计算机网络通信基础

Communication Technologies of Computer Network

(For Postgraduate)

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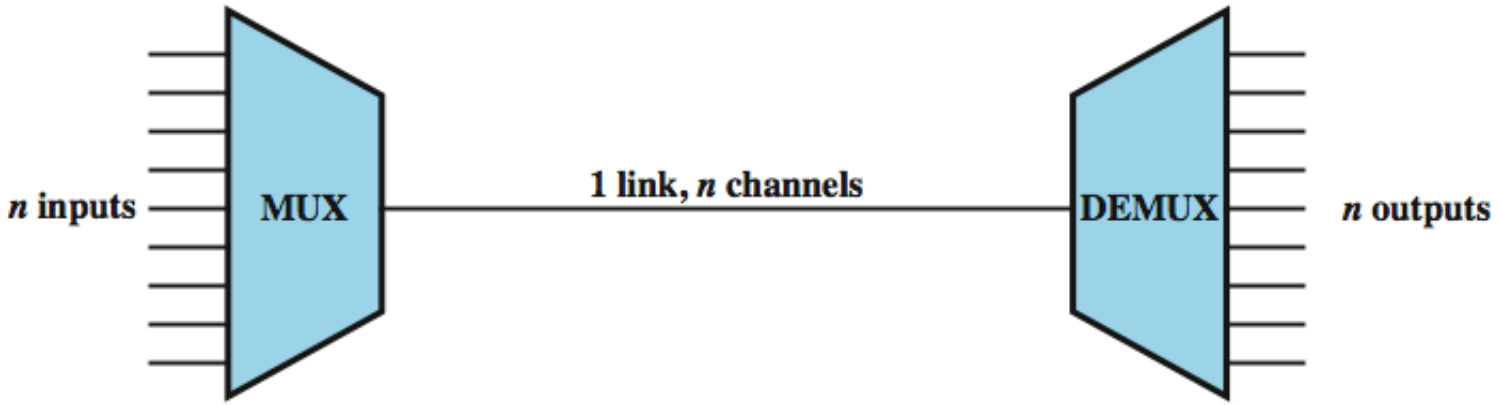
第3章 Multiplexing（复用）

3. 1 Introduction

--- multiple channels on 1 physical link.



--- common on long-haul/long-distance, high capacity, links (e.g. fiber, coaxial, or microwave).

--- have FDM (Frequency division multiplexing), TDM (Time division multiplexing, or Synchronous TDM), STDM (Statistical TDM)/Asynchronous TDM/Intelligent TDM alternatives.

3. 1 Introduction

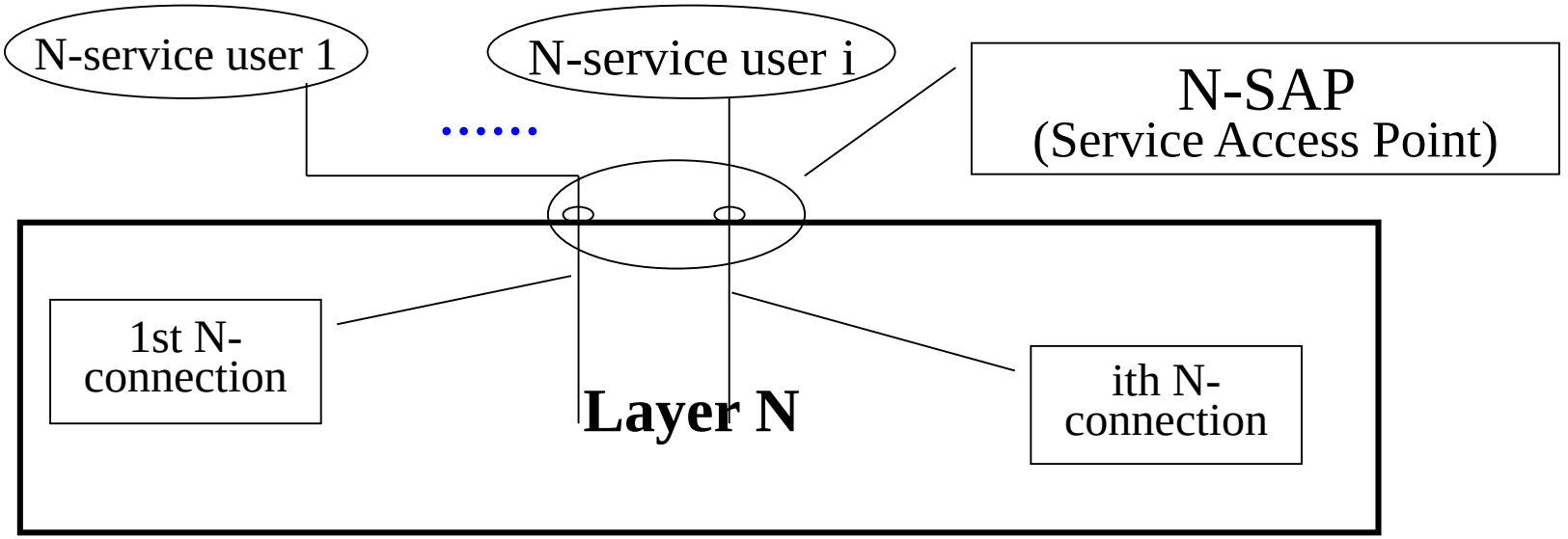
--- In the context of **communications**

- Multiplexing is a mechanism for multiple data or data streams (virtual connections) to share a physical channel/line/lambda (λ) transmission capability. (曾华燊, 2004).
- FDM: use of different frequency bandwidth to carry the data from different users (sharing the physical transmission service). e.g. WDM (Wavelength Division Multiplexing) is a special case for FDM.
- TDM: use of different time periods (or timeslots) to carry data from different users, e.g., PDH, SDH.
- CDM (Code Division Multiplexing), e.g. mobile phone system CDMA.
- OFDM(Orthogonal Frequency Division Multiplexing), divides a wide band of spectrum into many narrow slices over which different bits are sent in parallel. 802.11 b/g/n/ad.

3. 1 Introduction

--- In the context of **OSI/RM**

- multiplexing is defined as a mechanism for multiple n-service users to share the n-service. (曾华燊, 2004)



Multiplexing in Connection oriented service

第3章 Multiplexing（复用）

3.1 Introduction

3.2 FDM

3.3 TDM

3.4 Statistical TDM

3.5 ADSL

3.6 CDM (Code Division Multiplexing)

3.7 OFDM (Orthogonal Frequency Division Multiplexing)

3. 2 FDM

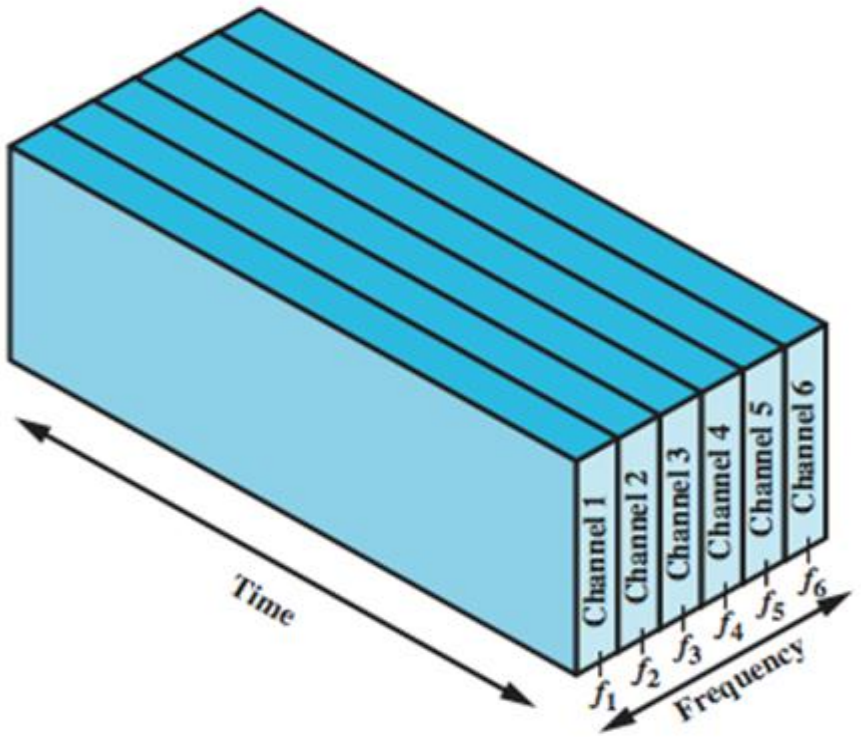
1. General concept

--- the useful bandwidth of the transmission medium **exceeds** the required bandwidth of signals to be transmitted.

--- each input signal must be moved to the appropriate frequency band by modulation equipment.

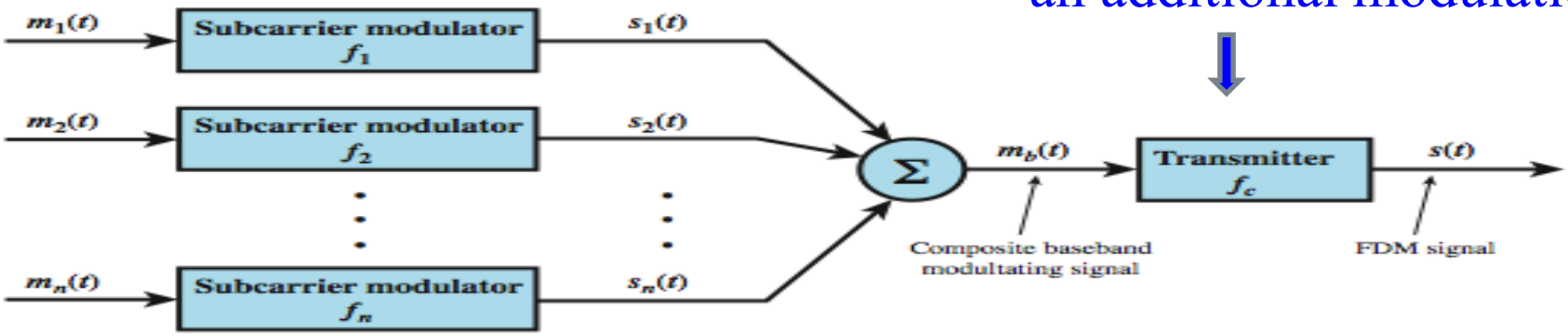
--- each frequency band is referred to as a channel.

--- the channels are separated by guard bands to prevent interference .

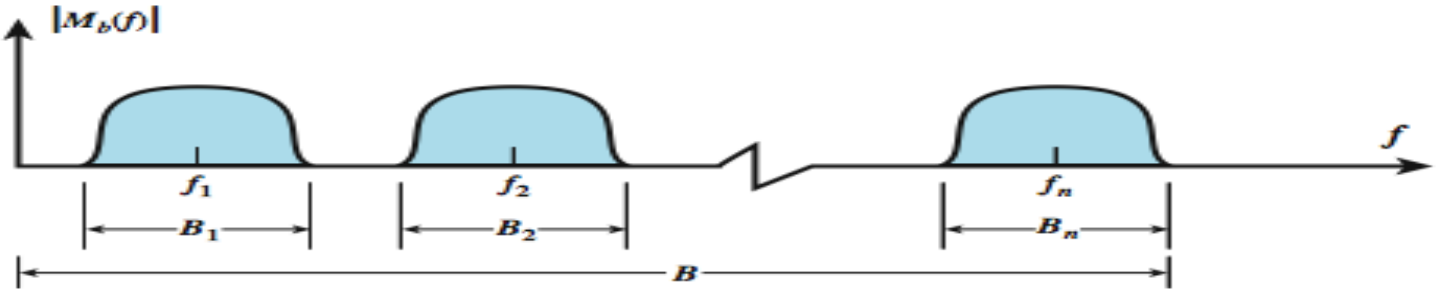


FDM system

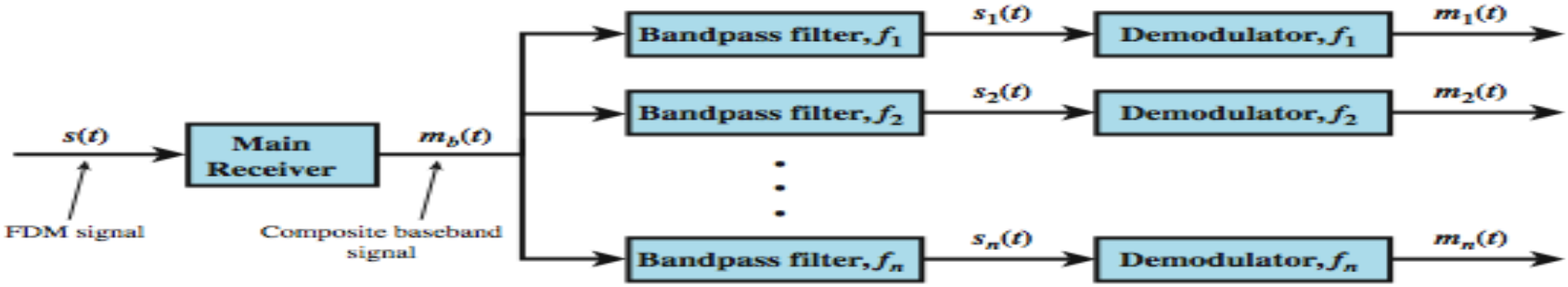
an additional modulation



(a) Transmitter

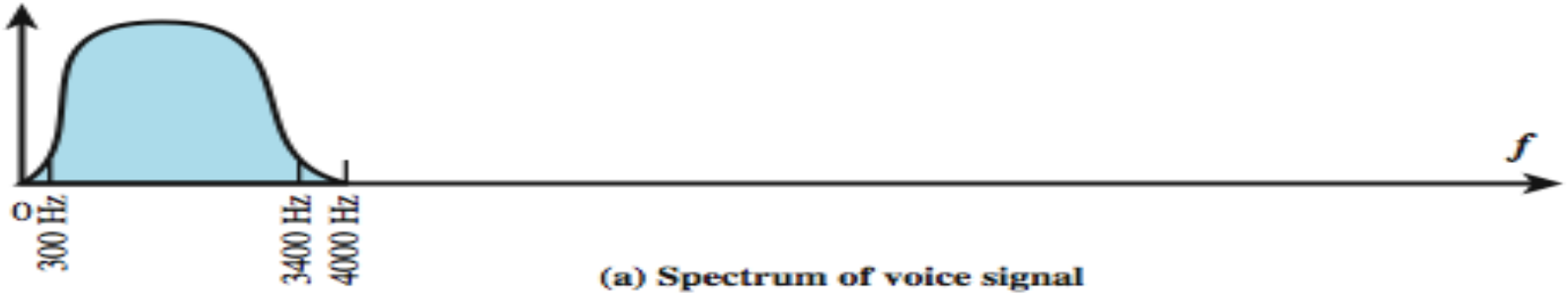


(b) Spectrum of composite baseband modulating signal

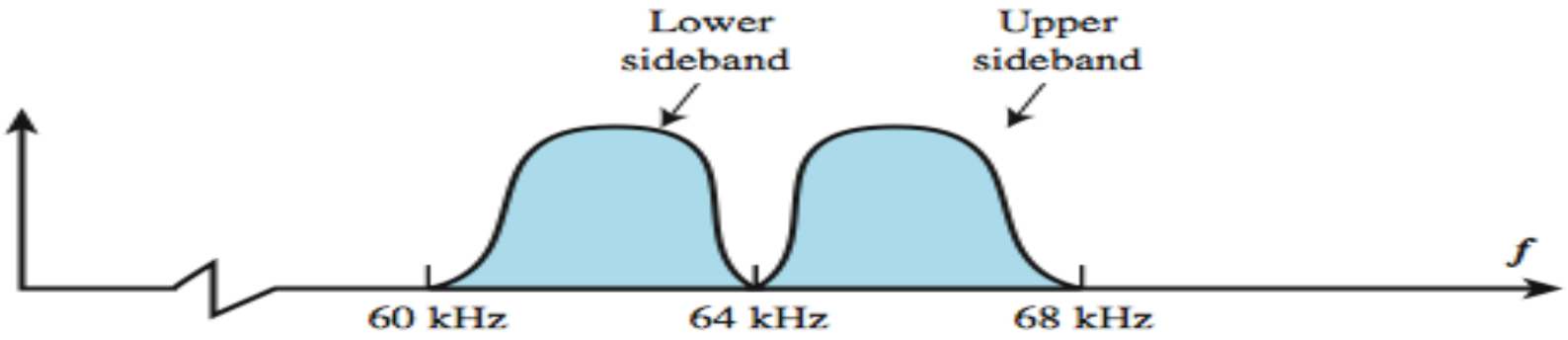


(c) Receiver

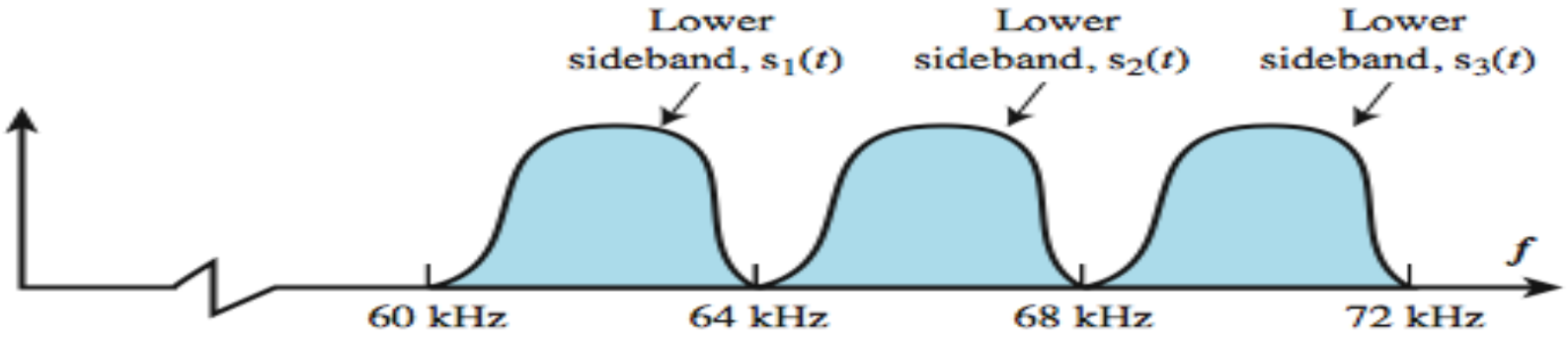
FDM Voiceband Example



(a) Spectrum of voice signal

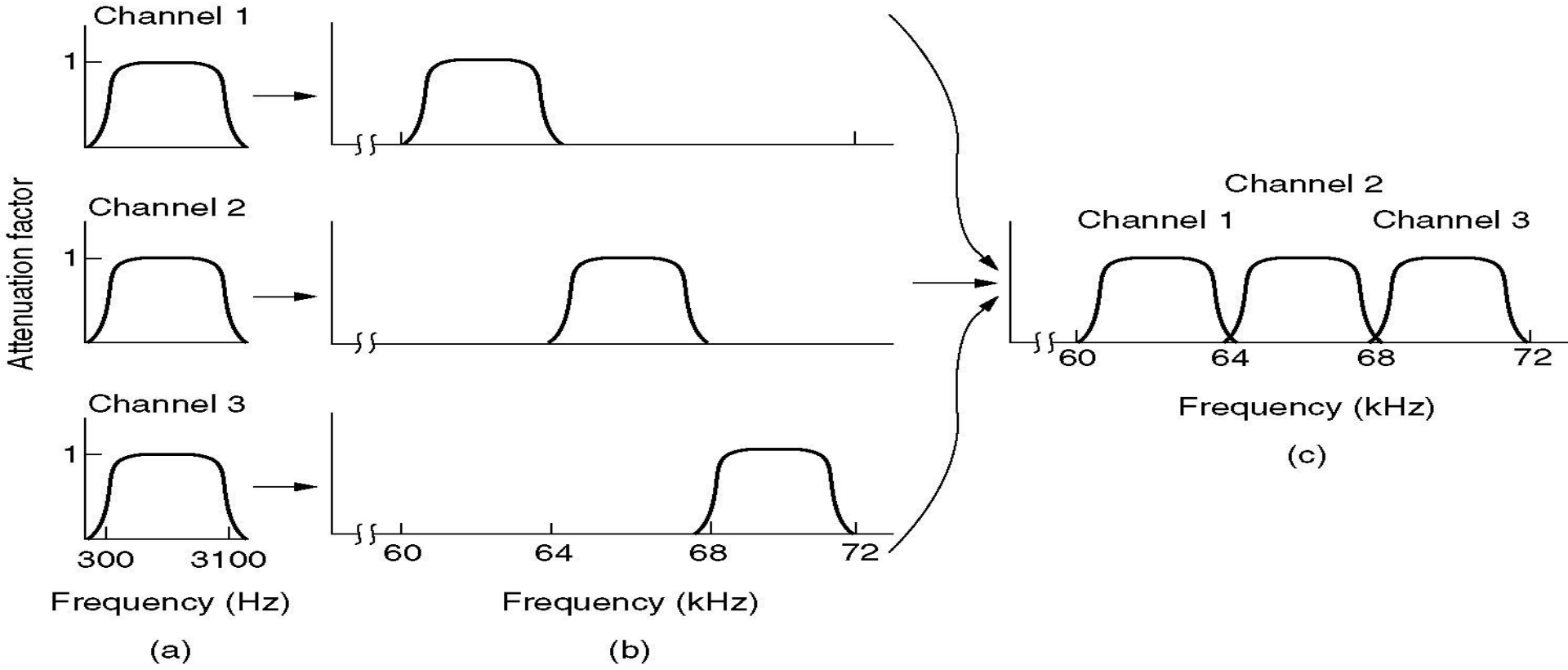


(b) Spectrum of voice signal modulated on 64 kHz frequency



(c) Spectrum of composite signal using subcarriers at 64 kHz, 68 kHz, and 72 kHz

3. 2 FDM



(a) The original bandwidths. (b) The bandwidths raised in frequency.
(c) The multiplexed channel.

引自Tanenbaum(4e)

3. 2 FDM

2. Analog Carrier Systems

--- long-distance links use an **FDM hierarchy** (FDM层次，即多次使用FDM形成多个等级系列).

--- AT&T (USA) and ITU-T (International) **variants**

--- **Group (基群)**

- 12 voice channels (4kHz each) = 48kHz (Bandwidth)
- in range 60kHz to 108kHz

--- **Supergroup (超群)**

- FDM of 5 group signals supports 60 voice channels (5×12×4kHz =240kHz bandwidth)
- on carriers between 420kHz and 612 kHz

--- **Mastergroup (主群)**

- FDM of 10 supergroups supports 600 voice channels (2.52 MHz bandwidth)

--- **Jumbogroup (巨群)**

- 6 mastergroups, 3600 channels (16.984 MHz bandwidth)

--- so original signal can be modulated/moved many times

3. 2 FDM

North American and International FDM Carrier Standards

Num of voice channels	Bandwidth	Spectrum	AT&T	ITU-T
12	48 kHz	60-108 kHz	Group	Group
60 (5×12)	240 kHz	312-552 kHz	Supergroup	Supergroup
300	1.232 MHz	812-2044 kHz		Mastergroup
600 (10×60)	2.52 MHz	564-3084 kHz	Mastergroup	
900	3.872 MHz	8.516-12.388 MHz		Supermaster group
N×600			Mastergroup multiplexing	
3,600	16.984 MHz	0.564-17.548 MHz	Jumbogroup	
10,800	57.442 MHz	3.124-60.566 MHz	Jumbogroup multiplexing	

3. 2 FDM

3. Wavelength Division Multiplexing (WDM)

--- **a form of FDM**, multiple beams of light at different frequencies transmitted on the same fiber.

