计算机网络通信基础

Communication Technologies of Computer Network

(For Postgraduate)

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第2章 数据传输基础

2.1 传输相关的概念与术语

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2.3 Transmission Impairments(传输损耗)

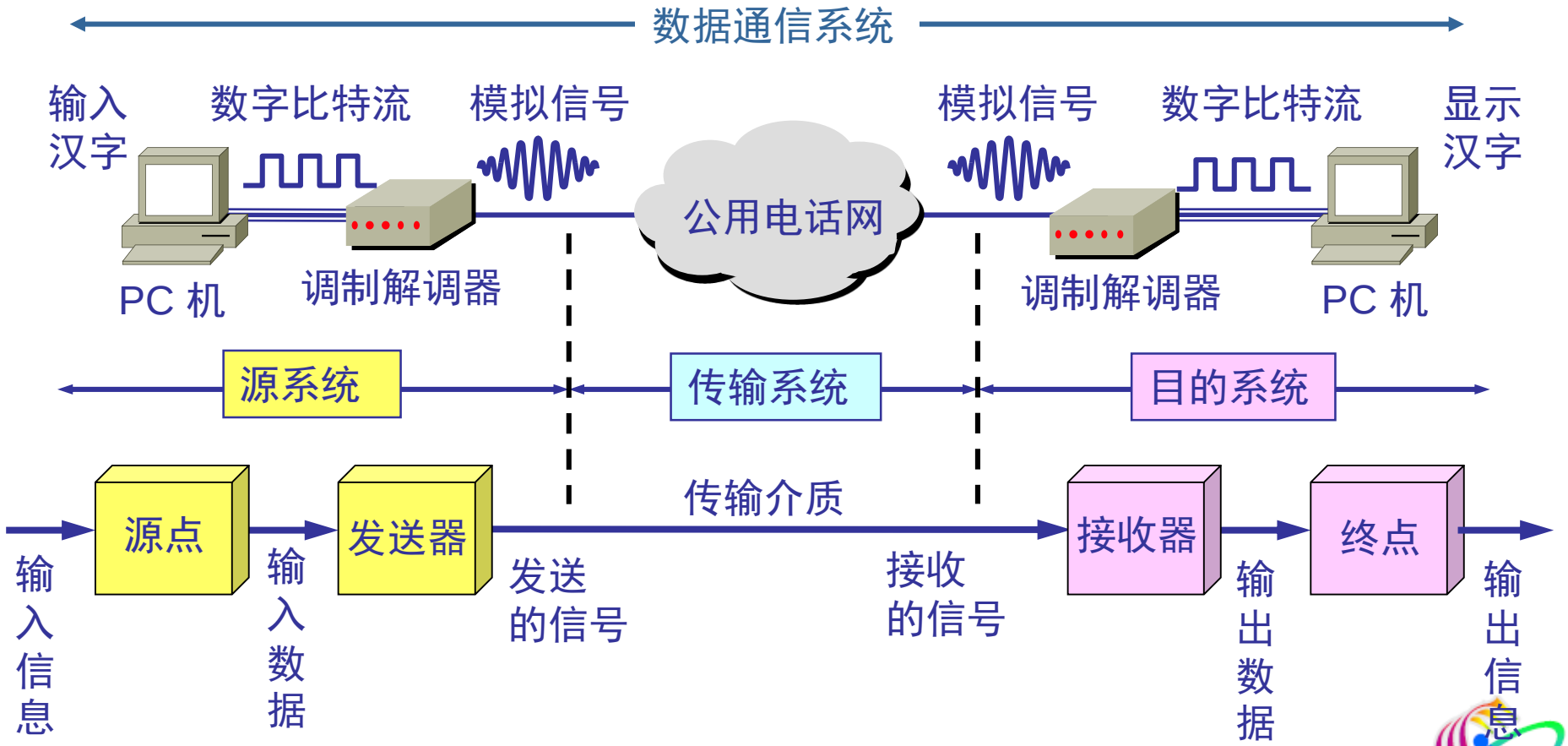
2.4 Channel Capacity(信道容量)

2.5 基带与调制技术

2.6 数字基带信号传输的波形与编码

2.1 传输相关的概念与术语

◆ 数据传输系统模型(谢希仁, 5e)



2.1 传输相关的概念与术语

- **Data transmission** occurs between a transmitter & receiver via some medium (guided or unguided, in both cases, communication is in the form of **electromagnetic waves**).

  ---**Electromagnetic wave**: created when electrons moving, can propagate through space, **predicted** by James Clerk Maxwell (1865, British physicist), **observed** by Heinrich Hertz (1887, German physicist). In vacuum, travel at the speed of light (*c*), no matter what their frequency; In copper or fiber, the speed slows to about *c**2/3, and becomes slightly frequency dependent.

2.1 传输相关的概念与术语

- **Guided medium** (导向介质/媒介/媒体): the waves are guided along a physical path.

  ---e.g., twisted pair, coaxial cable, optical fiber

- **Unguided (wireless) medium**: provide a means for transmitting electromagnetic waves but do not guide them.

  ---e.g., air, water, vacuum

2.1 传输相关的概念与术语

- **Direct link**: no intermediate devices (other than amplifiers or repeaters)
- **Point-to-point**

  ---direct link

  ---only 2 devices share link
- **Multi-point**: more than two devices share the link

2.1 传输相关的概念与术语

- **Simplex** (单工)

  ---one direction, e.g. television（模拟，非数字）

- **Half duplex** (半双工)

  ---either direction, but only one way at a time, e.g. 对讲机

- **Full duplex** (全双工)

  ---both directions at the same time, e.g. Telephone

2.1 传输相关的概念与术语

Note: The definitions above are the ones in common use in the United States (ANSI definitions). Elsewhere (ITU-T definitions), the term **simplex** is used to correspond to **half duplex** and **duplex** is used to correspond to **full duplex**.

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2.3 Transmission Impairments(传输损耗)

2.4 Channel Capacity(信道容量)

2.5 基带与调制技术

2.6 数字基带信号传输的波形与编码

2.2 频率、频谱与带宽

1. 时域(Time domain)概念

The signal is a function of time, but it can also be expressed as a function of frequency; that is, the signal consists of components of different frequencies.

(1) 信号分类

- Analog signal (模拟信号, 或连续信号): various in a smooth way over time, e.g. speech, music.

2.2 频率、频谱与带宽

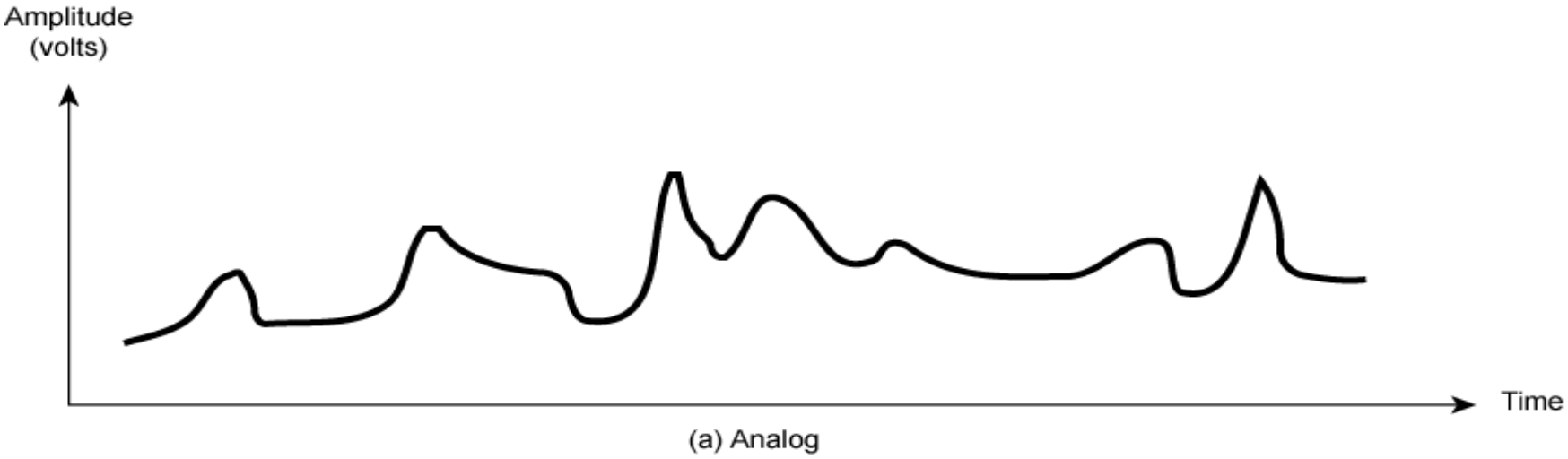
- Digital signal (数字信号, 或离散信号): maintains a constant level then changes to another constant level. 一般指二进制数字信号，分别用两个不同的参量代表0和1，如+5V电压代表1，-5V电压代表0，或者以电流的通代表1，断代表0等，每一个数字信号叫比特。

  ---An electromagnetic signal can be either analog or digital (Stallings, 8e)

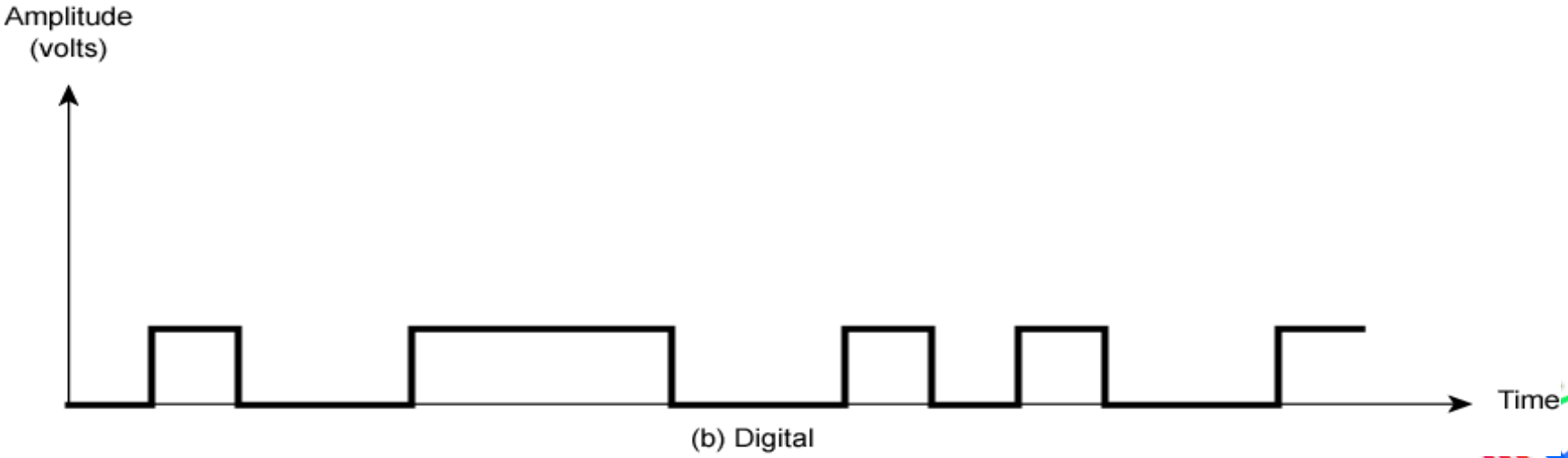
- Periodic signal (周期信号): pattern repeated over time，信号$s(t)$满足$s(t+T)=s(t)$，T即周期时间.

- Aperiodic signal (非周期信号): pattern not repeated over time

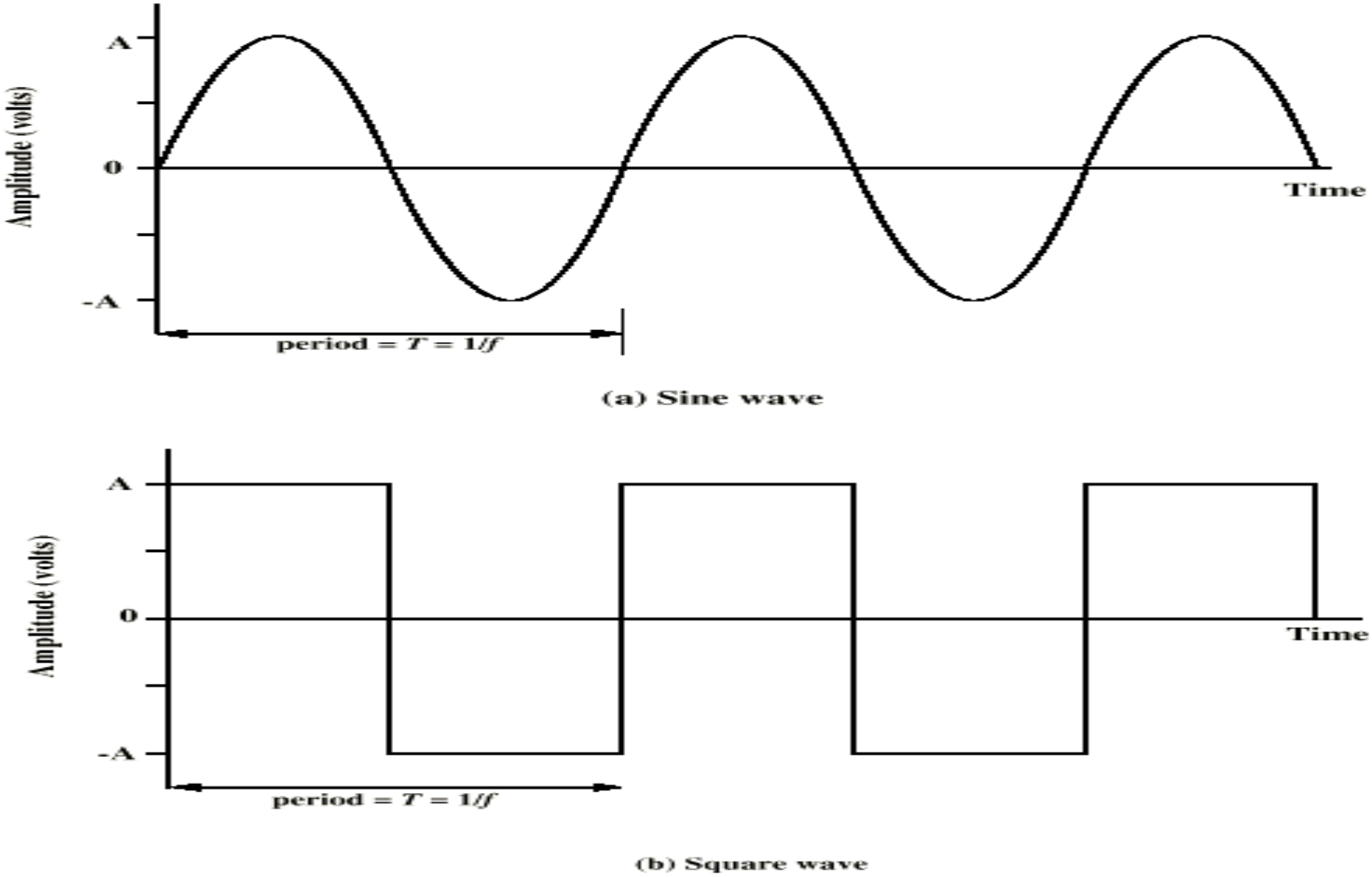
2.2 频率、频谱与带宽



(a) Analog



(b) Digital



Periodic signals

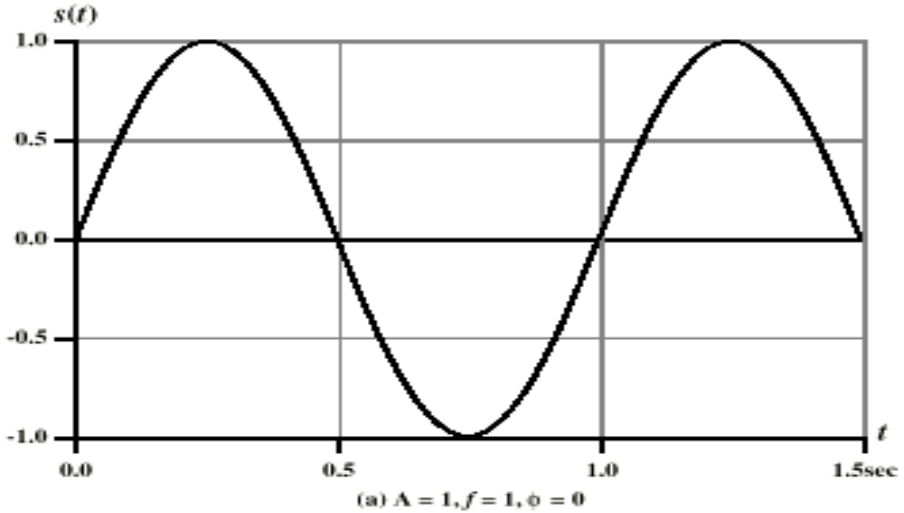
2.2 频率、频谱与带宽

(2) Sine Wave (正弦波)

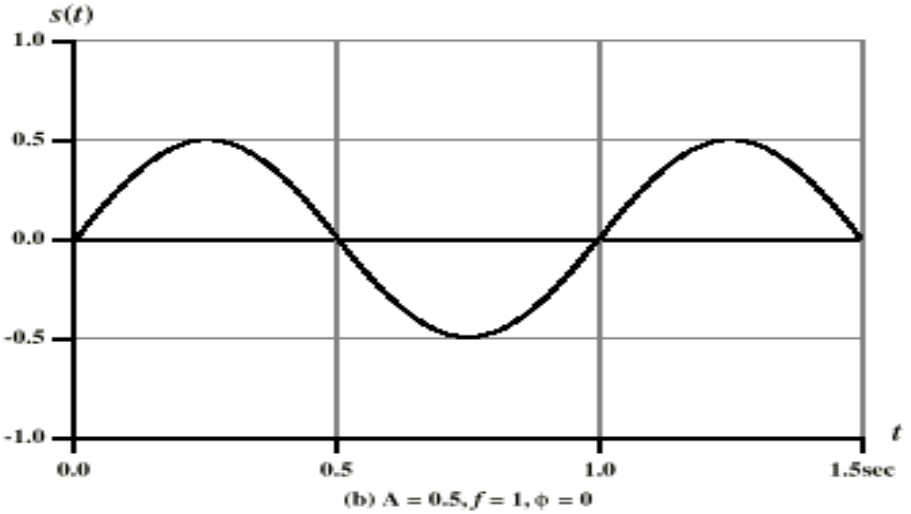
- Peak amplitude (*A*)
  - ---maximum strength of signal
  - ---typically measured in volts
- Frequency (*f*)
  - ---rate of change of signal
  - ---Hertz (Hz) or cycles per second
  - ---period = time for one repetition (*T*)
  - ---$T = 1/f$
- Phase (ϕ)
  - ---relative position in time
  - ---描述周期信号在时间轴上的相对位置，用弧度表示。

2.2 频率、频谱与带宽

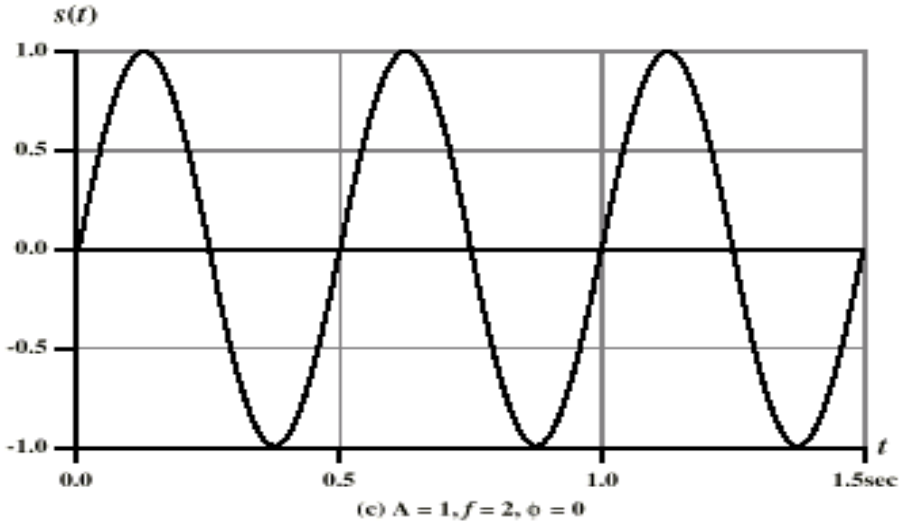
The general sine wave can be written as: $s(t) = A\sin(2\pi ft + \phi)$.



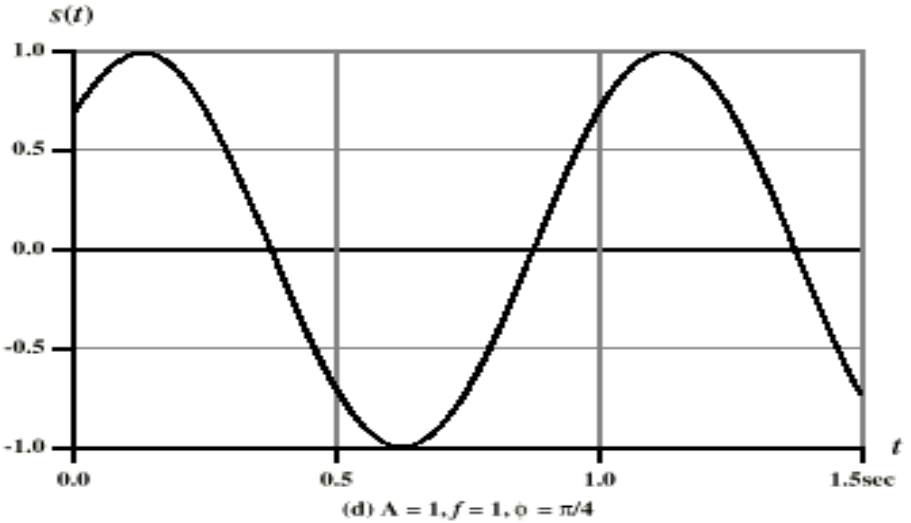
(a) A = 1, f = 1, ϕ = 0



(b) A = 0.5, f = 1, ϕ = 0

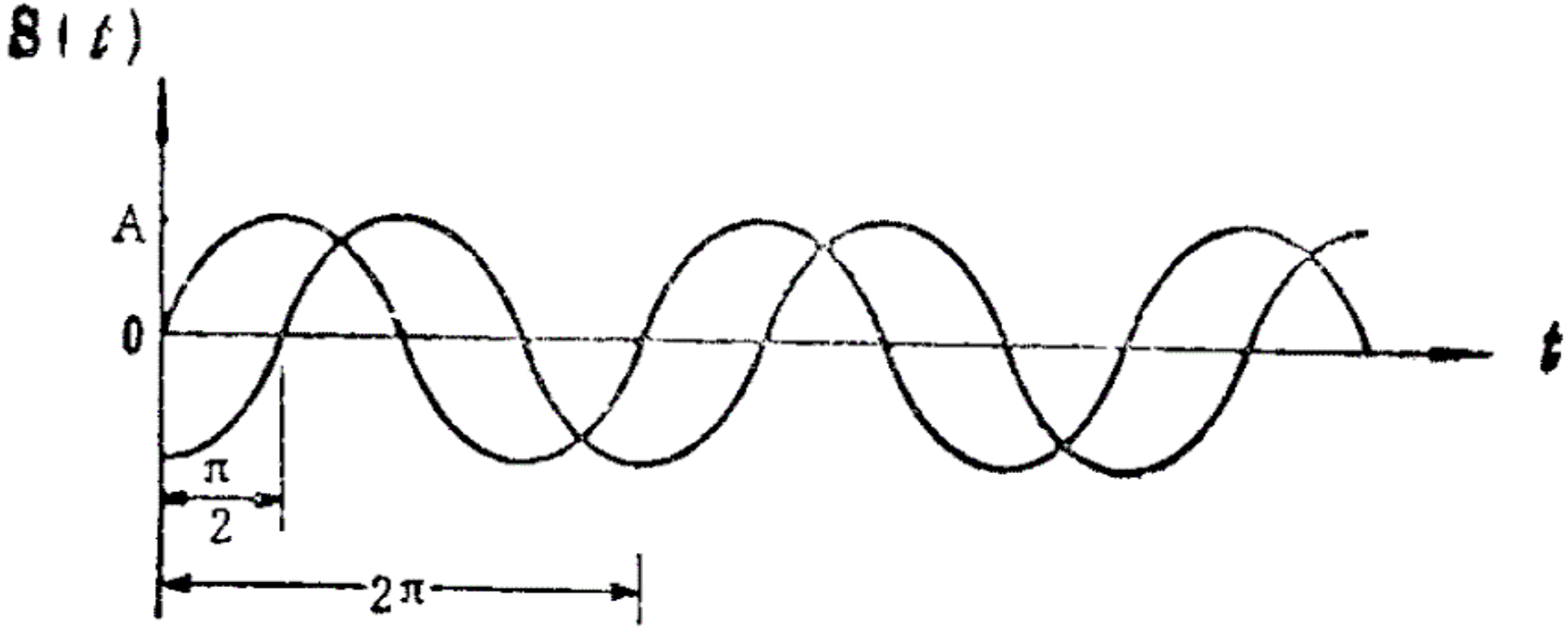


(c) A = 1, f = 2, ϕ = 0



(d) A = 1, f = 1, ϕ = π/4

2.2 频率、频谱与带宽



信号的相位差

2.2 频率、频谱与带宽

(3) Wavelength (λ): 波长

---is distance occupied by one cycle.

