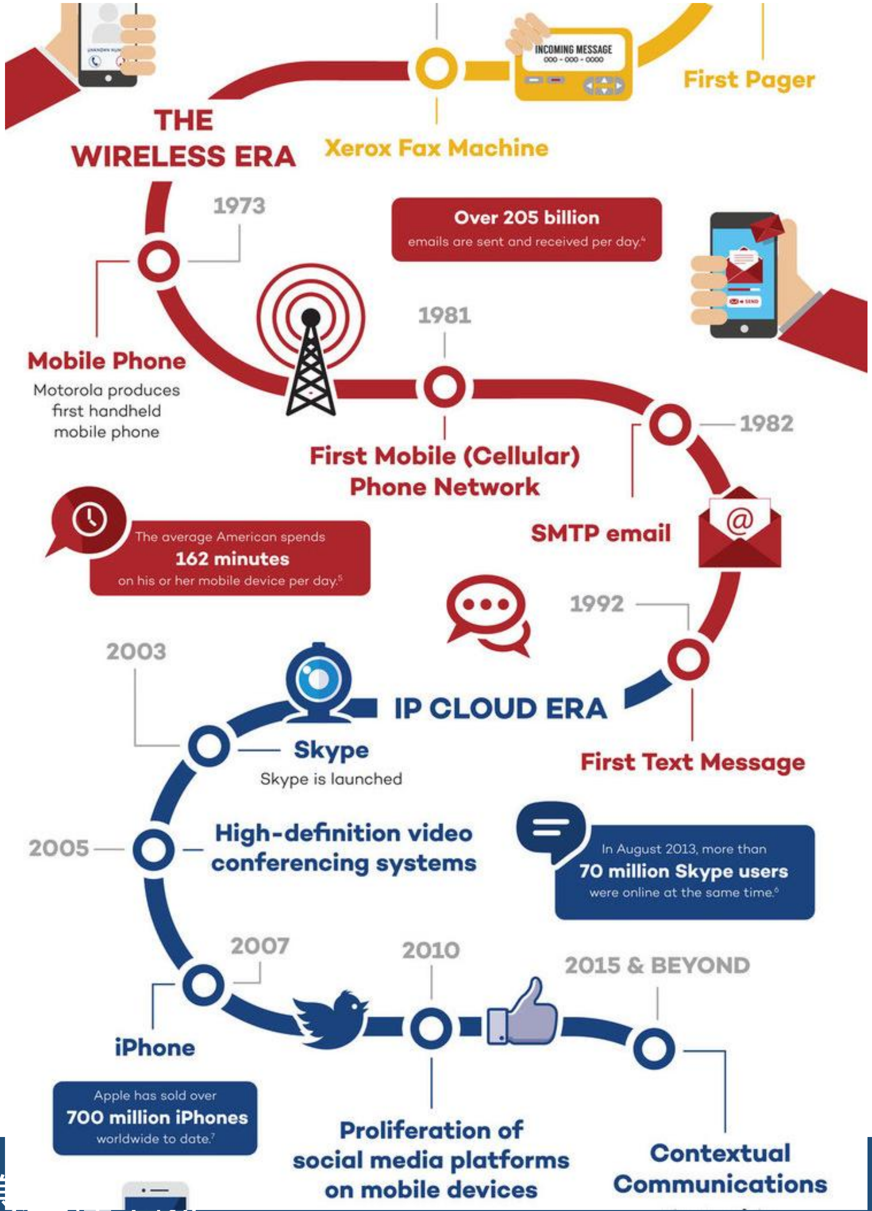
- Historical Review of Communication
- Message, information & signal
- Digital Communication
- Channel
- Noise in Channel

Historical Review of Communication

- ◆Historical Review of Communication
- ◆Message, information & signal
- ◆Digital Communication
- ◆Channel
- ◆Noise in Channel

Historical Review of Communication





Historical Review of Communication

Milestone events：

Time	Who	Invention/Contribution
1837	Morse	wired telegraph
1875	Emile Baudot	fixed-length telegraph encoding
1924	Nyquist	gives the maximum usable signaling rate without inter-symbol interference
1928	Hartley	maximum data rate for reliable communication
1939 and 1942	Kolmogorov and Wiener	optimal linear (Kolmogorov-Wiener) filters
1947	Kotelnikov	coherent demodulation based on geometric methods
1948	Shannon	information theory
1950	Hamming	error control coding method

Message, information & signal

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Message, information & signal

Differences of the three terms

- Message: The physical form of the information ,such as image, letter, speech
- Information: The effective content of message, what ever you wish to communicate
- Signal: The carrier of message, which be transferred on physical channels

◆ The uncertainties in the message make up the information

◆ The uncertainties of the event can be described with the probability of event occurring

◆ The information amount in the message is closely related to the probability of the message occurring.