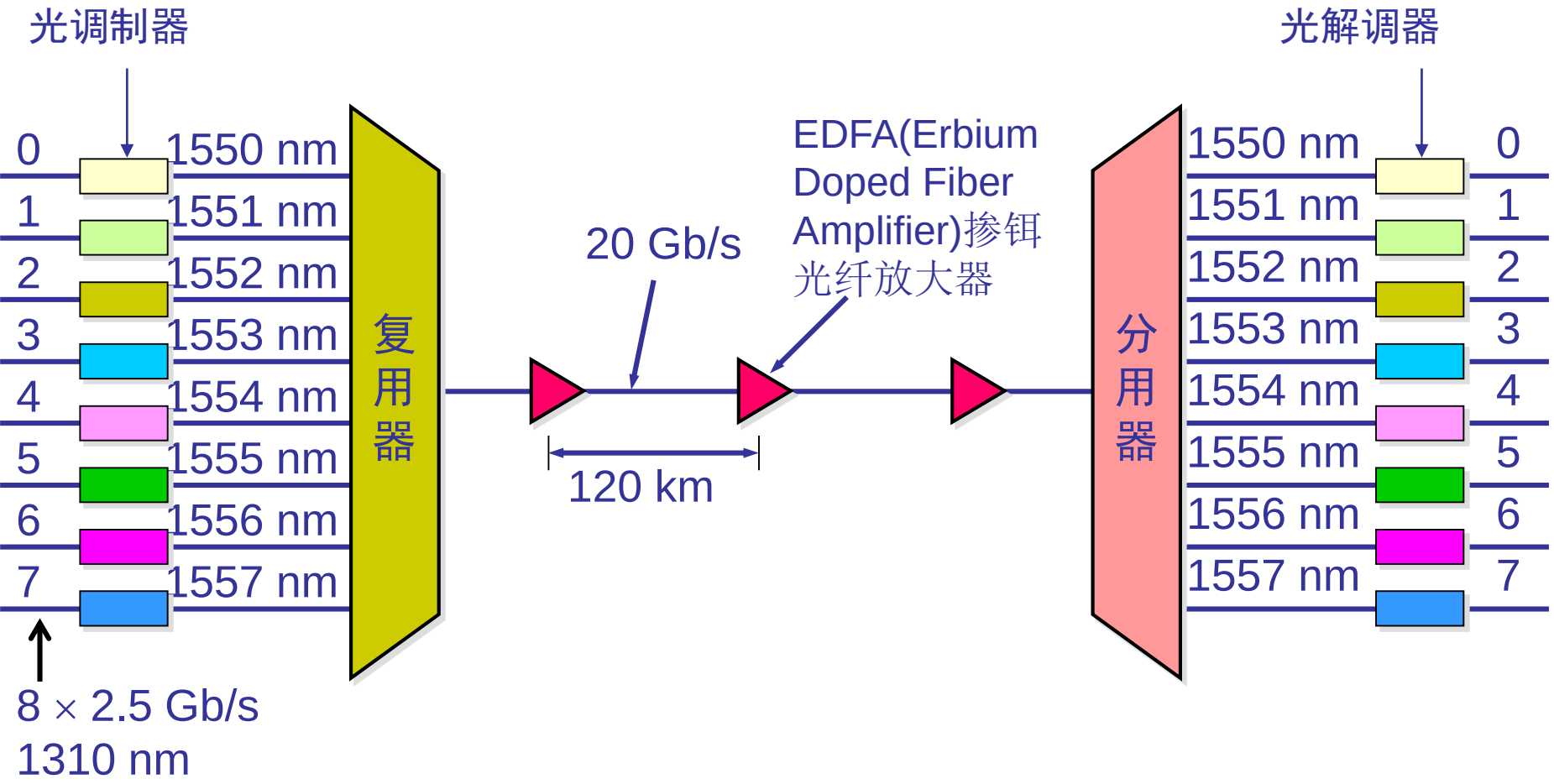
--- carried over optical fiber links.

- commercial systems with 160 channels of 10 Gbps per channel, a total of **1.6 Tbps**.
- lab demo of 256 channels at 39.8 Gbps each, a total of **10.1 Tbps**, over a 100-km span.

--- **architecture** similar to other FDM systems.

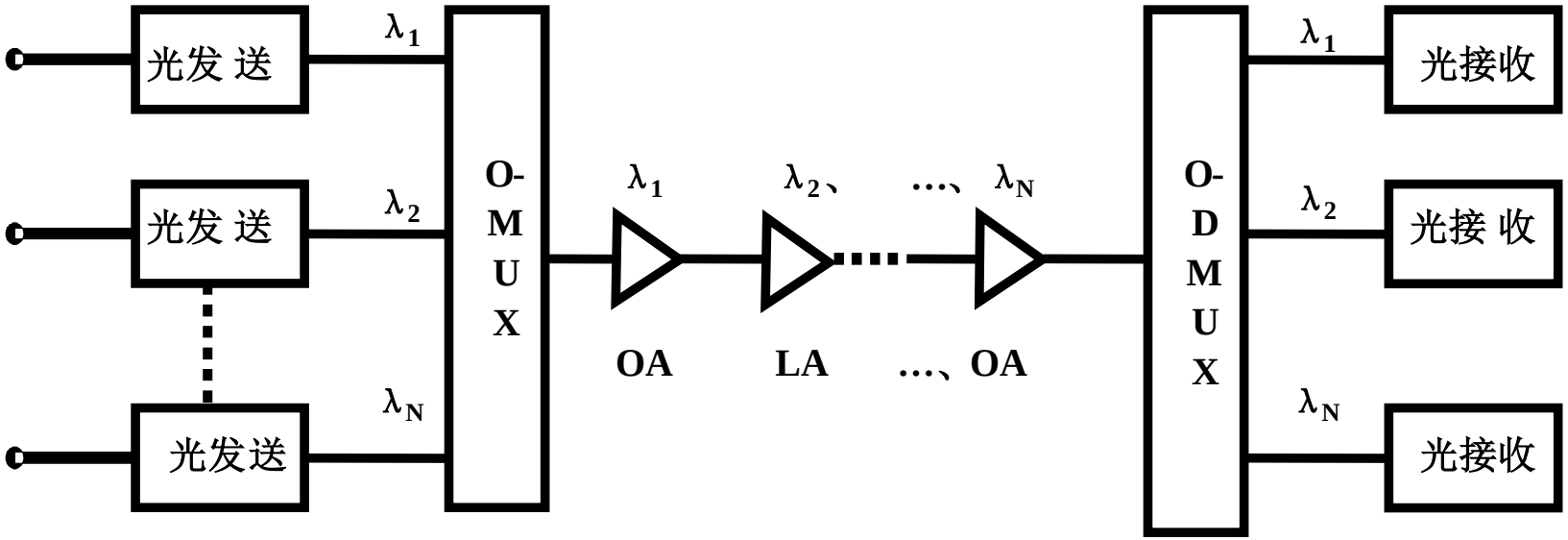
- multiplexer consolidates laser sources (1550-nm range, approx. 80+ channels) for transmission over single fiber.
- Optical amplifiers (tens of km apart) amplify all wavelengths.
- Demux (demultiplexer) separates channels at the destination.

3. 2 FDM



引自谢希仁(5e)

3. 2 FDM

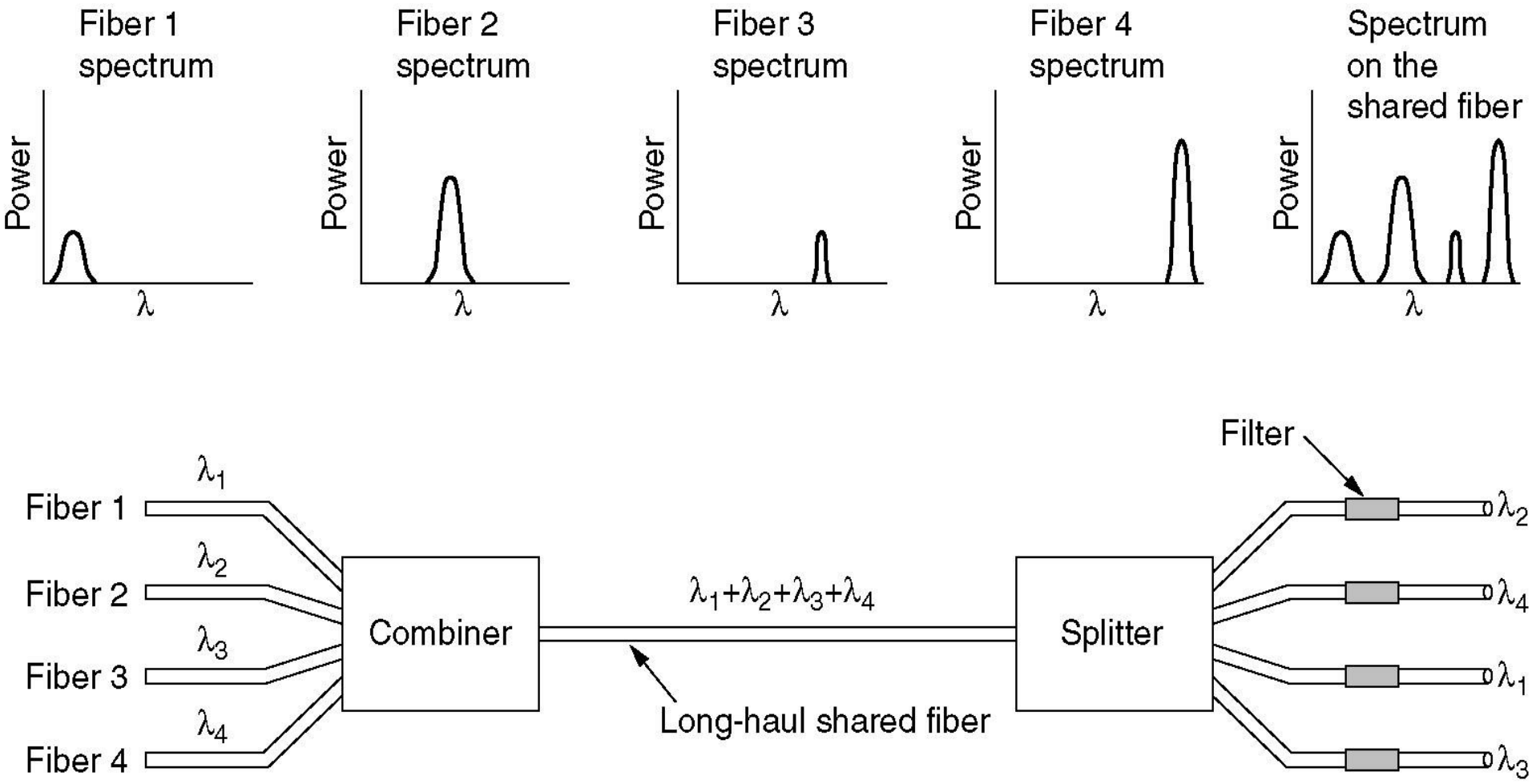


OA—光放大器（掺铒光纤放大器EDFA）； LA –线路放大器（多波长再生器）；
O-MUX—光多路复用器； O-DMUX—多路光解复用器；

The optic fiber is multiplexed into multi-lambda channels

引自曾华燊(2004)

3. 2 FDM



引自Tanenbaum(4e)

3. 2 FDM

--- WDM system

- Most operate in the 1550-nm range.
- Spacing of each channel, early 200GHz, today 50GHz
- ITU-T G.692 WDM Channel Spacing, 80 50GHz channels.

--- also have Dense Wavelength Division Multiplexing (DWDM).

- No official or standard definition.
- A channel spacing of 200GHz or less could be considered dense.

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3.4 Statistical TDM

3.5 ADSL

3.6 CDM (Code Division Multiplexing)

3.7 OFDM (Orthogonal Frequency Division Multiplexing)

3. 3 TDM

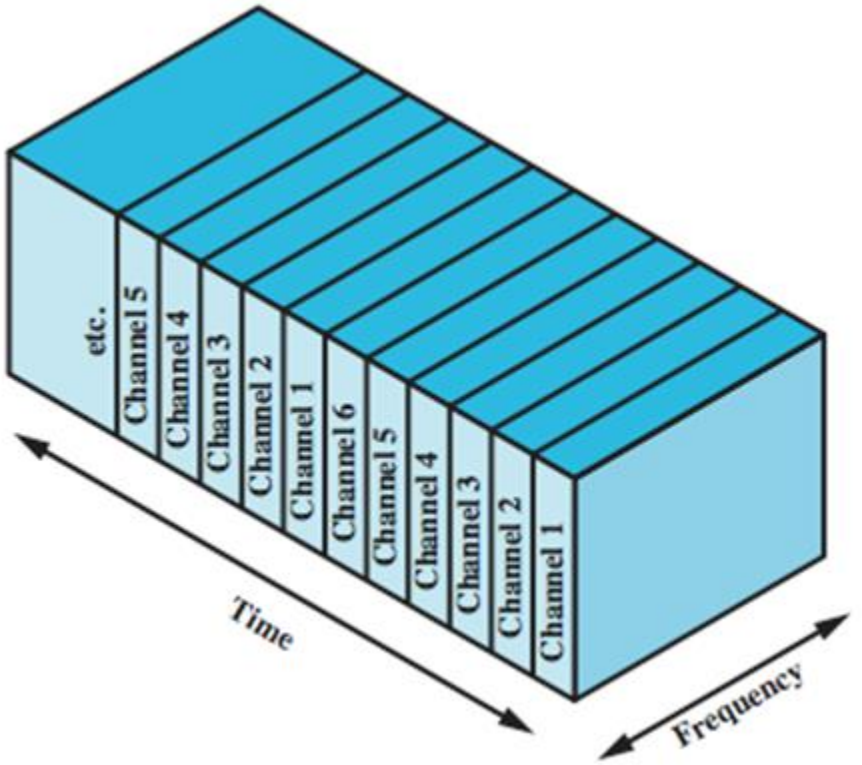
1. General concept

--- the achievable data rate (or bandwidth) of the transmission medium **exceeds** the data rate of digital signals to be transmitted.

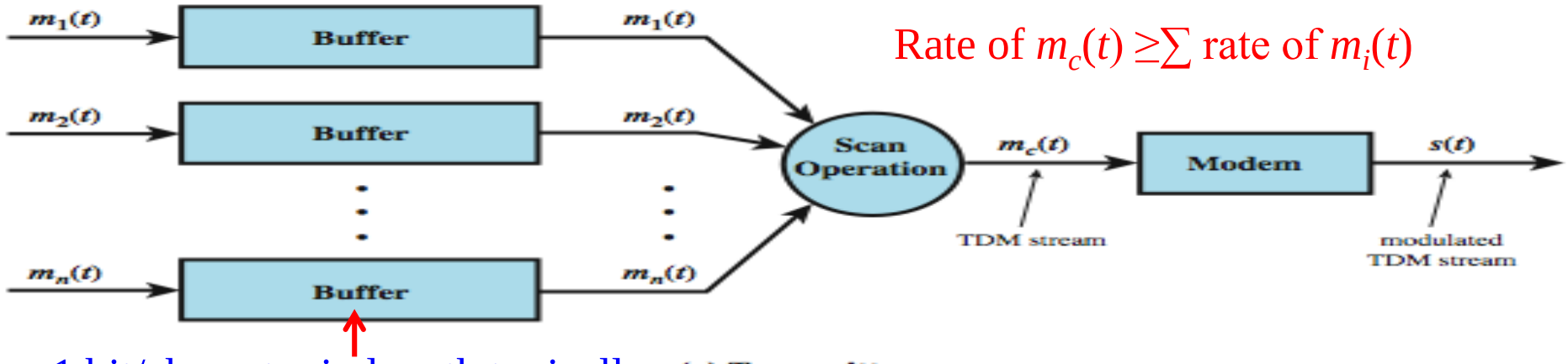
--- data from various sources are carried in **repetitive** frames.

--- **Each frame** consists of a set of time slots (时槽/时隙), and **each source** is **assigned** one or more time slots per frame. The effect is to **interleave** (交织) **bits** of data from the various sources.

--- The sequence of slots **dedicated to one source**, from frame to frame, is called a channel.



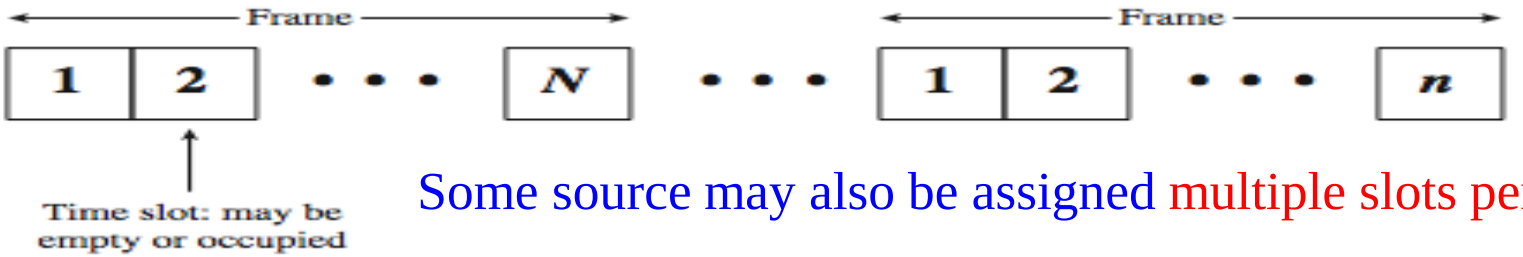
Synchronous TDM System



Rate of $m_c(t) \geq \sum$ rate of $m_i(t)$

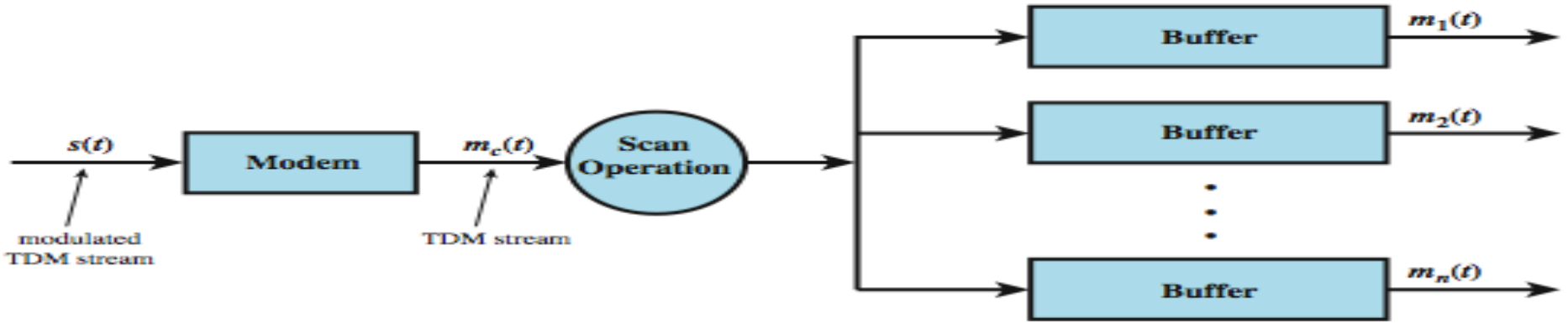
1 bit/character in length typically

(a) Transmitter



Some source may also be assigned multiple slots per cycle

(b) TDM Frames



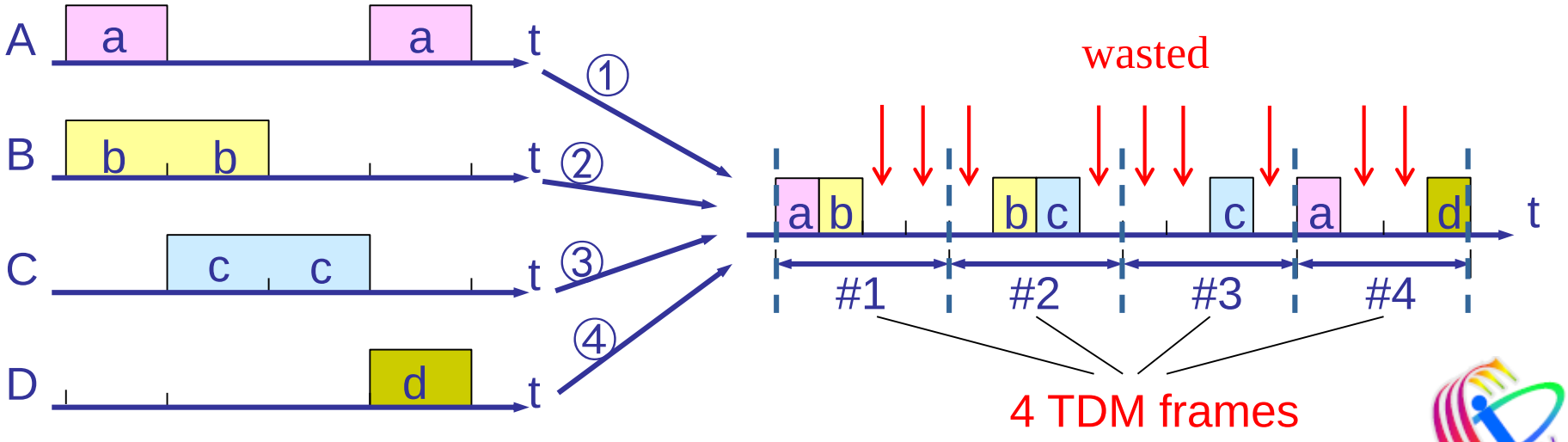
(c) Receiver

3. 3 TDM

--- The interleaving can be at the bit level or byte level or in blocks of bytes or larger quantities.

--- Synchronous TDM is **called synchronous** not because synchronous transmission is used, but **because** the time slots are pre-assigned to sources and fixed.

--- The time slots for each source are transmitted whether or not the source has data to send. So, if no data to transmitted, the slot is wasted.



3. 3 TDM

2. TDM Link Control

--- distinguish **current** TDM frame from the frame of DLL (data link layer).

- no headers and trailers.