---between two points of corresponding phase in two consecutive cycles. 两个相邻波峰/波谷间的距离(Tanenbaum, 4e).

---assuming signal velocity v, have $\lambda = vT$

---or equivalently $\lambda f = v$

---especially when $v=c$, $\lambda f = c$

$c = 3*10^8$ m/s (speed of light in free space), when λ is in meters and f is in MHz, $\lambda f \approx 300$. 1 cm→30G ($3*10^{10}$) Hz.

---光通信中的3个典型波长：0.85μm (850nm)→$3.53*10^{14}$Hz, 1.3μm (1310nm)→$2.31*10^{14}$Hz, 1.55μm (1550nm)→$1.93*10^{14}$Hz.

2.2 频率、频谱与带宽

(4) 度量单位(Metric units)

---数据大小(长度)度量（各级以2^{10}倍增）

1 KB(kilobyte) =1024 Bytes; 1 MB(megabyte)=1024 KB

1 GB(gigabyte)=1024 MB; 1 TB (terabyte) =1024 GB

1 PB (petabyte)=1024 TB; 1 EB (exabyte) =1024 PB

1 ZB(zettabyte)=1024 EB; 1 YB (yottabyte)=1024 ZB

2.2 频率、频谱与带宽

---其它度量（各级以10^3倍增或以10^{-3}倍减），如速率、频率、带宽等。

1 kbps = 10^3 bps;　　1 Mbps= 10^3 kbps

1 Gbps= 10^3 Mbps;　　1 Tbps = 10^3 Gbps

Exp.	Explicit	Prefix	Exp.	Explicit	Prefix
10^{-3}	0.001	milli	10^3	1,000	Kilo
10^{-6}	0.000001	micro	10^6	1,000,000	Mega
10^{-9}	0.000000001	nano	10^9	1,000,000,000	Giga
10^{-12}	0.000000000001	pico	10^{12}	1,000,000,000,000	Tera
10^{-15}	0.000000000000001	femto	10^{15}	1,000,000,000,000,000	Peta
10^{-18}	0.000000000000000001	atto	10^{18}	1,000,000,000,000,000,000	Exa
10^{-21}	0.000000000000000000001	zepto	10^{21}	1,000,000,000,000,000,000,000	Zetta
10^{-24}	0.000000000000000000000001	yocto	10^{24}	1,000,000,000,000,000,000,000,000	Yotta

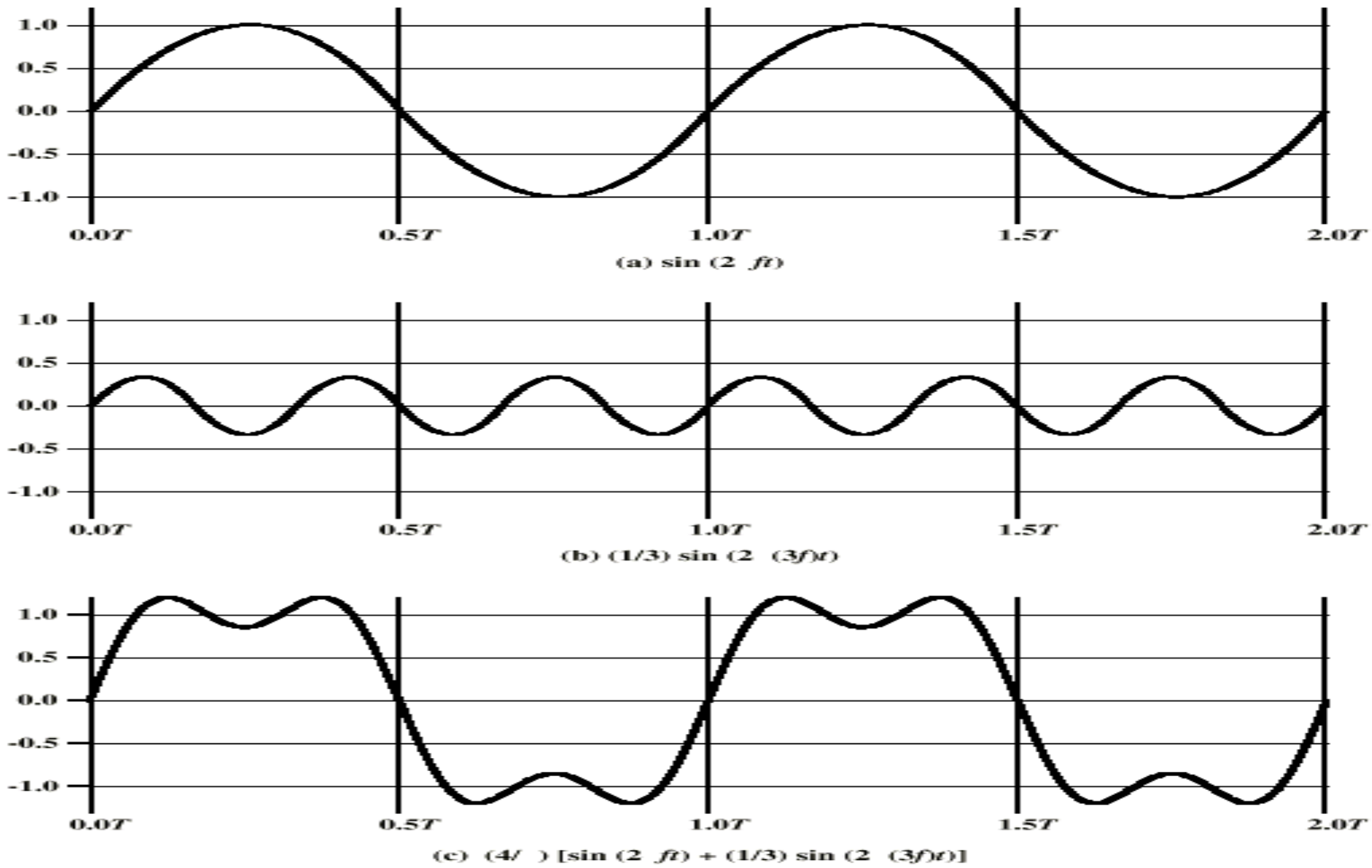
2.2 频率、频谱与带宽

2. 频域(Frequency domain)概念

---Fourier analysis can show that any signal is made up of components at various frequencies.

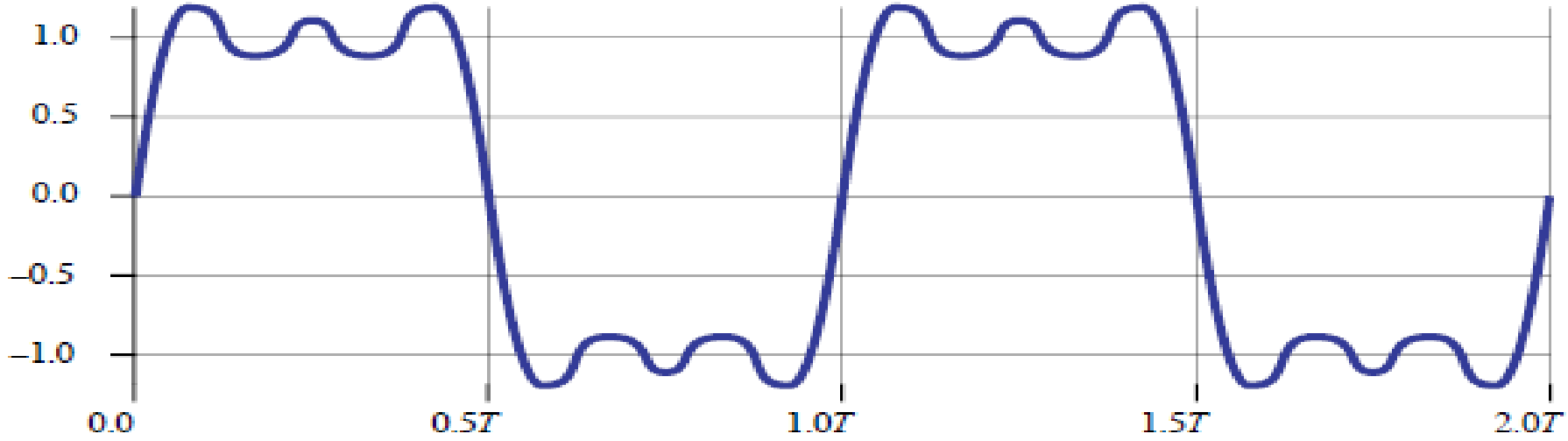
---Each component is a sinusoid (正弦曲线).

---By adding together enough sinusoidal signals, each with the appropriate **amplitude**, **frequency**, and **phase**, any electromagnetic signal can be constructed.

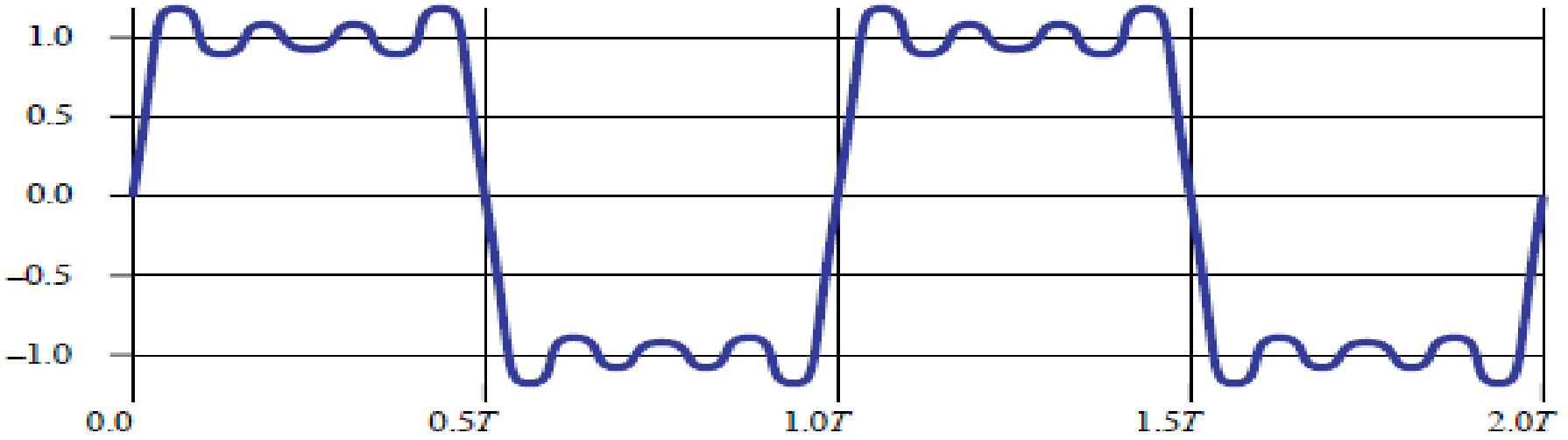


(c) is sum of f & $3f$

Fig. 3.4 Addition of frequency components (T=1/f)



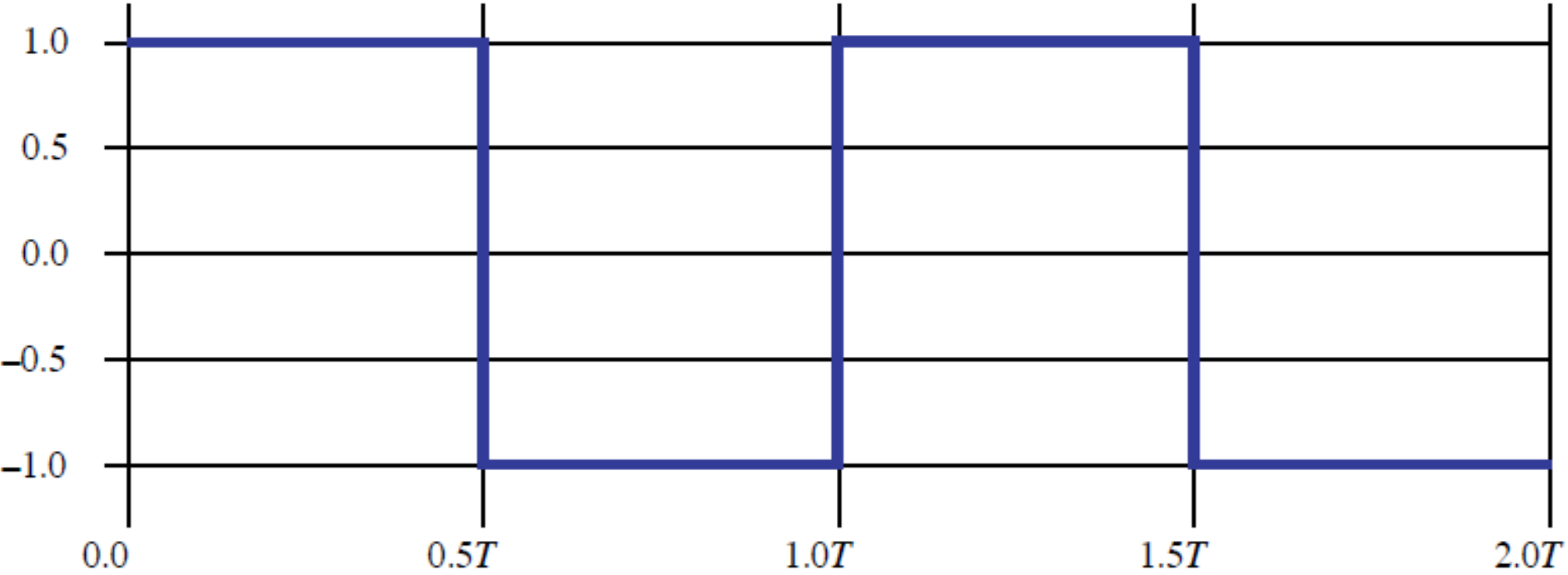
(a) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t)]$



(b) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t) + (1/7)\sin(2\pi(7f)t)]$

(a) is sum of *f*, 3*f* & 5*f* (b) is sum of *f*, 3*f*, 5*f* & 7*f*

2.2 频率、频谱与带宽



(c) $(4/\pi) \sum (1/k) \sin (2\pi(kf)t)$, for k odd

Figure 3.7 Frequency Components of Square Wave ($T = 1/f$)

2.2 频率、频谱与带宽

3. Spectrum & Bandwidth

- Spectrum

  ---range of frequencies contained in signal

- Absolute bandwidth (信号)

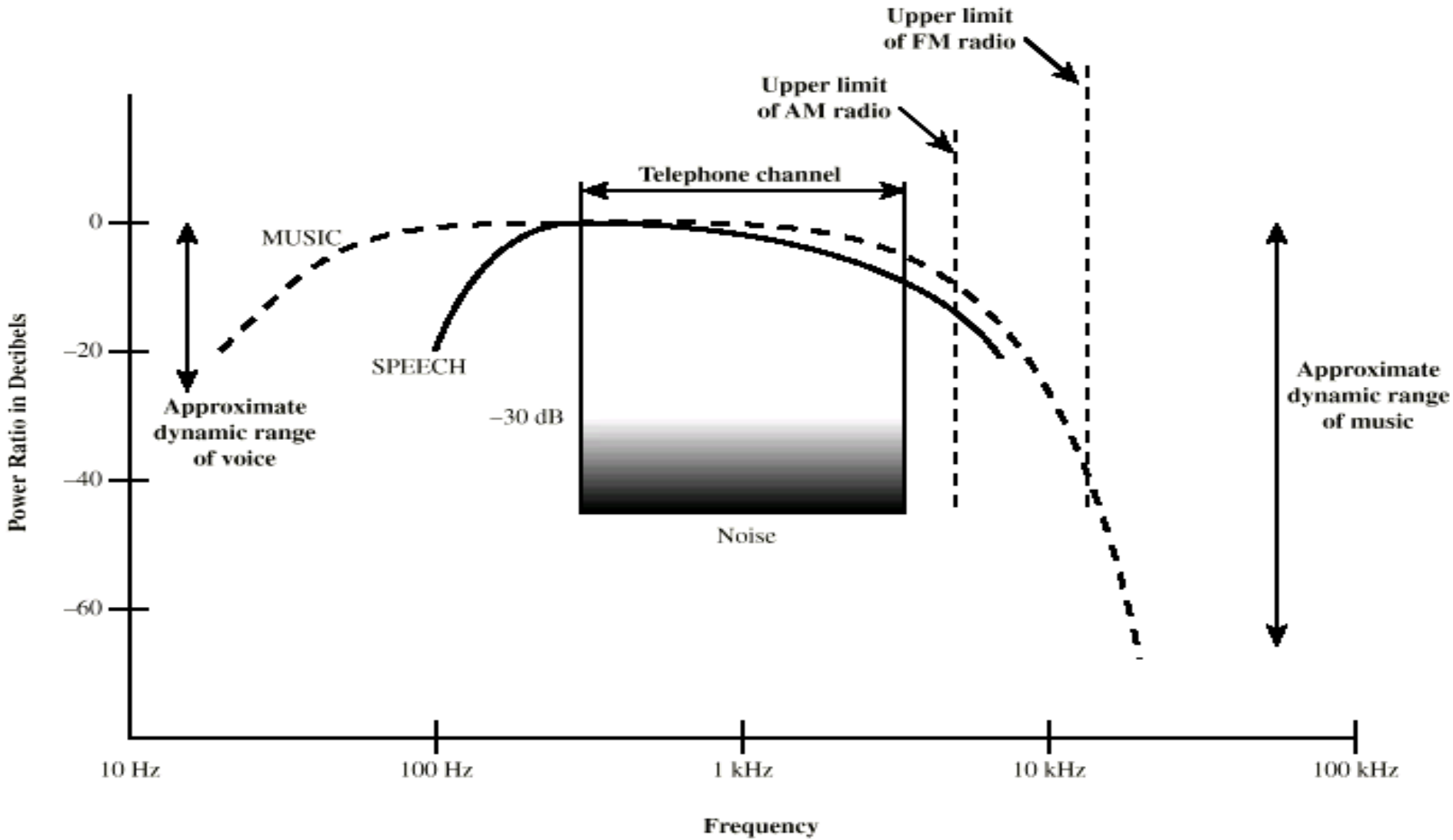
  ---width of spectrum

  ---某个信号具有的频带宽度，即该信号所包含的各种不同频率成分所占据的频率范围。单位为Hz。(谢希仁, 5e)

  ---e.g., 由Acoustic (听觉) Spectrum (Analog)可知声音信号(Speech and Music)所占据的频率范围为20Hz~20kHz，Speech为100Hz~7kHz。The standard spectrum for a voice channel is 300 to 3400 Hz.

2.2 频率、频谱与带宽

Acoustic (听觉) Spectrum (Analog)



2.2 频率、频谱与带宽

---e.g., Video signal (produced by a TV camera): max frequency of 4.2MHz.

---e.g., Square have infinite components and hence bandwidth

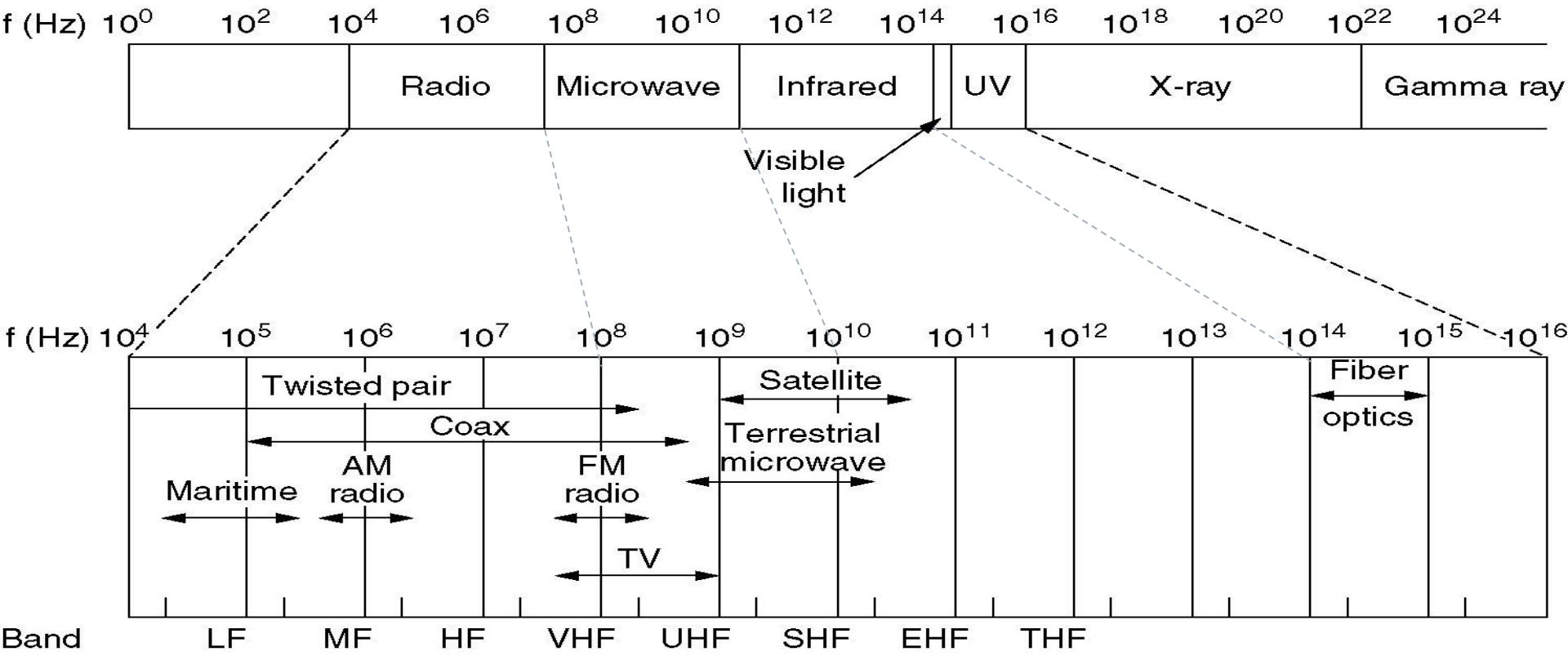
---e.g., Digital signal, 具有无限带宽，但它们不得不被近似为有限带宽信号，其带宽依赖于data rate, 而数据速率又由**信道容量**(见后)决定。

---e.g., Electromagnetic signal spectrum.

Q: 中国5G频谱？

2.2 频率、频谱与带宽

The Electromagnetic Spectrum (Tanenbaum, 4e)



ITU定义→L: Low (低); M: Medium (中); H: High (高); VH: Very high (甚高); UH: Ultra high (特高) ; SH: Super high (超高); EH: Extremely high (极高); TH: Tremendously high (至高); **IH**: Incredibly high (?); **AH**: Astonishingly high (?); **PH**: Prodigiously high (巨高?).

2.2 频率、频谱与带宽

注：Audio/acoustic sound can be easily converted to an electromagnetic signal for transmission (可不调制).

In this graph of a typical analog signal, the variations in amplitude and frequency convey the gradations of loudness and pitch in speech or music. Similar signals are used to transmit television pictures, but at much higher frequencies.

All of the sound frequencies, whose amplitude is measured in terms of loudness, are converted into electromagnetic frequencies, whose amplitude is measured in volts. The telephone handset contains a simple mechanism for making such a conversion. In the case of acoustic data (voice), the data can be represented directly by an electromagnetic signal occupying the same spectrum.