Message, information & signal

The relationship : information amount I & the probability $P(x)$:

- The amount of information is a function of the probability, i.e. $I = f\left[P(x)\right]$
- Smaller $P(x)$, the larger I
- $P(x) \to 1$, $I \to 0$; $P(x) \to 0$, $I \to \infty$
- If the events in the message are mutually independent , the information is additive, i.e.

$$I\left[p(x_1)\,p(x_2)\cdots\right] = I\left[p(x_1)\right] + I\left[p(x_2)\right] + \cdots$$

Message, information & signal

The relationship between the information amount I and the probability $P(x)$ can be formulated as:

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

Note:

When a=2, the unit is bit

When a=e, the unit is nit

When a=10, the unit is hartley

Message, information & signal

Example-1： The binary discrete information source transmits symbol 0 or 1 with equal probability, then the information amount of each symbol is

$$I(0) = I(1) = \log_2 \frac{1}{1/2} = \log_2 2 = 1(bit)$$

Example-2： For a discrete source, M waveforms are transmitted with equal probability (P=1/M), and the appearance of each waveform is independent (memoryless source), and the amount of information of each M-ary waveforms is

$$I = \log_2 \frac{1}{P} = \log_2 \frac{1}{1/M} = \log_2 M\,(bits)$$

$$M = 2^k \Longrightarrow I = \log_2 2^K = k$$

Message, information & signal

The discrete source is a symbol set consisting of n symbols

the probability of each symbol xi (i=1, 2, 3, ..., n) occurrence is $P(x_i)$ $\sum_{i=1}^{n} P_i = 1$

The amount of information of each symbol is

$$x_1, x_2, \cdots, x_n$$

$$-\log_2 P(x_1) \quad -\log_2 P(x_2), \cdots, -\log_2 P(x_n)$$

The average amount of information of each symbol is

$$H(x) = P(x_1)\left[-\log_2 P(x_1)\right] + P(x_2)\left[-\log_2 P(x_2)\right] + \cdots + P(x_n)\left[-\log_2 P(x_n)\right]$$

$$= -\sum_{i=1}^{n} P(x_i)\left[-\log_2 P(x_i)\right]$$ bits/symbol

Message, information & signal

Example-3: A discrete information source is composed of four symbols 0, 1, 2, and 3. Their occurrence probabilities are 3/8, 1/4, 1/4, 1/8, respectively, and the occurrence of each symbol is independent. Try to find the information amount of the message:

20102, 01302, l3001, 20321, 0l003, 2l0l0, 02310, 20020, 10312, 03210, 01202, l0

Solution:

In this message, 0 appears 23 times, 1 appears 14 times, 2 appears 13 times, 3 appears 7 times, and there are 57 symbols in total, so the information volume of this message is

$$I = 23\log_2\frac{8}{3} + 14\log_2 4 + 13\log_2 4 + 7\log_2 8 = 108 \ \text{bits}$$

The average information amount of each symbol is

$$\bar{I} = \frac{I}{\text{symbol number}} = \frac{108}{57} = 1.89 \quad \text{bits/symbol}$$

Message, information & signal

Example-3: A discrete information source is composed of four symbols 0, 1, 2, and 3. Their occurrence probabilities are 3/8, 1/4, 1/4, 1/8, respectively, and the occurrence of each symbol is independent. Try to find the information amount of the message:

20102, 01302, I3001, 20321, 0I003, 2I0I0, 02310, 20020, 10312, 03210, 01202, I0

Solution:

Calculate the entropy

$$H = -\frac{3}{8}\log_2\frac{3}{8} - \frac{1}{4}\log_2\frac{1}{4} - \frac{1}{4}\log_2\frac{1}{4} - \frac{1}{8}\log_2\frac{1}{8} = 1.906 \quad \text{bits/symbol}$$

The information amount of the message

$$I = 57 \times 1.906 = 108.64 \quad \text{bits}$$

Question: why we obtain two different amount of information using the 2 methods?

Digital Communication

- Historical Review of Communication
- Message, information & signal
- **Digital Communication**
- Channel
- Noise in Channel

Digital Communication

Basic concept

Two categories of signals

1、Analog signal: The parameter is continuous (infinite values within a certain range)

E.g. speech signal

Attention: not necessarily continuous in time.

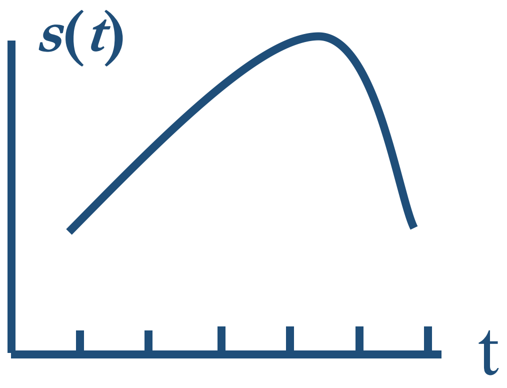
2、Digital signal: The parameters are discrete or countable

E.g. digital computer data signal

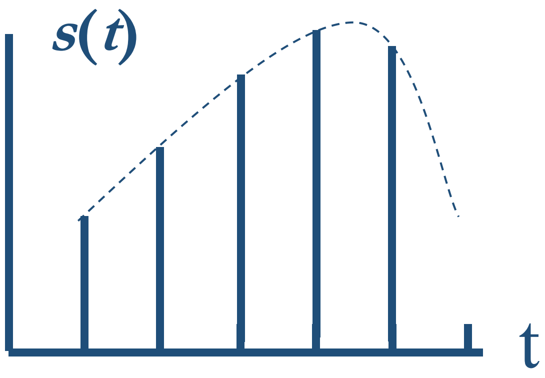
Attention: not necessarily discrete in time.