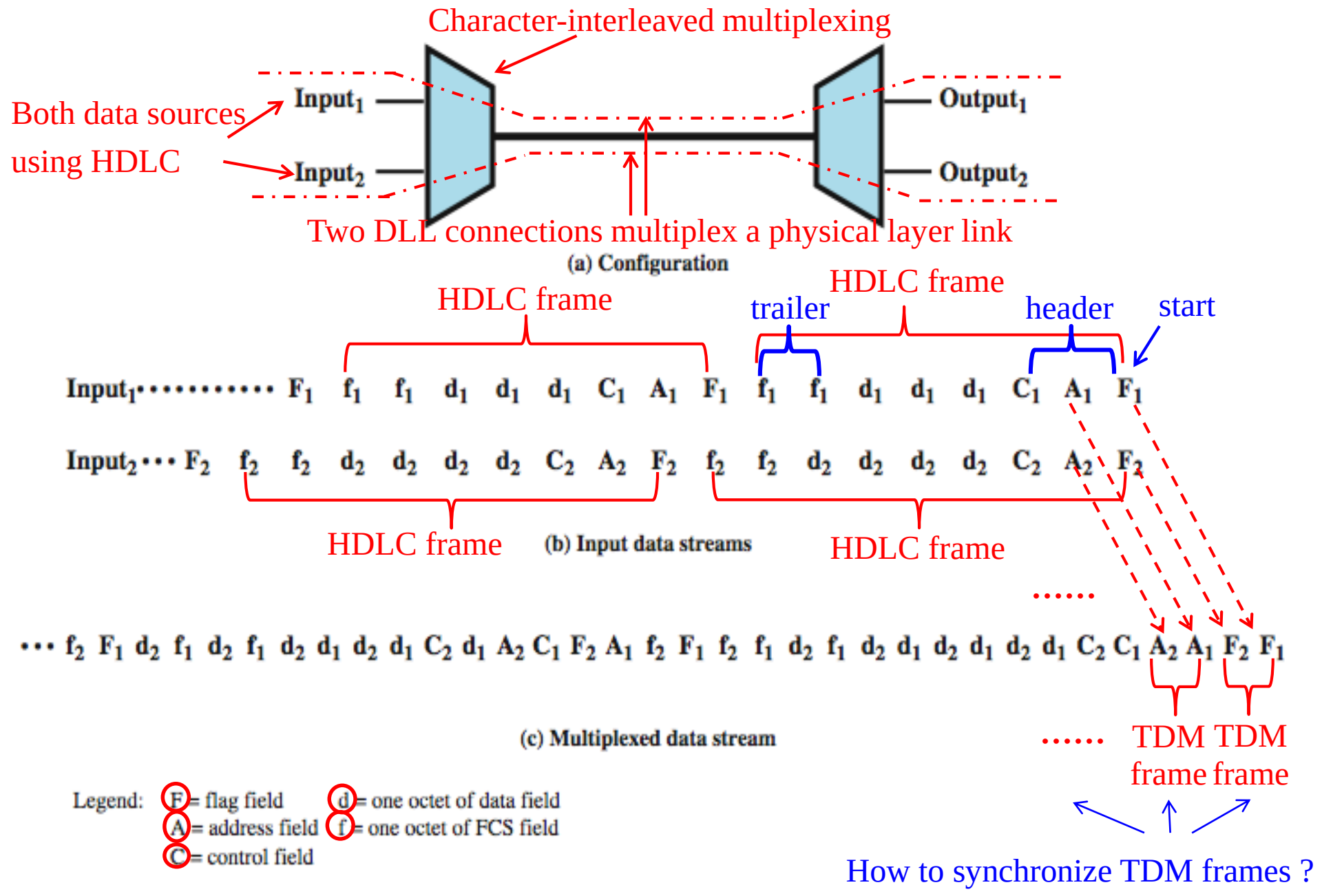
--- data link control protocols not needed between **multiplexer and demultiplexer**.

- data rate of multiplexed line is fixed.
- if one channel receiver can not receive data, the others still carry on.
- corresponding source must be quenched, and the channel in question carries empty slots.

--- flow control and error control

- On a per-channel basis, not on TDM link basis.

3. Use of Data Link Control on TDM Channels



3. 3 TDM

--- How to synchronize those **TDM frames**?

- **Framing**

  (a) one control bit (framing bit, 帧位)is added to each TDM frame.

  (b) identifiable bit pattern (eg. Alternating 1010101…) used.

--- How to synchronize **data sources**?

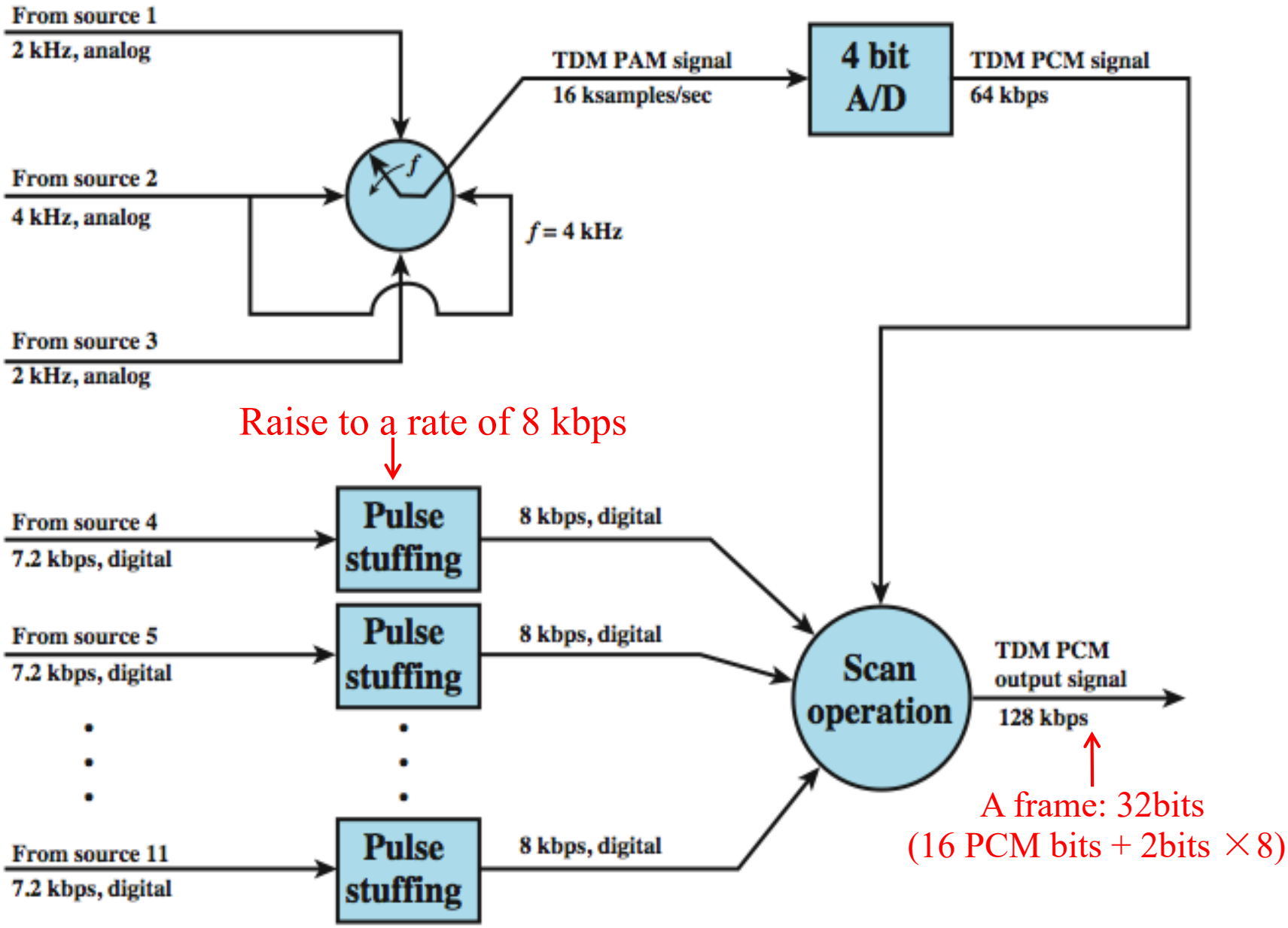
- with clocks in different sources drifting.
- also issue of data rates from different sources not related by simple rational number (有理数).
- **Pulse Stuffing**

  (a) have outgoing data rate (excluding framing bits) higher than sum of incoming rates.

  (b) stuff extra dummy bits or pulses into each incoming signal until it matches local clock.

  (c)stuffed pulses inserted at fixed locations in frame and removed at demultiplexer.

TDM Example


From source 1
2 kHz, analog
From source 2
4 kHz, analog
From source 3
2 kHz, analog
f
f = 4 kHz
TDM PAM signal
16 ksamples/sec
4 bit
A/D
TDM PCM signal
64 kbps
Raise to a rate of 8 kbps
From source 4
7.2 kbps, digital
From source 5
7.2 kbps, digital
From source 11
7.2 kbps, digital
Pulse
stuffing
Pulse
stuffing
Pulse
stuffing
8 kbps, digital
8 kbps, digital
8 kbps, digital
Scan
operation
TDM PCM
output signal
128 kbps
A frame: 32bits
(16 PCM bits + 2bits ×8)

3. 3 TDM

4. Digital Carrier Systems

--- long-distance links use an **TDM hierarchy**.

--- AT&T (USA) and ITU-T (International) **variants**

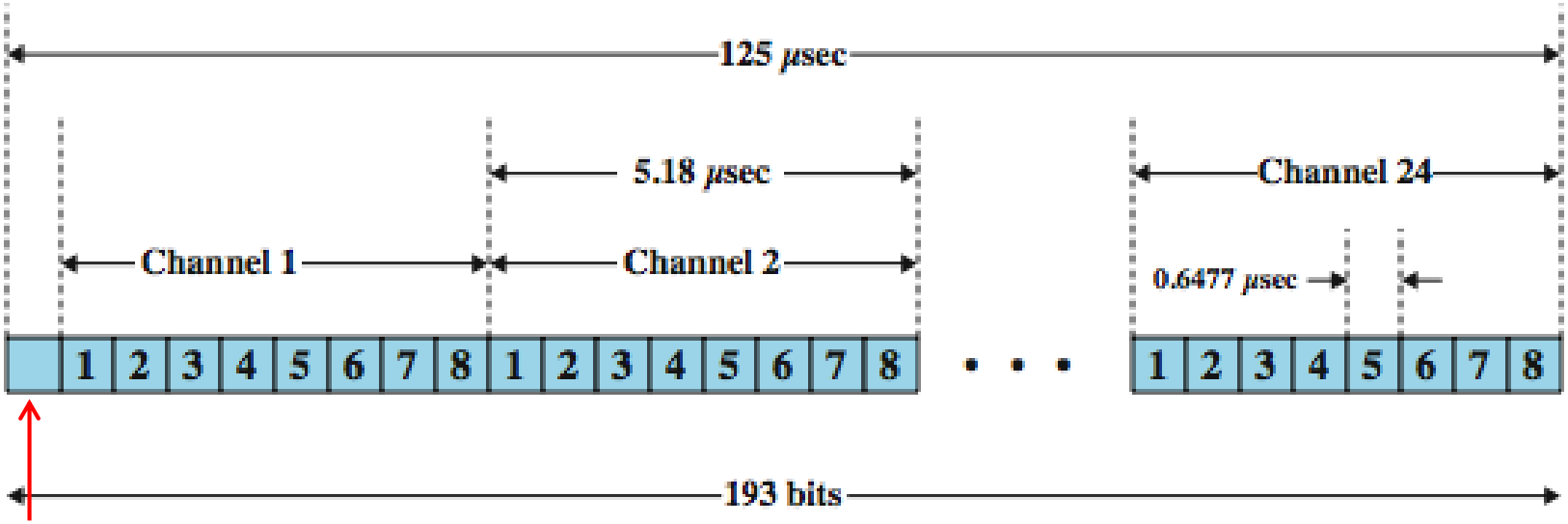
--- **USA** system based on **DS-1** format

- can carry mixed voice and data signals
- 24 channels used for total data rate 1.544Mbps (**T1**)
- each voice channel contains one word of digitized data (PCM, 8000 samples per sec)
- same format for 56kbps digital data

--- can interleave DS-1 channels for higher rates

- DS-2 is **four** DS-1 at 6.312Mbps

DS-1 Transmission Format (T1 system)



Framing bit
alternatively 10101010…

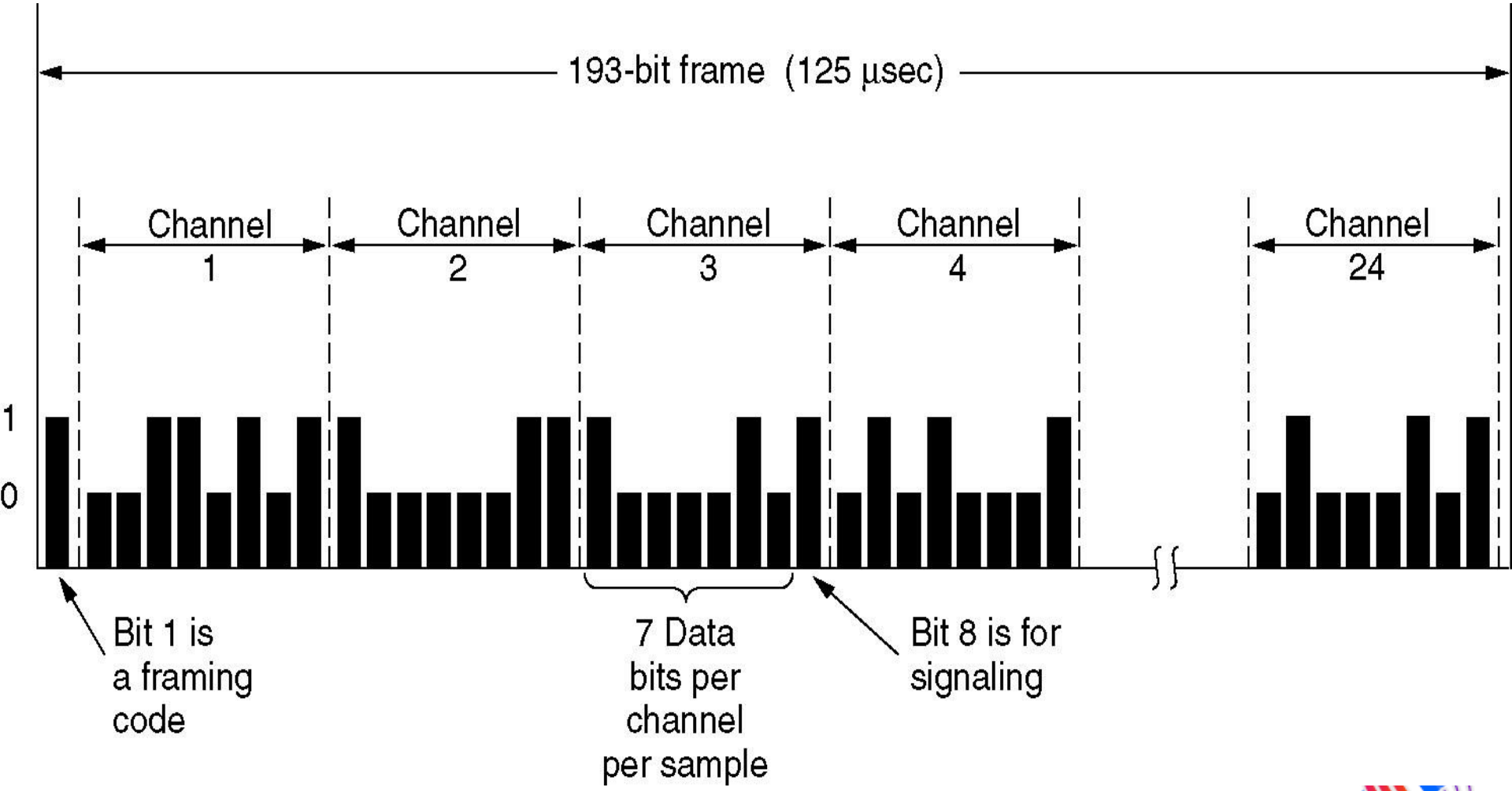
Sampling 24 channels in 125μs, each channel: 8 bits.
A TDM frame: 24×8 (bits) +1 (framing bit)=193 bits.
Rate=193(bits)/125(μs)=**1.544 Mbps**

Notes:

1. The first bit is a framing bit, used for synchronization.
2. Voice channels: ⟵ For Voice channels, PCM applied.
   - 8-bit PCM used on five of every six frames.
   - 7-bit PCM used on every sixth frame; bit 8 of each channel is a signaling bit.
3. Data channels:
   - Channel 24 is used for signaling only in some schemes.
   - Bits 1-7 used for 56 kbps service
   - Bits 2-7 used for 9.6, 4.8, and 2.4 kbps service.

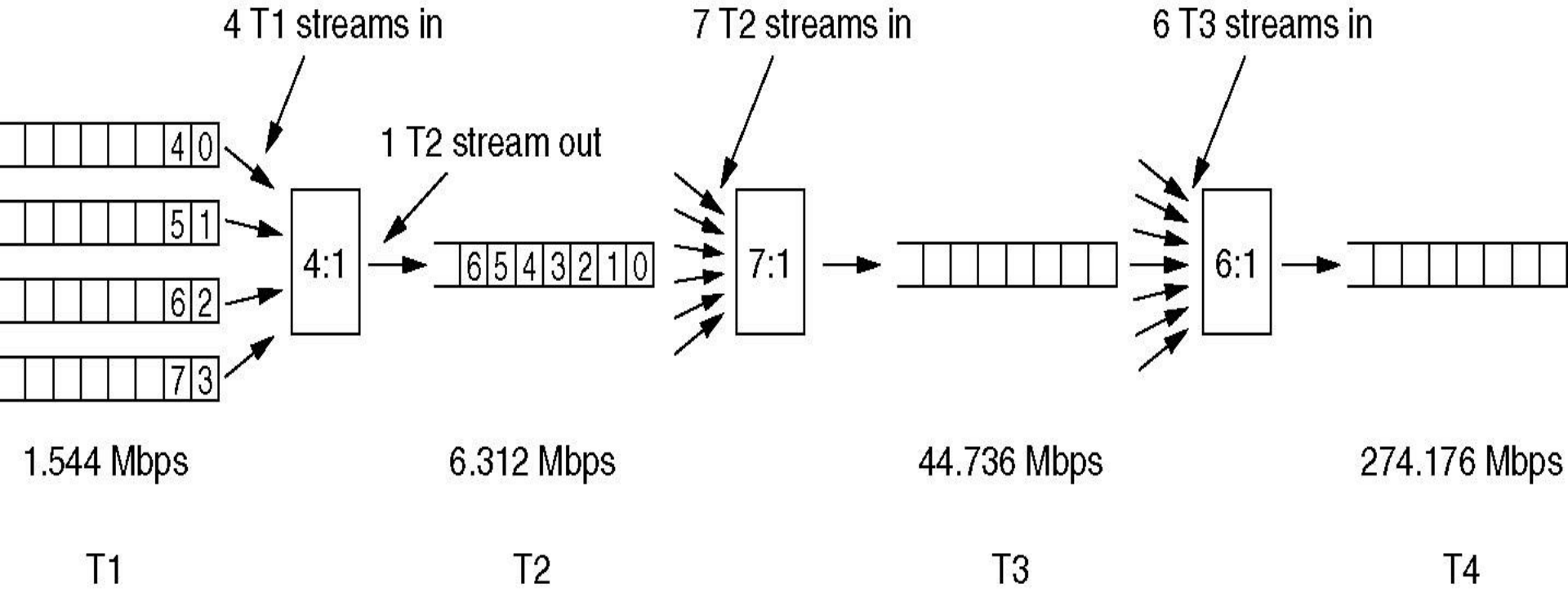
3. 3 TDM

The T1 carrier (1.544 Mbps) (Tanenbaum, 4e)



3. 3 TDM

Multiplexing T1 streams into higher-order (高次) carriers (Tanenbaum, 4e)



3. 3 TDM

North American and International TDM Carrier Standards

North American			International (ITU-T)		
Designation	Number of Voice Channels	Data Rate (Mbps)	Level	Number of Voice Channels	Data Rate (Mbps)
DS-1 (T1)	24	1.544	1 (E1)	30	2.048
DS-1C	48	3.152	2 (E2)	120	8.448
DS-2 (T2)	96	6.312	3 (E3)	480	34.368
DS-3 (T3)	672	44.736	4 (E4)	1920	139.264
DS-4 (T4)	4032	274.176	5 (E5)	7680	565.148

Notes:

- Higher-level multiplexing is achieved by interleaving bits from DS-1 inputs.
- E.g., DS-2 combines 4 DS-1 inputs into a 6.312-Mbps stream.
- $1.544 \times 4 = 6.176$ Mbps, $\neq 6.312$Mbps. The remaining capacity is used for framing and control bits.
- T1 and T3 widely used, whereas T2 and T4 only used within the telephone system.

3. 3 TDM

PCM数字传输系统的高次群的话路数和数据率(谢希仁, 5e)

系统类型		一次群	二次群	三次群	四次群	五次群
欧洲体制	符号	**E1**	**E2**	**E3**	**E4**	**E5**
	话路数	30	120	480	1920	7680
	数据率(Mbps)	2.048	8.448	34.368	139.264	565.148
北美体制	符号	**T1**	**T2**	**T3**	**T4**	
	话路数	24	96	672	4032	
	数据率(Mbps)	1.544	6.312	44.736	274.176	

注：中国采用欧洲体制标准。

3. 3 TDM

5. SONET/SDH

---In the early days of fiber, different hierarchies are used in TDM system. E.g., PDH(Plesiochronous Digital Hierarchy, 准同步数字体系) has three hierarchies as follows.

表 2.1　3 种 PDH 的复用等级规范

群	以 1.5 Mbps 为基础的系列（单位：kbps）		以 2 Mbps 为基础的系列（单位：kbps）
	日本体制	北美体制	欧 洲 体 制
0 次群	64	64	64 （可传 1 路话音）
1 次群	1 554	1 554	2 048（可传 30 路话音）
2 次群	6 312	6 312	8 448（可传 120 路话音）
3 次群	32 064	44 736	34 368（可传 480 路话音）
4 次群	97 728		139 264（可传 1920 路话音）
5 次群			565 148（可传 7680 路话音）

3. 3 TDM

--- PDH does not use the same clock but two clocks with approximately the same frequencies (within the limit of required precision).

--- need to unify the U.S., European, and Japanese digital systems, all of which were based on 64-kbps PCM channels, but all of which multiplexed them in different (and incompatible) ways.

--- **SONET** (Synchronous Optical Network, 同步光纤网) is an optical transmission interface, controlled by **a master clock** with an accuracy of about 1 part in 10^9, originally proposed by BellCore, standardized by ANSI (USA).

- All the long-distance telephone traffic in USA uses trunks running SONET in **the physical layer**.

--- **SDH** (Synchronous Digital Hierarchy, 同步数字系列) is published by ITU-T, differs from SONET only in minor ways.

3. 3 TDM

- Signal Hierarchy

---The **lowest level**, STS-1 (Synchronous Transport Signal level 1) or OC-1 (**Optical** Carrier level 1) is 51.84Mbps.

- carries one DS-3 or multiple (DS1, DS1C, DS2) plus ITU-T rates (eg. 2.048Mbps).

---multiple STS-1 combine into STS-N signal.

---**ITU-T** lowest rate, STM-1 (Synchronous Transport Module) is 155.52Mbps.