2.2 频率、频谱与带宽

- Effective bandwidth (信号)

  ---often just bandwidth

  ---narrow band of frequencies containing most energy，信号大部分能量集中的那段频带为信号的有效频带。

- **信道带宽**

  ---信号中的许多高频分量往往不能通过信道(衰减&噪声/滤波)，故通信线路允许通过的信号频带范围为**线路带宽**(或通频带)。(谢希仁, 5e)

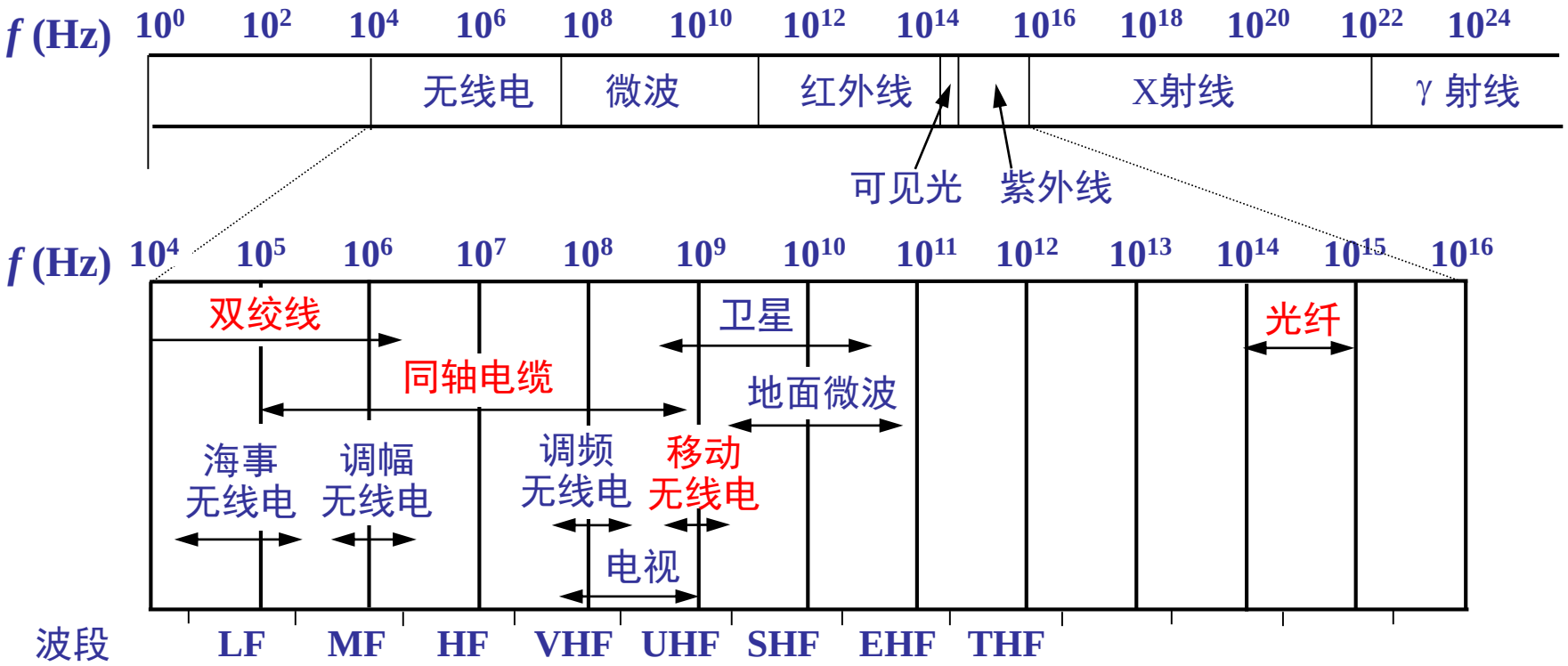
  ---带宽**最早**在通信电路技术中用于描述**信道**或电路的频率特性，表征信道允许通过的模拟信号频率的范围，即“通频带”的宽度。(曾华燊, 2004)

  ---信道带宽是指信道中传输的信号在不失真的情况下所占用的频率范围，通常称为信道的通频带。信道带宽由信道的物理特性所决定。

  --- The bandwidth of a medium is the range of frequencies that pass through it with minimum attenuation. (Tanenbaum, 4e)

2.2 频率、频谱与带宽

电信领域使用的电磁波频谱 (谢希仁, 5e)



由此图可见，不同**介质**(双绞线、同轴电缆、光纤等等)形成的信道可允许通过的**电磁信号**的频率及频率范围是不同的，或不同无线电(海事、调幅、调频、移动2G/3G/5G/6G等等)使用不同的频率范围。---将介质与信号结合起来理解带宽。

2.2 频率、频谱与带宽

---光纤带宽的大致计算

(A) $f = c/\lambda \rightarrow \frac{df}{d\lambda} = -\frac{c}{\lambda^2} \rightarrow \Delta f = \frac{c\Delta\lambda}{\lambda^2}$

(B) λ=1.3μm, $\Delta\lambda$(频段宽度)=0.17*10^{-6}μm, 则Δf(带宽)大约为30T (30*10^{12}) Hz. (注：其中的c最好用c*2/3代替)

(C) 光纤中所用3个波段(0.85μm, 1.3μm, 1.55μm)的带宽大约为25~30THz. (Tanenbaum, 4e)

---e.g., 3/5(5E)类UTP的带宽分别为16MHz/100MHz; 6/7类UTP的带宽分别为250MHz/600MHz. (Tanenbaum, 4e)

---e.g., 现代同轴电缆带宽为1GHz.(Tanenbaum, 4e)

---带宽的引申→网络带宽：表示在单位时间内从网络的某一点到另一点所能通过的最高数据率(bps)。(谢希仁, 5e)

◆ DC (Direct current, 直流) Component

---component of zero frequency (零频)

2.2 频率、频谱与带宽

◆信道的截止频率与信道带宽 (信道带宽的进一步理解)

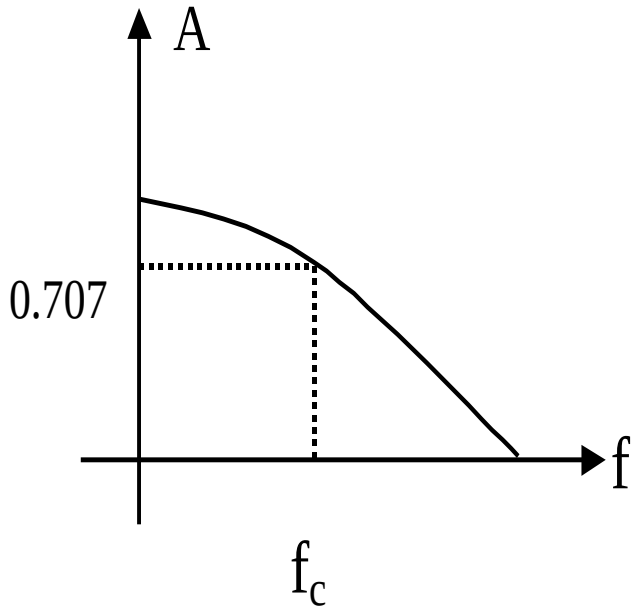
---任何信号通过信道时都会发生衰减，从而引起信号失真。

---信道对不同频率的信号其衰减幅度是不相同的；一般来说，频率越高的信号，其衰减幅度越大。

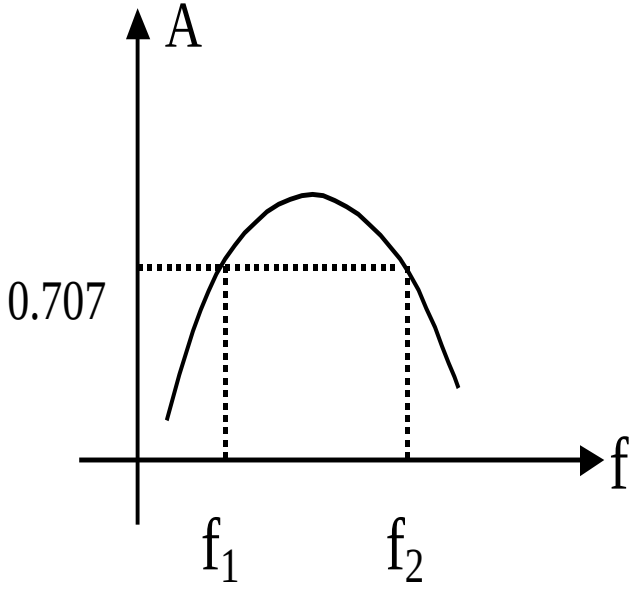
---把信号在经过信道时其中某个频率分量的振幅衰减到原来的0.707(即信号的能量衰减到原来的一半)时所对应的频率称为信道的截止频率f_c (cut-off frequency)，即信道的带宽。

---任何信道都有f_c，信道的截止频率或带宽是由其固有的物理特性决定的，或者可能被故意限制了带宽，以防止干扰或为了多路复用。

2.2 频率、频谱与带宽



(a) 单通滤波器



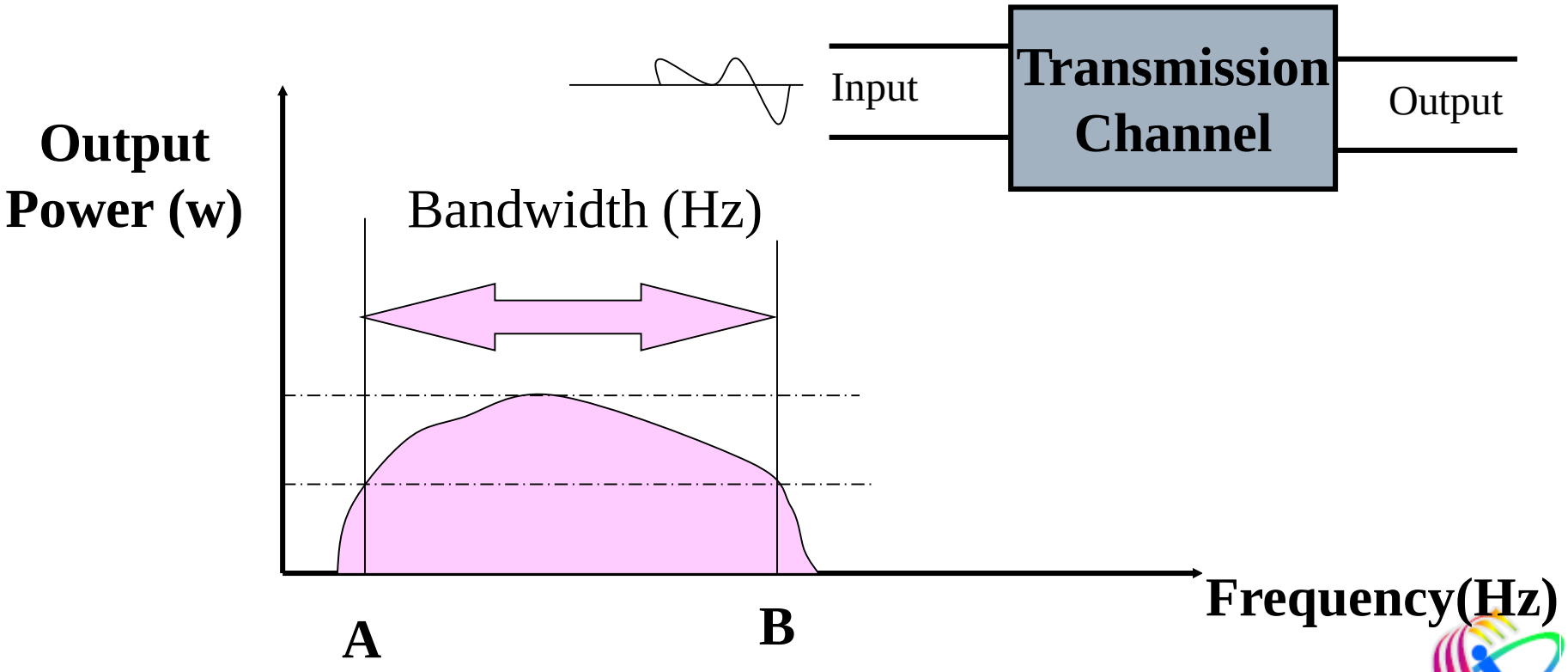
(b) 双通滤波器

---For (a): Bandwidth=f_c

---For (b): Bandwidth=f_2-f_1

2.2 频率、频谱与带宽

---Bandwidth (in Hz) for a channel: frequency range between two points (A & B) at which the output power drops to half of the max level. (曾华燊, 2004)



2.2 频率、频谱与带宽

◆信道带宽与信号带宽的关系

---信道的带宽决定对其通过信号的带宽，因而对于有限带宽信道必须限制信号的带宽(有限带宽信号)；信道带宽越受限制，信号失真越严重，接收器(Receiver)产生差错的概率越大。

---信道的带宽也决定了其中所能传输的信号频率。

---如信道带宽超过传输信号的频带宽度，则在传输过程中就不会引起信号失真。

---e.g.，一般，一路**话音(**指信号)**信道**的有效带宽取4kHz（可保话音信号不失真)。如果信道带宽够大，则其可以划分为多路话音通路。

---**宽带**(Broadband)：源于电信业，泛指高于4kHz话音信号的频带。

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2.2 频率、频谱与带宽

2.3 Transmission Impairments(传输损耗)

2.4 Channel Capacity(信道容量)

2.5 基带与调制技术

2.6 数字基带信号传输的波形与编码

2. 3 Transmission Impairments (传输损耗)

- signal received may differ from signal transmitted causing
  - ---analog - degradation of signal quality
  - ---digital - bit errors
- most significant impairments are
  - ---attenuation and attenuation distortion (衰减失真)
  - ---delay distortion (时延失真)
  - ---noise

2. 3 Transmission Impairments (传输损耗)

(1) Attenuation (衰减)

- where signal strength falls off with distance
- depends on medium
- received signal strength must be:

  ---strong enough to be detected

  ---sufficiently higher than noise to receive without error
- so increase strength using amplifiers/repeaters
- attenuation varies with frequency, **noticeable for analog signals**

  ---e.g. using loading coils (电感线圈) or amplifiers

注1：电感线圈是由导线一圈一圈地绕在绝缘管上形成。导线彼此互相绝缘，而绝缘管可以是空心的，也可以包含铁芯或磁粉芯。---使衰减对各个频率的影响都比较均匀。

注2：电感线圈的电特性为“阻高频，通低频“。高频信号通过电感线圈时会遇到很大的阻力（称阻抗），很难通过；而低频信号通过它时所遇阻力较小，即低频信号易通过它。电感线圈对直流电的电阻几乎为零。

2. 3 Transmission Impairments (传输损耗)

(2) Delay distortion

- only occurs in guided media.
- propagation velocity varies with frequency.
- hence various frequency components arrive at different times.
- particularly **critical for digital data**, since parts of one bit spill over into others.
- causing inter-symbol interference (码间串扰), which is a major limitation to maximum bit rate over a transmission channel.

2. 3 Transmission Impairments (传输损耗)

(3) Noise

- Additional signals inserted between transmitter and receiver
- Thermal (热噪声)

  ---due to thermal agitation of electrons

  ---uniformly distributed across the bandwidths

  ---亦称white noise (白噪声)

  ---particularly **significant for satellite communication**

- Inter-modulation (互调/交调噪声)

  ---signals that are the sum and difference of original frequencies sharing a medium

2. 3 Transmission Impairments (传输损耗)

- Crosstalk (串扰)

  ---a signal from one line is picked up by another.

- Impulse (冲激/脉冲噪声)

  ---irregular pulses or spikes, e.g. external electromagnetic interference. 主要来源于雷电、工业火花。

  ---short duration.

  ---high amplitude.

  ---a minor annoyance for analog signals.

  ---but a major source of error in digital data, a noise spike could corrupt many bits.

2. 3 Transmission Impairments（传输损耗）

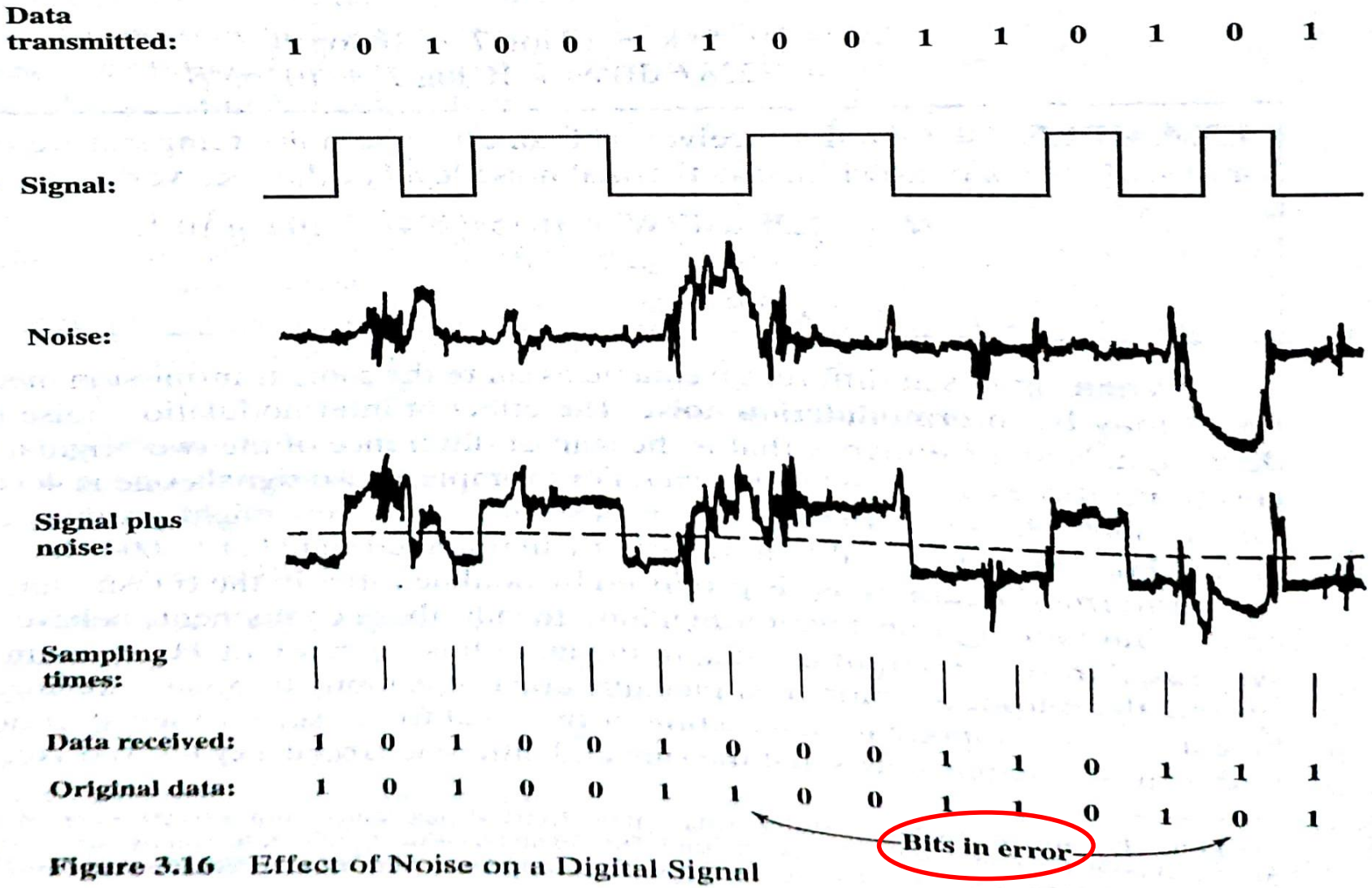


Figure 3.16 Effect of Noise on a Digital Signal

第2章 数据传输基础

2.1 传输相关的概念与术语

2.2 频率、频谱与带宽

2.3 Transmission Impairments(传输损耗)

2.4 Channel Capacity(信道容量)

2.5 基带与调制技术

2.6 数字基带信号传输的波形与编码

2. 4 Channel Capacity (信道容量)

1. 概述

- **max possible data rate** on communication channel
- is a function of

  ---data rate - in bits per second

  ---bandwidth - in cycles per second or Hertz

  ---noise - on communication link

  ---error rate - of corrupted bits
- limitations due to physical properties
- want most efficient use of capacity

2. 4 Channel Capacity (信道容量)

2. Nyquist Bandwidth (奈奎斯特带宽)

- consider noise free channels
- if rate of signal transmission is 2B then can carry signal with frequencies no greater than B, i.e. given **bandwidth B**, highest **signal rate** is 2B
- for binary signals, 2B (bps) needs bandwidth B (Hz)
- can increase rate by using M signal levels
- Nyquist Formula is: $C = 2B \log_2 M$

  ---e.g., 一个带宽为3000Hz的无噪声**话音信道**在传输**2/4/8/16电平/状态数字信号**时，其最大数据传输率不超过6/12/18/24 kbps.

- so increase rate by increasing signals

  ---at cost of receiver complexity.

  ---limited by noise & other impairments.

2. 4 Channel Capacity (信道容量)

3. Shannon (仙农) Capacity Formula

- consider relation of data rate, noise & error rate
  - ---faster data rate shortens each bit so bursts of noise affects more bits.
  - ---given noise level, higher rates means higher errors.
- Claude Shannon (1916-2001) developed formula relating these to signal to noise ratio (信噪比, S/N) in decibels (dB, 分贝)
- $SNR_{db}=10\ \mathbf{log_{10}}\ (S/N)$
- Capacity $C=B\ \mathbf{log_2}(1+SNR)$
  - ---theoretical maximum capacity.
  - ---get lower in practice, in part because formula only assumes white noise (thermal noise).
  - ---e.g.,一个**带宽**为3000Hz，SNR_{db}为35dB(即S/N为3165)的**话音信道**其最大数据传输率不超过34.86 kbps，不论其用多少电平信号发送。

第2章 数据传输基础

2.1 传输相关的概念与术语

2.2 频率、频谱与带宽

2.3 Transmission Impairments(传输损耗)

2.4 Channel Capacity(信道容量)

2.5 基带与调制技术

2.6 数字基带信号传输的波形与编码

2.5 基带与调制技术

1. 基带相关概念

◆ 基带(Baseband)

---**信源**(Signal source)发出的没有经过调制(进行频谱搬移和变换)的原始电信号所固有的频带(频率带宽)，称为基本频带，简称基带。(百度百科)

---数据终端输出信号占有的频带。(曾华燊, 2004)

2.5 基带与调制技术

◆ 基带信号

---信源发出的没有经过调制的原始电信号，其特点是频率较低，信号频谱从零频附近开始，具有低通形式。说得通俗一点，基带信号就是发出的直接表达了要传输的信息的信号，例如我们说话的声波就是基带信号。(百度百科)

---基带信号即基本频带信号，来自**信源**的信号。像计算机输出的代表各种文字或图像文件的数据信号都属于基带信号。(谢希仁, 5e)

2.5 基带与调制技术

---根据原始电信号的特征，基带信号可分为**数字基带信号和模拟基带信号**(相应地，信源也分为**数字信源**和**模拟信源**)，由信源决定，如计算机输出的为基带数字信号，而人说话发出的声波则为基带模拟信号。

---一般说来，大多数信源发出的基带信号为数字信号。

2.5 基带与调制技术

◆ 基带传输

---基带信号在低通型有线信道中，特别是传输距离不太远的情况下，可以直接进行传输。这种传输方式叫做基带传输。

--- Signals (A/D) directly transmitted without modulation. 直接将数据终端的输出信号在信道中传输。(曾华燊, 2004)

---在信道中直接传送基带信号时，称为**基带传输**。传输介质的整个信道被一个基带信号占用。进行基带传输的系统称为**基带传输系统**。(百度百科)

2.5 基带与调制技术

---在**近距离**范围内基带信号的衰减不大，从而信号内容不会发生变化。因此，在传输距离较近时，**计算机**都采用基带传输方式。如从计算机到监视器、打印机等外设的信号就是基带传输的。

---大多数的**局域网**使用基带传输，如以太网、令牌环网。常见的网络设计标准10/100/1000Base-T使用的就是基带信号(其中的Base取自Baseband)。

---只有频率特性为低通型(只允许低频通过)的信道才能直接传输基带信号，如**双绞线**和**同轴电缆**。

---基带信号的频带很宽(理论上是无限宽)，由于几乎不存在无限带宽的传输介质，所以基带信号无法在普通介质上进行远距离传输，否则码间干扰和衰减无法使信号得到恢复。

2.5 基带与调制技术

2. 调制技术

(1) 调制(Modulation)

---基带信号往往包含有较多的低频成分，甚至有直流成分(如果两个电平均在0V以上(单极性))，而许多信道并不能传输这种低频分量或直流分量，这时必须对基带信号进行**调制**（？）来完成传输。(谢希仁, 5e)

---所谓**调制**，就是用基带信号对**载波**(Carrier)波形的某些参量(如幅度、频率或相位)进行控制，使载波的这些参量随基带信号而改变。(潘启敬, 1993)

---其中，基带信号为**调制信号**；调制后得到的信号称为**已调信号**，或**带通**(Bandpass)/**通带**/**频带**(Frequency band)**信号**。这种信号一般只包含一种频率的交流成份或者有限几种频率的交流成份。