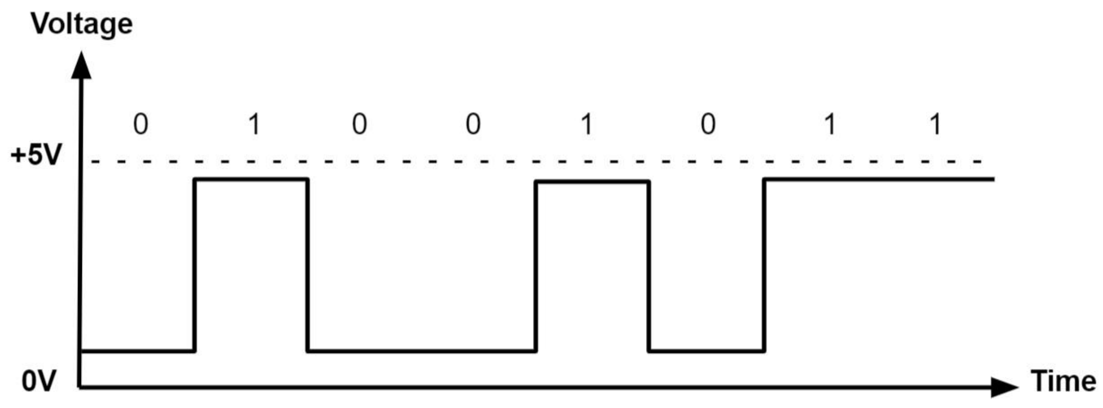
Digital Communication

Basic concept

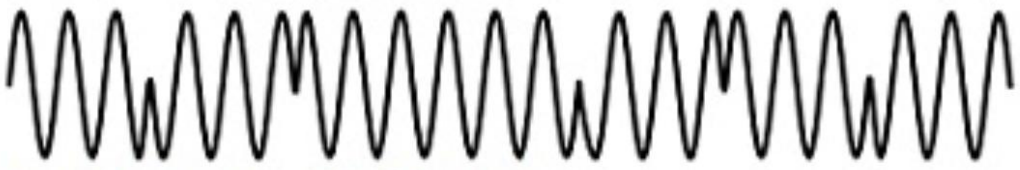


Analog signal





Digital signal



Digital Communication

Two kinds of comm. systems

1、 Analog communication system: uses analog signals to convey information.

Requirement － High fidelity

Criterion － Signal to noise ratio

Basic issue － parameter estimation

2、 Digital communication system : digital signal is used as a carrier to transmit a message, or a carrier is digitally modulated before transmission.

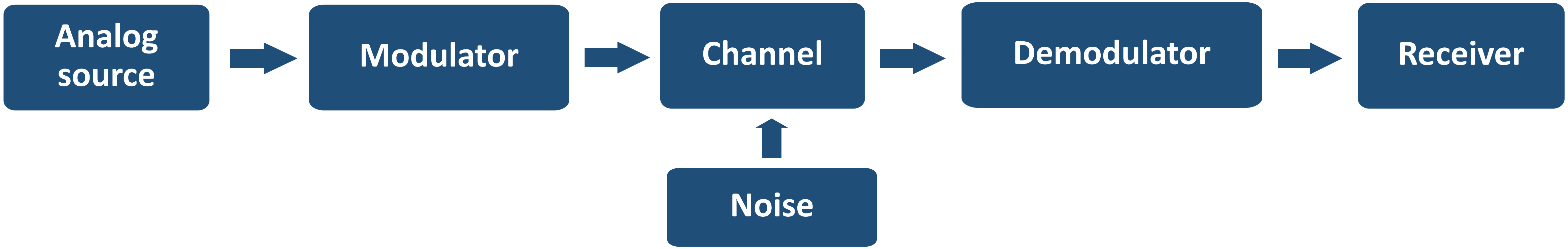
Requirement － correct decision

Criterion － Error probability

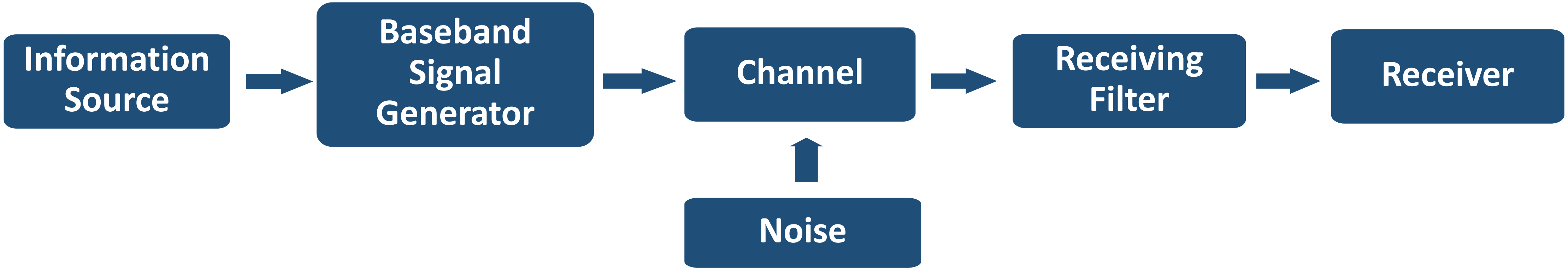
Basic issue － statistical decision theory