3. 3 TDM

SONET and SDH multiplex rates (Tanenbaum, 4e)

SONET		SDH	Data rate (Mbps)		
Electrical	Optical	Optical	Gross	SPE	User
STS-1	OC-1		51.84	50.112	49.536
STS-3	OC-3	STM-1	155.52	150.336	148.608
STS-9	OC-9	STM-3	466.56	451.008	445.824
STS-12	OC-12	STM-4	622.08	601.344	594.432
STS-18	OC-18	STM-6	933.12	902.016	891.648
STS-24	OC-24	STM-8	1244.16	1202.688	1188.864
STS-36	OC-36	STM-12	1866.24	1804.032	1783.296
STS-48	OC-48	STM-16	2488.32	2405.376	2377.728
STS-192	OC-192	STM-64	9953.28	9621.504	9510.912

3. 3 TDM

SONET 的 OC 级/STS 级与 SDH 的 STM 级的对应关系 (谢希仁, 5e)

线路速率 (Mb/s)	SONET 符号	SDH 符号	表示线路速率的常用近似值
51.840	OC-1/STS-1	—	
155.520	OC-3/STS-3	STM-1	**155 Mb/s**
466.560	OC-9/STS-9	STM-3	
622.080	OC-12/STS-12	STM-4	**622 Mb/s**
933.120	OC-18/STS-18	STM-6	
1244.160	OC-24/STS-24	STM-8	
2488.320	OC-48/STS-48	STM-16	**2.5 Gb/s**
4976.640	OC-96/STS-96	STM-32	
9953.280	OC-192/STS-192	STM-64	**10 Gb/s**
39813.120	OC-768/STS-768	STM-256	**40 Gb/s**

3. 3 TDM

◆ **SONET**的体系结构(由低到高)

---光子层(Photonic Layer)

- 处理跨越光缆的比特传送。

--- 段层(Section Layer)

- 在光缆上传送 STS-N 帧。

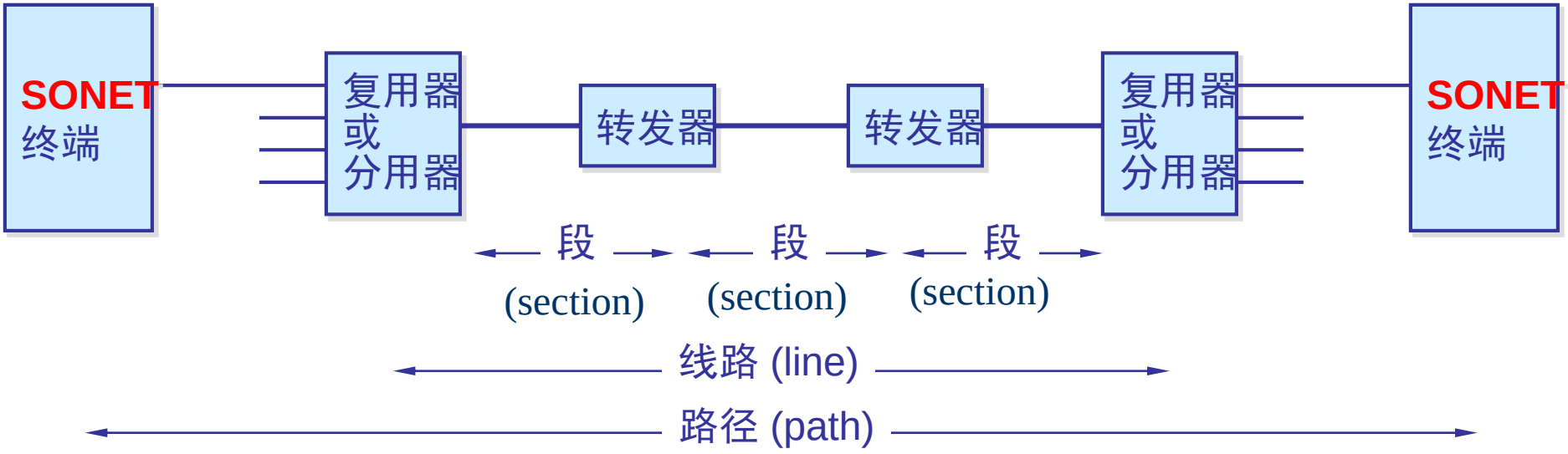
--- 线路层(Line Layer)

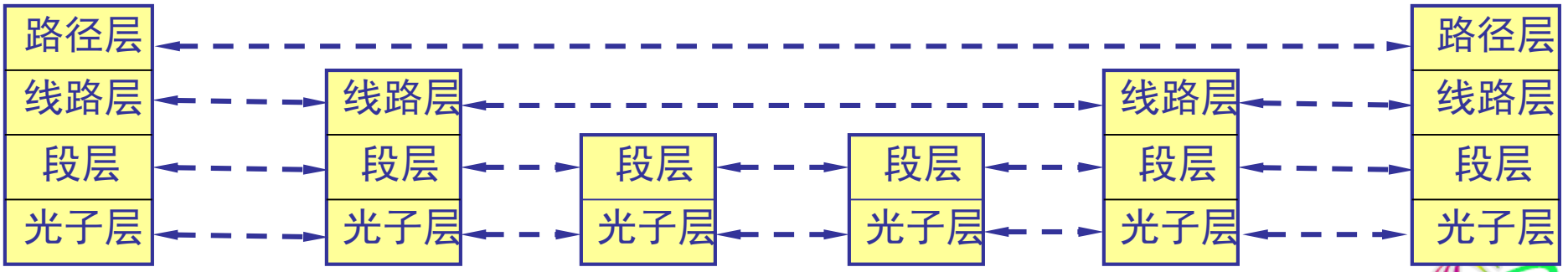
- 负责路径层的同步和复用。

--- 路径层(Path Layer)

- 处理路径端接设备 PTE (Path Terminating Element)之间的业务的传输。

3. 3 TDM


SONET
终端
复用器
或
分用器
转发器
转发器
复用器
或
分用器
SONET
终端
段
(section)
段
(section)
段
(section)
线路 (line)
路径 (path)


路径层
线路层
段层
光子层
线路层
段层
光子层
段层
光子层
段层
光子层
线路层
段层
光子层
路径层
线路层
段层
光子层

3. 3 TDM

◆ **SDH**的体系结构(注意与SONET比较)

--- Transmission Media Layer (传输介质层)

- 由段层(Section layer)和物理介质层(Physical media layer, PML)组成。
- 段层负责为两个结点间的信息传递提供所需的功能。
- PML处理与实际介质收发有关的问题，为段层提供服务。

--- Path Layer (通路/路径层)

- 具有管理与控制连接能力。
- 由低阶通路(Low-order path)和高阶通路(High-order path)组成。高/低阶指**传输速率的高低**。
- VC (Virtual container)为信息结构抽象，由相应的容器加上通路开销(Path overhead)组成。

--- Circuit Layer (电路层)

- 为用户提供电信业务，如电路交换、分组交换和线路租用等。

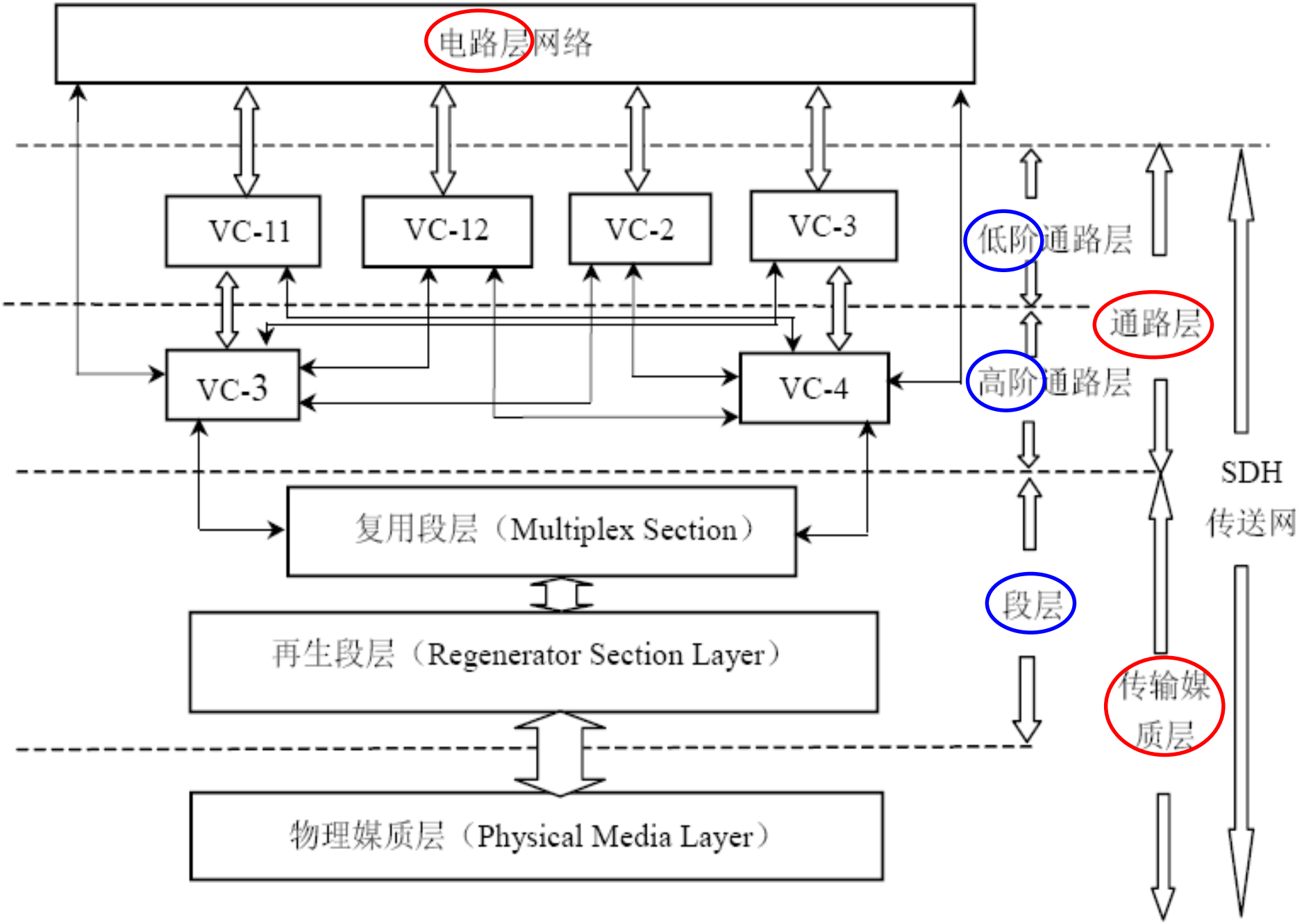


图 2.14　SDH 分层结构模型示意图

3. 3 TDM

◆ SONET Frame Format

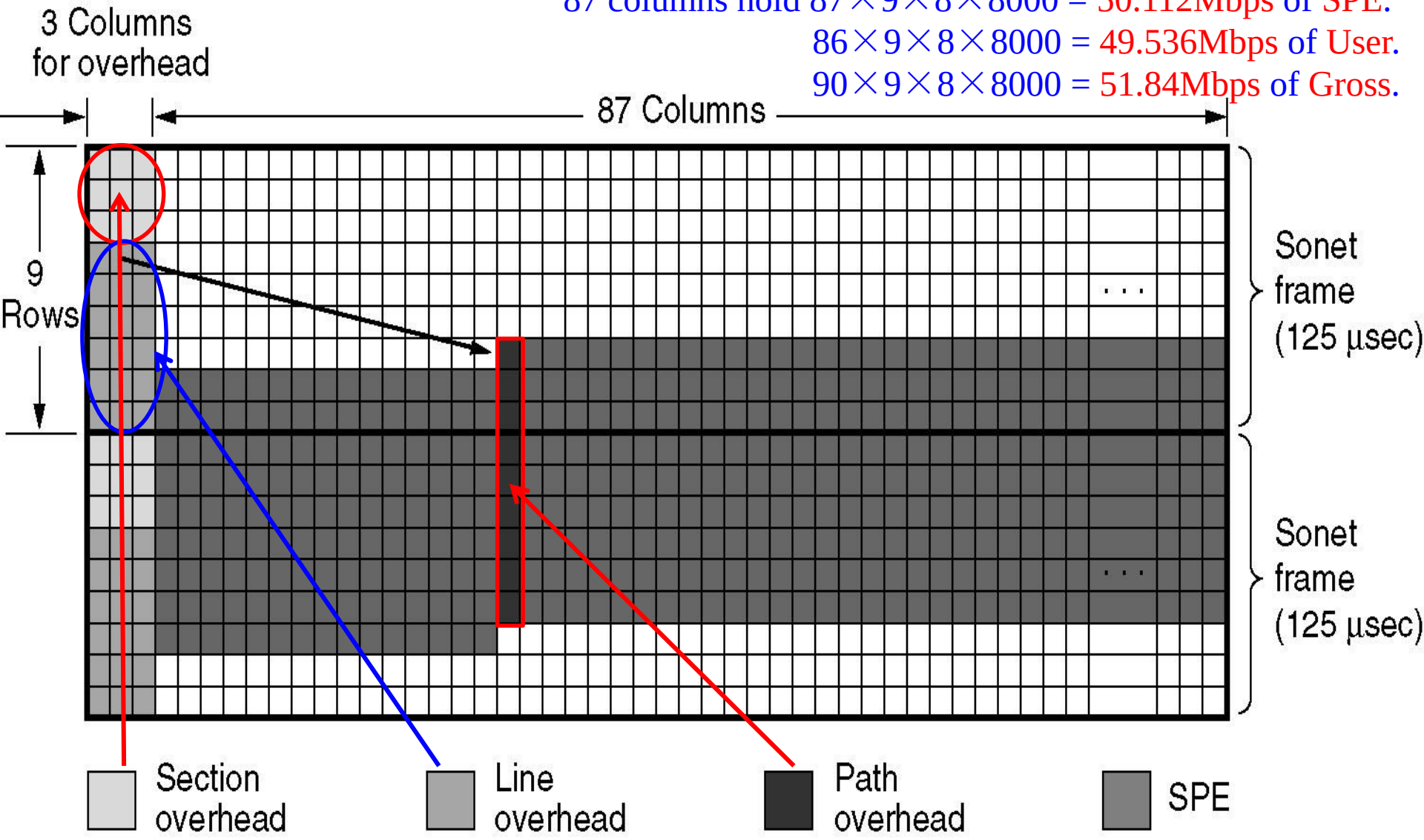
--- the basic SONET frame, STS-1 frame, a block of 810 bytes put out every 125μs (**exactly matches** the **sampling** rate of the **PCM** channels).

- Since SONET is **synchronous**, frames are emitted **whether or not** there are any useful data to send.
- **Gross data rate**: 810×8×8000= 51.84 Mbps.
- Basic SONET channel, called STS-1. All SONET trunks are a multiple of STS-1.

---described as a matrix of 9 rows of 90 octets each.

Two **back-to-back** SONET frames (Tanenbaum, 4e)

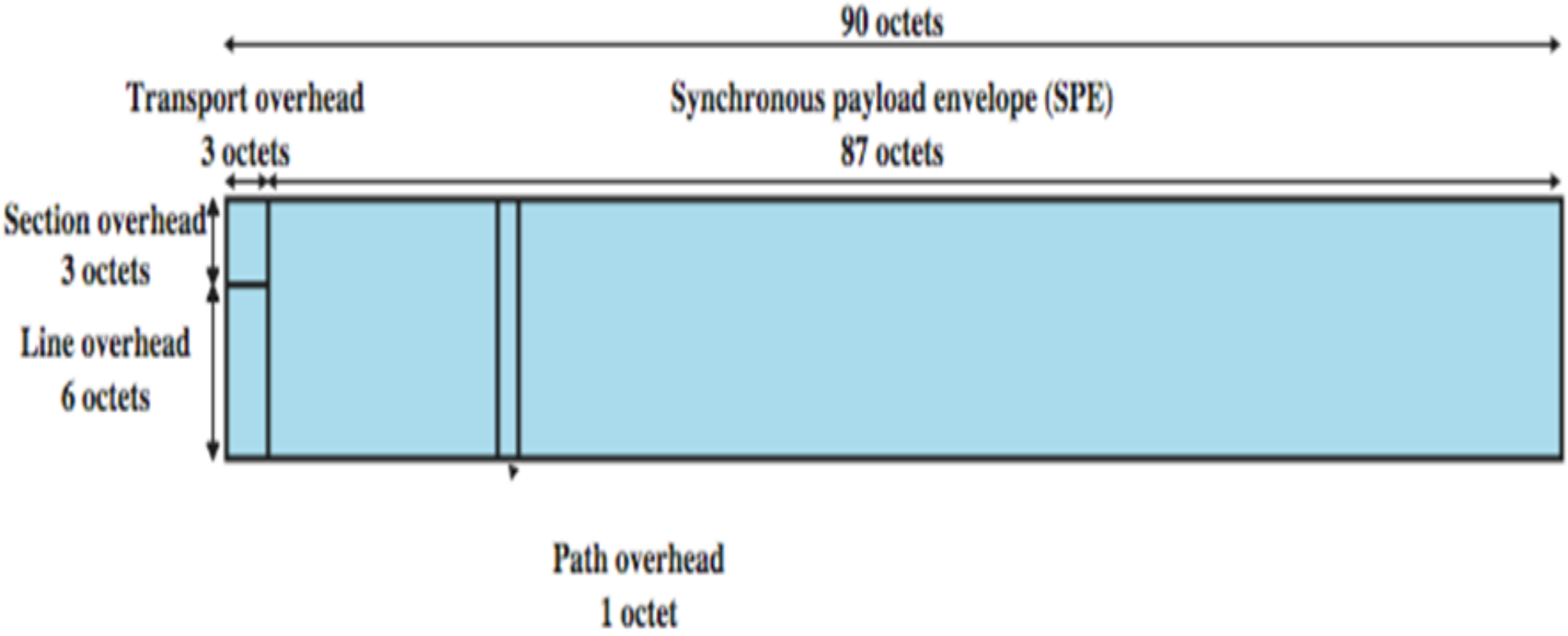
87 columns hold 87×9×8×8000 = 50.112Mbps of SPE.
86×9×8×8000 = 49.536Mbps of User.
90×9×8×8000 = 51.84Mbps of Gross.



SPE: Synchronous payload envelop (同步净荷包)

3. 3 TDM

SONET frame format (William Stallings, 8e)



(a) STS-1 frame format

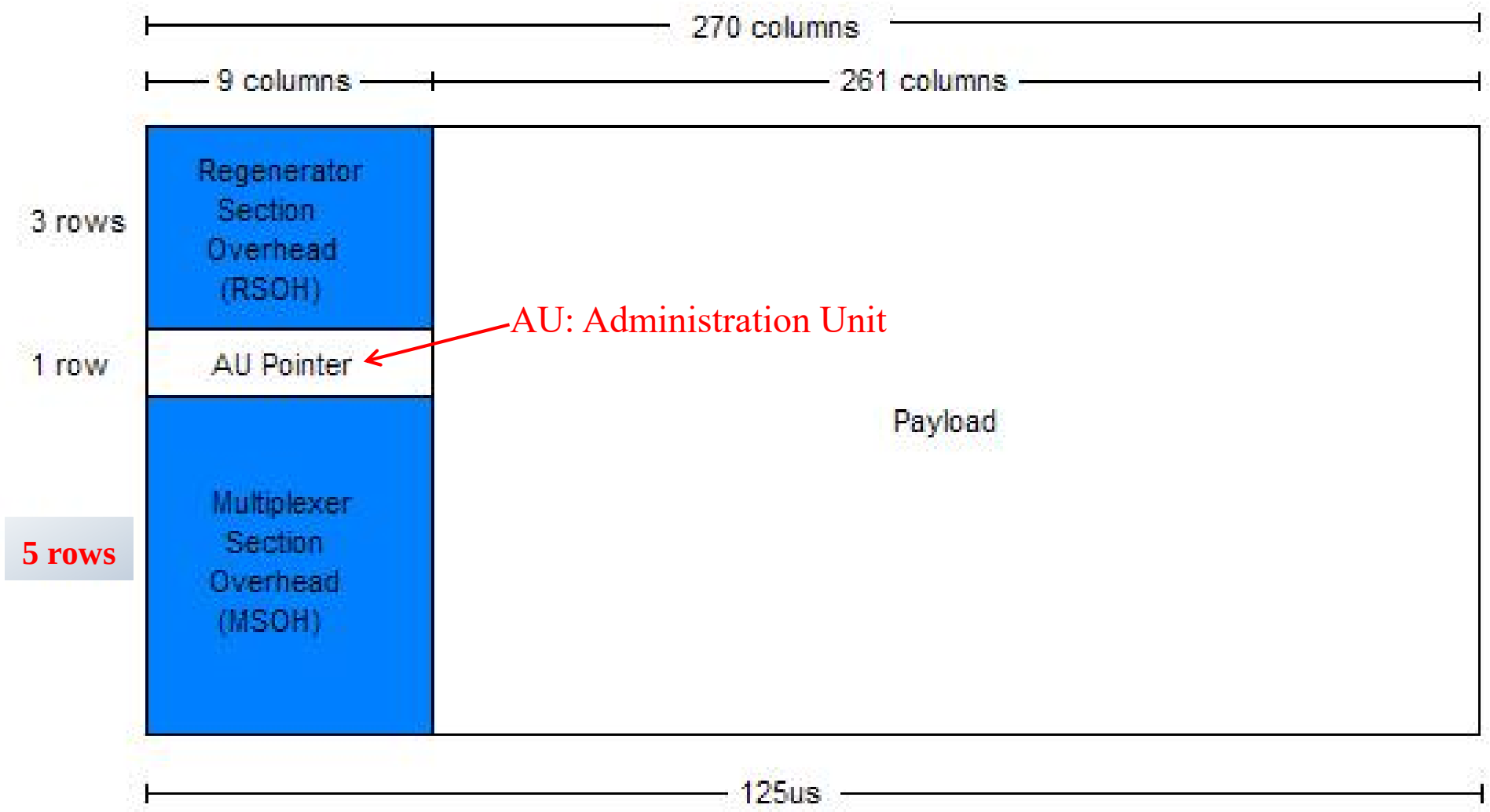
3. 3 TDM

◆ SDH Frame Format

--- STM-1 frame, a matrix of 9 rows of 270 octets each.

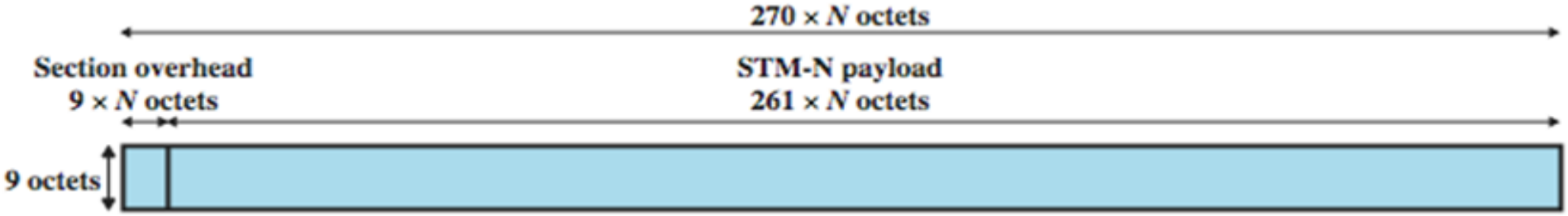
- Total content : 9 × 270 octets = 2430 octets
- Overhead (开销) : 8 rows × 9 octets
- Pointers (指针) : 1 row × 9 octets
- Payload (净载荷) : 9 rows × 261 octets
- Period : 125 μsec
- Bit rate : 155.52 Mbps (2430 octets×8 bits×8000 frame/s) or 270×9×64 kbps : 155.52 Mbps; Actual payload capacity : 150.336 Mbps (9×261×8 bits×8000 frame/s)
- The transmission of the frame is done row by row, from the left to right and top to bottom.