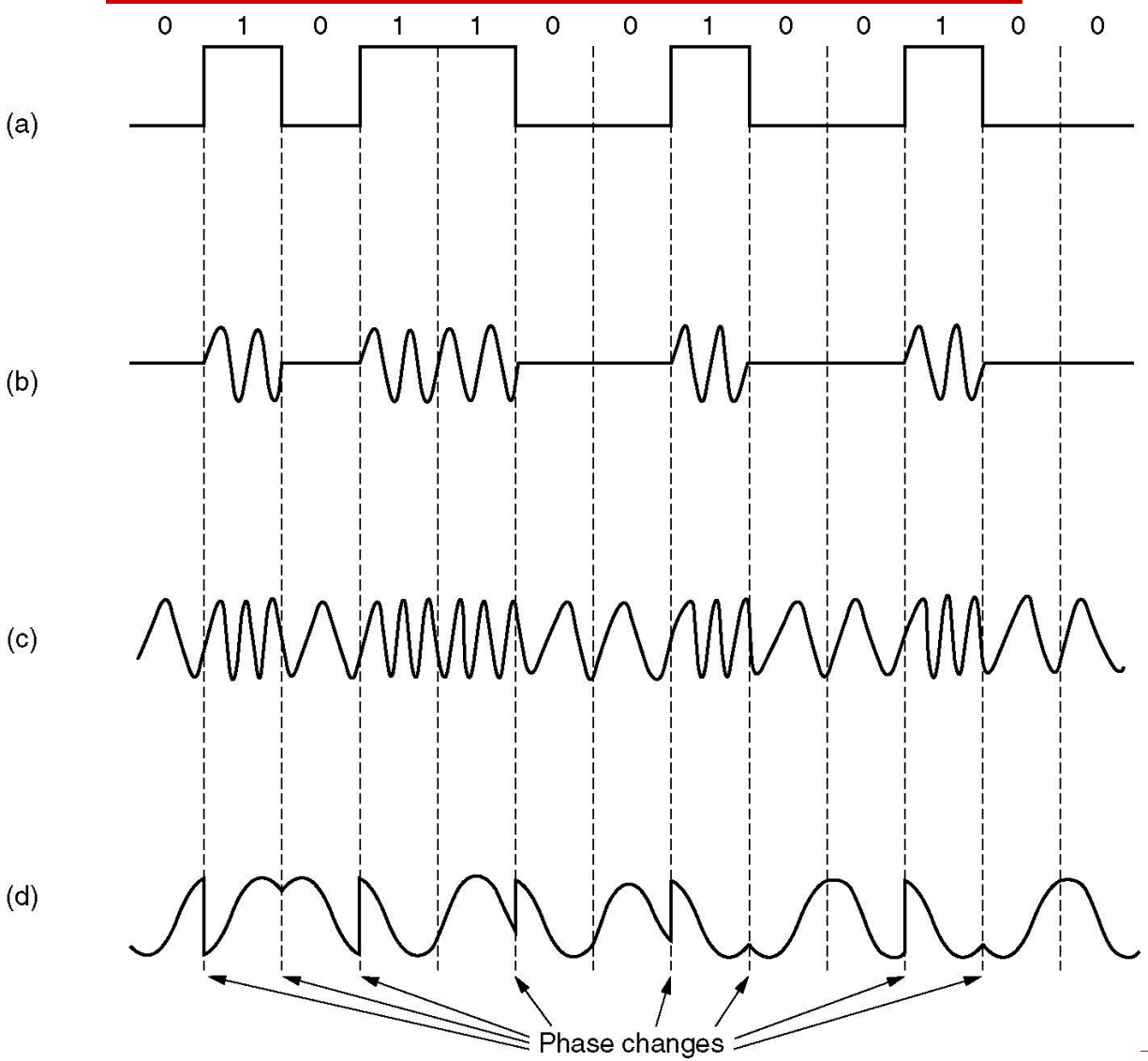
2.5 基带与调制技术

---将低频的模拟基带信号搬移到适于信道传输的高频段去发送，这种频谱搬移过程就称为**调制**，经调制后的信号称为已调信号。已调信号通过信道传输到接收端后，则需要将收到的已调信号再搬移到低频的原始基带频谱上，以恢复原始信号，这一搬移过程称为**解调**。(华为培训资料, 2009)

---经过基带信号对载波进行调制后，可把信号的频率范围搬移到较高的频段以便在信道中传输，此种方式称为频带传输。

---Frequency-band transmission (频带传输): signals to be transmitted were first used to modulate the amplitude, frequency, phase，width(宽度), or position(位置) of other signals (called the carrier – 载波) before sending over transmission media. (曾华燊, 2004)

2.5 基带与调制技术



(a) A binary signal

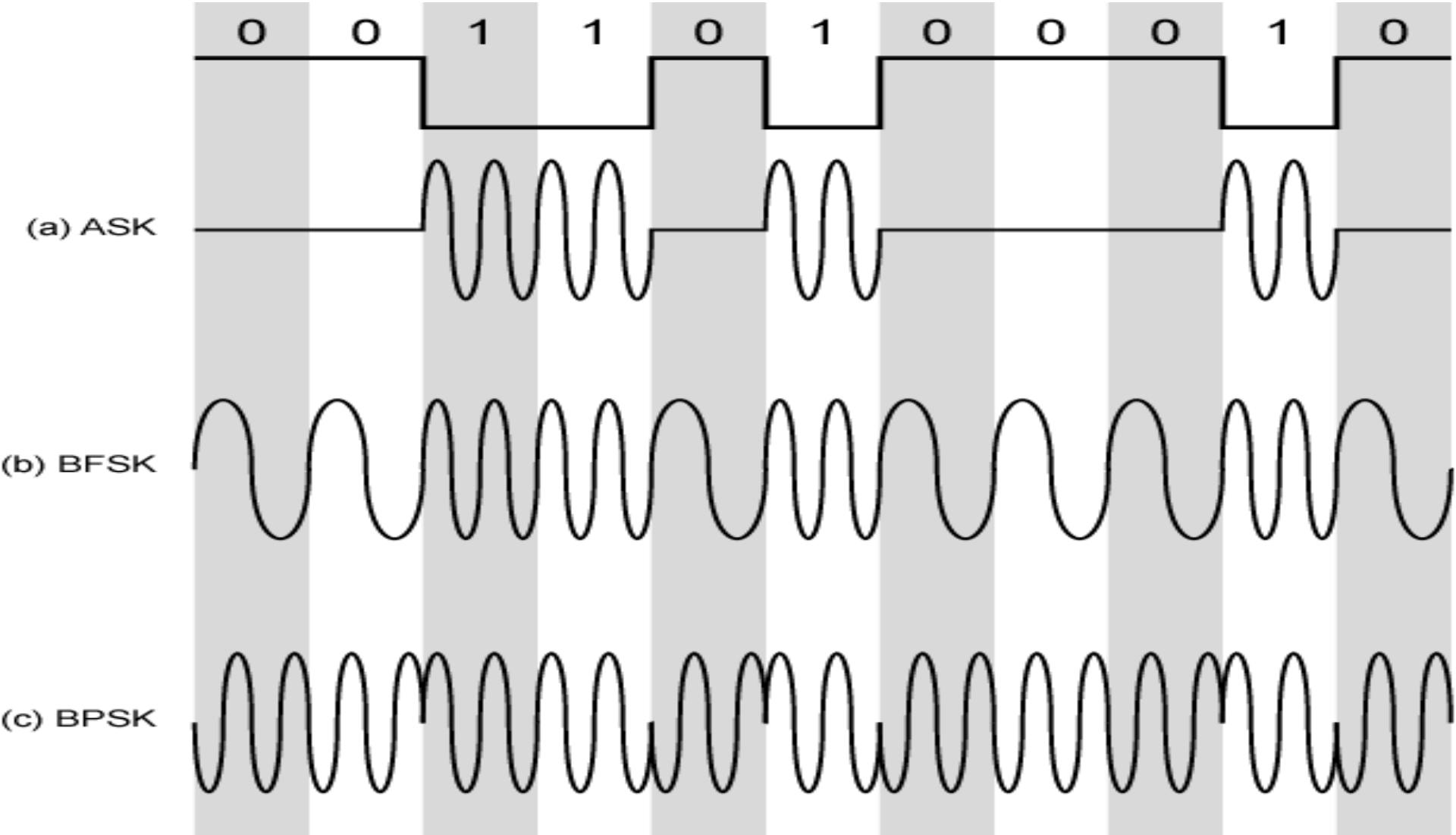
(b) ASK, Amplitude shift keying

(c) FSK, Frequency shift keying

(d) PSK, Phase shift keying

2.5 基带与调制技术

引自William Stallings (8e)



2.5 基带与调制技术

(2) 载波(Carrier)

---载波是指被调制以传输信号的波形，一般为**正弦波**(当然，还有其它的，如**脉冲**、**光波**)。并且，一般要求正弦载波的频率远远高于调制信号的带宽，否则会发生混叠，使传输信号失真。

---载波频率较为单一，因此调制后的**信号的带宽**较小。所以用基带信号对载波调制后，可以减小带宽，使信号可靠传输，减少衰减。

2.5 基带与调制技术

(3) 调制的种类

---**按调制信号**(基带信号)的形式可分为模拟调制和数字调制。用模拟信号调制称为模拟调制，如：用连续变化的信号去调制一个高频正弦波；用数据或数字信号调制称为数字调制，如：用数字信号对正弦或余弦高频振荡进行调制。

(A)**模拟调制**主要包括：幅度调制(AM)、频率调制(FM)和相位调制(PM)，后两者有时合称为角度调制。

(B)**数字调制**主要有：幅移键控(ASK, Amplitude shift keying)、频移键控(FSK)和相移键控(PSK)。因数字信号在通信中有时也叫**键控信号**，故相应于模拟调制中的AM、FM和PM，在数字基带信号调制中分别称为ASK、FSK和PSK。

2.5 基带与调制技术

---**按被调信号**(载波)的种类可分为脉冲调制、正弦波调制和光波调制等。**被调制的载波**分别是脉冲，正弦波和光波等。

(A)脉冲调制：用脉冲序列作为载波。主要有：①脉冲幅度调制(**PAM**, Pulse amplitude modulation)；②脉宽调制(PWM, Pulse width modulation, 或PDM, Pulse duration modulation)；③脉位调制(PPM, Pulse position modulation)；④脉速调制(PRM, Pulse rate modulation, 或 PFM, Pulse frequency modulation)；⑤脉冲编码调制(**PCM**,Pulse code modulation)。

(B)正弦波调制：包括幅度调制、频率调制和相位调制三种基本方式，后两者合称为角度调制。

(C) 光波调制：包括强度(Intensity)调制(IM)和偏振态(Polarization)调制(PLM)。

2.5 基带与调制技术

---其它调制方式

(A)由于数字通信具有建网灵活，容易采用数字差错控制技术和数字加密，便于集成化等优点，所以通信系统都在由模拟制式向数字制式过渡。因此，系统中必须采用**数字调制技术**。

(B)然而，一般的数字调制技术，如ASK、PSK和FSK因传输效率低而无法满足移动通信的要求。为此，需要专门研究一些抗干扰性强、误码性能好、频谱利用率高的数字调制技术，尽可能地提高单位频谱内传输数据的比特率，以适用于移动通信窄带数据传输的要求。

(C)因此，在原有键控基础上扩展出新的数字调制技术。

2.5 基带与调制技术

(D) ASK的扩展

二进制的ASK主要指二进制数字信号去调制正弦波，可记为**2ASK** or **BASK**。对其**扩展**有：多进制ASK (**MASK**)、单边带(SSB, Single side band)调制、残留边带(VSB, Vestigial side band)调制和正交振幅调制(**QAM**, Quadrature amplitude modulation)。

由QAM，又有**MQAM** (如4/8/16/64/128/256QAM等等)，其中，$M=2^L$，L为基带信号的电平数。

(E) FSK的扩展

二进制的FSK可记为**BFSK**。对其**扩展**有：多进制FSK (**MFSK**)、最小频移键控(MSK, Minimum shift keying)和高斯滤波最小频移键控(GMSK, Gaussian filtered minimum shift keying。

2.5 基带与调制技术

(F)PSK的扩展

二进制的PSK可记为**BPSK**。对其**扩展**有：四相相移键控(**QPSK**, Quadrature reference phase shift keying)、交错正交四相相移键控(OQPSK, Offset quadrature reference phase shift keying)、四相相对相移键控(DQPSK, Differential quadrature reference phase shift keying)、π/4正交相移键控(π/4-DQPSK)。

---正交(Quadrature)：最早出现于三维空间中的向量分析。在3维向量空间中，两个向量的内积如果是零，那么就说这两个向量是正交的。换句话说，两个向量正交意味着它们是相互垂直的。

2.5 基带与调制技术

(G)小结

- 最简单的调制/解调技术是2ASK，2FSK，2PSK，其它的则是在它们的基础上发展起来的；
- 在2ASK基础上，产生了正交幅度调制QAM(又称星座调制)等等；
- 2FSK向多进制调制技术上发展，产生了MFSK等调制；
- 在2PSK向多进制的发展方向上,产生了QPSK、OQPSK、MPSK，以及DPSK等等调制。

2.5 基带与调制技术

(4) 调制方式汇总表

基带信号 \ 载波		数字	模拟	
		脉冲	正弦波	光波
数字信号	狭义数字基带	—	BASK/MASK/SSB/VSB/QAM/MQAM; BFSK/MFSK/MSK/GMSK; BPSK/QPSK/OQPSK/DQPSK/π/4-DQPSK	IM/PLM
	扩展 数字基带 (PAM/PCM等)			
模拟信号		PAM/PCM/PWM/PPM/PRM	AM/FM/PM	IM/PLM

2.5 基带与调制技术

(5) 基带数字信号调制模拟信号的一些典型方式

◆ ASK

---encode 0/1 by different carrier amplitudes, usually have one amplitude zero

---ASK实际上以键控(开/关)方式产生，即基带数字信号为1时，发送一正弦信号$\cos(2\pi f_c t)$；为0时，不发送载波信号。于是，ASK的输出信号可表示为一个单极性矩形脉冲序列与一个正弦载波的相乘，即：

$$e_c = [\sum_{k=-\infty}^{\infty} a_k g(t - kT_s)]\cos(2\pi f_c t)$$ (曾华燊, 2004)

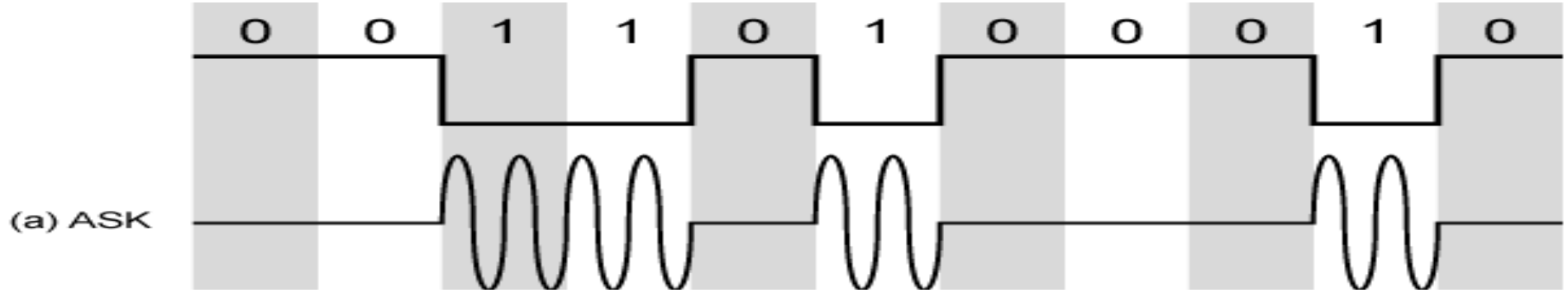
式中，$g(t)$为单个矩形脉冲，脉宽为T_s，a_k=1/0。

2.5 基带与调制技术

---The resulting transmitted signal for one bit time is

$$ASK \quad s(t)=\begin{cases} A\cos(2\pi f_c t) & binary 1 \\ 0 & binary 0 \end{cases}$$ (Stallings, 8e)

式中，$A\cos(2\pi f_c t)$为载波。



---susceptible to sudden gain changes.

---inefficient.

---used for

(A) up to 1200bps on voice grade (话音级) lines.

(B) very high speeds over optical fiber, where one signal element is represented by a light pulse while the other signal element is represented by the absence of light.

◆ MASK(多进制ASK)

---多进制亦称多电平。MASK的已调信号可以看成是时间上互不相容的M个不同振幅值的通断键控信号的叠加。

---在相同码元传输速率下，MASK的信号带宽与ASK相同，但其单个码元的信息量比二电平大，故其比ASK效率高。

2.5 基带与调制技术

◆ BFSK (Binary frequency shift keying)

---most common is binary FSK (BFSK).

---two binary values represented by two different frequencies, f_1, f_2 (near carrier frequency f_c)

$$BFSK \quad s(t) = \begin{cases} A\cos(2\pi f_1 t) \ binary1 \\ A\cos(2\pi f_2 t) \ binary0 \end{cases}$$

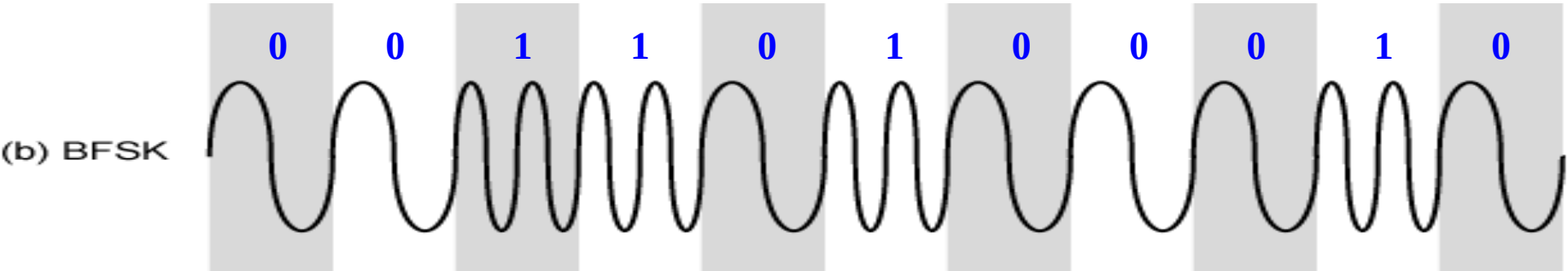
---less susceptible to error than ASK

---used for

(A) up to 1200bps on voice grade lines.

(B) high frequency radio.

(C) even higher frequency on LANs using co-ax.



2.5 基带与调制技术

◆ MFSK (Multiple FSK)

---each signaling element represents more than one bit (L bits).

---more than two frequencies ($M=2^L$) used

$$MFSK \quad s_i(t) = A\cos(2\pi f_i t),\ 1 \le i \le M$$

where $f_i=f_c+(2i-1-M)f_d$,

f_d: the difference frequency

M: number of different signal elements, $=2^L$

L: number of bits per signal element

---more bandwidth efficient

● The total bandwidth $W_d=f_M-f_1=2Mf_d$

---more prone to error.

2.5 基带与调制技术

Example:

---With f_c=250kHz, f_d =25kHz, and M=8 (L=3)

000 f_1= 75 kHz　　001 f_2=125 kHz

010 f_3=175 kHz　　011 f_4=225 kHz

100 f_5=275 kHz　　101 f_6=325 kHz

110 f_7=375 kHz　　111 f_8=425 kHz

2.5 基带与调制技术

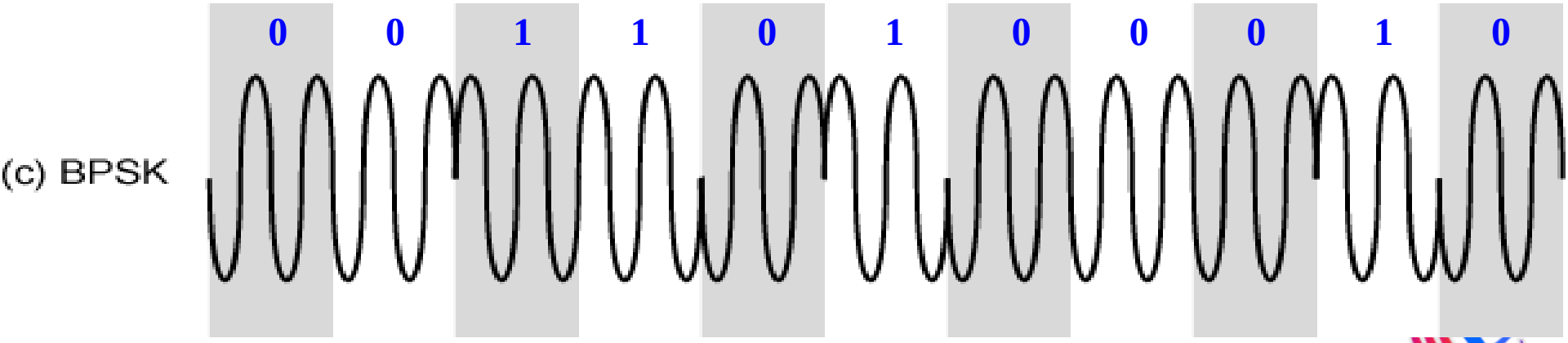
◆ PSK (Phase shift keying)

---phase of carrier signal is shifted to represent data

---binary PSK (BPSK): two phases represent two binary digits

$$s(t)=\begin{cases}A\cos(2\pi f_c t)\\ A\cos(2\pi f_c t+\pi)\end{cases}=\begin{cases}A\cos(2\pi f_c t) & binary\,1\\ -A\cos(2\pi f_c t) & binary\,0\end{cases}=Ad(t)\cos(2\pi f_c t)$$

---differential (差分/相对) PSK (DPSK): phase shifted relative to previous transmission rather than some reference signal



2.5 基带与调制技术

◆ Quadrature PSK (QPSK/4PSK, 正交PSK/四相相位键控)

--- get more efficient use if each **signal element** represents more than one bit (利用载波的4种不同相位来表征输入的数字信息)

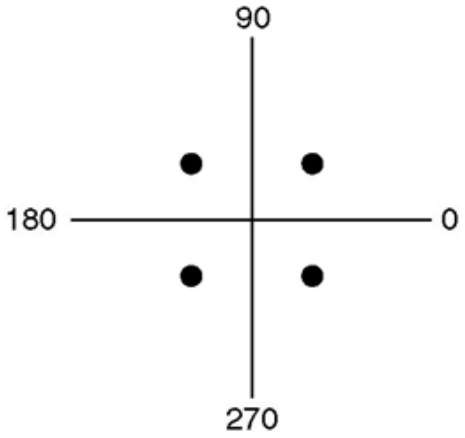
$$QPSK \quad s(t)=\begin{cases} A\cos(2\pi f_c t+\frac{\pi}{4}) & 11 \\ A\cos(2\pi f_c t+\frac{3\pi}{4}) & 01 \\ A\cos(2\pi f_c t-\frac{3\pi}{4}) & 00 \\ A\cos(2\pi f_c t-\frac{\pi}{4}) & 10 \end{cases}$$

- each element represents two bits, shifts of π/2 (90°), 不同双比特码元间的相位变化都以90°为基础(如：3π/4-π/4=π/2)。
- split input data stream in two & modulate onto carrier & phase shifted carrier

2.5 基带与调制技术

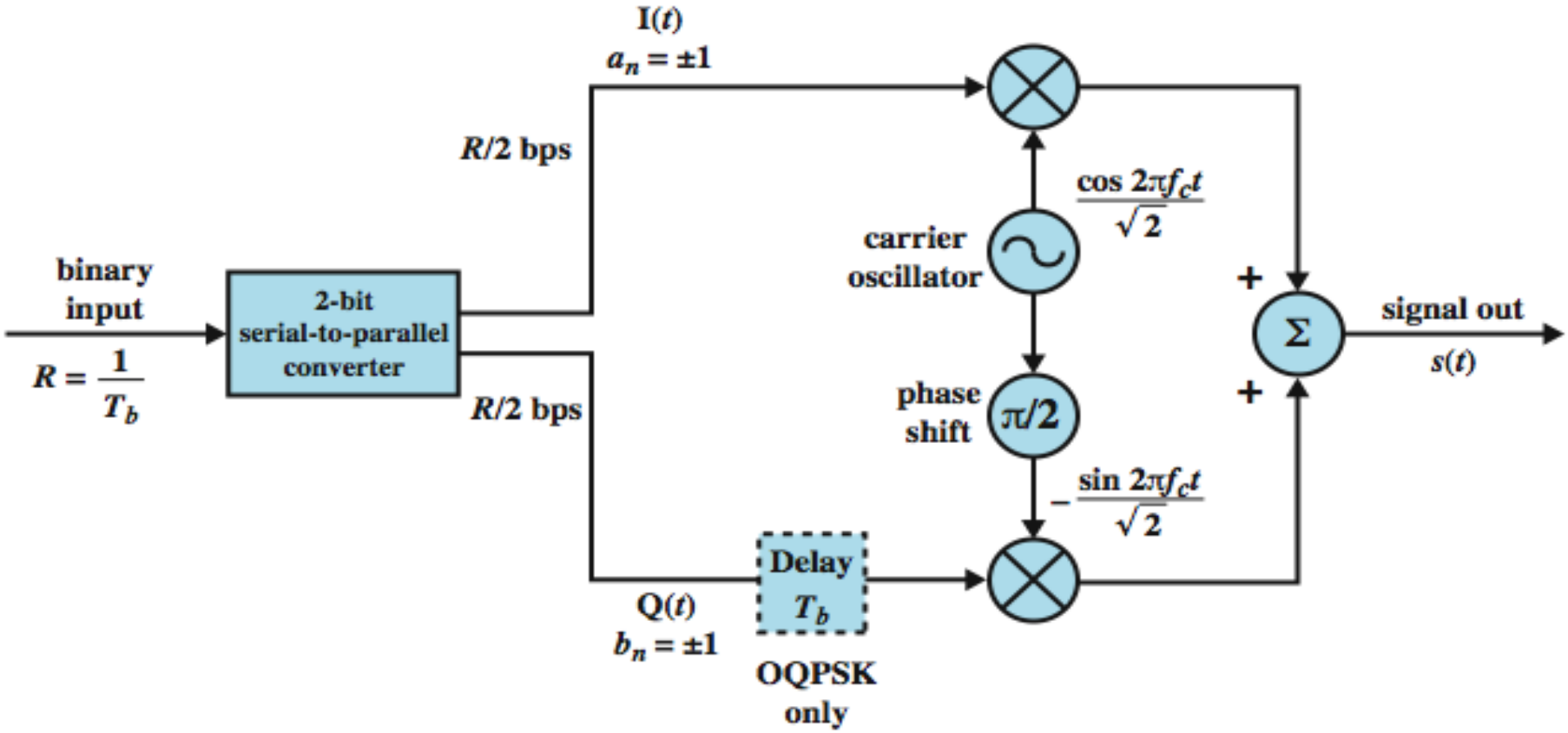
引自曾华燊(2004)