Digital Communication

A framework of analog communication system

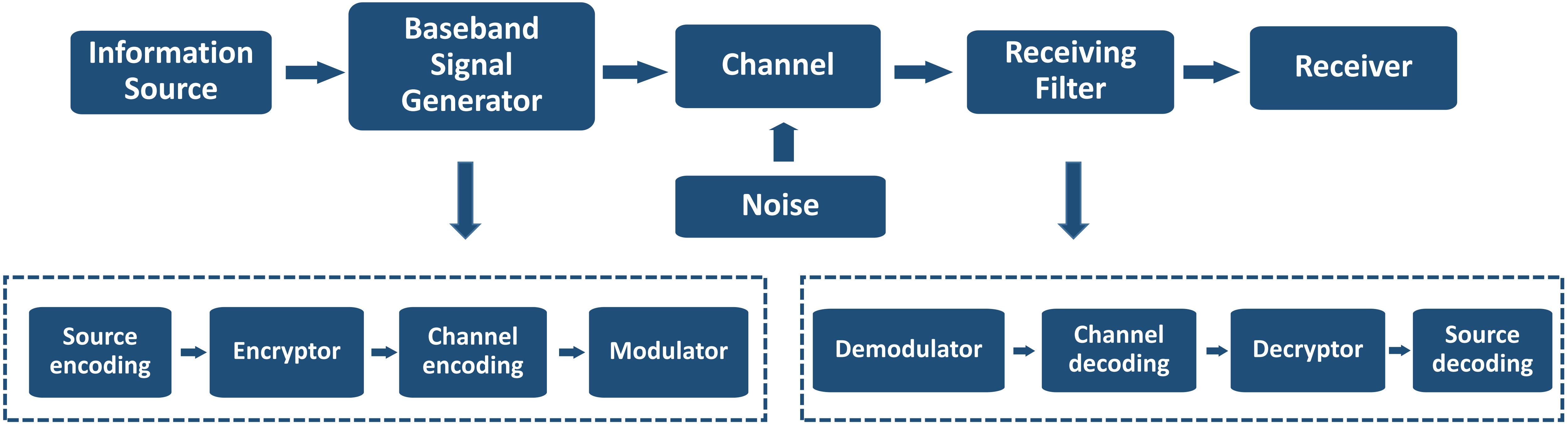


A framework of digital communication system



Digital Communication

The framework of digital communication system



Digital Communication

- Source encoding & decoding:
  - Convert the analog signal into a digital signal (ADC)
  - Reduce the redundancy (data compression).
  - Source decoding is the inverse process of source encoding.
- Channel encoding & decoding:
  - Errors will be caused due to the noise and interference.
  - Improve the anti-interference ability
  - Decoding is the reverse process of encoding.

Digital Communication

- Encryption & Decryption:
  - To ensure the security of the transmitted information.
  - Encryption: The input plaintext signal is artificially disturbed (add password).
  - Decrypt the received signal at the receiving end to recover the plaintext
- Modulation & Demodulation:
  - Move the baseband signal to high frequency spectrum at the transmitting end
  - Move the high-frequency signal to baseband at the receiving end

Digital Communication

Advantages & Disadvantages of digital communication system

Main advantages:

(1) Anti-interference

(2) Error controllable

(3) Easy to interface with various digital terminals, process, and store signals with computer technology

(4) Easy to integrate to miniaturized equipment

(5) Easy to encrypt with high confidentiality

Main disadvantage： The occupied bandwidth is wide

Digital Communication

Metrics of Communication Systems:

Efficiency & Reliability (rate & accuracy)

Efficiency: The amount of information content transmitted in a given channel

Reliability: Accuracy of received information

- Analog Communication System
  - Transmission Rate
  - Signal-to-noise ratio
- Digital Communication System
  - Frequency Band Utilization
  - Pe & Pb