3. 3 TDM


270 columns
9 columns
261 columns
3 rows
Regenerator Section Overhead (RSOH)
AU: Administration Unit
1 row
AU Pointer
Payload
Multiplexer Section Overhead (MSOH)
5 rows
125us

3. 3 TDM

--- **STM-N** frame, a matrix of 9 rows of 270×**N** octets each.



270 × N 列 • 字节

9×N 列 • 字节(段开销)　　261 × N 列 • 字节（净荷区）

3 行	再生段开销 RSOH Regeneration Section Overhead	高阶通路开销	净荷区（Payload）：存放有效业务数据 对 STM-1（即 N 为 1），净荷区为 261 字节，其中第 10 列字节为通路开销。对 STM-N，其 261N 列 •字节中，第 10N 列 •字节为高阶通路开销。[注：高阶（High level）通路系指高速传输通路]
1 行	管理单元(AU)指针		
5 行	复用段开销 MSOH Multiplexing Section Overhead		

第3章 Multiplexing（复用）

3.1 Introduction

3.2 FDM

3.3 TDM

3.4 Statistical TDM

3.5 ADSL

3.6 CDM (Code Division Multiplexing)

3.7 OFDM (Orthogonal Frequency Division Multiplexing)

3. 4 Statistical TDM

1. General concept

--- in Synch TDM many slots are wasted.

--- Statistical TDM allocates time slots dynamically based on demand.

--- multiplexer scans input lines and collects data until frame full.

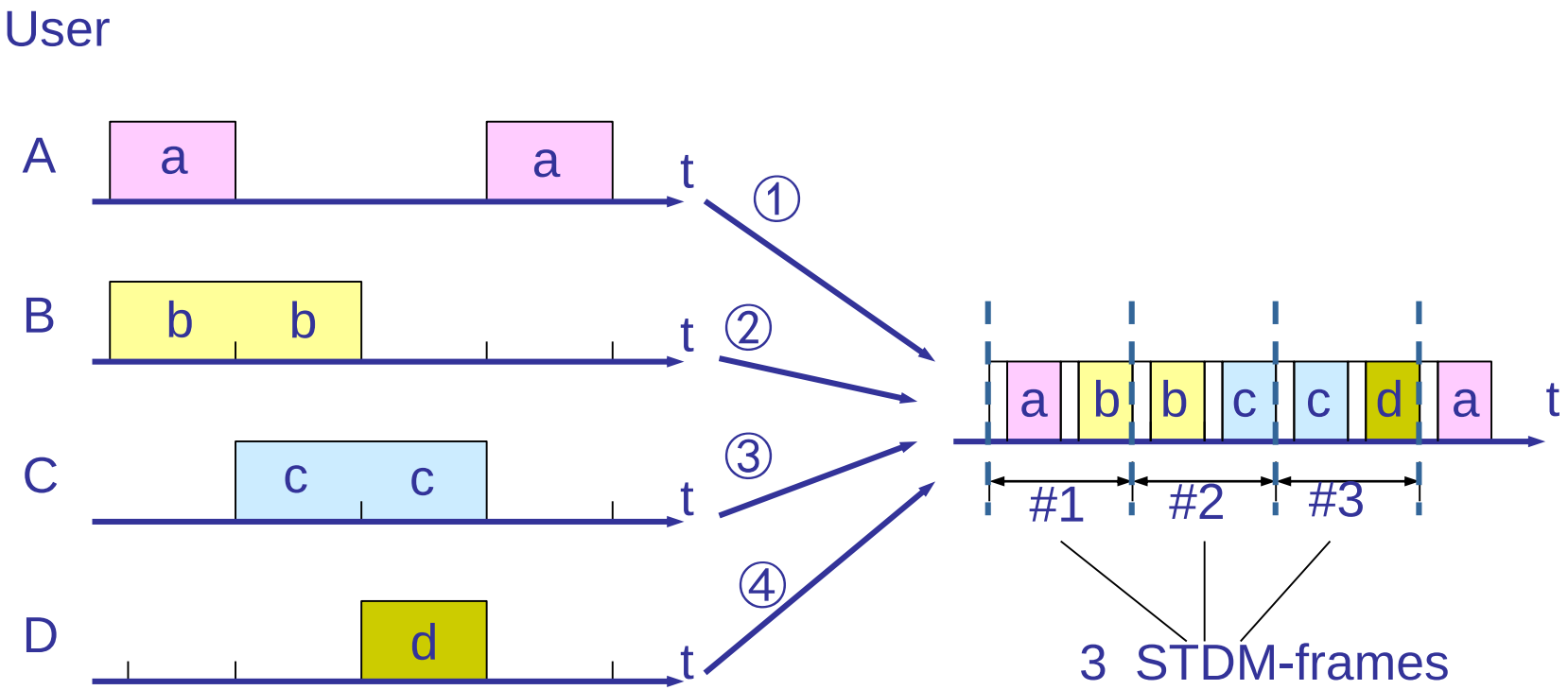
--- line data rate lower than aggregate input line rates.

--- may have problems during peak periods.

- must buffer inputs.

3. 4 Statistical TDM

Statistical TDM (谢希仁, 5e)



Statistical TDM frame format (William Stallings, 8e)

(a) Overall frame ?

(b) Subframe with one source per frame

(c) Subframe with multiple sources per frame

3. 4 Statistical TDM

2. Cable Modem: an application of Statistical TDM

--- dedicate two cable TV channels(Down/Up) to data transfer.

--- each channel shared by number of subscribers, using statistical TDM.

--- **Downstream** (下行) **channel**

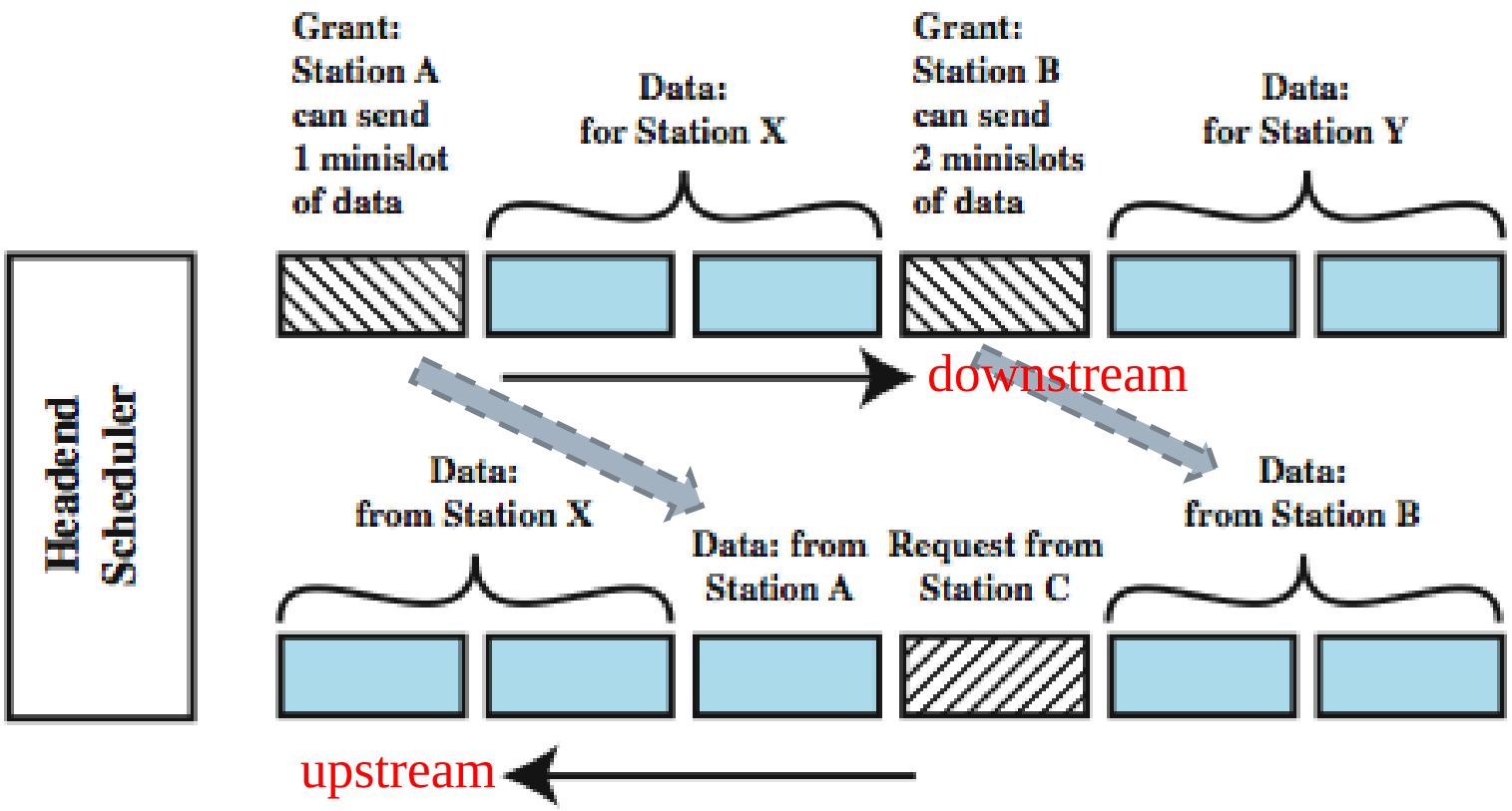
- cable scheduler delivers data in small packets.
- active subscribers share downstream capacity.
- also allocates upstream time slots to subscribers.

--- **Upstream** (上行) **channel**

- user requests timeslots on shared upstream channel.
- Headend (头端) scheduler notifies subscriber of slots to use.

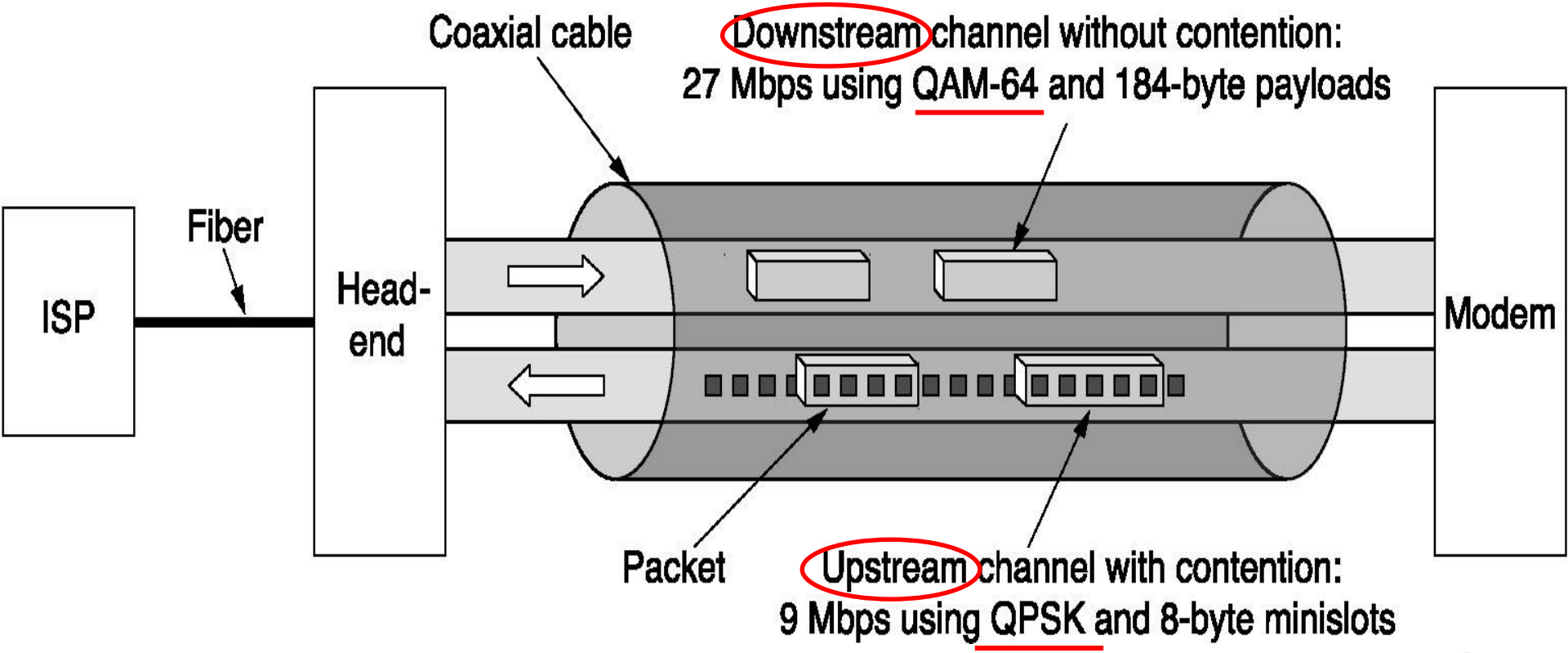
3. 4 Statistical TDM

Cable Modem Scheme (William Stallings, 8e)



3. 4 Statistical TDM

Typical details of the upstream and downstream channels in North America (Tanenbaum, 4e)



第3章 Multiplexing（复用）

3.1 Introduction

3.2 FDM

3.3 TDM

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3.5 ADSL

3.6 CDM (Code Division Multiplexing)

3.7 OFDM (Orthogonal Frequency Division Multiplexing)

3. 5 ADSL

1. General concept

--- ADSL: Asymmetric digital subscriber line, 非对称数字用户线.

--- a family of new modem technologies designed to provide high-speed digital data transmission over ordinary telephone wire. Defined in an **ANSI** standard. In 1999, also standardized by **ITU**, G.992.1 (G.992.2 as G.Lite ADSL/ADSL Lite/U-ADSL) or G.dmt, i.e., using **DMT** (Discrete multi-tone, 离散多音) technology.

--- link between subscriber and network.

--- uses currently installed twisted pair wire

- Get rid of the low-pass filter (4 kHz) in the PABX(程控交换机).
- Extend the bandwidth (1MHz or more) for transmission.

Note that the frequency limitation on the subscriber line is not 4kHz and that for Cat 3 UTP is 16 MHz for 100 meters.

3. 5 ADSL

--- is Asymmetric: **bigger** downstream (from carrier to customer) than upstream (from customer to carrier), fit for the Internet requirement.

- Multiple 4kHz-subchannels (or called container) divided using DMT(FDM) for upstream and downstream.

Each sub-channel modulated with 64-QAM at max 15bits/Hz,

$$C/B=\mathbf{log}_2(1+SNR)$$

and for the poorer sub-channel, QPSK applied to decrease the data rate.

3.5 ADSL

注：早先的ADSL使用**CAP** (Carrierless amplitude-phase modulation, 无载波幅相调制，由Bell实验室提出，但非工业标准) 而不是**DMT** (Telebit公司提出，ANSI T1.413)。

CAP是一种**单载波**调制技术（或无载波的QAM），它将电话线的可用频率空间分割为3个波段：

①0～4kHz被分配给POTS传输；

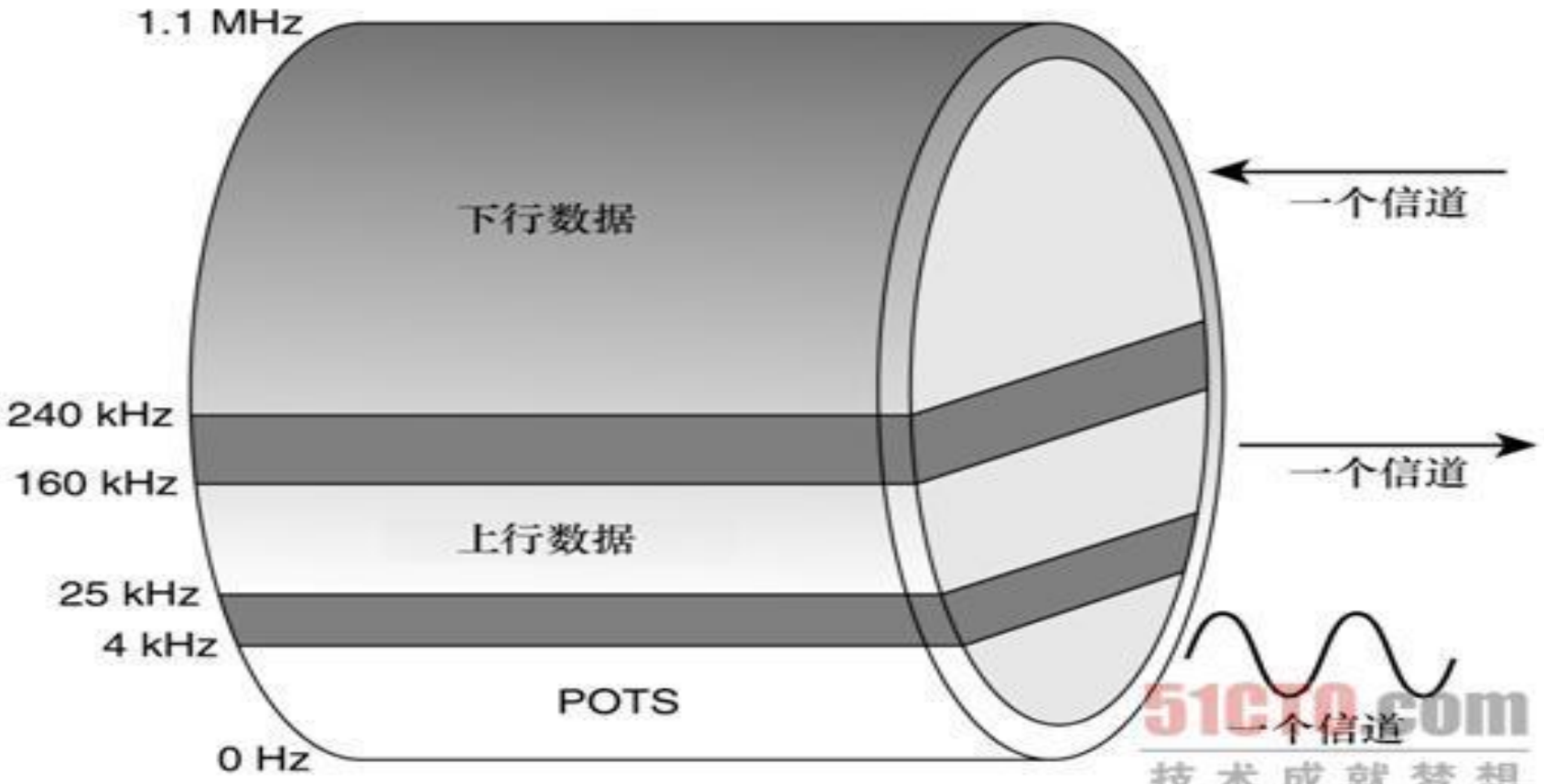
②25kHz～160kHz被分配给上行数据流量；

③240kHz～1.1MHz被分配给下行数据流量。

每个波段不再划分子信道。其优点为：载波频率可变，在一个频率周期或波特内传输2到9位二进制数据，因此在相同的传输速率下，占用更少的带宽，传输距离更远。有了DMT后，CAP已基本不使用。

3.5 ADSL

CAP Modulation



3. 5 ADSL

--- ADSL **channel configuration**

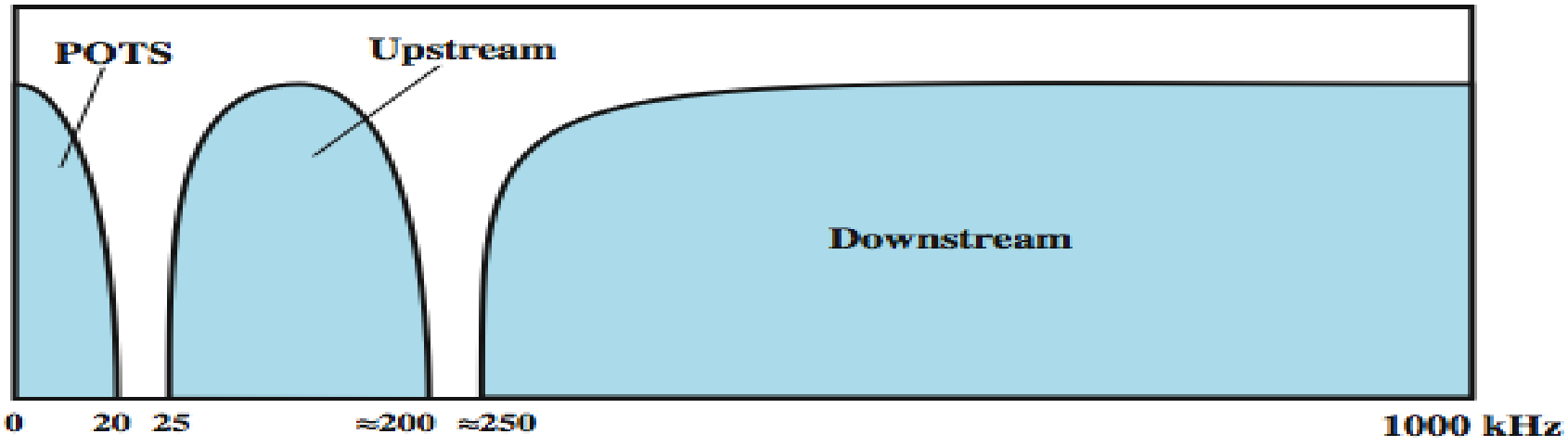
- lowest 25kHz for voice (POTS, plain old telephone service): 0 to 4 kHz band for voice; the additional bandwidth is to prevent crosstalk between the voice and data channels.
- uses echo cancellation (回波抵消) or FDM to allocate two bands: a smaller **upstream** band and a larger **downstream** band.

  Echo cancellation: a signal processing technique that allows transmission of digital signals in **both directions** on a **single** transmission line simultaneously.
- Use FDM within the upstream and downstream bands.

  a single bit stream is split into multiple parallel bit streams and each portion is carried in a separate frequency band.