双比特码元	4PSK载波相位		4DPSK相位变化
	Mode A	Mode B	
00	0^o	$225^o(-3\pi/4)$	0^o
10	90^o	$315^o(-\pi/4)$	90^o
11	180^o	$45^o(\pi/4)$	180^o
01	270^o	$135^o(3\pi/4)$	270^o



2.5 基带与调制技术

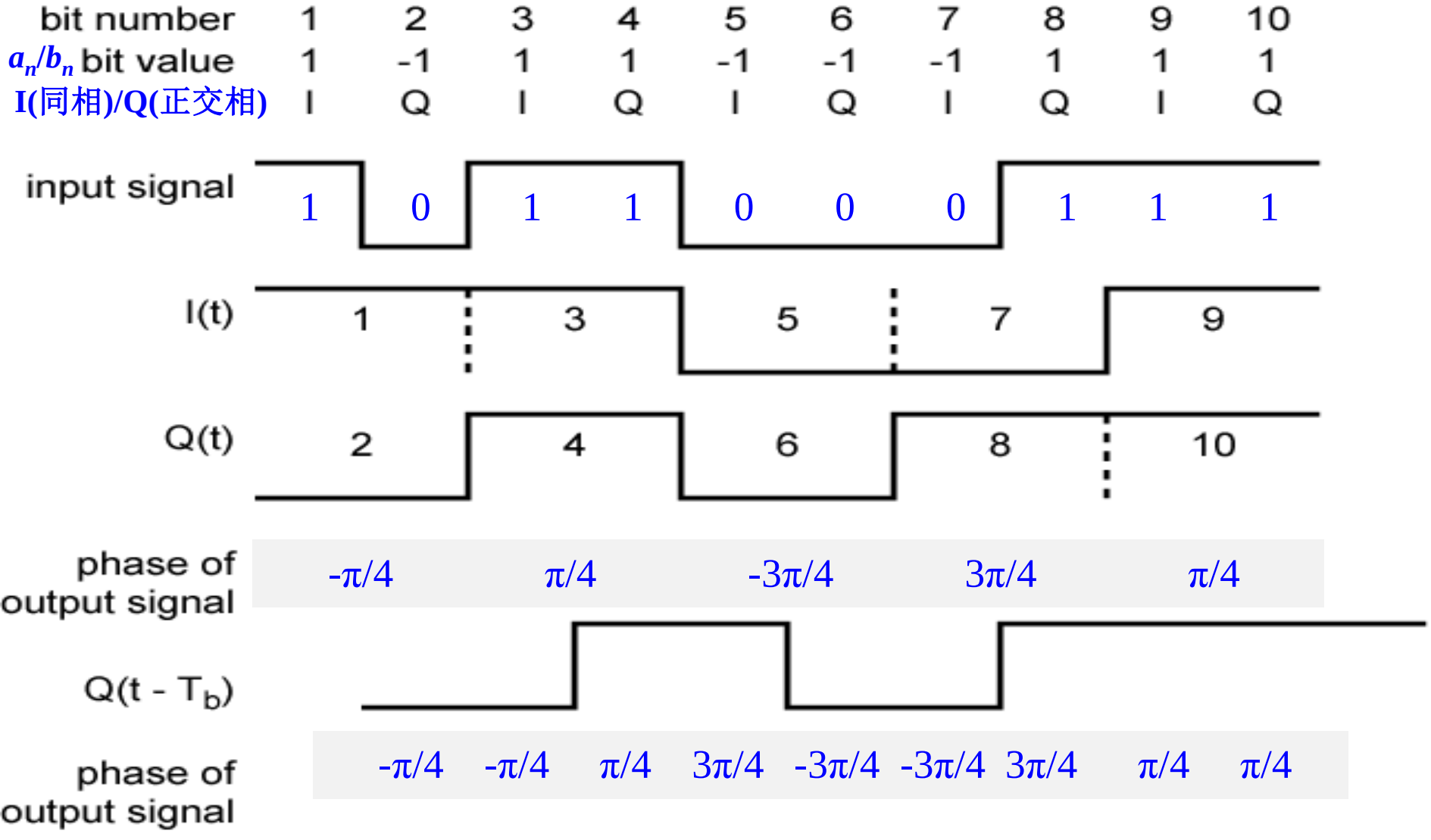
QPSK and OQPSK Modulators



$$QPSK \quad s(t) = \frac{1}{\sqrt{2}} I(t)\cos(2\pi f_c t) - \frac{1}{\sqrt{2}} Q(t)\sin(2\pi f_c t)$$

2.5 基带与调制技术

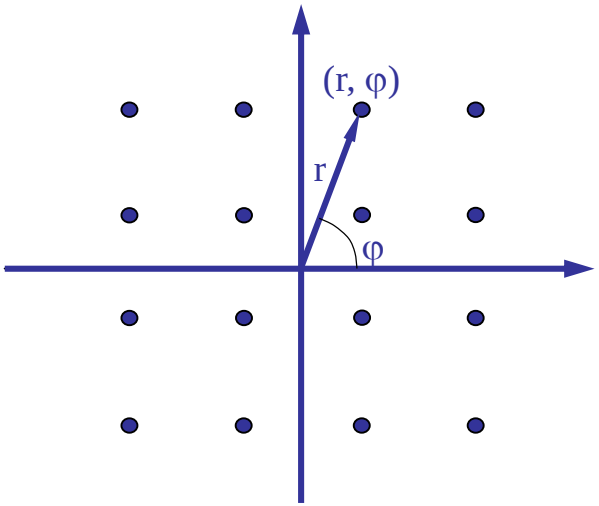
Examples of QPSF and OQPSK Waveforms



2.5 基带与调制技术

---其它扩展

- can use 8 phase angles & more than one amplitude, then each element represents three bits (8DPSK)
- 9600bps modem uses 12 angles, four of which have two amplitudes, for a total of 16 different signal elements (可供选择的相位有 12 种，其中4种相位又有 2 种振幅可供选择，故有16种不同的组合。此时，16个点中的每个点可对应于一种 4 bit 的编码)



引自谢希仁(5e)

2.5 基带与调制技术

◆ QAM (Quadrature amplitude modulation)

--- QAM used on asymmetric digital subscriber line (ADSL) and some wireless standards (802.11 a/g/n/ac/ad).

---combination of ASK and PSK.

---can also be considered a logical extension of QPSK.

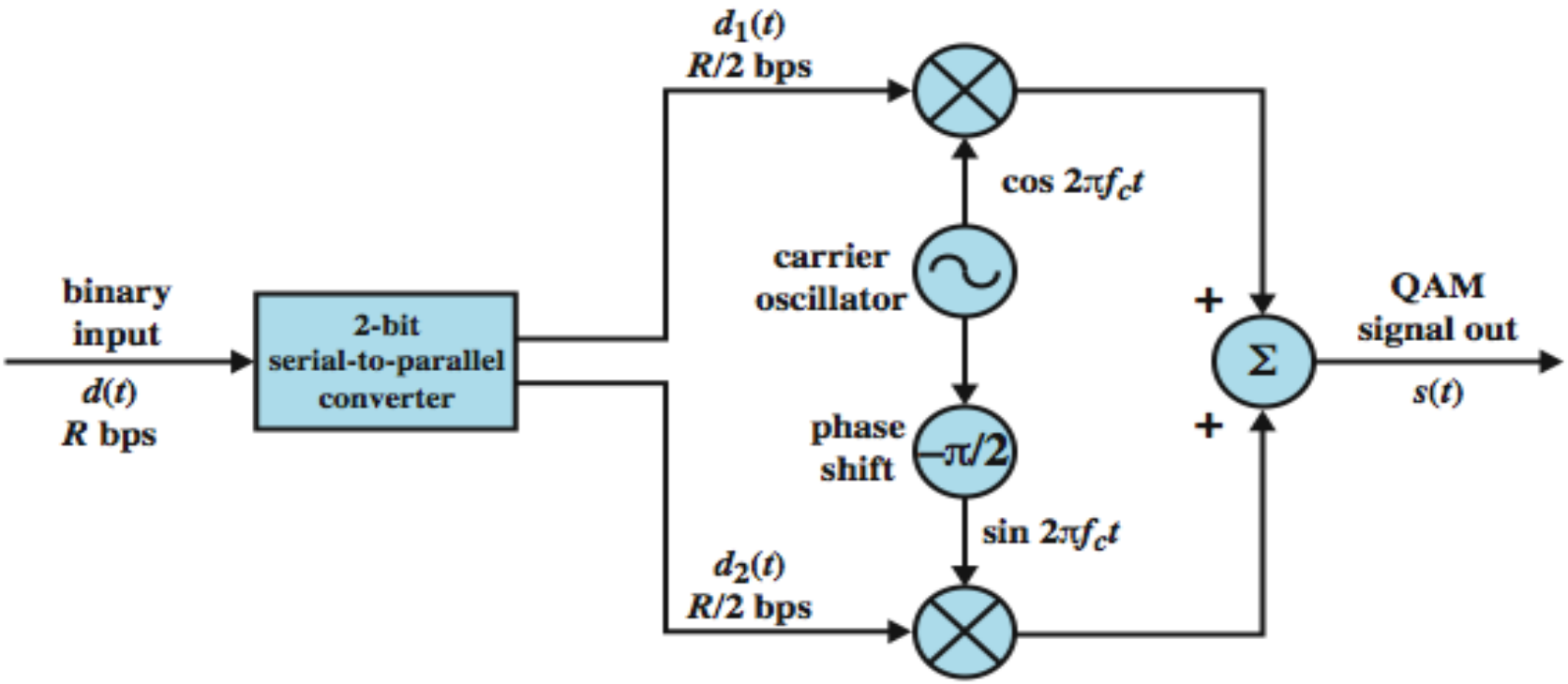
---send two different signals simultaneously on same carrier frequency

$$QAM \quad s(t) = d_1(t)\cos(2\pi f_c t) + d_2(t)\sin(2\pi f_c t)$$

- use two copies of carrier, one shifted 90° .
- each carrier is ASK modulated.
- two independent signals over same medium.
- demodulate and combine for original binary output.

2.5 基带与调制技术

QAM Modulator (William Stallings, 8e)



2.5 基带与调制技术

◆ QAM Variants

--- two level ASK

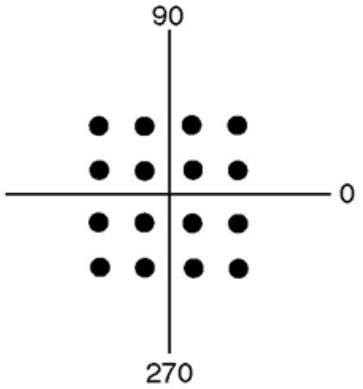
- each of two streams in one of two states
- four state system
- essentially QPSK

---four level ASK (**16QAM**)

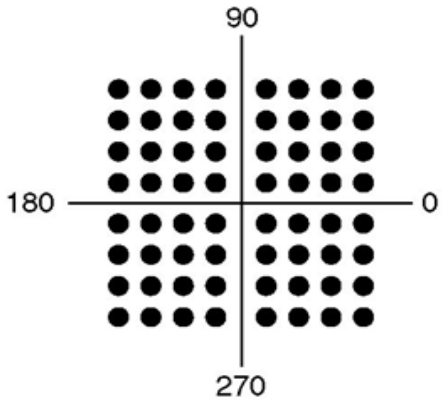
- i.e., four different amplitude levels
- combined stream in one of 16 states

--- **64QAM** and **256QAM**

- The greater the number of states, the higher the data rate that is possible within a given bandwidth.
- Of course, the greater the number of states, the higher the potential error rate due to noise and attenuation.



16QAM



64QAM

2.5 基带与调制技术

(6) 基带模拟信号调制数字脉冲信号的几个典型方式

--- digitization (数字化) is conversion of analog data into digital data.

--- analog to digital conversion done using a codec (编译码器)

- pulse code modulation (PCM, 脉码调制).
- delta modulation (Δ调制).

◆ PCM

---脉冲调制实质上是对模拟基带信号进行**采样**并**量化**的过程。

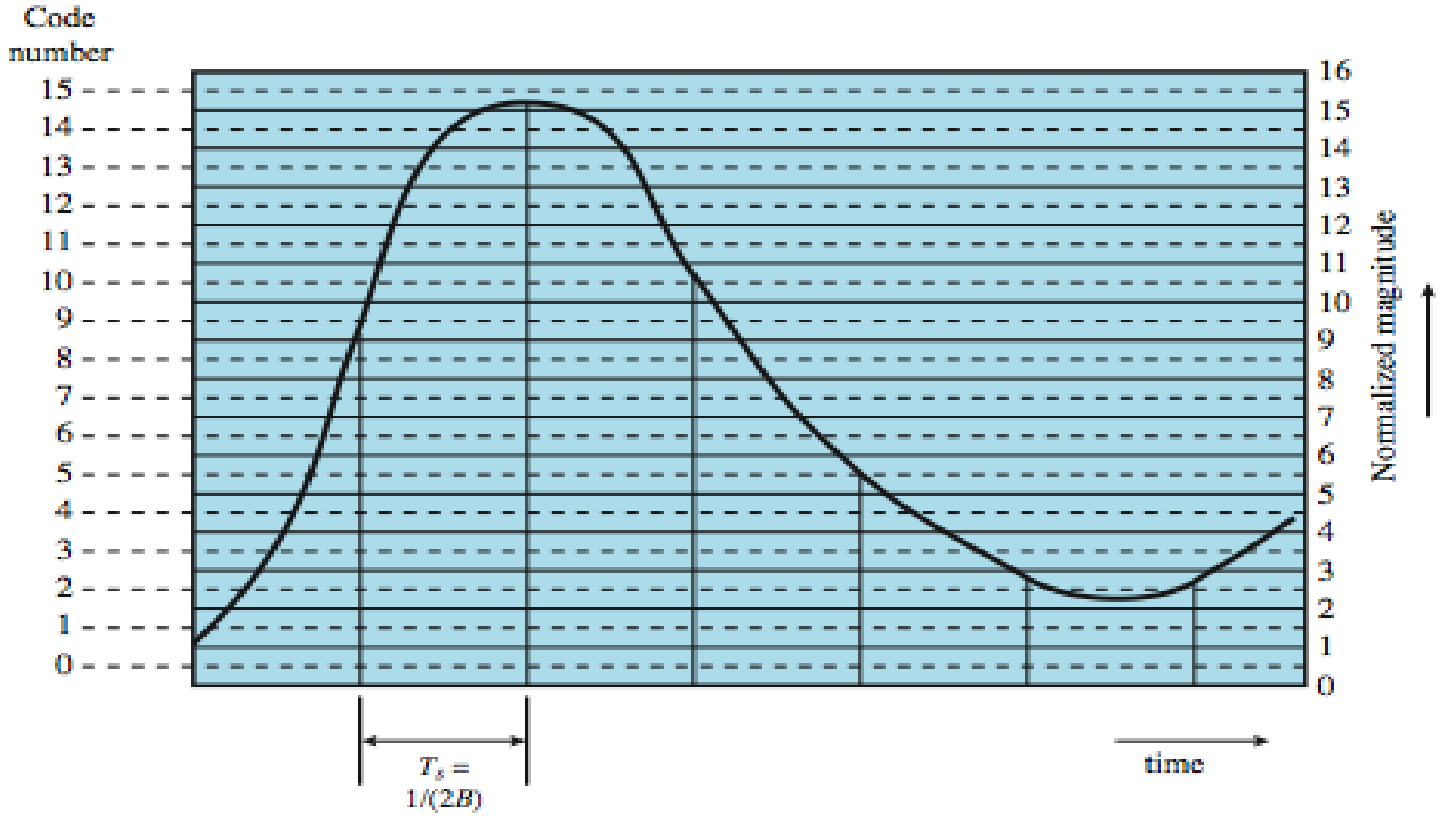
---Sampling theorem (采样定理): "If a signal is sampled at regular intervals at a rate higher than twice the highest signal frequency, the samples contain all information in original signal"

- e.g. 4000Hz voice data, requires 8000 sample/sec (125μs/样本).
- strictly have analog samples, called Pulse Amplitude Modulation (PAM) samples.

---To convert to digital, each of these analog samples must be assigned a binary code.

2.5 基带与调制技术

PCM Example (William Stallings, 8e)



PAM value	1.1	9.2	15.2	10.8	5.6	2.8	2.7
quantized code number	1	9	15	10	5	2	2
PCM code	0001	1001	1111	1010	0101	0010	0010

2.5 基带与调制技术

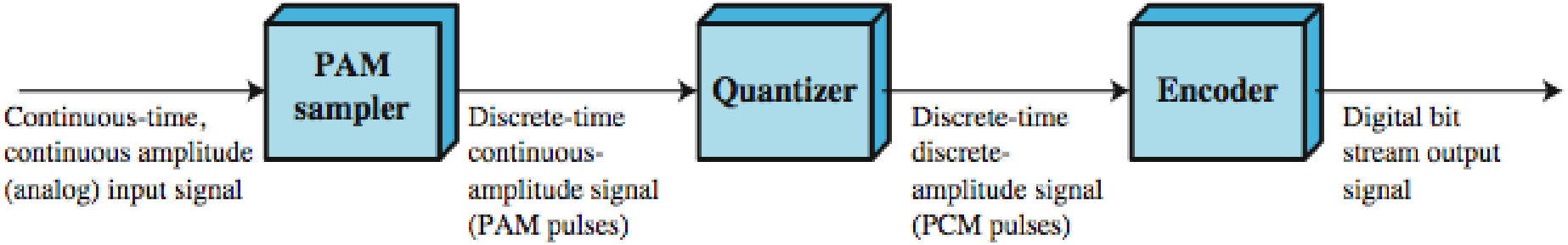
Notes:

---Because the quantized values are only approximations, it is impossible to recover the original signal exactly.

---By using an 8-bit sample, which allows 256 quantizing levels, the quality of the recovered voice signal is comparable with that achieved via analog transmission.

---Above implies that a data rate of 8000 samples per second×8 bits per sample = 64 kbps is needed for a single voice signal.

PCM Block Diagram (William Stallings, 8/e)



2.5 基带与调制技术

◆ Delta modulation (DM, Δ调制)

--- to improve the performance of PCM or to reduce its complexity.

---also called Differential PCM (差分脉码调制).

---analog input is approximated by a staircase function (楼梯函数)

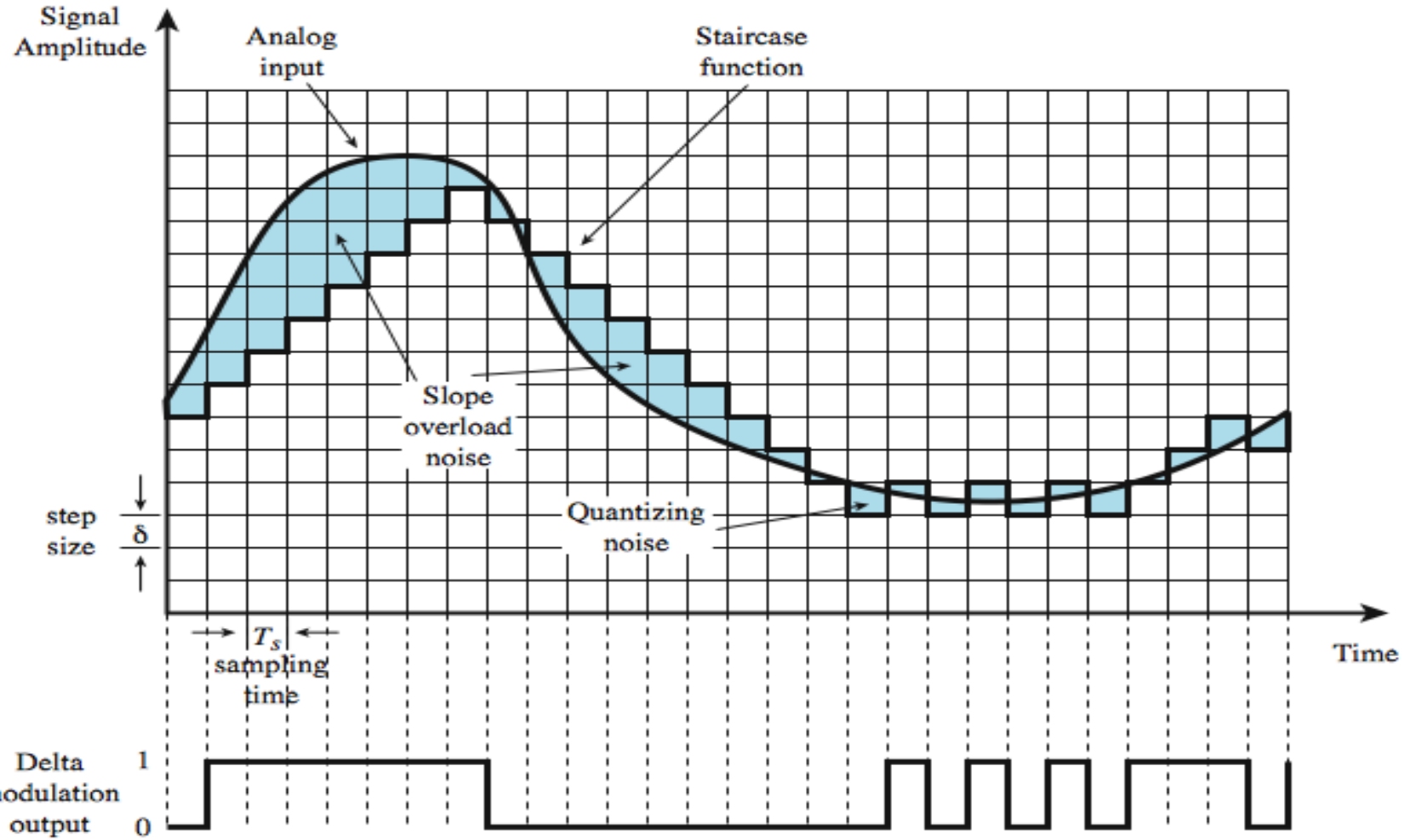
- can move up or down one level (δ) at each sample interval (T_s).

---has binary behavior

- since function only moves up or down at each sample interval.
- hence can encode each sample as single bit.
- 1 for up or 0 for down.