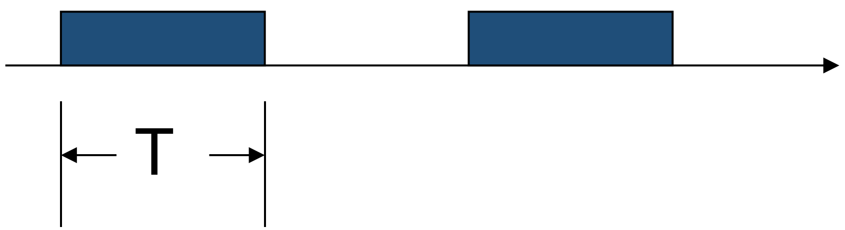
Digital Communication

Symbol transmission rate

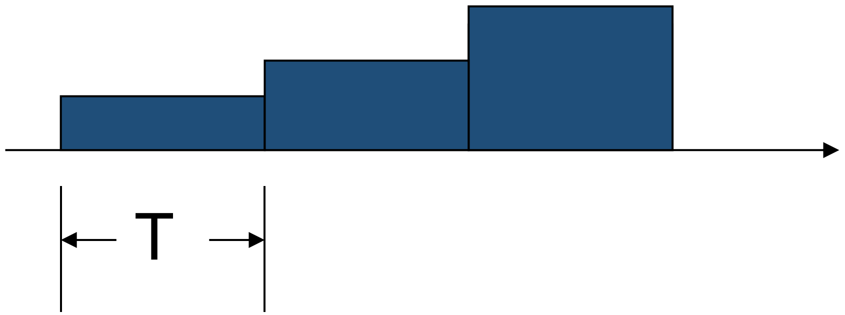
Definition: The amount of information transmitted per second, denoted $R_B = \dfrac{1}{T}$

Unit: baud (B)

Binary(0、1)



Quaternary(0、1、2、3)



Length of a symbol (interval)

The symbol rate is only determined by the transmitted symbol length T

Digital Communication

Example-4：In a binary system，a symbol lasts for $T = 833 \times 10^{-6}\,s$

please determine the symbol rate of the system

Solution：$R_B = \dfrac{1}{T} = \dfrac{1}{833 \times 10^{-6}} = 1200$ Baud

Information transmission rate

Definition: The amount of information conveyed per second, usually denoted as R_b

Unit: bit/s

$$R_b = R_B \bullet H \quad \text{bit/s}$$

H is the average amount of information (entropy) in each symbol

When all the events have equal occurring probabilities

$$R_b = R_B \log_2 M \quad \text{bit/s}$$

Digital Communication

Example-5: A digital system transmits binary symbols at a rate of 1200Baud

(1) find the information rate of the system;

(2) If the system transmits hexadecimal signal symbols, and the symbol rate is 2400 Baud, find the information rate of the system?

Solution:

$$R_b = R_B \times \log_2 M = R_B \times \log_2 2 = 1200 \quad \text{bit/s}$$

$$R_b = R_B \times \log_2 16 = 2400 \times 4 = 9600 \quad \text{bit/s}$$

Example-6: The transmission rate of the binary digital signal is 2400b/s, find the transmission rate when it is converted into a quaternary digital signal.

Solution：

$$R_B = R_b / \log_2 4 = 2400 / 2 = 1200 \quad \text{Baud}$$

Frequency Band Utilization

For effectiveness of different communication systems:

- not only care about the transmission rate
- but also the frequency bandwidth occupied.

Therefore, the transmission efficiency :

the symbol or information transmission rate within the unit frequency band, i.e.

$$\eta = \frac{R_B}{B} \quad \text{B/Hz} \qquad\qquad \eta = \frac{R_b}{B} \quad \text{b/s/Hz}$$

Error rate

Measure the reliability of digital communication system transmission message

Two types: Symbol error rate (SER) & Bit error rate (BER)

SER Pe: The ratio of error symbols received to the total symbols transmitted, i.e.

$$P_e = \frac{\text{error symbols}}{\text{total symbols}}$$

BER Pb: The ratio of the error information bit received to the total amount of information bit, i.e.

$$P_b = \frac{\text{error bits}}{\text{total bits}}$$

In binary,

$$P_b = P_e$$

Example-6: In a binary digital communication system, the symbol rate is 10000 baud. The transmission lasts for 2 seconds, and the number of error symbols received in the receiver is 10, find the bit error rate.

Solution:

$$P_b = \frac{10}{10000 \times 2} = 5 \times 10^{-4}$$

Channel

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Channel

Wireless channel

- Electromagnetic energy is radiated via antenna to the environment.
- The physical size and configuration of the antenna is determined by the frequency.

Extremely Low Frequency	ELF	3 Hz - 30 Hz	10,000 km – 100,000 km
Super Low Frequency	SLF	30 Hz - 300 Hz	1,000 km – 10,000 km
Ultra Low Frequency	ULF	300 Hz - 3 kHz	100 km – 1,000 km
Very Low Frequency	VLF	3 kHz - 30 kHz	10 km – 100 km
Low Frequency	LF or LW	30 kHz - 300 kHz	1 km – 10 km
Medium Frequency	MF or MW	300 kHz – 3,000 kHz	100 m – 1 km
High Frequency	HF or SW	3 MHz – 30 MHz	10 m – 100 m
Very High Frequency	VHF	30 MHz – 300 MHz	1 m – 10 m
Ultra High Frequency	UHF	300 MHz – 3,000 MHz	10 cm – 100 cm
Super High Frequency	SHF	3 GHz – 30 GHz	1 cm – 10 cm
Extremely High Frequency	EHF	30 GHz – 300 GHz	1 mm – 10 mm

Channel

Wireless channel

- there are three modes of electromagnetic wave propagation
  - ground-wave propagation

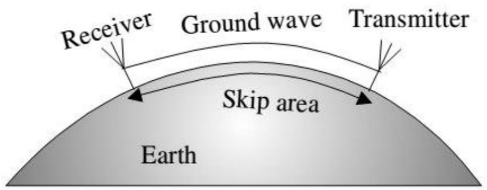
    Propagation covers the area between
    the earth's surface and the ionosphere
    for signal transmission