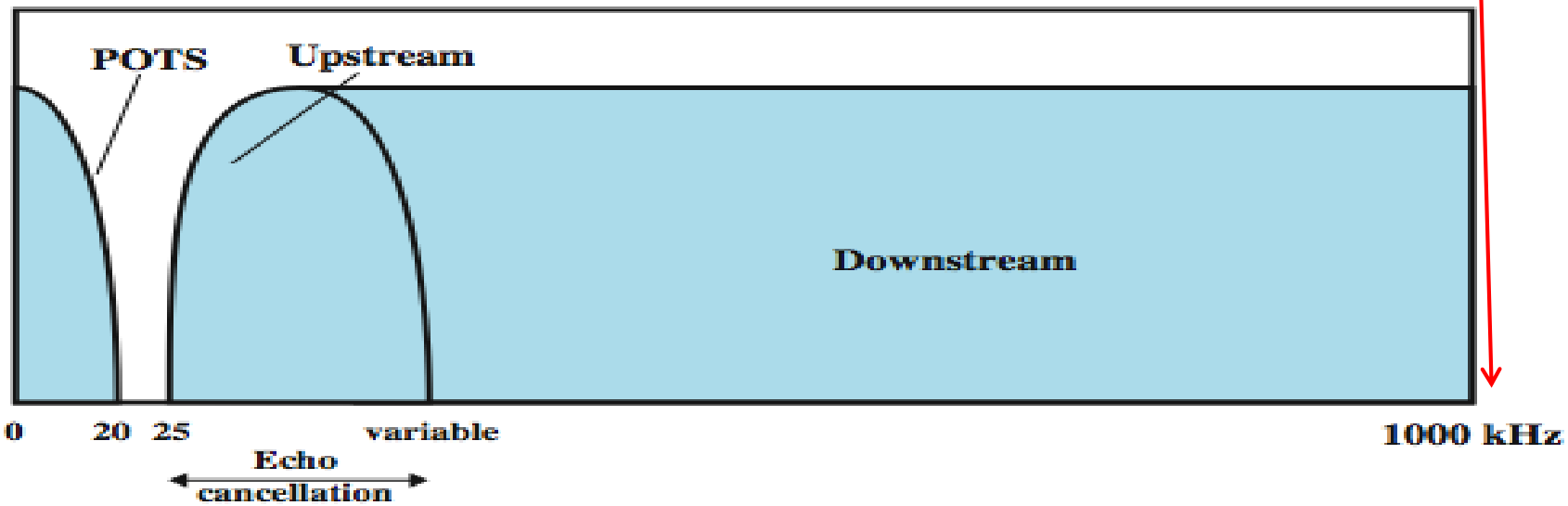
--- has a range of up to 5.5km.

ADSL Channel Configuration



(a) Frequency-division multiplexing

似应1.1MHz



(b) Echo cancellation

3. 5 ADSL

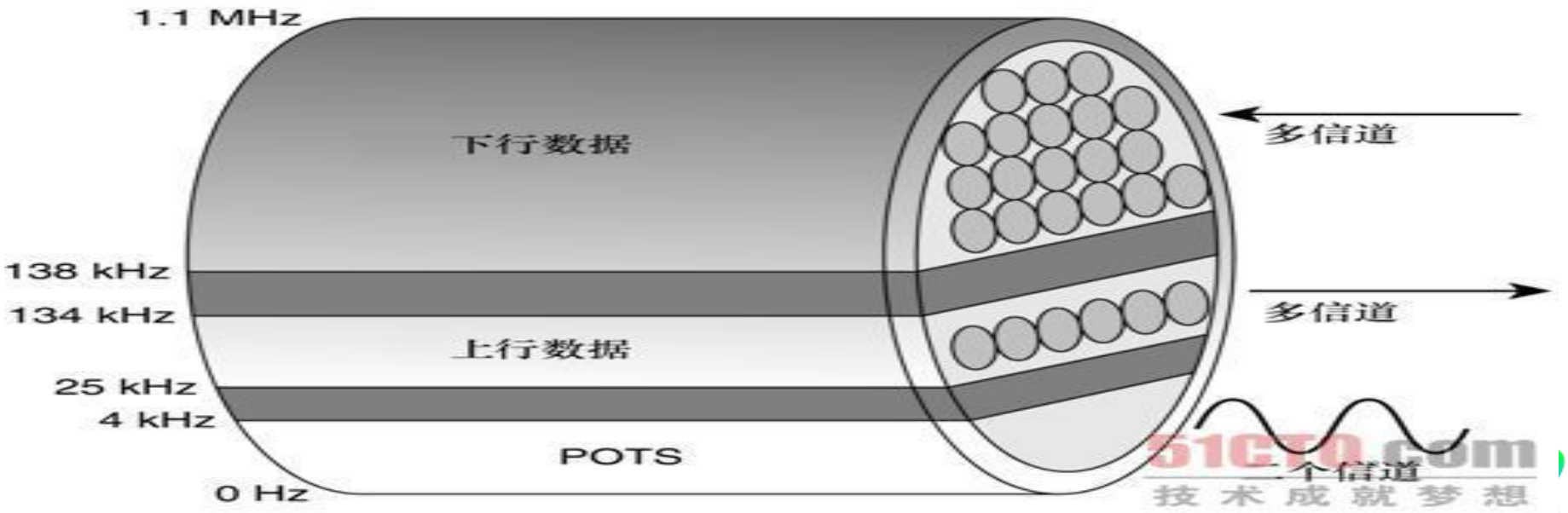
2. DMT

◆ From William Stallings (8e)

--- multi-tone, means multiple carriers or multiple sub-channels.

--- multiple carrier signals at different frequencies.

--- **upstream or downstream** is divided into 4kHz **sub-channels**.

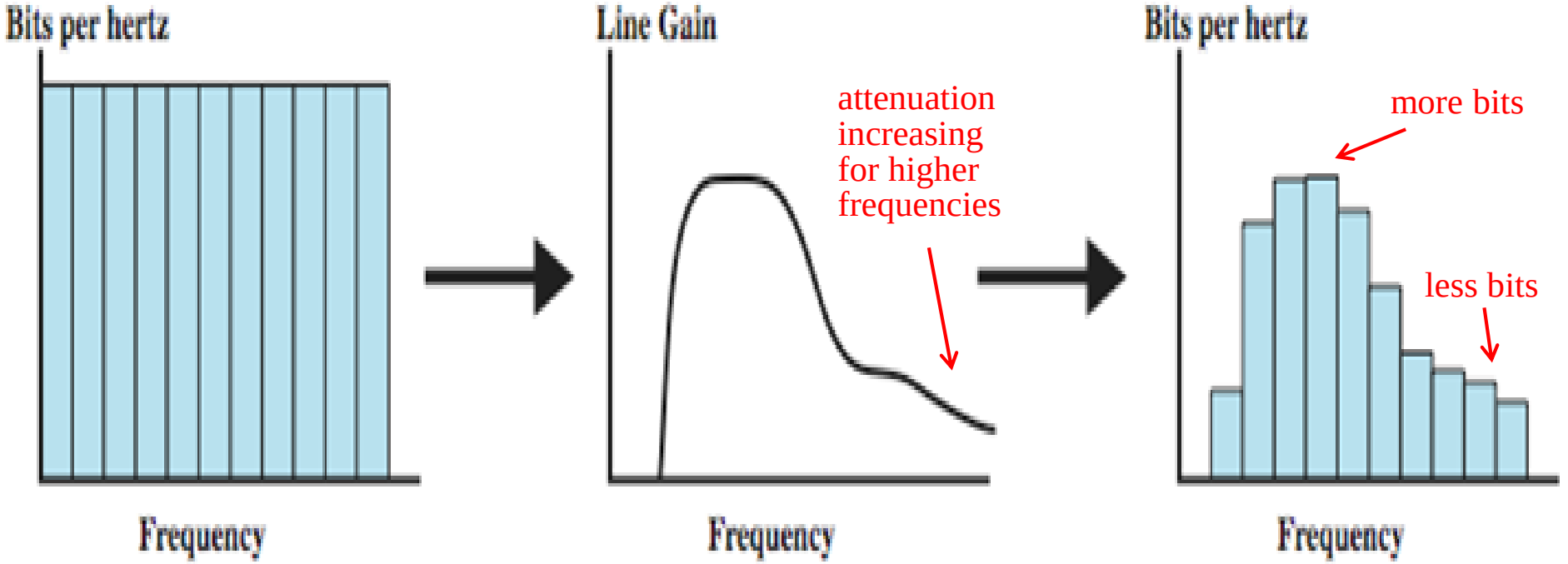


3. 5 ADSL

--- on initialization, DMT modem sends out test signals on each sub-channel to determine SNR (Signal-noise ratio), then assigns:

- more bits to sub-channels with better signal transmission qualities.
- less bits to sub-channels with poorer signal transmission qualities.

Fig. DMT bits per sub-channel allocation

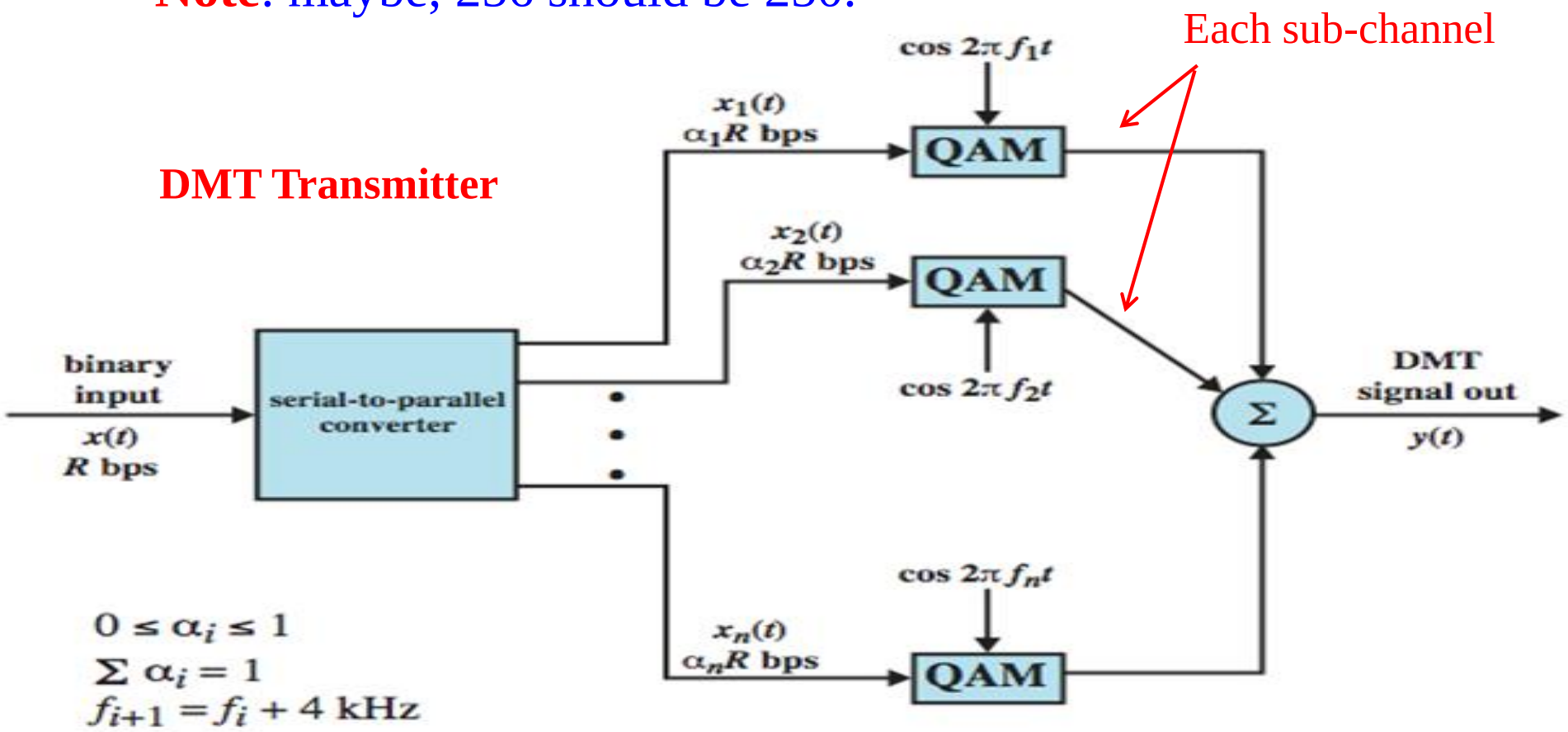


3. 5 ADSL

--- 256 **downstream** sub-channels at 4kHz (0~60kbps each)

- in theory 15.36Mbps (256×60kbps), in practice 1.5~9Mbps, depending on line distance and quality.

Note: maybe, 256 should be 250.



3.5 ADSL

--- 影响ADSL实际传输速率的因素还有传输距离和线径

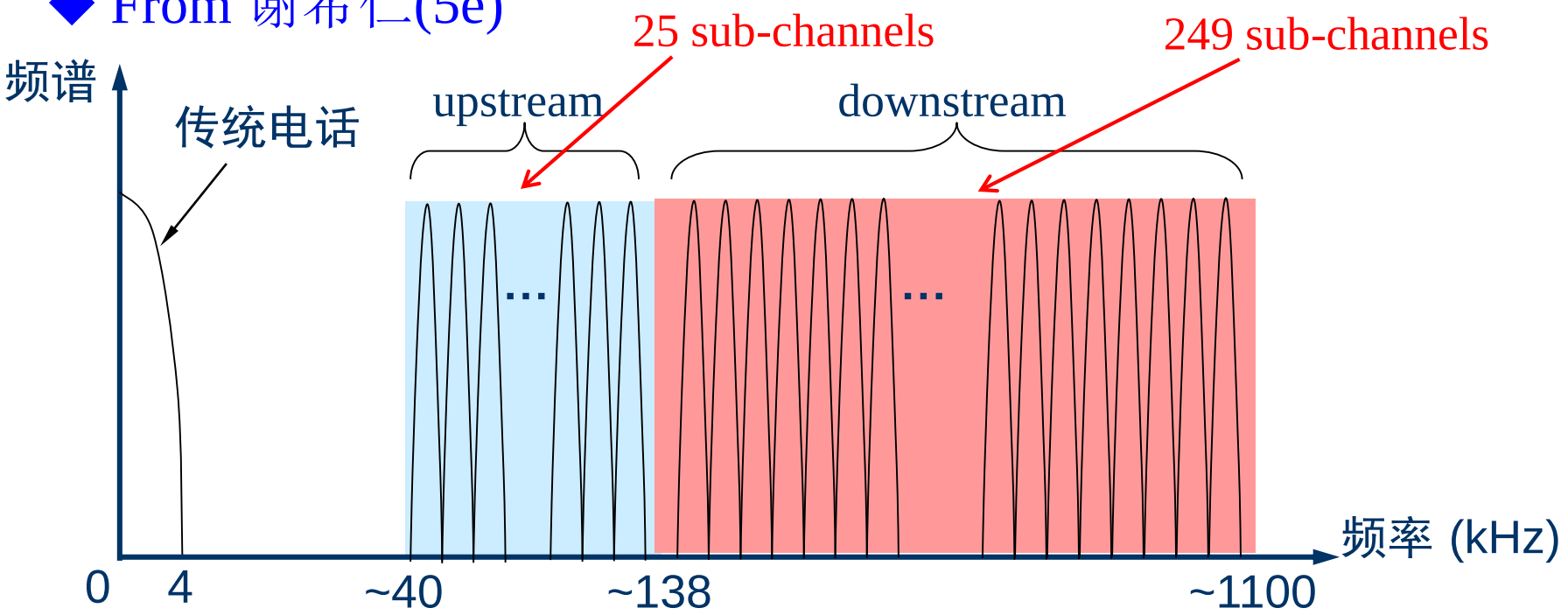
- 距离增加，速率下降；
- 线越细，信号传输时的衰减就越大，速率下降。

ADSL Forum: 标称速率与线径、传输距离的关系

下行速率 (Mbps)	传输距离	
	24AWG(American wire gauge) 线直径**0.5mm**	美国线径标准：26AWG 线直径**0.4mm**
1.544 (T1)	18000 ft (**6 km**)	15000 ft (5 km)
2.048 (**E1**)	16000 ft (**5.33 km**)	12000 ft (4 km)
3.088 (2×T1)	无实验数据，待定	无实验数据，待定
4.096 (**2×E1**)	无实验数据，待定	无实验数据，待定
4.632 (3×T1)	14000 ft (**4.67 km**)	12000 ft (4 km)
6.312 (T2)	12000 ft (**4 km**)	9000 ft (3 km)
8.448 (**E2**) 上限速率	9000 ft (**3 km**)	无实验数据，待定

3.5 ADSL

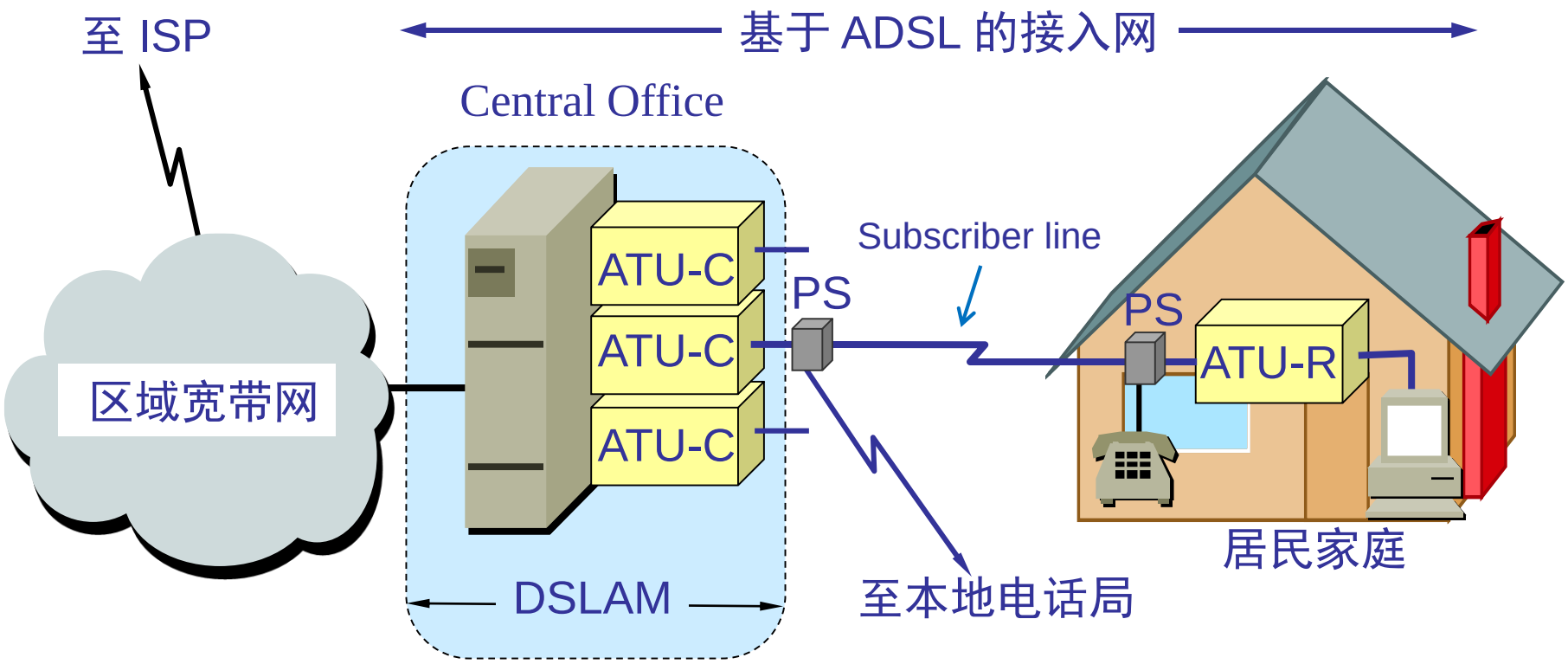
◆ From 谢希仁(5e)



- using FDM to divide 40~1100 kHz into sub-channels.
- Each sub-channel occupies 4kHz (strictly, 4.3125kHz) bandwidth, and uses different carriers (i.e., tones) to be modulated.
- In theory, upstream max rate: 25×60kbps=1.5Mbps, downstream max rate: 249×60kbps=14.9Mbps.

3. 5 ADSL

3. ADSL Structure



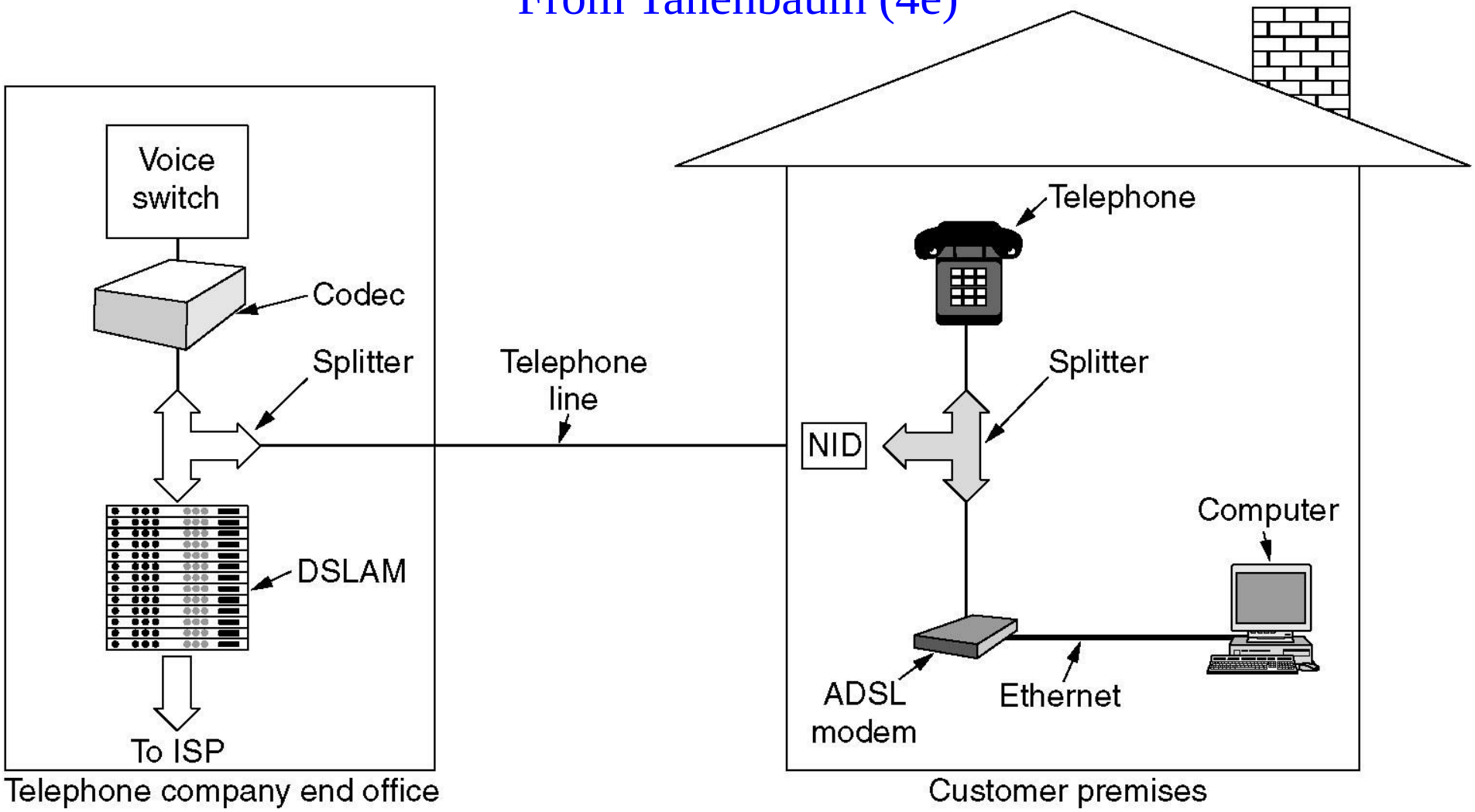
DSLAM: DSL Access Multiplexer, supports 500~1000 subscribers;

ATU: Access Termination Unit, i.e., ADSL modem; ATU-C: ATU Central office;

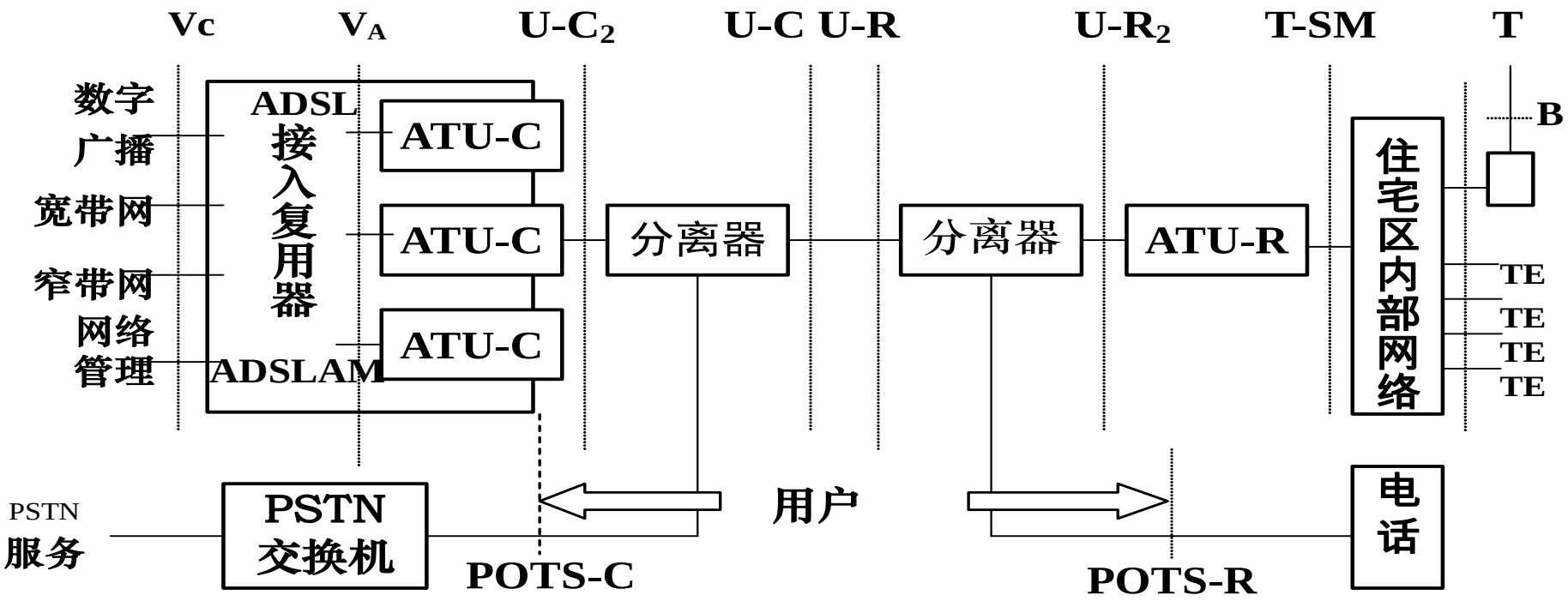
ATU-R: ATU Remote; PS: POTS Splitter

3.5 ADSL

From Tanenbaum (4e)



3.5 ADSL



ATU-C (ADSL Transmission Unit-Central office side)
ATU-R (ADSL Transmission Unit-Remote side)
POTS-C (Plain Old Telephony Service-Central office side)
POTS-R (Plain Old Telephony Service-Remote side)
V、U、T Interfaces; B—Auxiliary device, e.g. STB (Set Top Box);
TE (Terminal Equipment)

ADSL水平方向的组成结构

3. 5 ADSL

4. 2nd Generation of ADSL

--- contains **ADSL2** (G.992.3, G.992.4) and **ADSL2+** (G.992.5).