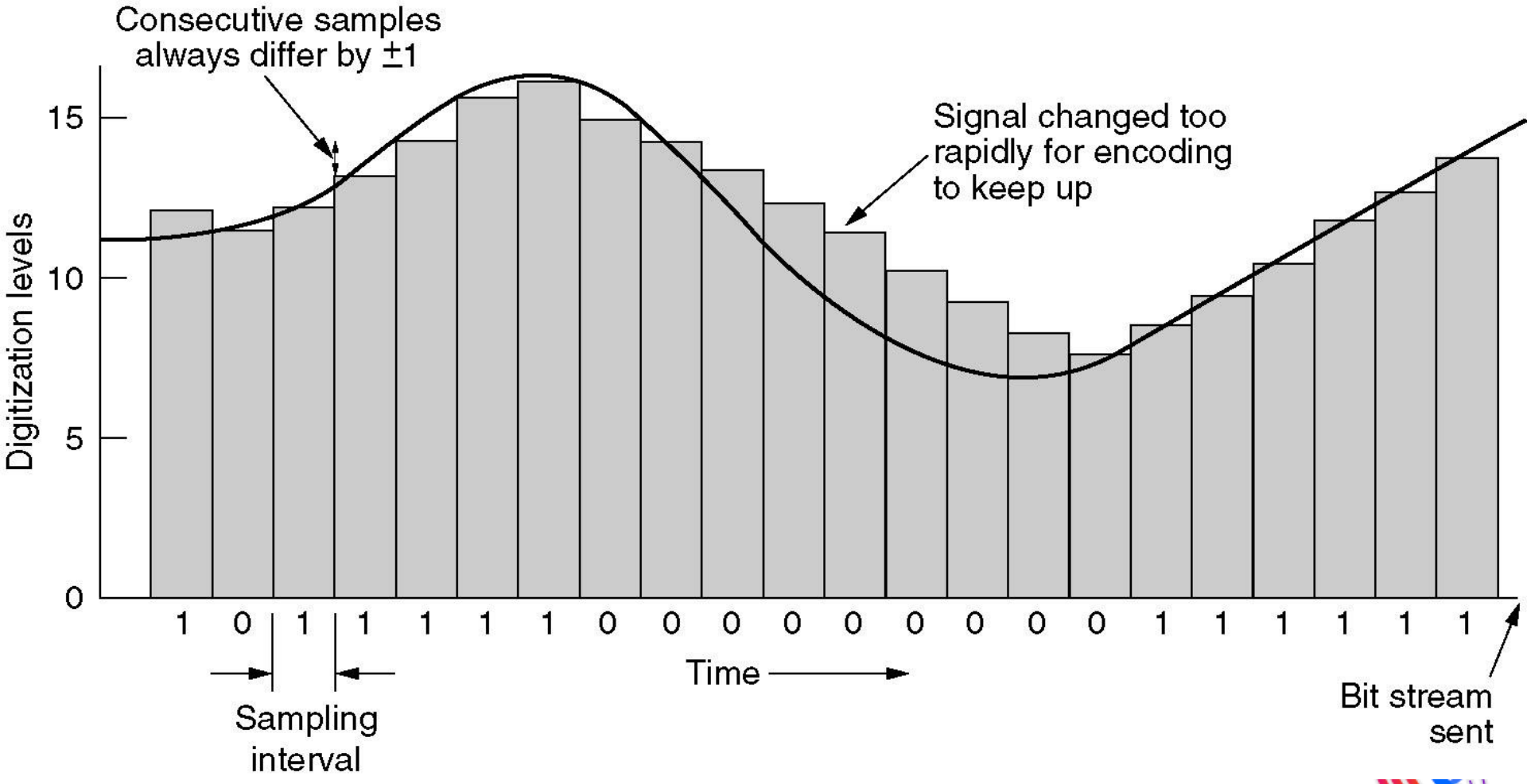
2.5 基带与调制技术

DM Example (William Stallings, 8e)



2.5 基带与调制技术

Delta modulation (Tanenbaum, 4e)



2.5 基带与调制技术

(6) 基带模拟信号调制模拟正弦信号的典型方式

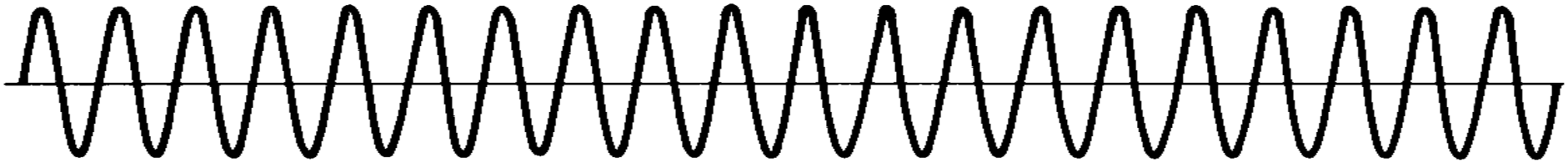
--- modulate carrier frequency with analog data.

--- why modulate analog signals?

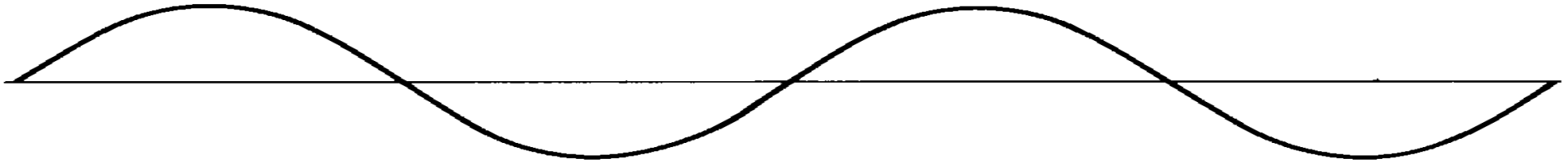
- higher frequency can give more efficient transmission.
- permits frequency division multiplexing (FDM, 频分多路复用).

---types of modulation

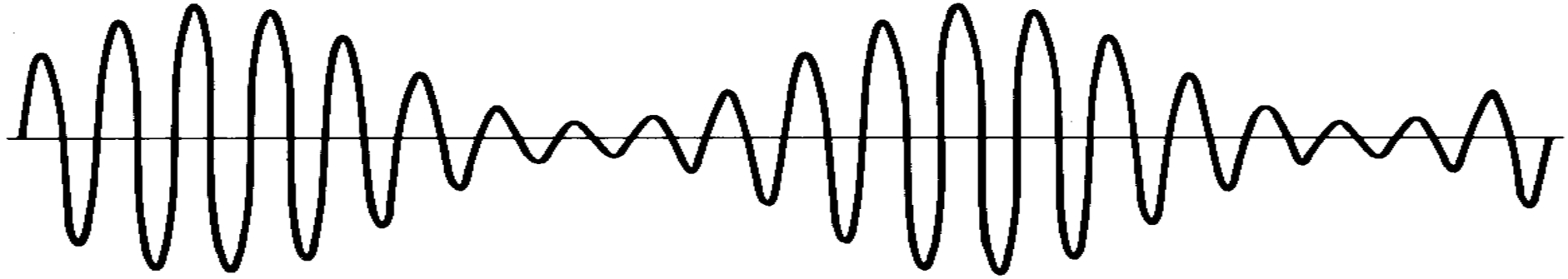
- Amplitude.
- Frequency.
- Phase.



Carrier

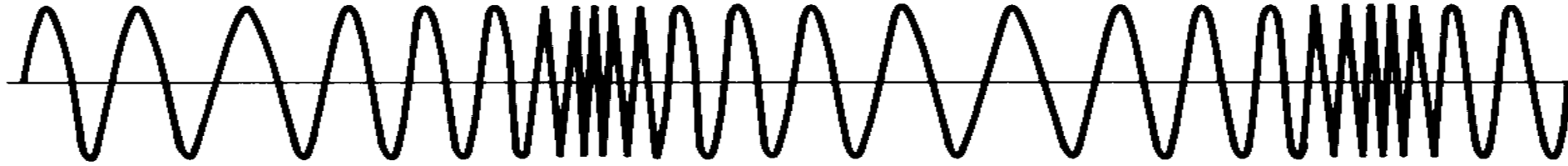


Modulating sine–wave signal



Amplitude–modulated (DSBTC) wave

Phase–modulated wave



Frequency–modulated wave

第2章 数据传输基础

2.1 传输相关的概念与术语

2.2 频率、频谱与带宽

2.3 Transmission Impairments(传输损耗)

2.4 Channel Capacity(信道容量)

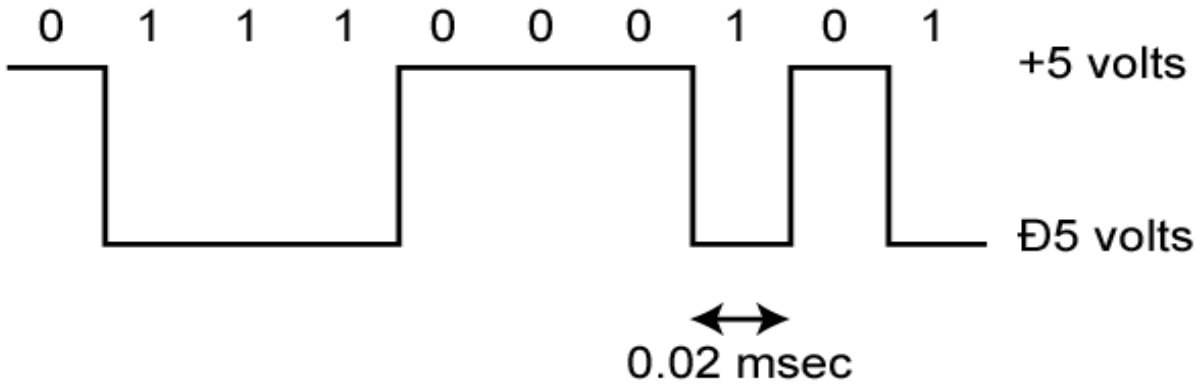
2.5 基带与调制技术

2.6 数字基带信号传输的波形与编码

2.6 数字基带信号传输的波形与编码

1. 概述

--- A digital signal is a sequence of discrete, discontinuous voltage pulses, each of which is a signal element.



2.6 数字基带信号传输的波形与编码

---Key data transmission **terms**

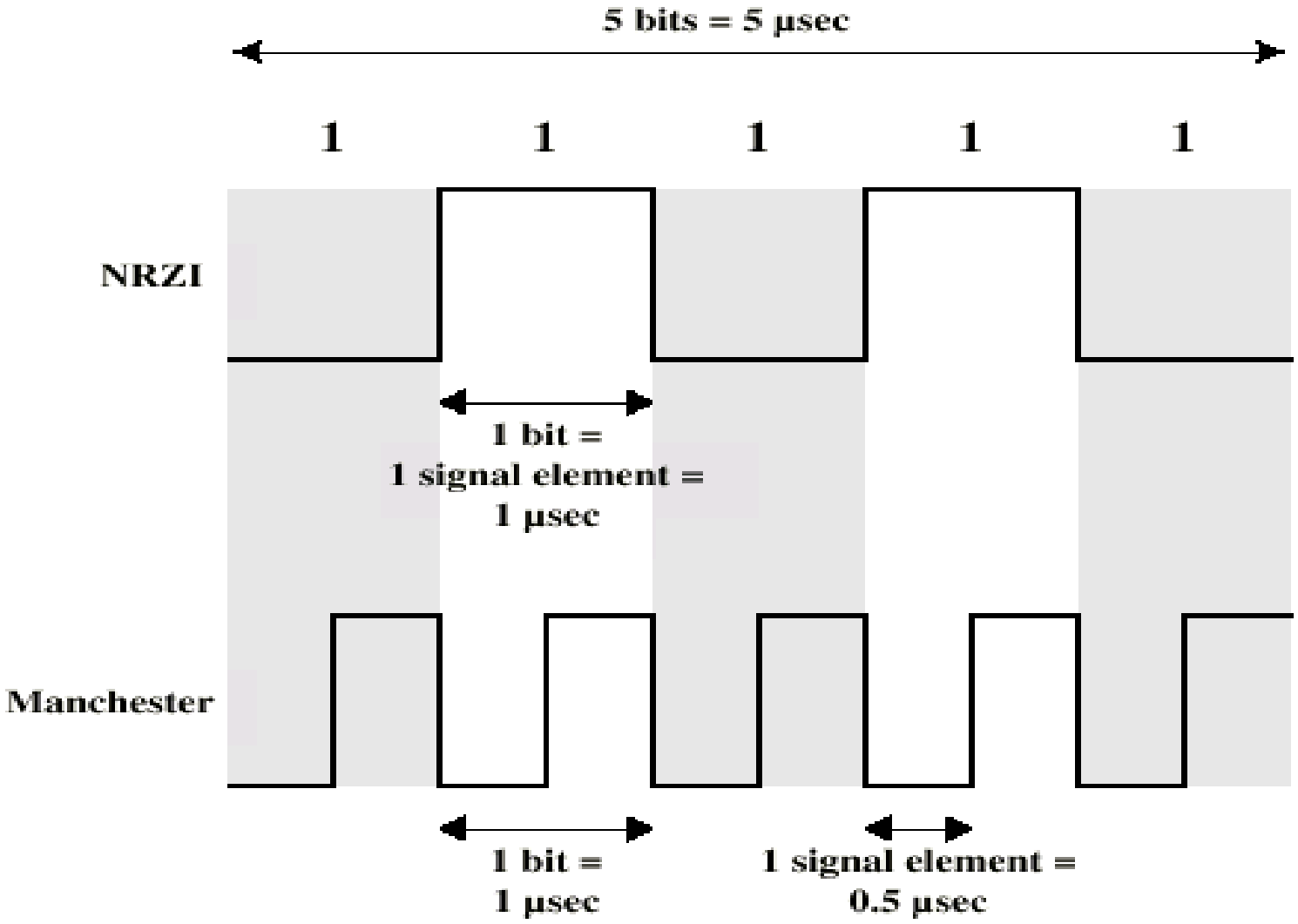
- Data element (码元): a single binary **one or zero** (bit).
- Data rate (数据速率): the rate at which data elements are transmitted (bps), =1/*T*, *T* is the length of a bit.
- Signal element (信元): that part of a signal that occupies the shortest interval of a signaling code
- Signaling rate or modulation (非严格意义) rate: the rate at which the signal level changes (baud, 波特), depends on type of digital encoding used.

波特率：$B=1/T$，T为单位脉冲宽度

信号速率：$S=B\log_2 n$，n为脉冲可表达的状态数

——如为2电平，则：波特率＝信号速率＝B。

2.6 数字基带信号传输的波形与编码



2.6 数字基带信号传输的波形与编码

---Binary data are transmitted by encoding each data bit into signal elements.

- In the simplest case, there is a one-to-one correspondence between **bits and signal elements**.
- More complex encoding schemes are used to improve performance, by altering the spectrum of the signal and providing synchronization capability.

2.6 数字基带信号传输的波形与编码

2. 波形(Waveform)

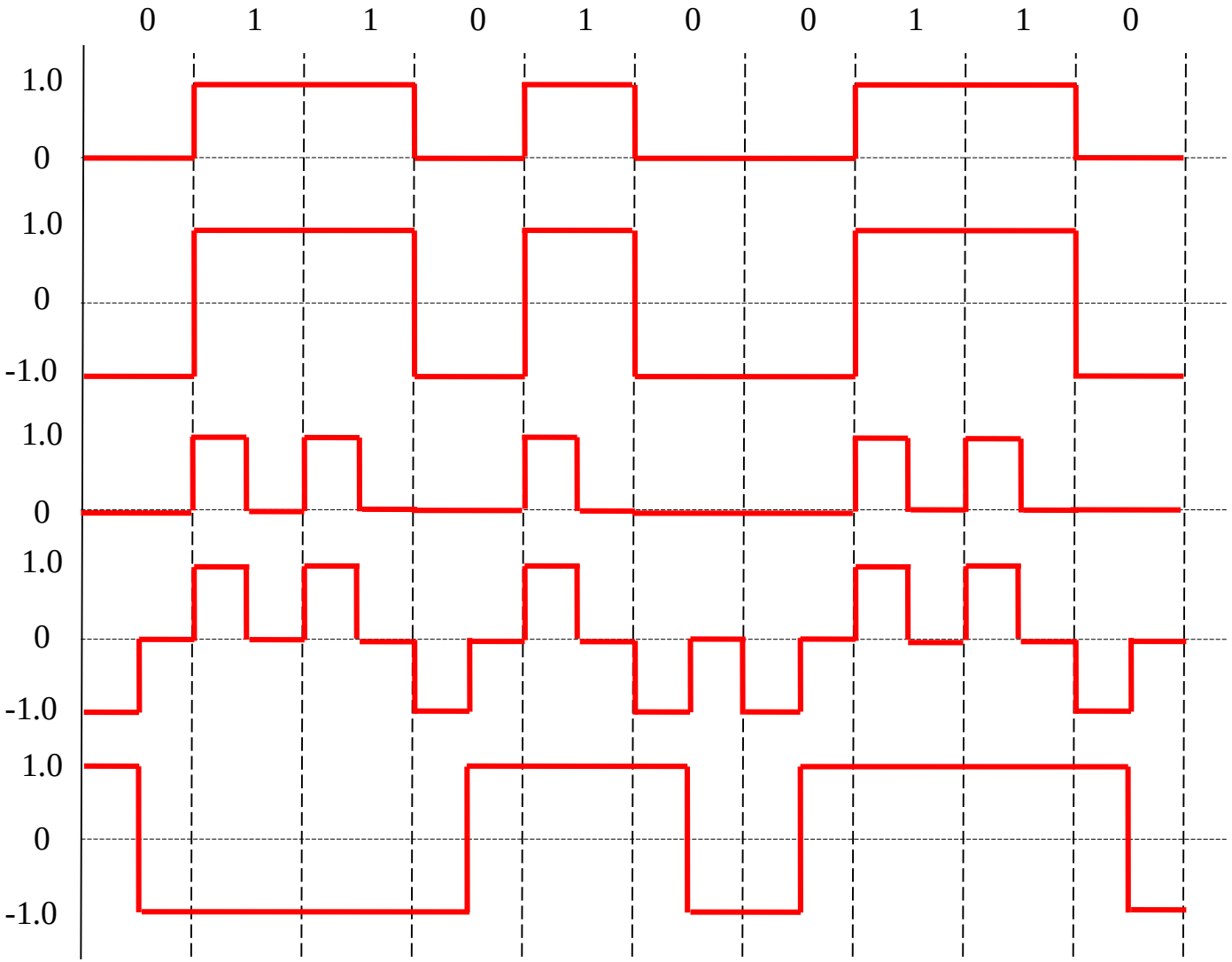
---shape and variation pattern.

---They are usually classified according to the following criteria:

- Numbers of electric level (电平) in representing digital information
- Polarity of the signal (positive or/and negative swinging): 正负极性
- Whether or not always return to the base line (0 volt) within each clock cycle: 是否归零.

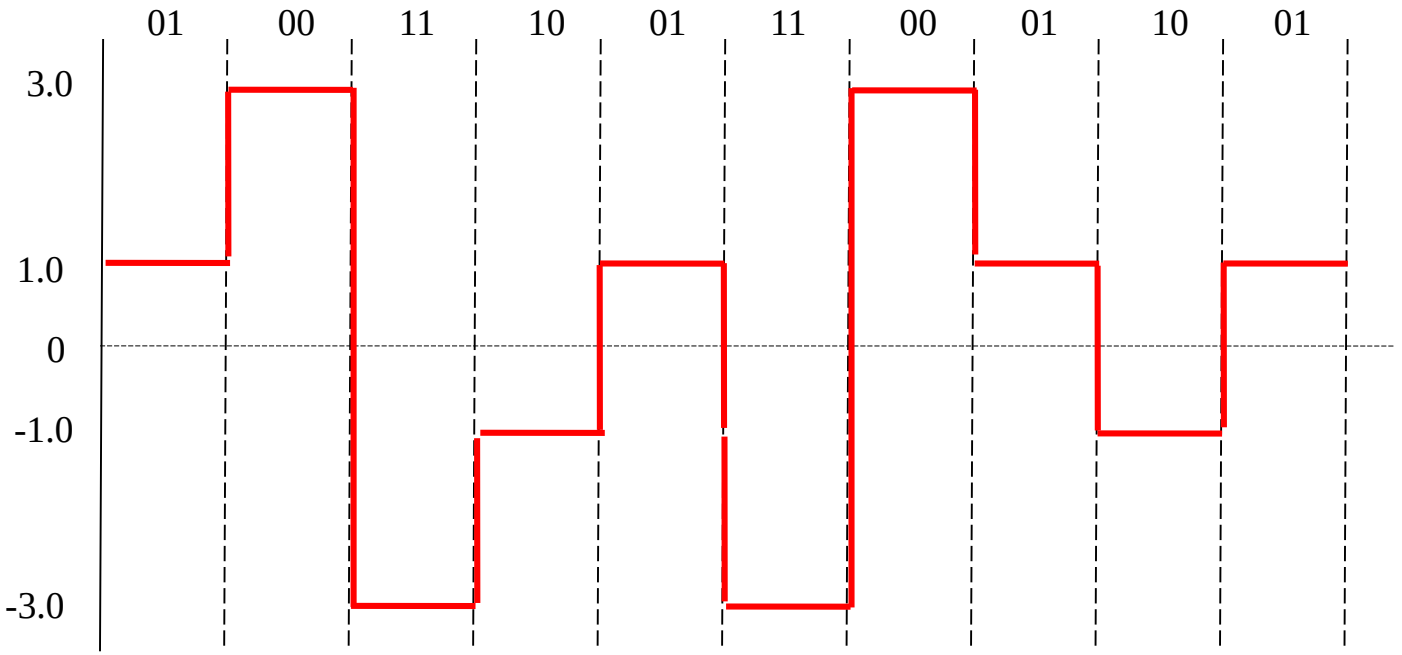
---原理性基本的、二电平/二进制脉冲波形：单极(Unipolar)不归零(Nonreturn to Zero-level, NRZL)脉冲、双极(Bipolar)不归零脉冲、单极归零脉冲、双极归零脉冲、差分脉冲。(潘启敬, 1993)

2.6 数字基带信号传输的波形与编码



2.6 数字基带信号传输的波形与编码

---双极4电平不归零脉冲(曾华燊, 2004).