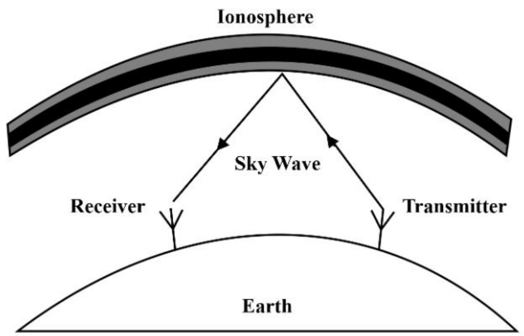
  - sky-wave propagation

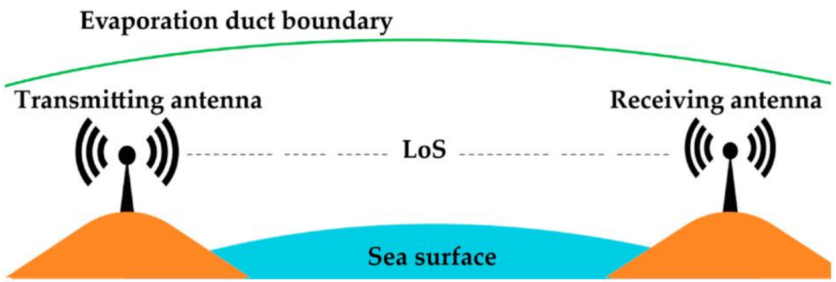
    Propagation of radio waves reflected or
    refracted back toward Earth from the ionosphere,
    an electrically charged layer of the upper atmosphere

  - line-of-sight (LOS) propagation

    waves travel in a direct path
    from the source to the receiver







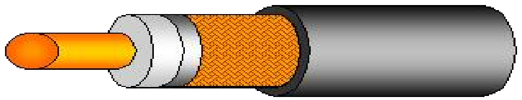
Channel

Wired channel

Symmetrical Cable

- Many pairs of mutually insulated twin wires
- the wire material is aluminum or copper
- To reduce the mutual interference between wires, wires are a twisted shape
- the transmission loss is larger than open wire, but its transmission are relatively stable

Coaxial cables



Two coaxial conductors

- Outer conductor: cylindrical empty tube (wire mesh)
- Inner conductor: metal wire (core wire)
- Middle:filled with a medium

Channel

Channel Models

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

where

$e_i(t)$: input signal

$e_o(t)$: output signal

$n(t)$: additive noise

$f[\cdot]$: function defining input and output signals

Usually, we consider a linear model, such that $e_o(t) = k(t)e_i(t) + n(t)$

$k(t) = const$:a constant parameter channel. Example: coaxial cable

$k(t) \neq const$:a random parameter channel. Example: vehicular cellular network communication channel

Influence of Channel Characteristics on Signal Transmission

Constant parameter channel (time-invariant linear network)

The constant parameter channel changes extremely slowly.

Signal input is $s_i(t)$, the output signal is written as

$$s_0(t) = K_0 s_i(t - t_d)$$

Where

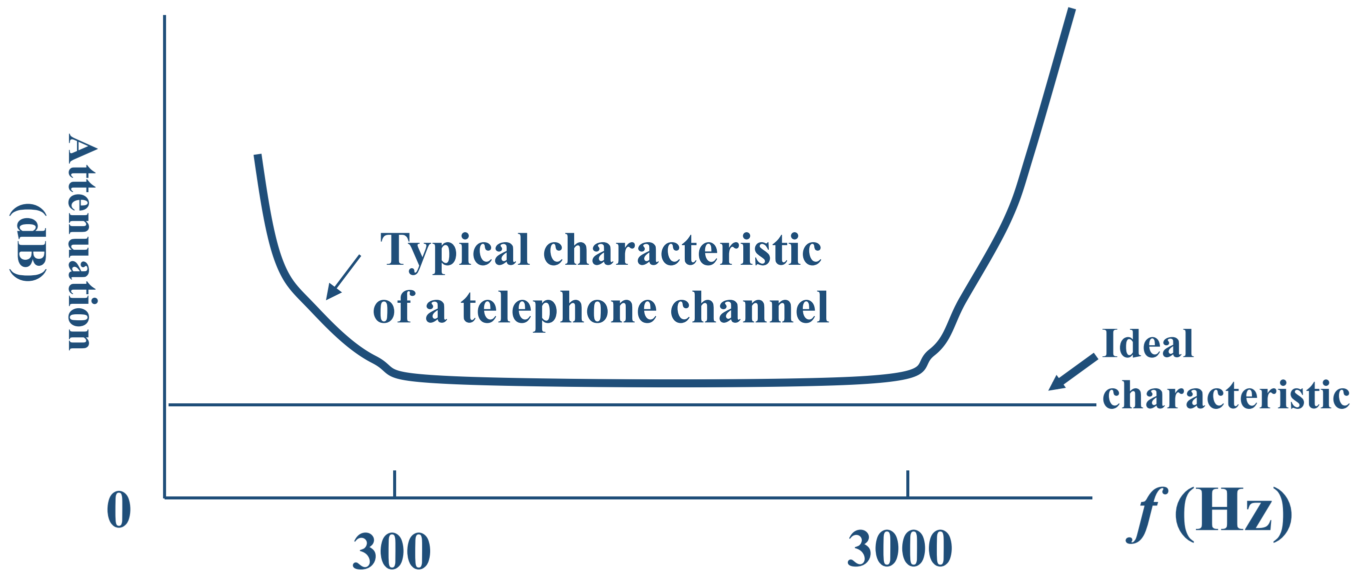
K_0 : transmission coefficient (a fixed value of amplification or attenuation)