--- improvements to ADSL:

- Higher rate gained by raising modulation efficiency:

  (A) **ADSL2**: downstream, 8 Mbps; upstream, 800 kbps;

  (B) **ADSL2+**: bandwidth, 2.2MHz; downstream, 16~25 Mbps; upstream, 800 kbps.

- applies SRA (Seamless rate adaptation) to adjust data rate adaptively.
- line quality evaluation and fault location.

3. 5 ADSL

5. xDSL

- High data rate DSL (HDSL)
  - developed in the late 1980s by BellCore for replacing existing T1 Line.
  - 2B1Q coding on **dual** twisted pairs.
  - up to 2Mbps over 3.7km.
- Single line DSL (SDSL)
  - 2B1Q coding on single twisted pair (residential) with echo cancelling.
  - up to 2Mbps over 3.7km.
- Very high data rate DSL (VDSL)
  - DMT/QAM for very high data rates.
  - over separate bands for separate services: **POTS**, 0-4kHz; **ISDN**, 4-80kHz; **Upstream**, 300-700kHz; **Downstream**, **≥1MHz**.

3. 5 ADSL

	ADSL	HDSL	SDSL	VDSL
Data rate	1.5 to 9 Mbps **downstream** 16 to 640 kbps **upstream**	1.544 or 2.048 Mbps	1.544 or 2.048 Mbps	13 to 52 Mbps **downstream** 1.5 to 2.3 Mbps **upstream**
Mode	**Asymmetric**	Symmetric	Symmetric	**Asymmetric**
Copper pairs	1	2	1	1
Range (24-gauge UTP)	3.7 to 5.5 km	3.7 km	3.0 km	1.4 km
Signaling	**Analog**	Digital	Digital	**Analog**
Line code	CAP/DMT	2B1Q	2B1Q	DMT
Frequency	1 to 5 MHz	196 kHz	196 kHz	≥10 MHz
Bits/cycle	Varies	4	4	Varies

第3章 Multiplexing（复用）

3.1 Introduction

3.2 FDM

3.3 TDM

3.4 Statistical TDM

3.5 ADSL

3.6 CDM (Code Division Multiplexing)

3.7 OFDM (Orthogonal Frequency Division Multiplexing)

3. 6 CDM (Code Division Multiplexing)

1. Spread Spectrum (扩频/扩谱)

◆ Concept

---important encoding method for wireless communications.

---analog or digital data with analog signal.

---**spreads data over wide bandwidth**.

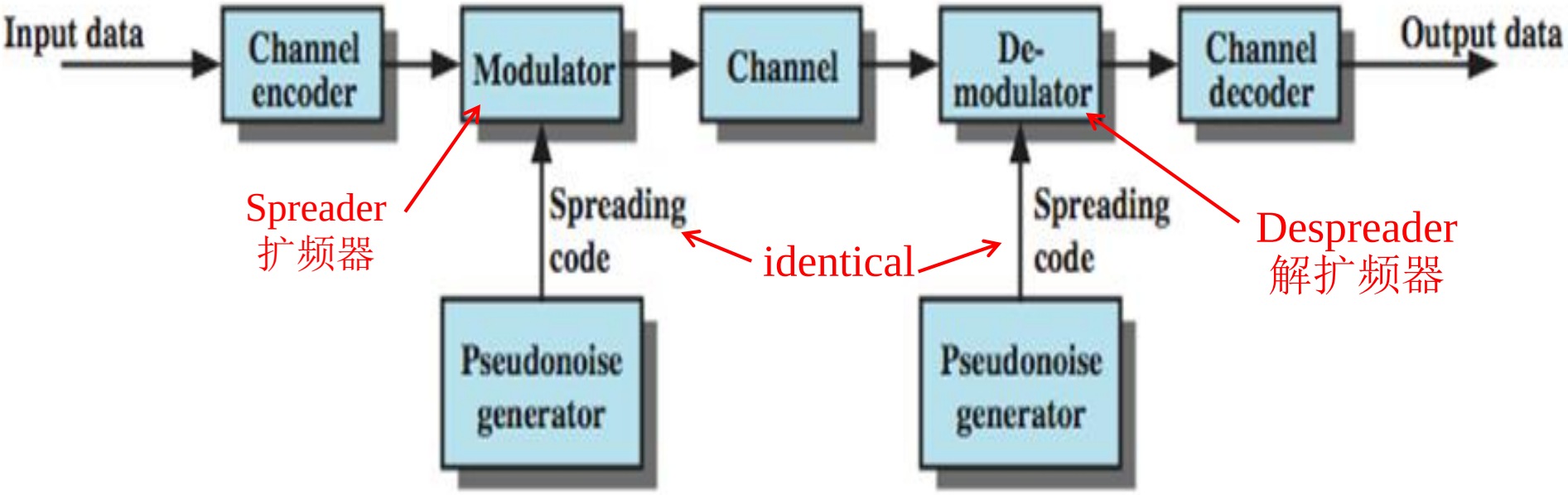
---makes jamming (堵塞/阻塞) and interception (拦截) **harder**.

---two approaches, both in use:

- First type: Frequency hopping spread spectrum (FHSS, 跳频扩频)
- More recent: Direct sequence spread spectrum (DSSS, 直接序列扩频), mainly used in CDMA (CDM access, 码分多址).

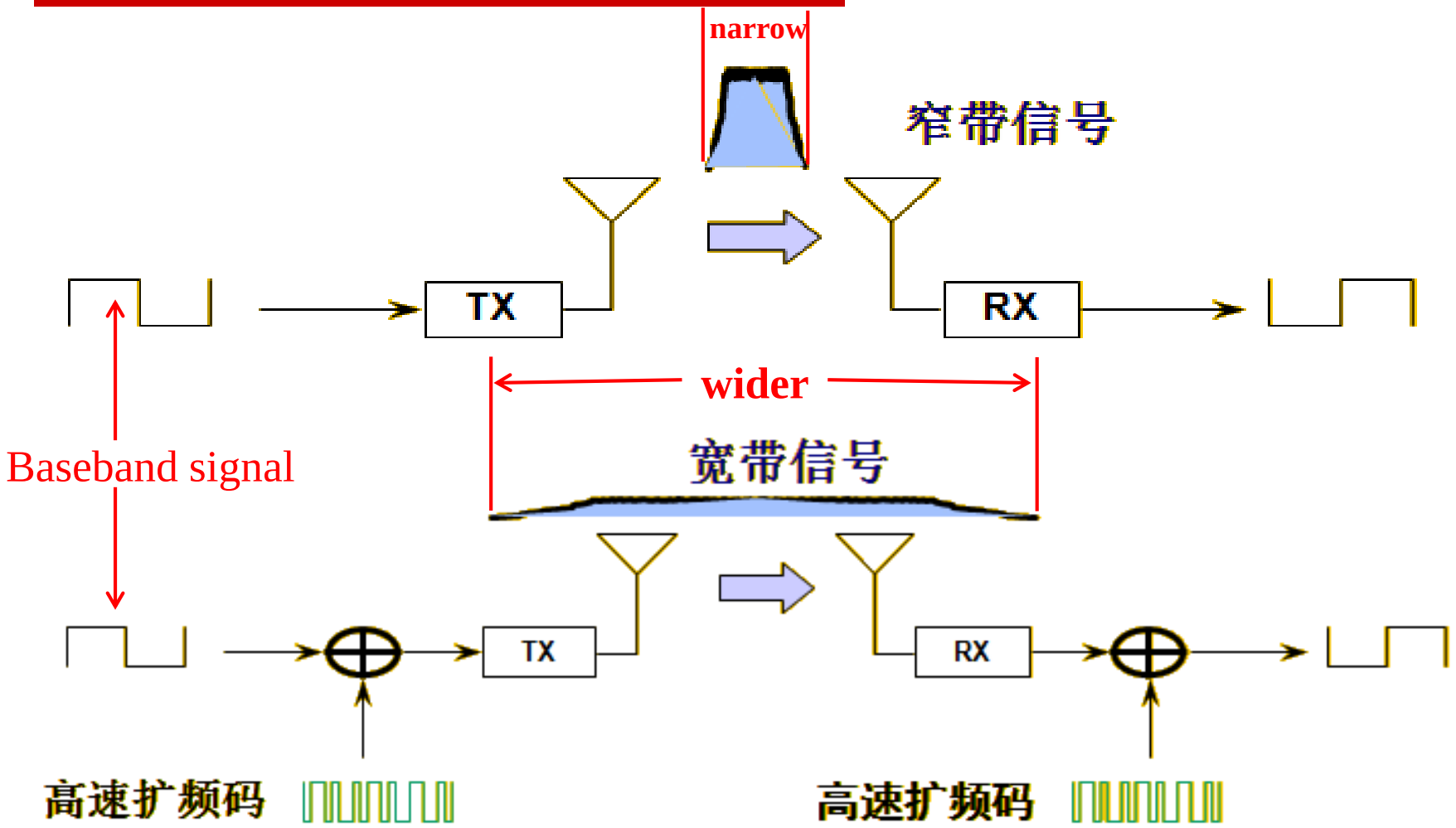
3. 6 CDM (Code Division Multiplexing)

General Model of Spread Spectrum System



Note: spreading code (扩频码), also called pseudonoise, or pseudorandom number (PN), 具有类似噪声序列的性质，是一种貌似随机但实际上有规律的周期性二进制序列。

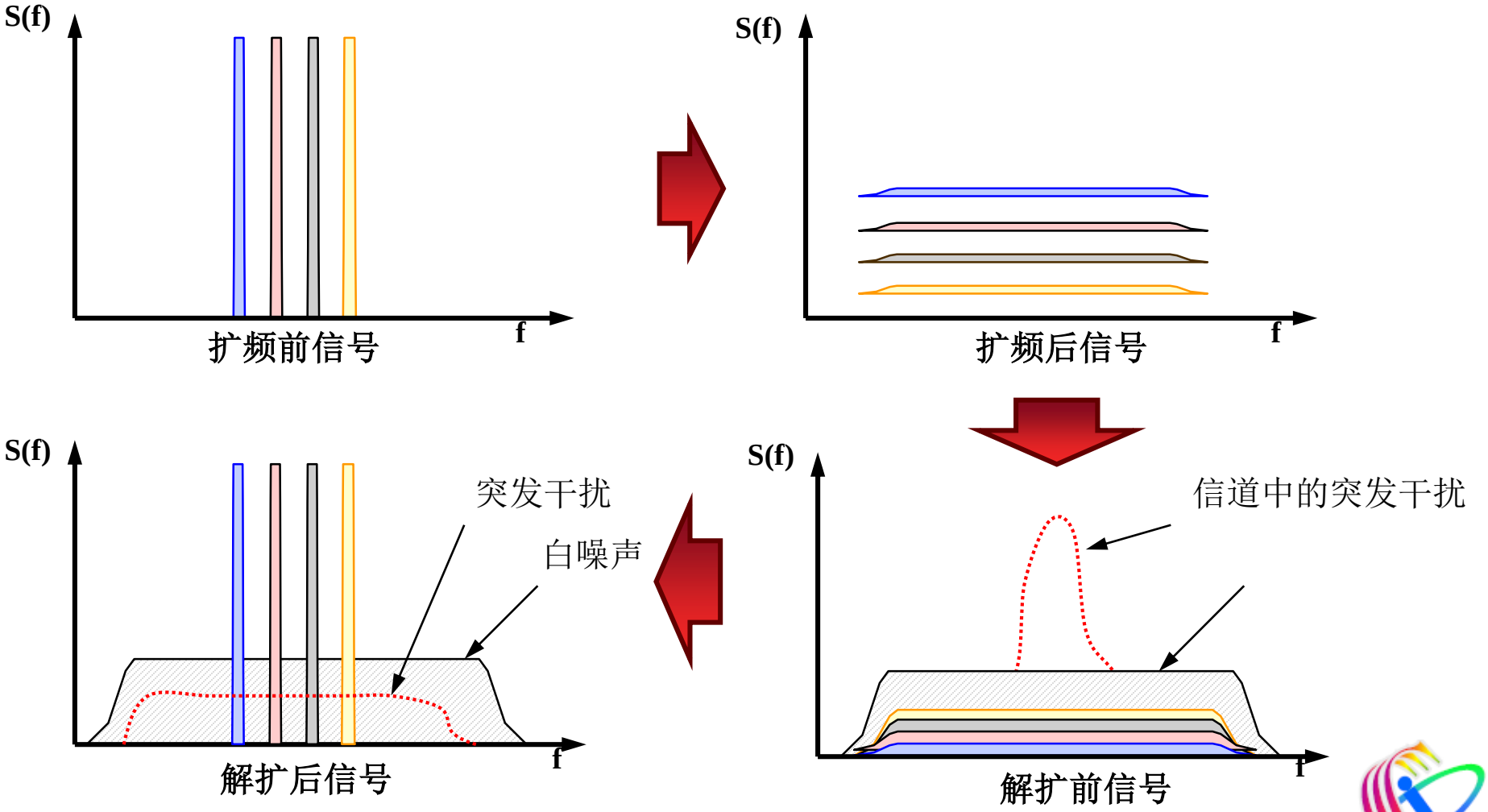
3. 6 CDM (Code Division Multiplexing)



Direct Sequence Spread Spectrum (DSSS) System (中兴通讯)

3. 6 CDM (Code Division Multiplexing)

扩频/解扩频 (华为资料)



3. 6 CDM (Code Division Multiplexing)

◆ Spread Spectrum **Advantages**

---immunity from noise and multipath (多径) distortion.

---can hide / encrypt signals.

---several users can share same higher bandwidth with little interference.

● CDM/CDMA Mobile telephones

3. 6 CDM (Code Division Multiplexing)

2. HPSS (Frequency Hopping Spread Spectrum)

◆ Concept

---signal is broadcast over seemingly random series of frequencies.

---**receiver** hops among frequencies in **synchronization** with **transmitter**.

---eavesdroppers (窃听者) hear unintelligible blips.

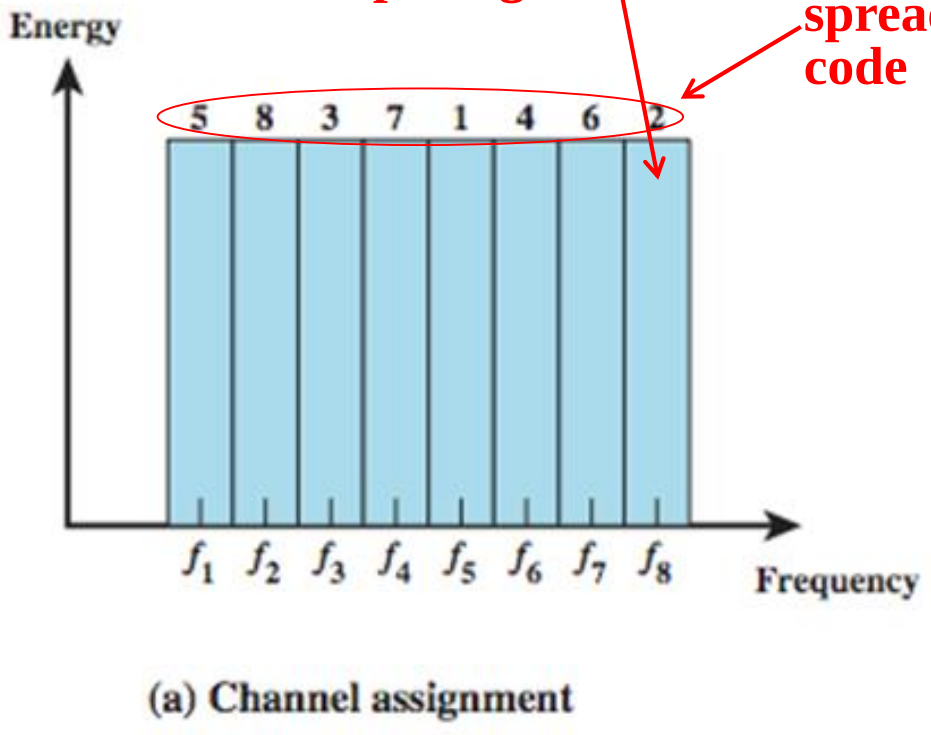
---jamming on one frequency affects only a few bits.

3. 6 CDM (Code Division Multiplexing)

Frequency Hopping Example

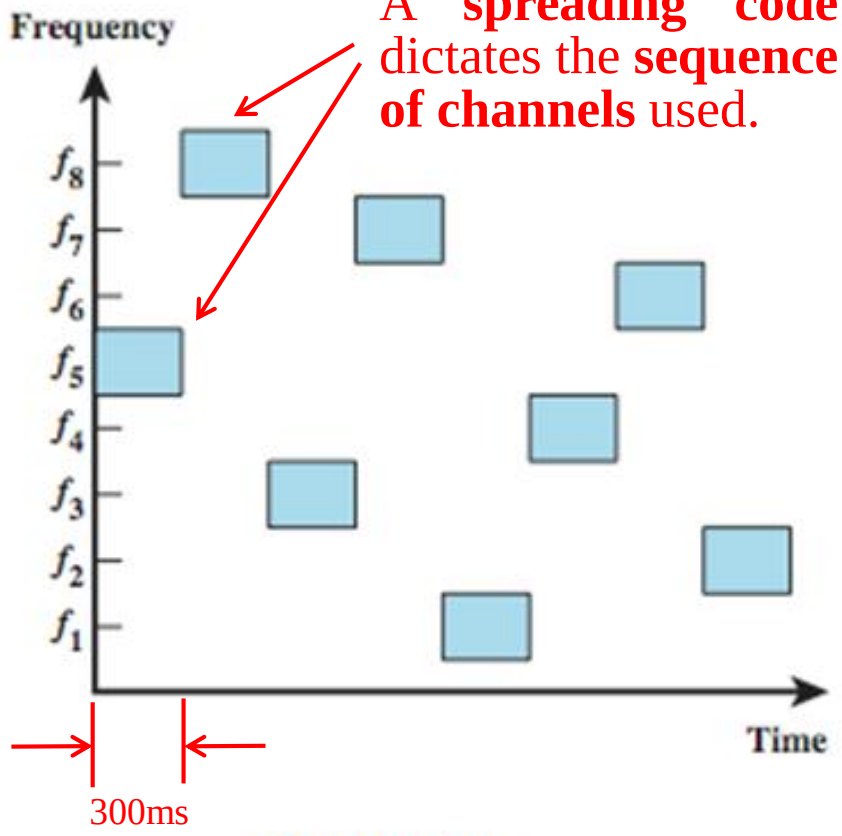
width of each channel usually corresponds to the **bandwidth of the input signal**.

spreading code



(a) Channel assignment

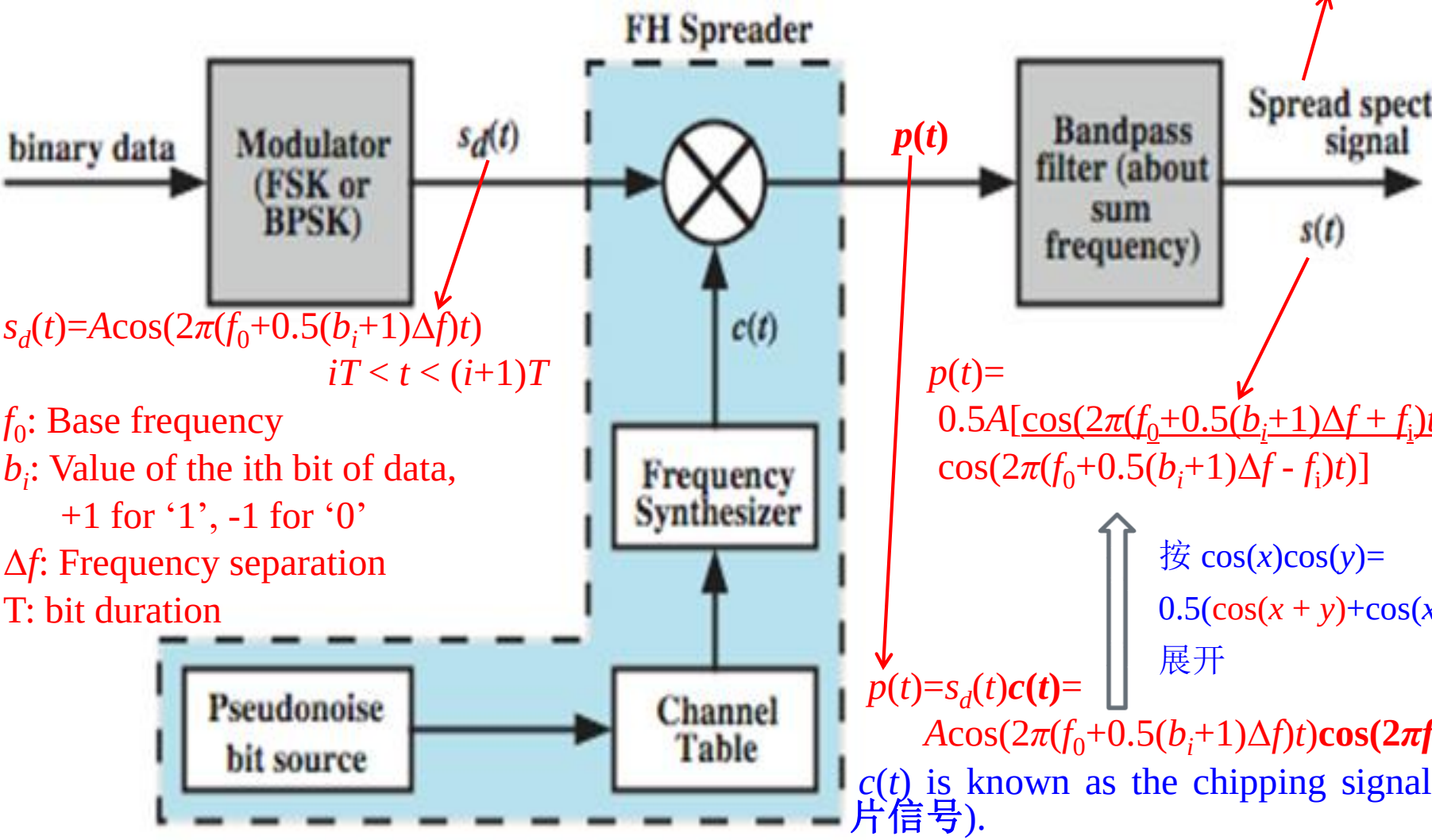
A **spreading code** dictates the **sequence of channels** used.