2.6 数字基带信号传输的波形与编码

---The more common waveforms (W. Stallings, 8e)

(A) NRZL

(B) NRZI (Nonreturn to Zero Inverted)

(C) Bipolar-AMI (Alternate mark inversion, 交替标志反转)

(D) Pseudoternary

(E) Manchester (曼彻斯特)

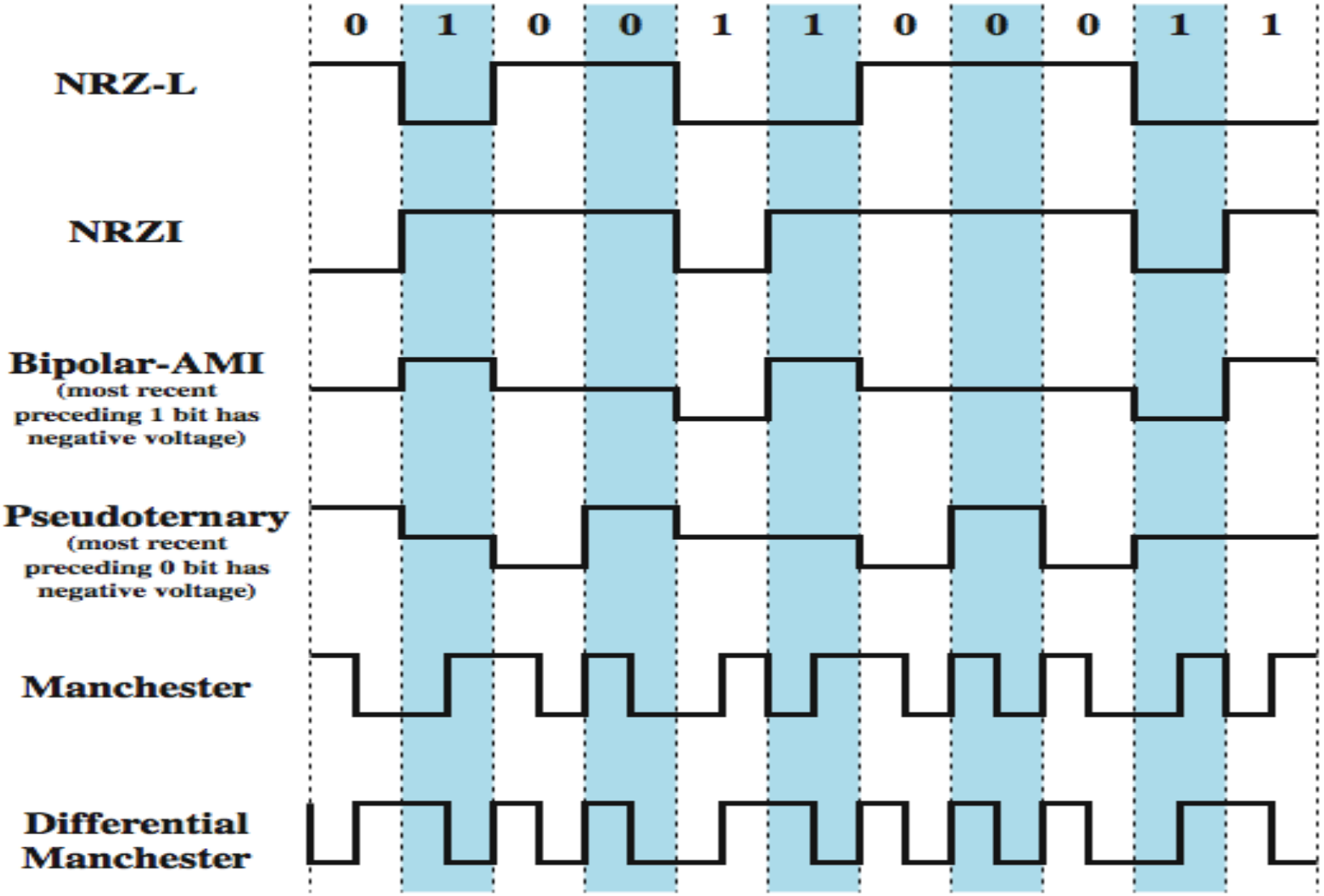
(F) Differential Manchester

(G) B8ZS (Bipolar with 8 zeros substitution)

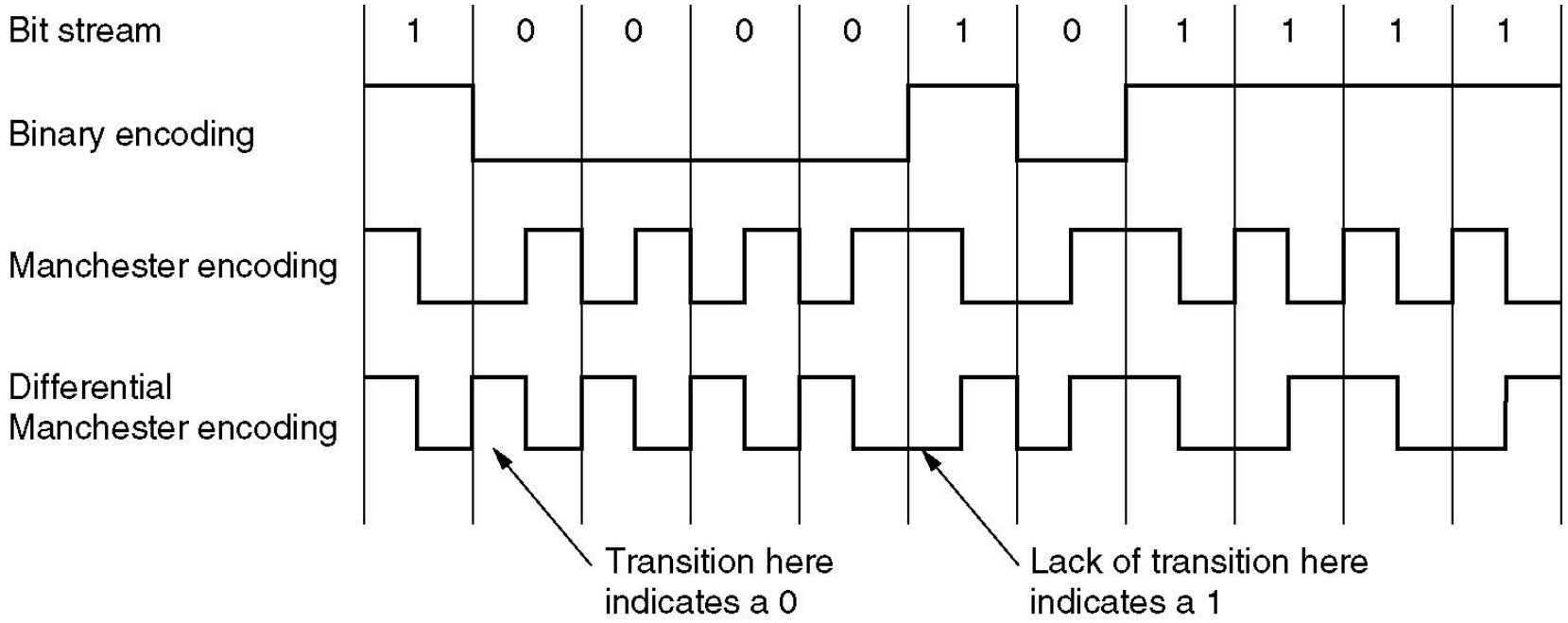
(H) HDB3 (High-density bipolar – 3 zeros)

注：B8ZS和HDB3实属编码。

2.6 数字基带信号传输的波形与编码



2.6 数字基带信号传输的波形与编码

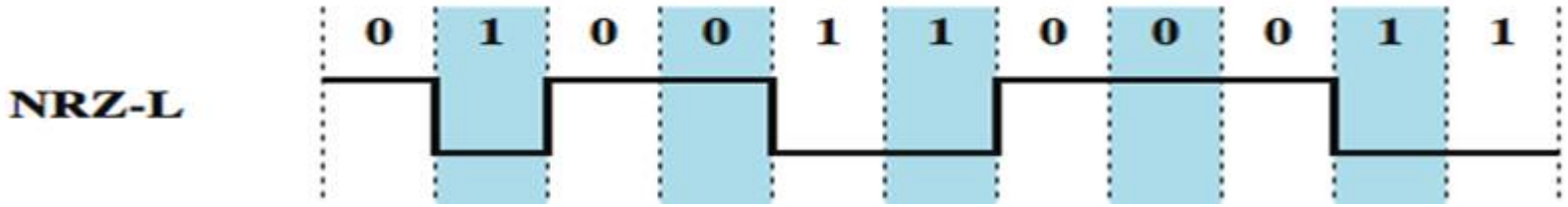


(a) Binary encoding, (b) Manchester encoding,

(c) Differential Manchester encoding. (Tanenbaum, 4e)

2.6 数字基带信号传输的波形与编码

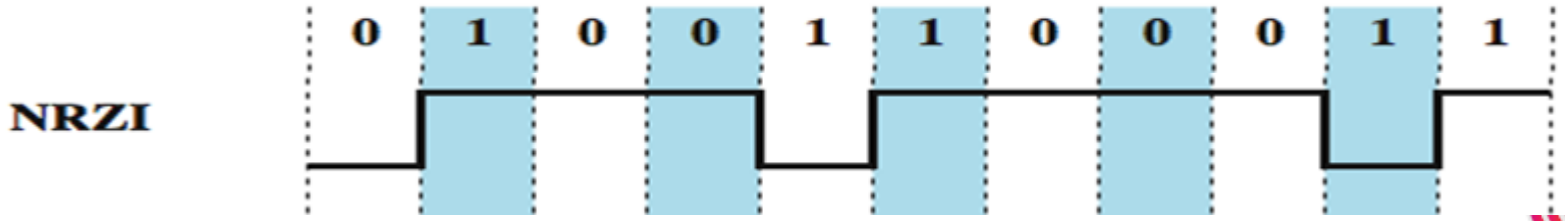
- NRZ-L: 0, high level; 1, low level.



- NRZI: 0, no transition at beginning of interval; 1, transition at beginning of interval.

  (A) lack of synchronization capability;

  (B) used for magnetic recording, not often used for signal transmission.



2.6 数字基带信号传输的波形与编码

- Bipolar-AMI: 0, no line signal; 1, positive or negative level, alternating for successive ones.

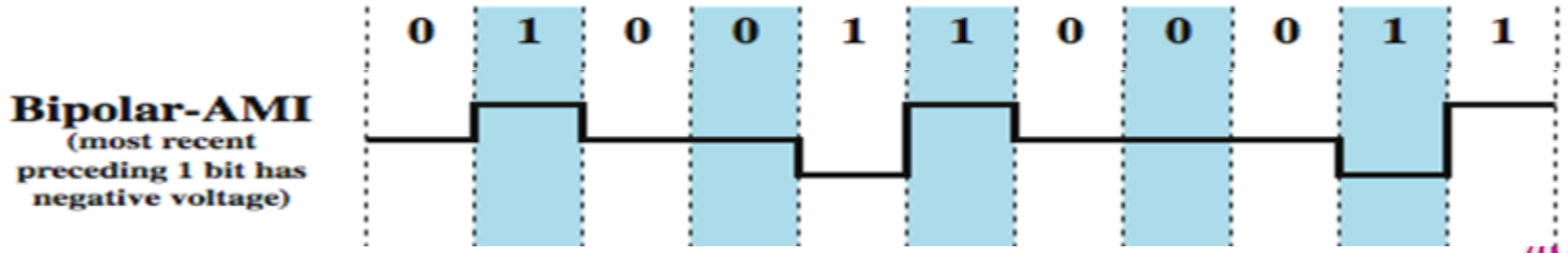
  (A) no loss of sync if a long string of ones;

  (B) long runs of zeros still a problem;

  (C) no net dc component;

  (D) lower bandwidth;

  (E) easy error detection.

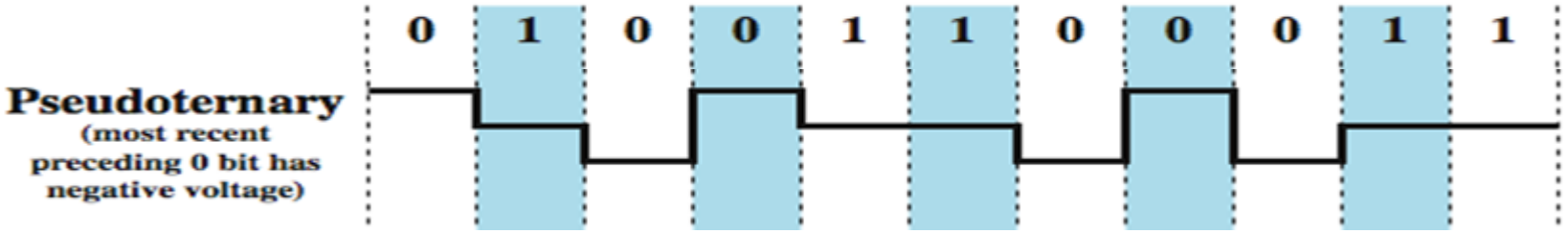


2.6 数字基带信号传输的波形与编码

- Pseudoternary

  (A) 1, no line signal; 0, positive or negative level, alternating for successive zeros.

  (B) used in some applications.



2.6 数字基带信号传输的波形与编码

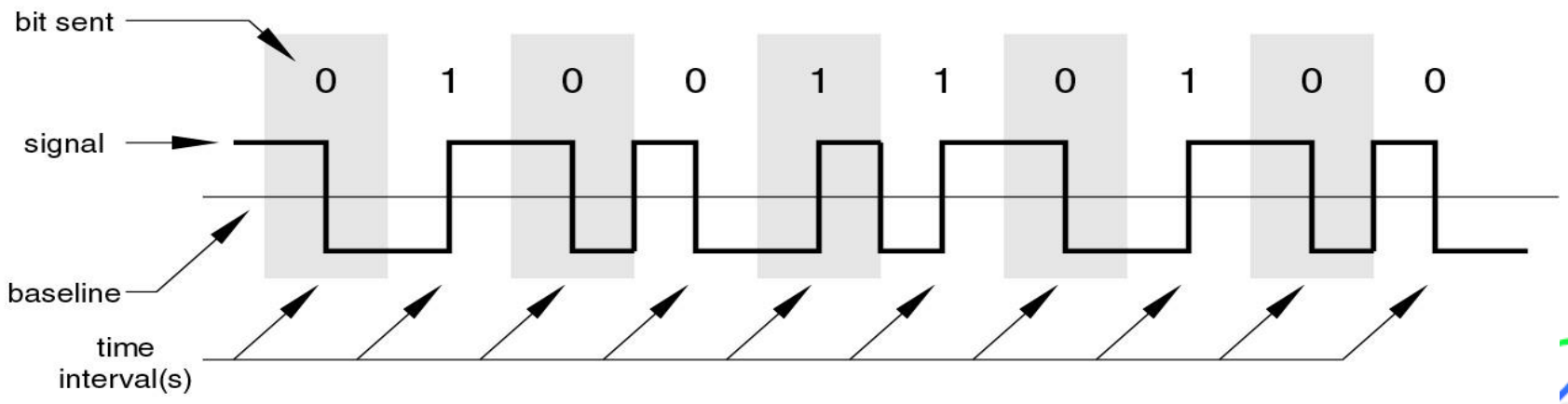
- Manchester

(A) 0, transition from **high to low** in middle of interval; 1, transition from **low to high** in middle of interval.

(B) transition serves as clock and data.

(C) used by IEEE 802.3 (Ethernet, for baseband coaxial cable and twisted-pair bus LANs).

Manchester Encoding



2.6 数字基带信号传输的波形与编码

- Differential Manchester

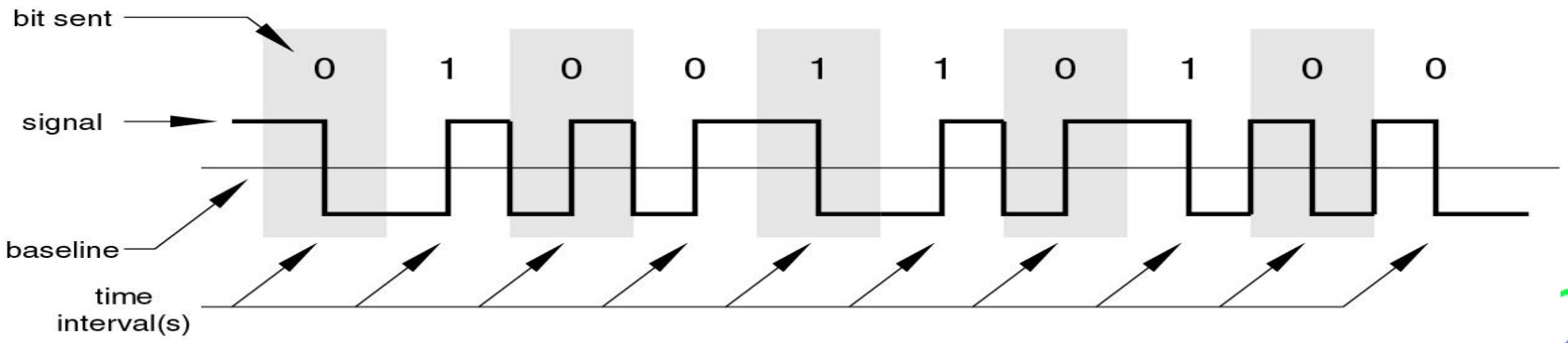
  (A) **always a transition** in middle of interval. 0, transition at beginning of interval; 1, no transition at beginning of interval.

  (B) **midbit transition** is clocking only.

  (C) used by IEEE 802.5 (Token-ring LAN, using STP).

  (D) not suitable for a long-distance application, like Manchester, for a high signaling rate relative to the data rate.

Differential Manchester Encoding



2.6 数字基带信号传输的波形与编码

- B8ZS

(A) same as Bipolar-AMI, **except** that any string of eight zeros is replaced by a string with two code violations.

(B) using scrambling (扰码) scheme to overcome the drawback of the AMI code (loss of synchronization for a long string of zeros). Design goals:

(a) No dc component;

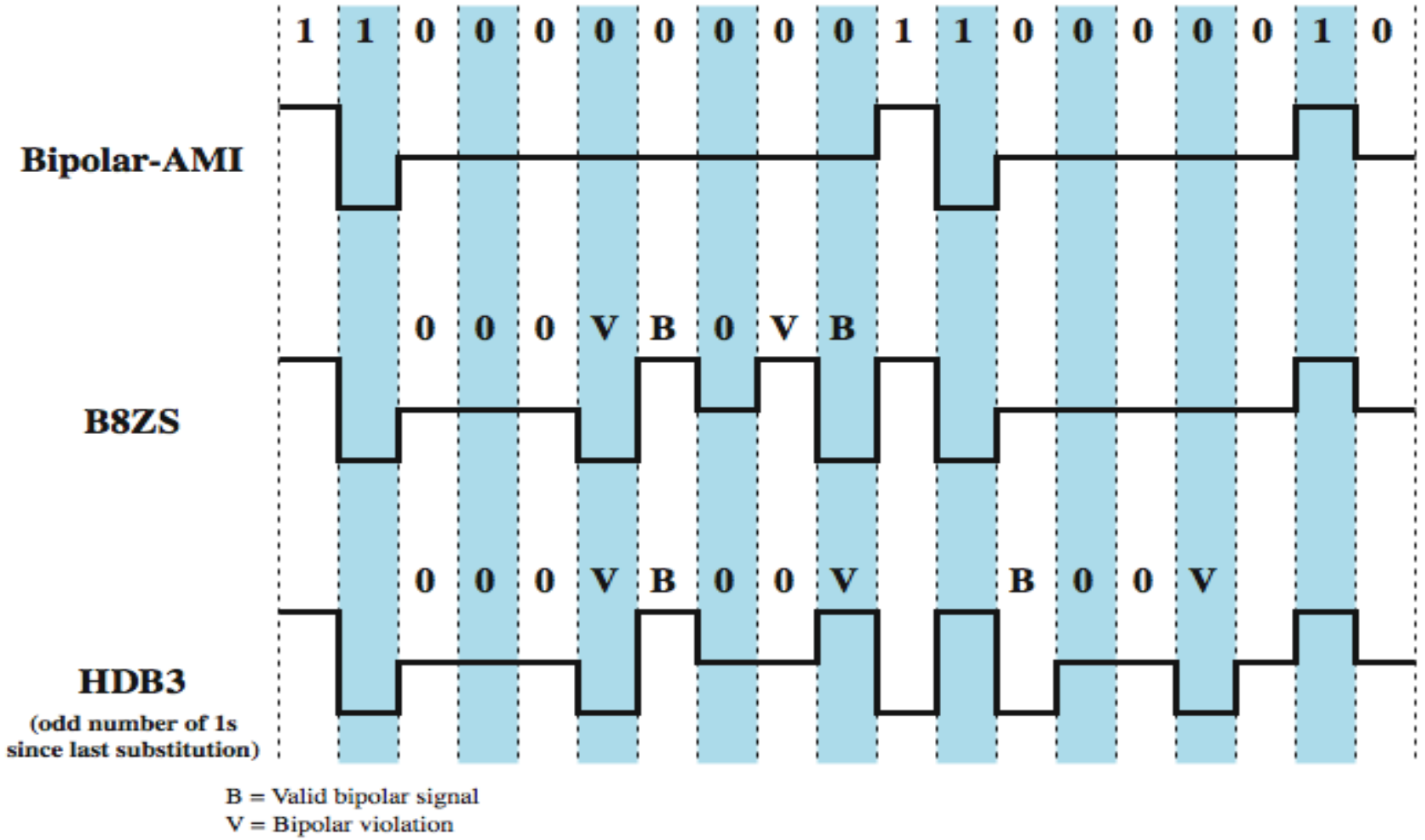
(b) No long sequences of zero-level line signals;

(c) No reduction in data rate;

(d) Error-detection capability.

(C) positive (polarity of preceding voltage pulse), 00000000 encoded as **000+-0-+**; otherwise, as **000-+0+-**.

2.6 数字基带信号传输的波形与编码



2.6 数字基带信号传输的波形与编码

- HDB3

  (A) same as Bipolar-AMI, **except** that any string of four zeros is replaced by a string with one code violation.

  (B) also using scrambling scheme.

  (C) substitution rule as follows.

  (D) well suited to high data rate transmission and commonly used in long-distance transmission, like B8ZS.

  (E) commonly used in Europe and Japan.

	Number of Bipolar Pulses (ones) since Last Substitution	
Polarity of Preceding Pulse	Odd	Even
-	000-	+00+
+	000+	-00-

2.6 数字基带信号传输的波形与编码

---Ways of evaluating or comparing the various techniques or waveforms (Stallings, 8e)

- Signal spectrum

  (A) Lack of high frequencies reduces required bandwidth;

  (B) Lack of dc component allows ac coupling via transformer, providing isolation;

  (C) Concentrate power in the middle of the bandwidth.

- Clocking (determine the beginning and end of each bit)

  (A) Synchronizing transmitter and receiver;

  (B) External clock (not good);

  (C) Sync mechanism based on signal (better).

2.6 数字基带信号传输的波形与编码

- Error-detection
- Signal interference and noise immunity
- Cost and complexity

(A) Higher signal rate (& thus data rate) lead to higher costs;

(B) Some codes require signal rate greater than data rate.

2.6 数字基带信号传输的波形与编码

3. 编码 (Encoding)

(1) Overview

--- In communications and information processing, **encoding** is the process by which **information** from a source is **converted** into **symbols** to be communicated. **Decoding** is the **reverse** process, converting these **code symbols** back into **information** understandable by a receiver. (http://en.wikipedia.org/wiki/)

--- In computers, **encoding** is the process of putting **a sequence of characters** (letters, numbers, punctuation, and certain symbols) into a specialized **format for efficient transmission or storage**. **Decoding** is the **opposite** process -- the conversion of an **encoded format** back into the **original sequence of characters**. Encoding and decoding are **used in** data communications, networking, and storage. (http://searchnetworking.techtarget.com/)

2.6 数字基带信号传输的波形与编码

Note: **Encoding** should not be confused with **encryption**, a process in which **data** is **deliberately altered** so as to **conceal its content**. Encryption can be done without changing the particular code that the content is in, and encoding can be done without deliberately concealing the content.

---**Encoding/decoding** can apply to **any form of data**, including binary digitals (bit streams), text, images, audio, video, multimedia, computer programs, or signals in sensors, telemetry (遥测), and control systems.

◆ Examples of en/decoding

---**Character encoding** is a code that pairs a set of natural language characters (such as an **alphabet or syllabary**) with a set of something else, such as numbers or electrical pulses. E.g. ASCII, Unicode, GB1303.

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---**Text encoding** uses a markup language to **tag** the structure and other features of a text to facilitate processing by computers, e.g., HTML, XML, etc.

---**Semantics encoding** of formal language A in formal language B is a method of representing all terms (e.g. programs or descriptions) of language A using language B.

---**Image encoding**: BMP, GIF, PNG, JPEG, etc.

---**Audio encoding**: WMA, MP3/4, …

---**Video encoding**: RM, RMVB, …

---**Codec in PABX and modems** (relevant to modulation)

……

2.6 数字基带信号传输的波形与编码

(2) Codes in computer network

◆ **nBmB**

---表示一类分组码，将原始信息流中的n比特作为一组，变为m比特的新码组，$m>n$。

---有2^m-2^n多余组合。除可表达原2^n各数字代码，其余的可作为上层使用的控制码或本层禁止使用的代码。

---光纤数字通信中，常选用$m=n+1$。

---1Gbps以太网使用8B10B。

1) **1B2B**

--- **1 bit** is represented by **2 bits** , in 2-clock cycles, only 1 bit is sent out, e.g., Manchester coding.

--- Characteristics

- Low efficiency (50%)
- Electric level rise or fall takes place between **2 clock cycles** for normal data: always has a change in electric level; no change codes: control symbol as in Token Bus: {LL HH} pairs used to define start delimiter, end delimiter etc.
- Easy to be **synchronized** between the sender and the receiver.

2) **5B6B**

--- Incentive: **Continuous '1s' or '0s'** will cause base line shift (基准电平累计漂移) that will lead the receiver to judge erroneously, also increase the low-frequency component, which is not suited to be transmitted in high-frequency channel.

--- represent 5 bits with 6 bits, then have 2^6=64 different codes.

--- **used in** high-speed fiber digital transmission.

--- use the codes with minimum difference between '1' and '0' to avoid continuous '1s' or '0s'.

2.6 数字基带信号传输的波形与编码

--- **RDS** (Running disparity sum): sum of the values of +1 (for '1') and -1 (for '0') in bit streams. If RDS value is positive, marking RD+; otherwise, RD-.

e.g., '110010': RDS=0; '111001': RDS=+2, belonging to RD+ code; '010001': RDS=-2, belonging to RD- code.

--- **Balanced code** (20) : numbers of '1s' & '0s' are equal, i.e., RDS=0; **Comparatively balanced** (30): RDS=+2 (15), RDS=-2 (15); **Unbalanced** (14): RDS=±4,±6, not good for transmission.

---Then, 50 codes can be used to represent $\mathbf{2^5}$=32 codes.

--- Codes used in 5B6B coding (with RDS=±2 & 0) as shown in the following Table.

- one code (5B) corresponds to two codes (RD+ & RD-) in 6B.
- choose RD+ or RD- code according to RDS's sign (+/-), so as to decrease |RDS|.

2.6 数字基带信号传输的波形与编码

5-bit input codes	6-bit output codes				5-bit input codes	6-bit output codes			
	RD+	RDS	RD-	RDS		RD+	RDS	RD-	RDS
00000	110010	0	110010	0	10000	110001	0	110001	0
00001	110011	+2	**100001**	−2	10001	111001	+2	010001	−2
00010	110110	+2	100010	−2	10010	111010	+2	010010	−2
00011	**100011**	0	**100011**	0	10011	010011	0	010011	0
00100	110101	+2	100100	−2	10100	110100	0	110100	0
00101	100101	0	100101	0	10101	010101	0	010101	0
00110	100110	0	100110	0	10110	010110	0	010110	0
00111	100111	+2	000111	0	10111	010111	+2	010100	−2
01000	101011	+2	101000	−2	11000	**111000**	0	**011000**	−2
01001	101001	0	101001	0	11001	011001	0	011001	0
01010	101010	0	101010	0	11010	011010	0	011010	0
01011	001011	0	001011	0	11011	011011	+2	001010	−2
01100	101100	0	101100	0	11100	011100	0	011100	0
01101	101101	+2	000101	−2	11101	011101	+2	001001	−2
01110	101110	+2	000110	−2	11110	011110	+2	001100	−2
01111	001110	0	001110	0	11111	001101	0	001101	0

2.6 数字基带信号传输的波形与编码

--- In a data stream, it is necessary to count the RDS to make balance by **alternatively using +RD/-RD** code.