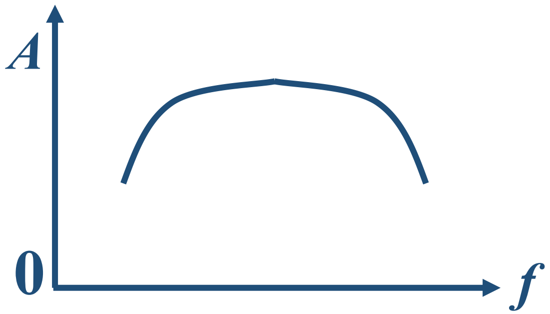
t_d : time delay, the output signal lags behind the input signal by a fixed time.

Frequency domain $$S_0(\omega) = K_0 e^{-j\omega t_d} S_i(\omega)$$

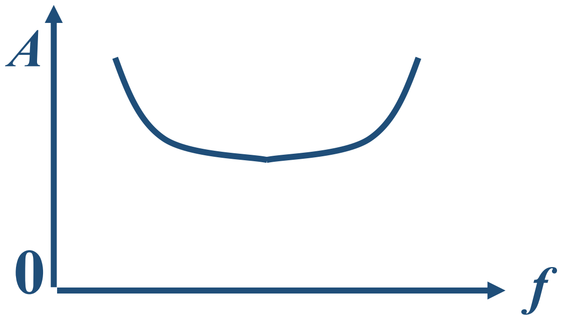
Channel

Amplitude–Frequency characteristic





(a) Channel characteristic with frequency distortion

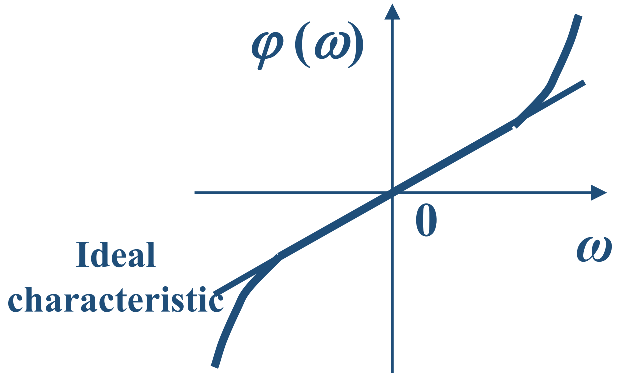


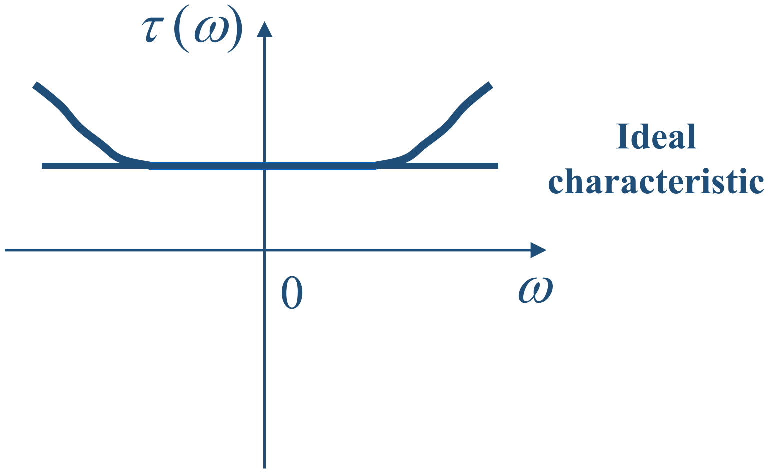
(b) Characteristic of linear compensation network

(c) Channel characteristic after compensation

Channel

Phase–Frequency characteristic





- Ideal phase characteristic: $\phi(\omega) = k\omega$

  group delay $\tau(\omega) = \dfrac{d\phi(\omega)}{d\omega} = k$

  Influence of distortion: waveform distortion, inter-symbol interference

Linear distortion: frequency distortion & phase distortion (corrected by linear compensation)

Nonlinear distortion: nonlinear amplitude characteristic, frequency deviation, phase jittering, …

Channel

Random parameter channel

Attenuation and transmission delay varies with time, multi-path propagation is fast fading.

Transmitting signal $cos\omega_0 t$

the received signal R(t) :

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

where

$r_i(t)$: amplitude of received signal passing over i-th path

$\tau_i(t)$: delay of the received signal passing over i-th path

$\varphi_i(t) = -\omega_0 \tau_i(t)$

Channel

Random parameter channel

$$R(t)=\underbrace{\sum_{i=1}^{n} r_i(t)\cos\varphi_i(t)}_{x_c(t)}\cos\omega_0 t-\underbrace{\sum_{i=1}^{n} r_i(t)\sin\varphi_i(t)}_{x_s(t)}\sin\omega_0 t$$

$$R(t)=x_c(t)\cos\omega_0 t-x_s(t)\sin\omega_0 t=V(t)\cos[\omega_0 t+\varphi(t)]$$

envelope phase

$$V(t)=\sqrt{x_c{}^2(t)+x_s{}^2(t)}$$

$$\varphi(t)=\arctan\frac{x_s(t)}{x_c(t)}$$

Channel

Frequency selective fading

Only two paths with identical attenuation and different delays

Transmitted signal $f(t)$ received signals $af(t-\tau_0)$

$af(t-\tau_0-\tau)$

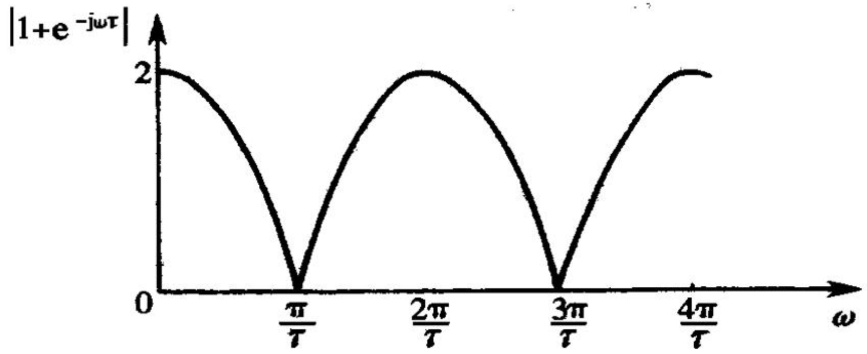
spectrum of transmitting signal $F(\omega)$

$$f(t) \Leftrightarrow F(\omega)$$

$$af(t-\tau_0) + af(t-\tau_0-\tau) \Leftrightarrow a\ F(\omega)\ e^{-j\omega\tau_0}(1+e^{-j\omega\tau})$$

$$af(t-\tau_0) \Leftrightarrow aF(\omega)\ e^{-j\omega\tau_0}$$

$$af(t-\tau_0-\tau) \Leftrightarrow aF(\omega)\ e^{-j\omega(\tau_0+\tau)}$$



$$H(\omega) = aF(\omega)\ e^{-j\omega\tau_0}(\ + e^{-j\omega\tau})\ \ F(\omega) = ae^{-j\omega\tau_0}(\ + e^{-j\omega\tau})$$

$$|1+e^{-j\omega\tau}| = |1+cos\omega\tau - jsin\omega\tau| = |[(1+cos\omega\tau)^2 + sin^2\omega\tau]^{\frac{1}{2}}| = 2\,|cos(w\tau/2)|$$

Noise in Channel

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Noise in Channel

- Classified according to origins：
  - Man-made noise： electric sparks, …
  - Natural noise： lightning, atmosphere noises, thermal noise,...
- Classified according to characteristics:
  - impulse noise
  - narrow band noise
  - fluctuation noise
- Main noise involved in the following discussion on communication systems is:
  - white noise – thermal noise is a kind of typical white noise following Gaussian distribution

Exercise

Ex1: A source sends messages at a rate of 2000 symbols per second, and the source consists of five symbols A, B, C, D, and E. The probability of sending A is 1/2, and the probability of sending the rest of the symbols is the same, and each symbol is assumed to be independent of each other

Find: (1) Average information amount of each symbol

(2) Average information rate of the source

(3) Possible maximum information rate

Exercise

Ex2:

(1) For a binary independent source, the symbol length is 0.5ms, and the symbols appear with equal probability, find Rb and RB.

(2) For a quaternary independent source, the symbol width is still 0.5ms, find the RB and rate Rb when the appearance probabilities are equal.

Exercise

Ex3: In a strong interference environment, a radio station receives a total of 355Mbit of correct information amount within 5min. Assume that the system information rate is 1200kbit/s.

Find: (1) What is the BER of the system?

(2) If the signal is a and the symbol transmission rate is 1200kB, what is Pb?

Ex4: Assuming that a random parameter channel has two paths, and the time difference between the paths is td=0.5ms, which frequency does the channel have the smallest transmission loss, and which frequency has the largest transmission loss?

MATLAB

Assume that the transmitter transmits a sinusoidal signal, the signal arrives at the still receiver via 2 different paths with different time delay. (Parameters can be determined by your own)

(1) Plot the transmit signal and the receiving signal in time domain and frequency domain

(2) Plot the amplitude-frequency and phase-frequency characteristic of the channel.

MATLAB

Learn by yourself about the Rayleigh channel and Rician channel.

(1) What are the Rayleigh channel and Rician channel?

(2) What is the difference between them? What is the relationship between them?

(3) In what case we can model the channel as Rayleigh channel and what case model as Rician channel

(4) Generate Rayleigh channel and Rician channel in MATLAB (SNR=5)

(5) Plot the PDF & CDF of the Rayleigh distribution and Rician distribution.

(6) Generate Gaussian white noise (a circular Gaussian random process)

Thank you!