--- The **penalty of 5B6B coding**: 83% channel utility.

- e.g., in 100BASE-TX, to get 100 Mbps data rate, the clock frequency has to be raised to 125 MHz.
- **Problem**: maximum working frequency for **Cat 5 UTP** is 100MHz.
- **Solution**: use 3-level (+1v, 0v, -1v) waveform to reduce the frequency to 31.25MHz.
- For 100 BASE-FX, 5B6B, 125MHz is not a problem.

2.6 数字基带信号传输的波形与编码

3) **3B4B**

--- similar to 5B6B.

3-bit Input codes	4-bit output codes			
	RD+	RDS	RD-	RDS
000	1011	+2	0100	-2
001	1001	0	1001	0
010	0101	0	0101	0
011	1100	0	0011	0
100	1101	+2	0010	-2

3-bit Input codes	4-bit output codes			
	RD+	RDS	RD-	RDS
101	1010	0	1010	0
110	0110	0	0110	0
111	1110	+2	0001	-2
111	0111	+2	1000	-2

Note : For special usage (e.g. control code) , the 4-bit output code for the 3-bit input code '111' must choose from the row in the red, but for data both black and red rows can be used.

2.6 数字基带信号传输的波形与编码

4) **4B5B-NRZI**

--- used in 100BASE-FX.

--- channel utility: 80%.

--- NRZI编码一串1有跳变。

--- 将要传输的数据首先用4B/5B编码保证后续用NRZI有跳变，以利同步。

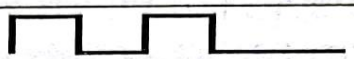
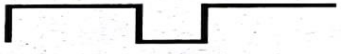
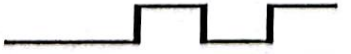
--- 4B/5B码进一步用NRZI编码，接收可靠性更好。

--- 从32(2^5)种模式中选择那些至少有两次跳变的5码组模式来代表16(2^4)个4比特的数据块，且不允许连续3个零出现。

--- 不用于表示数据的码组有些可用作控制字符，其它则无效。

- 空闲。该码组在数据传输序列之间传输。在CSMA/CD协议中表明信道空闲。
- 流开始/结束定界符。各两组。
- 传输错误。

表12.4　4B/5B码组

数据输入（4比特）	码组（5比特）	NRZI模式	解释
0000	11110		数据0
0001	01001		数据1
0010	10100		数据2
0011	10101		数据3
0100	01010		数据4
0101	01011		数据5
0110	01110		数据6
0111	01111		数据7
1000	10010		数据8
1001	10011		数据9
1010	10110		数据A
1011	10111		数据B
1100	11010		数据C
1101	11011		数据D
1110	11100		数据E
1111	11101		数据F
	11111		空闲
	11000		流开始定界符，第1部分
	10001		流开始定界符，第2部分
	01101		流结束定界符，第1部分
	00111		流结束定界符，第2部分
	00100		传输差错
	其他		无效码

2.6 数字基带信号传输的波形与编码

5) **MLT-3 (4B5B-NRZI变种)**

--- used in 100BASE-TX.

--- 从NRZI到NRZ的转换：将4B5B-NRZI信号转到NRZ.

--- 编码规则：

- 如下一输入为0，则输出电平同前；
- 如下一输入为1，则下一输出电平含有一个跳变：

  ① 如前面电平为+/-，则输出0电平；

  ② 如前面为0电平，则输出电平与上一个非0电平输出相反。

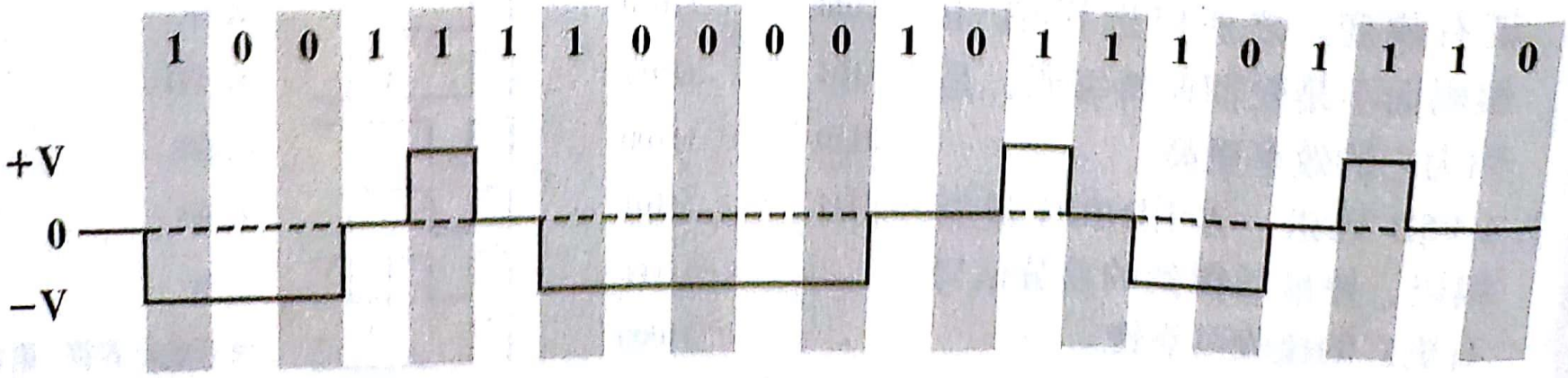


图12.13 MLT-3编码的例子

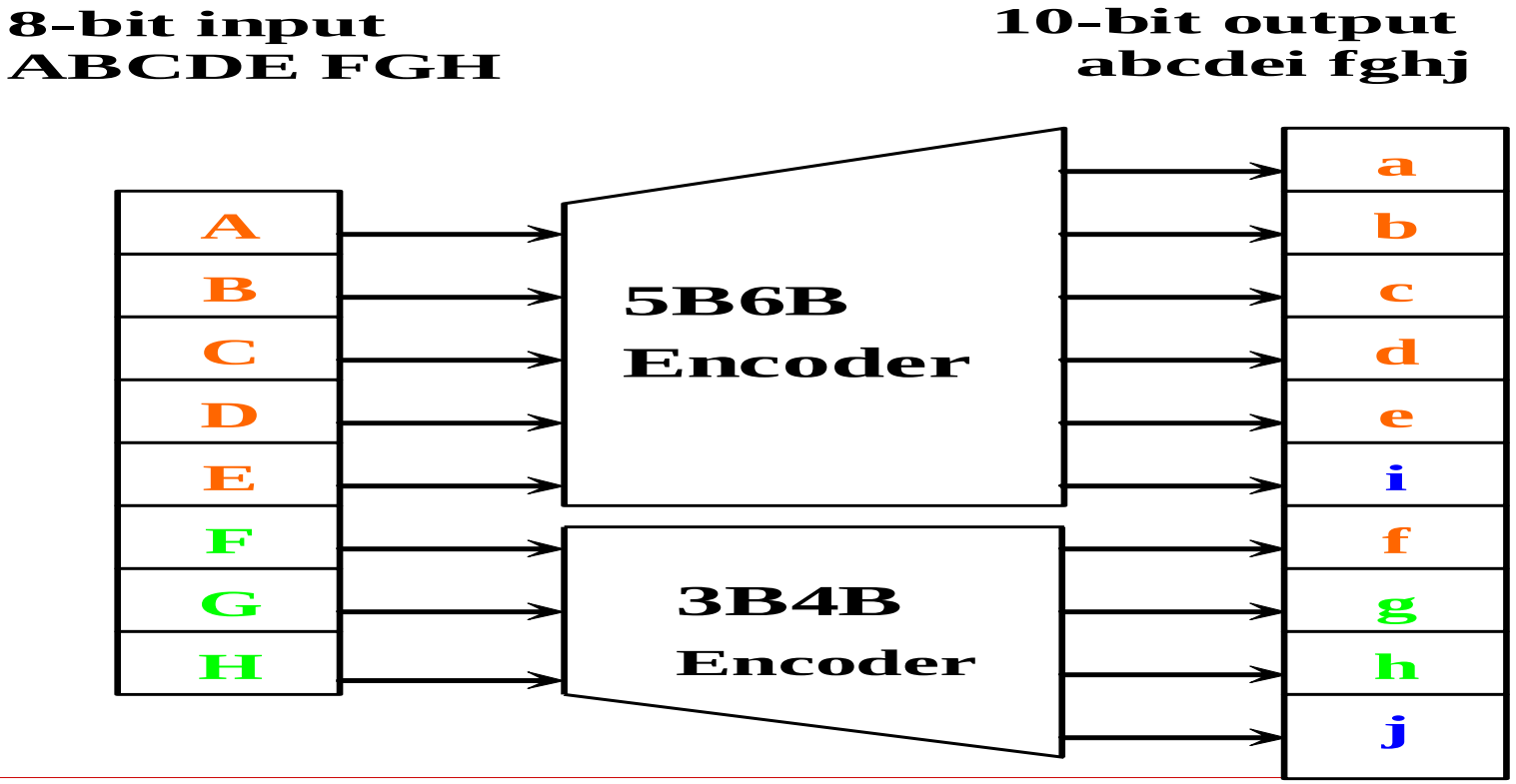
2.6 数字基带信号传输的波形与编码

6) **8B10B**

--- originally invented by **IBM**, representing 8 bits with 10 bits.

--- used in **optical fiber, copper cable, USB 3.0** for high-speed data transmission.

--- a **combination** of 3B4B & 5B6B, channel utility: 80%.



2.6 数字基带信号传输的波形与编码

--- **General rule for series transmission**: avoiding continuous '1s' or '0s' to reduce low frequency components and to prevent the DC base-line from up- or down-swinging.

--- Whether an RD+ or RD- should be used for the 5B6B encoder depends on the **RDS of previous 8-bit code** and for 3B4B encoder it depends on the **RDS of previous 5B6B** encoder.

--- **Not use** unbalanced codes, e.g. 100000 or 1000.

--- **Only use** the balanced & relatively balanced.

--- Use of RD+ or RD- to represent the same "code" to keep the RDS being +2, -2, or 0.

--- Only when RDS is positive, can a balanced code **000111** or **0011** be used; and only when RDS is negative, can a balanced code **111000** or **1100** be used.

2.6 数字基带信号传输的波形与编码

--- Let's take an example to explain how the 8B10B encoding scheme is working.

- use ASCII (American Standard Code for Information Interchange) to represent the content "**This is an example.**" to be transmitted with the 8B10B encoding.
- The corresponding Octal representation of the sentence "This is an example." is:

Character	**T**	**h**	**i**	**s**	**Space**	**i**	**s**
Octal	124	150	151	163	040	151	163
Character	**Space**	**a**	**n**	**Space**	**e**	**x**	**a**
Octal	040	141	156	040	145	170	141
Character	**m**	**p**	**l**	**e**	**.**		
Octal	155	160	154	145	056		

Dec	Hx	Oct	Char	Dec	Hx	Oct	Html	Chr	Dec	Hx	Oct	Html	Chr	Dec	Hx	Oct	Html	Chr
0	0	000	NUL (null)	32	20	040		Space	64	40	100	@	@	96	60	140	`	`
1	1	001	SOH (start of heading)	33	21	041	!	!	65	41	101	A	A	97	61	141	a	a
2	2	002	STX (start of text)	34	22	042	"	"	66	42	102	B	B	98	62	142	b	b
3	3	003	ETX (end of text)	35	23	043	#	#	67	43	103	C	C	99	63	143	c	c
4	4	004	EOT (end of transmission)	36	24	044	$	$	68	44	104	D	D	100	64	144	d	d
5	5	005	ENQ (enquiry)	37	25	045	%	%	69	45	105	E	E	101	65	145	e	e
6	6	006	ACK (acknowledge)	38	26	046	&	&	70	46	106	F	F	102	66	146	f	f
7	7	007	BEL (bell)	39	27	047	'	'	71	47	107	G	G	103	67	147	g	g
8	8	010	BS (backspace)	40	28	050	(	(	72	48	110	H	H	104	68	150	h	h
9	9	011	TAB (horizontal tab)	41	29	051	)	)	73	49	111	I	I	105	69	151	i	i
10	A	012	LF (NL line feed, new line)	42	2A	052	*	*	74	4A	112	J	J	106	6A	152	j	j
11	B	013	VT (vertical tab)	43	2B	053	+	+	75	4B	113	K	K	107	6B	153	k	k
12	C	014	FF (NP form feed, new page)	44	2C	054	,	,	76	4C	114	L	L	108	6C	154	l	l
13	D	015	CR (carriage return)	45	2D	055	-	-	77	4D	115	M	M	109	6D	155	m	m
14	E	016	SO (shift out)	46	2E	056	.	.	78	4E	116	N	N	110	6E	156	n	n
15	F	017	SI (shift in)	47	2F	057	/	/	79	4F	117	O	O	111	6F	157	o	o
16	10	020	DLE (data link escape)	48	30	060	0	0	80	50	120	P	P	112	70	160	p	p
17	11	021	DC1 (device control 1)	49	31	061	1	1	81	51	121	Q	Q	113	71	161	q	q
18	12	022	DC2 (device control 2)	50	32	062	2	2	82	52	122	R	R	114	72	162	r	r
19	13	023	DC3 (device control 3)	51	33	063	3	3	83	53	123	S	S	115	73	163	s	s
20	14	024	DC4 (device control 4)	52	34	064	4	4	84	54	124	T	T	116	74	164	t	t
21	15	025	NAK (negative acknowledge)	53	35	065	5	5	85	55	125	U	U	117	75	165	u	u
22	16	026	SYN (synchronous idle)	54	36	066	6	6	86	56	126	V	V	118	76	166	v	v
23	17	027	ETB (end of trans. block)	55	37	067	7	7	87	57	127	W	W	119	77	167	w	w
24	18	030	CAN (cancel)	56	38	070	8	8	88	58	130	X	X	120	78	170	x	x
25	19	031	EM (end of medium)	57	39	071	9	9	89	59	131	Y	Y	121	79	171	y	y
26	1A	032	SUB (substitute)	58	3A	072	:	:	90	5A	132	Z	Z	122	7A	172	z	z
27	1B	033	ESC (escape)	59	3B	073	;	;	91	5B	133	[	[	123	7B	173	{	{
28	1C	034	FS (file separator)	60	3C	074	<	<	92	5C	134	\	\	124	7C	174			|
29	1D	035	GS (group separator)	61	3D	075	=	=	93	5D	135	]	]	125	7D	175	}	}
30	1E	036	RS (record separator)	62	3E	076	>	>	94	5E	136	^	^	126	7E	176	~	~
31	1F	037	US (unit separator)	63	3F	077	?	?	95	5F	137	_	_	127	7F	177	&#127;	DEL

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- The corresponding binary string representation of the sentence "This is an example." is:

01010100 01101000 01101001 01110011 00100000 01101001 01110011 00100000 01100001 01101110 00100000 01100101 01111000 01100001 01101101 01110000 01101100 01100101 00101110

ABCDE	FGH	ABCDE	FGH	ABCDE	FGH	ABCDE	FGH
01010	100	01101	000	01101	001	01110	011
abcdei	fghj	abcdei	fghj	abcdei	fghj	abcdei	fghj
$101010/_{0}$ RDS=0	$1101/_{+2}$ $0010/_{-2}$	$101101/_{+2}$ $000101/_{-2}$	$1011/_{+2}$ $1011/_{-2}$	$101101/_{+2}$ $000101/_{-2}$	……		
ABCDE	FGH	ABCDE	FGH	ABCDE	FGH	ABCDE	FGH
00100	000	01101	001	01110	011	00100	000
abcdei	fghj	abcdei	fghj	abcdei	fghj	abcdei	fghj

2.6 数字基带信号传输的波形与编码

7) **64B66B**

--- 8B10B有25%的开销，而64B66B的额外开销为3%.

--- used in 10Gbps/100Gbps以太网.

--- 处理过程：

① 将输入数据切分为64bits块，再在前面加2 bits同步字段。

② 如输入数据均为数据八位组，则编码后的块为：

01(同步字段)+D0~D7(即8个数据八位组，且不变)

③ 否则，输入数据：或为8个控制八位组；或为控制八位组和数据八位组的混合，此时，编码后的块为：

10(同步字段)+控制类型(8位)+56位块

56位块的构成如下图。

输入数据	同步	纯数据字段比特							
DDDD DDDD	01	D0	D1	D2	D3	D4	D5	D6	D7

输入数据		类型	数据/控制字段比特							
CCCC CCCC	10	0x1E	C0	C1	C2	C3	C4	C5	C6	C7
CCCC ODDD	10	0x2D	C0	C1	C2	C3	O	D5	D6	D7
CCCC SDDD	10	0x33	C0	C1	C2	C3		D5	D6	D7
ODDD SDDD	10	0x66	D1	D2	D3	O		D5	D6	D7
ODDD ODDD	10	0x55	D1	D2	D3	O	O	D5	D6	D7
SDDD DDDD	10	0x78	D1	D2	D3	D4		D5	D6	D7
ODDD CCCC	10	0x4B	D1	D2	D3	O	C4	C5	C6	C7
TCCC CCCC	10	0x87		C1	C2	C3	C4	C5	C6	C7
DTCC CCCC	10	0x99	D0		C2	C3	C4	C5	C6	C7
DDTC CCCC	10	0xAA	D0	D1		C3	C4	C5	C6	C7
DDDT DDDT	10	0xB4	D0	D1	D2		C4	C5	C6	C7
DDDD TCCC	10	0xCC	D0	D1	D2	D3		C5	C6	C7
DDDD DTCC	10	0xD2	D0	D1	D2	D3	D4		C6	C7
DDDD DDTC	10	0xE1	D0	D1	D2	D3	D4	D5		C7
DDDD DDDT	10	0xFF	D0	D1	D2	D3	D4	D5	D6	

D = 数据八位组
C = 输入控制八位组
C_i = 7比特输出控制字段
S = 分组字段开始字界符
T(terminate) = 分组字段结束定界符
O = 规定集控制字符

图12.15 64B/66B块格式

2.6 数字基带信号传输的波形与编码

◆ **nBmT**

---用*m*位3进制码来表示*n*位2进制码。

1) **1B1T**

--- Bipolar-AMI, 0 level represents '0', positive or negative level for '1'. In fact, it uses 3 states to represent 2 states. So, it belongs to 1B1T.

--- HDB3, also a type of 1B1T. But, it improves AMI by limit 3+ continuous '0s'.

2) **2B2T**

--- PST (Paired selected ternary code), 即为一种2B2T码，它将两个二进制比特作为一组，变为两个三进制码，在9 (3^2)种组合中有选择地使用某种代码。

●如用0、1、2表示3进制数，则PST的编码关系如下表所示：

2.6 数字基带信号传输的波形与编码

两比特二进制代码	两位三进制码			
	Option 1		Option 2	
00	02	-+	02	-+
01	12	0+	10	0-
10	21	+0	01	-0
11	20	+-	20	+-

●表中用-、0和+三个电平分别表示3进制数0、1和2。

3) **4B3T**

--- 用3个三进制位传输4个二进制比特组。

--- used for Integrated Services Digital Network (ISDN) basic rate interfaces (BRI).

2.6 数字基带信号传输的波形与编码

4) **8B6T**

--- used in 100BASE-T4.

--- 3态信号技术中，每个信元取3种值之一：正/负/零 电压.

--- 每8比特块被映射到一个6位3进制的码组上.

--- 8B6T传输策略

$$\frac{6}{8} \times 33\frac{1}{3} = 25 \text{ Mbaud}$$

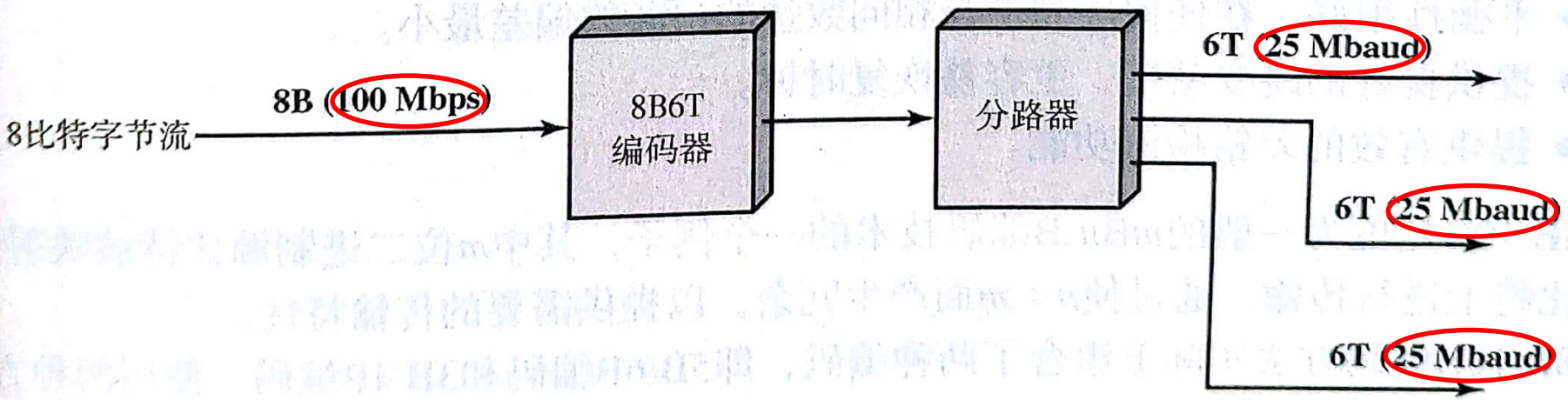

图12.14 8B6T的传输策略

2.6 数字基带信号传输的波形与编码

--- 8比特块到6位3进制的映射条件：

- 同步：码选择应使每个码组的平均跳变次数最大；
- 直流平衡：要维持直流平衡，即线路上电压平均为0，须使所选码组 ---- 正负符号个数相同，或 正符号比负符号多一个。

--- 8B6T部分码表

表12.5　8B6T的部分码表

数据八位组	6T码组	数据八位组	6T码组	数据八位组	6T码组	数据八位组	6T码组
00	+ − 0 0 + −	10	+ 0 + − − 0	20	0 0 − + + −	30	+ − 0 0 − +
01	0 + − + − 0	11	+ + 0 − 0 −	21	− − + 0 0 +	31	0 + − − + 0
02	+ − 0 + − 0	12	+ 0 + − 0 −	22	+ + − 0 + −	32	+ − 0 − + 0
03	− 0 + + − 0	13	0 + + − 0 −	23	+ + − 0 − +	33	− 0 + − + 0
04	− 0 + 0 + −	14	0 + + − − 0	24	0 0 + 0 − +	34	− 0 + 0 − +
05	0 + − − 0 +	15	+ + 0 0 − −	25	0 0 + 0 + −	35	0 + − + 0 −
06	+ − 0 − 0 +	16	+ 0 + 0 − −	26	0 0 − 0 0 +	36	+ − 0 + 0 −
07	− 0 + − 0 +	17	0 + + 0 − −	27	− − + + + −	37	− 0 + + 0 −
08	− + 0 0 + −	18	0 + − 0 + −	28	− 0 − + + 0	38	− + 0 0 − +
09	0 − + + − 0	19	0 + − 0 − +	29	− − 0 + 0 +	39	0 − + − + 0
0A	− + 0 + − 0	1A	0 + − + + −	2A	− 0 − + 0 +	3A	− + 0 − + 0
0B	+ 0 − + − 0	1B	0 + − 0 0 +	2B	0 − − + 0 +	3B	+ 0 − − + 0
0C	+ 0 − 0 + −	1C	0 − + 0 0 +	2C	0 − − + + 0	3C	+ 0 − 0 − +
0D	0 − + − 0 +	1D	0 − + + + −	2D	− − 0 0 + +	3D	0 − + + 0 −
0E	− + 0 − 0 +	1E	0 − + 0 − +	2E	− 0 − 0 + +	3E	− + 0 + 0 −
0F	+ 0 − − 0 +	1F	0 − + 0 + −	2F	0 − − 0 + +	3F	+ 0 − + 0 −

2.6 数字基带信号传输的波形与编码

◆ 2B1Q

---Two-binary, one-quaternary (2B1Q) is a physical layer encoding used for ISDN BRI implementations.

--- 2B1Q uses **four signal levels**, which are -450mV, -150mV, 150 mV and 450mV, each (1Q) equivalent to **two bits** (2b), as follows:

- 10: 450mV; 11: 150mV; 01: -150mV; 00: -450mV

--- 2B1Q is also used for some variants of HDSL (High-speed digital subscriber line).