IEEE 802.11 (b) Channel use

3. 6 CDM (Code Division Multiplexing)

FHSS Transmitter



-1: f_0+f_i

+1: $f_0+f_i+\Delta f$

$s_d(t)=A\cos(2\pi(f_0+0.5(b_i+1)\Delta f)t)$

$iT < t < (i+1)T$

f_0: Base frequency

b_i: Value of the ith bit of data,

+1 for '1', -1 for '0'

Δf: Frequency separation

T: bit duration

$p(t)=0.5A[\cos(2\pi(f_0+0.5(b_i+1)\Delta f + f_i)t) + \cos(2\pi(f_0+0.5(b_i+1)\Delta f - f_i)t)]$

按 $\cos(x)\cos(y)=0.5(\cos(x+y)+\cos(x-y))$ 展开

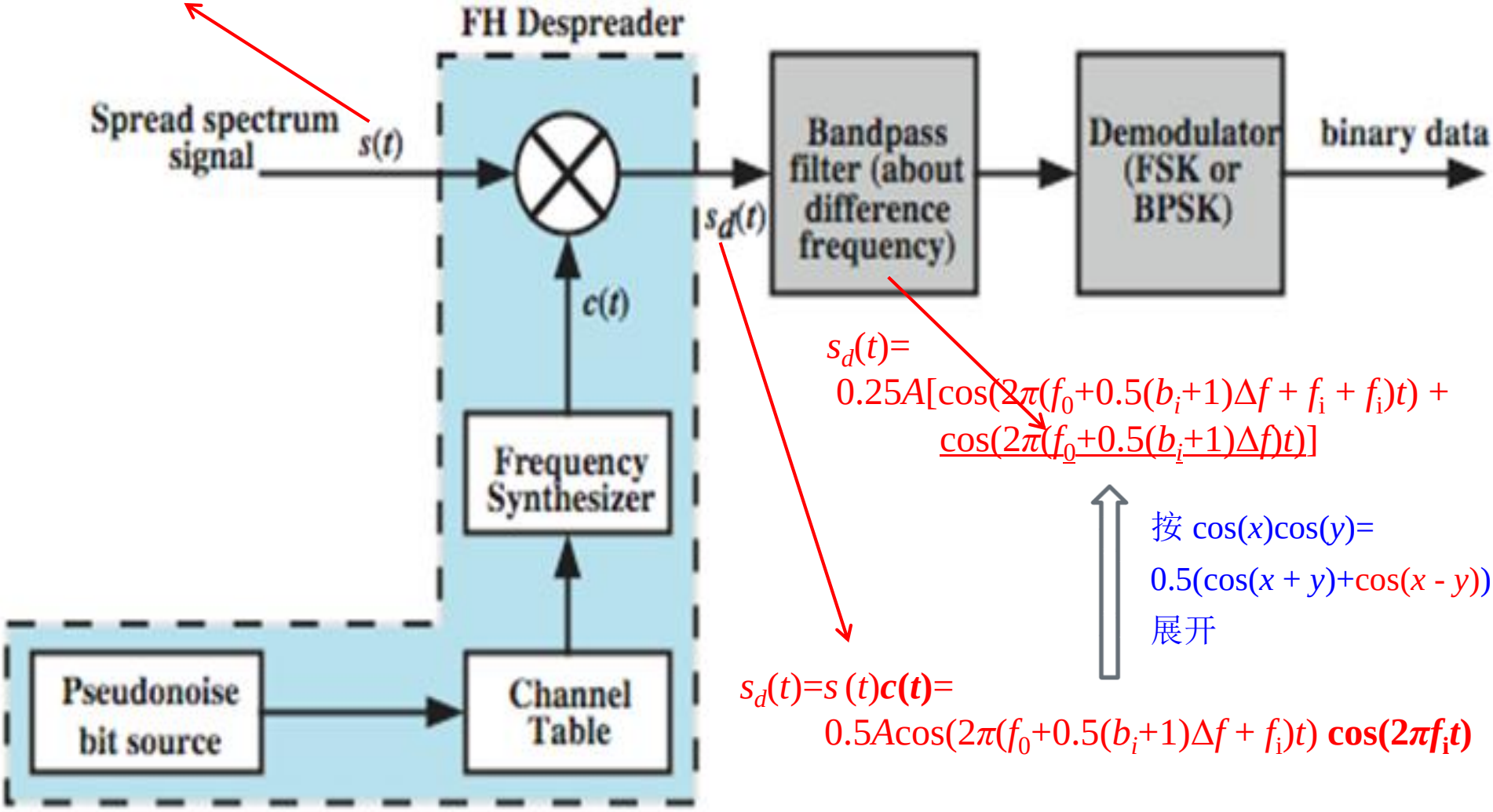
$p(t)=s_d(t)\boldsymbol{c(t)}=A\cos(2\pi(f_0+0.5(b_i+1)\Delta f)t)\boldsymbol{\cos(2\pi f_i t)}$

$c(t)$ is known as the chipping signal (码片信号).

3. 6 CDM (Code Division Multiplexing)

FHSS Receiver

$s(t)=0.5A\cos(2\pi(f_0+0.5(b_i+1)\Delta f + f_i)t)$



$s_d(t)=0.25A[\cos(2\pi(f_0+0.5(b_i+1)\Delta f + f_i + f_i)t) + \cos(2\pi(f_0+0.5(b_i+1)\Delta f)t)]$

按 $\cos(x)\cos(y)=0.5(\cos(x+y)+\cos(x-y))$ 展开

$s_d(t)=s(t)\boldsymbol{c(t)}=0.5A\cos(2\pi(f_0+0.5(b_i+1)\Delta f + f_i)t)\ \boldsymbol{\cos(2\pi f_i t)}$

3. 6 CDM (Code Division Multiplexing)

◆ Slow and Fast FHSS

---commonly use multiple FSK (MFSK).

---MFSK uses $M = 2^L$ different frequencies to encode the digital input L bits at a time.

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

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

and total MFSK bandwidth $W_d = 2Mf_d$.

---For FHSS, the MFSK signal is translated to a new frequency every T_c seconds by modulating the FHSS carrier signal with the MFSK signal

● i.e., translating MFSK signal into appropriate FHSS channel.

3. 6 CDM (Code Division Multiplexing)

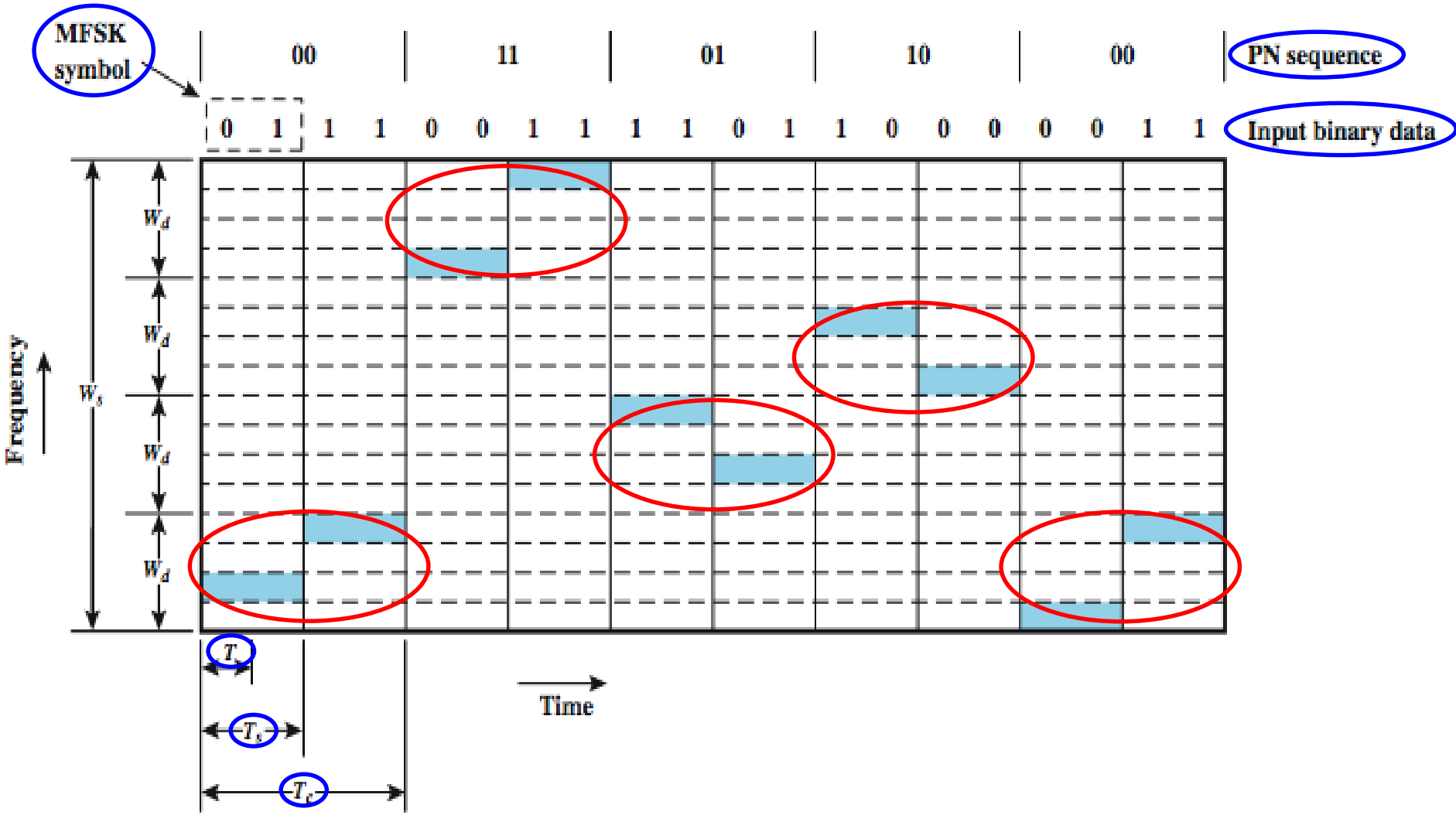
---Suppose R is the data rate, the duration of **a bit** is $T=1/R$ seconds.

---the duration of a **signal element** of MFSK is $T_s=LT$ seconds.

- Slow FHSS has $T_c \geq T_s$
- Fast FHSS has $T_c < T_s$

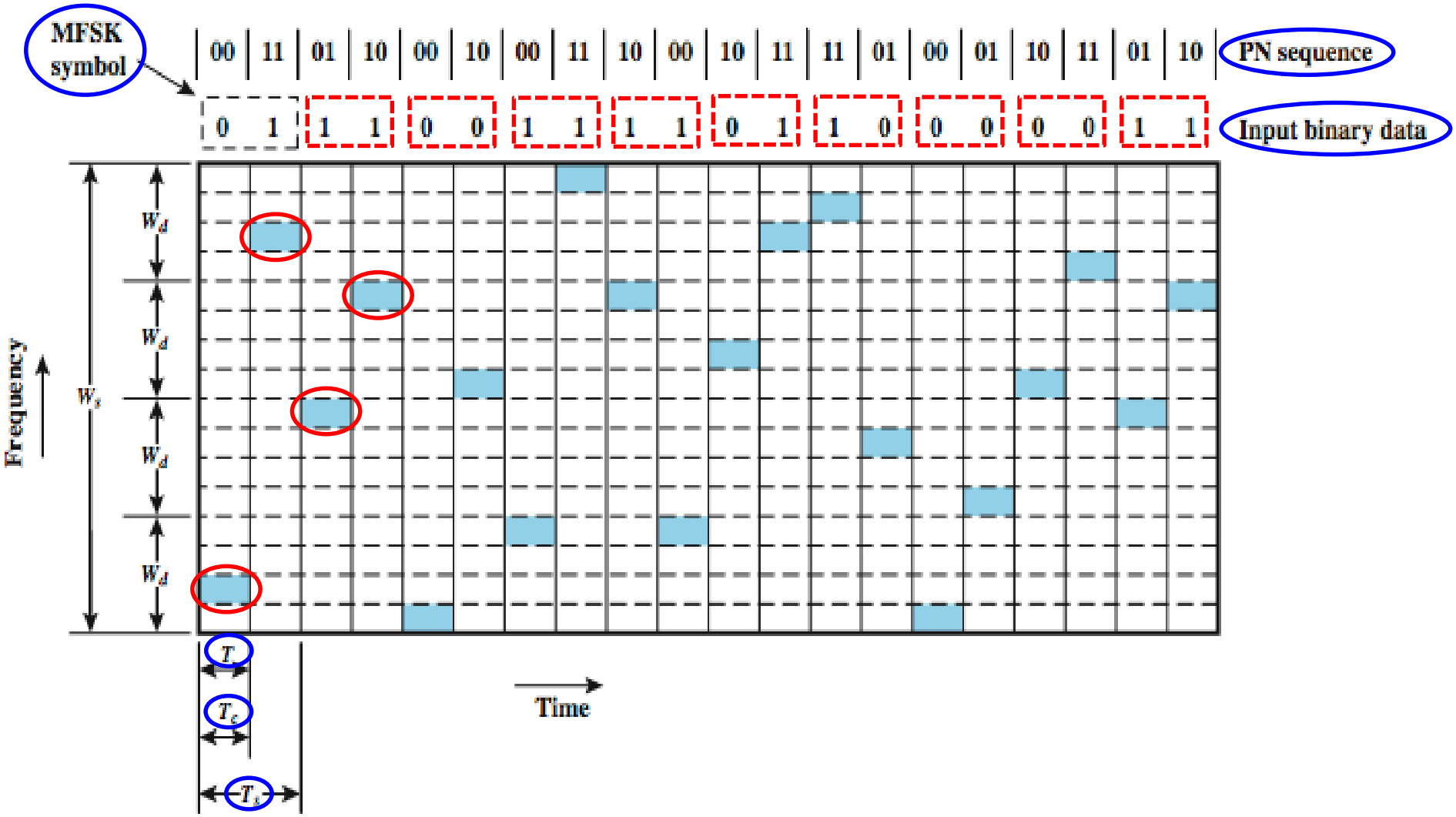
3. 6 CDM (Code Division Multiplexing)

Slow FHSS Example (M=4, L=2, 4=2^k different channels)



3. 6 CDM (Code Division Multiplexing)

Fast FHSS Example (M=4, L=2, 4=2^k different channels)



3. 6 CDM (Code Division Multiplexing)

3. DSSS (Direct Sequence Spread Spectrum)

◆ Concept

---Mainly used in CDMA and 802.11b/g

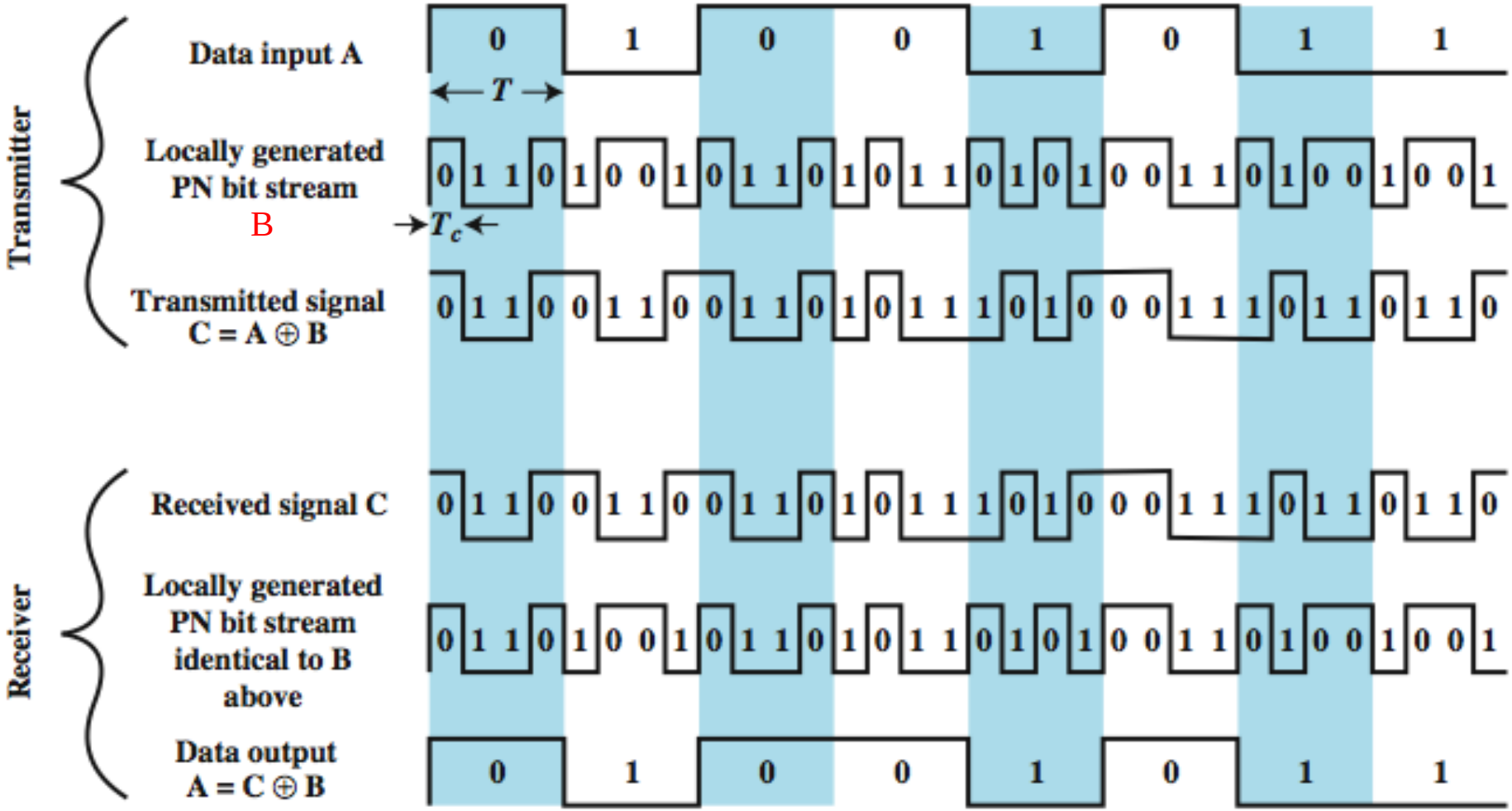
---each bit in the original signal is represented by multiple bits in the transmitted signal using a spreading code., i.e., pseudorandom number (PN).

---this spreads signal across a wider frequency band.

---One technique: combine the **digital** information stream with the **spreading code** bit stream using an exclusive-OR (XOR).

3. 6 CDM (Code Division Multiplexing)

- DSSS Example (William Stallings, 8e)



3. 6 CDM (Code Division Multiplexing)

◆ CDMA

---**各用户**使用经过特殊挑选的**不同码型**(码片序列)，因此彼此不会造成干扰。

---这种系统发送的信号有很强的抗干扰能力，其频谱类似于白噪声，不易被敌人发现。

---**每一个比特（码元）时间**划分为 *m* 个短的间隔，称为码片(chip)。*m*通常取值64或128。

---**每个站**被指派一个**唯一**的 *m* bit 码片序列 (chip sequence)。

- 如发送比特 1，则发送自己的 *m* bit 码片序列；
- 如发送比特 0，则发送该码片序列的二进制反码。

3. 6 CDM (Code Division Multiplexing)

---e.g.，假定S站的 8 bit 码片序列是 00011011，则

- 发送比特 1 时，就发送序列 00011011；
- 发送比特 0 时，就发送序列 11100100。
- 一般，码片序列中的0记为-1，1记为+1，则S站的码片序列为：(–1 –1 –1 +1 +1 –1 +1 +1)。

---假定某站的数据率为*b* bps。由于每一比特转换为*m*比特码片，因此该站实际数据率应为*mb* bps。同时，该站所占用的频带宽度也为原来的*m*倍。此种扩频(Spread spectrum)称为直接序列扩频(Direct sequence spread spectrum, DSSS)。

---每个站分配的码片序列不仅必须各不相同，并且还必须互相正交(orthogonal)。

3. 6 CDM (Code Division Multiplexing)

◆ 码片序列的正交关系

---令向量 S 表示站 S 的码片向量，令 T 表示其他任何站的码片向量。

---两个不同站的码片序列正交，要求(以下4项)：

- 向量 S 和T 的规格化内积(inner product)都是 0：

$$\mathbf{S} \bullet \mathbf{T} \equiv \frac{1}{m} \sum_{i=1}^{m} S_i T_i = 0$$

(A) 令向量 S 为(–1 –1 –1 +1 +1 –1 +1 +1)，向量 T 为(–1 –1 +1 –1 +1 +1 +1 –1)。

(B) 把向量 S 和 T 的各分量值代入上式，可看出这两个码片序列是正交的。

- 向量 S 和各站码片反码的向量内积也是 0。

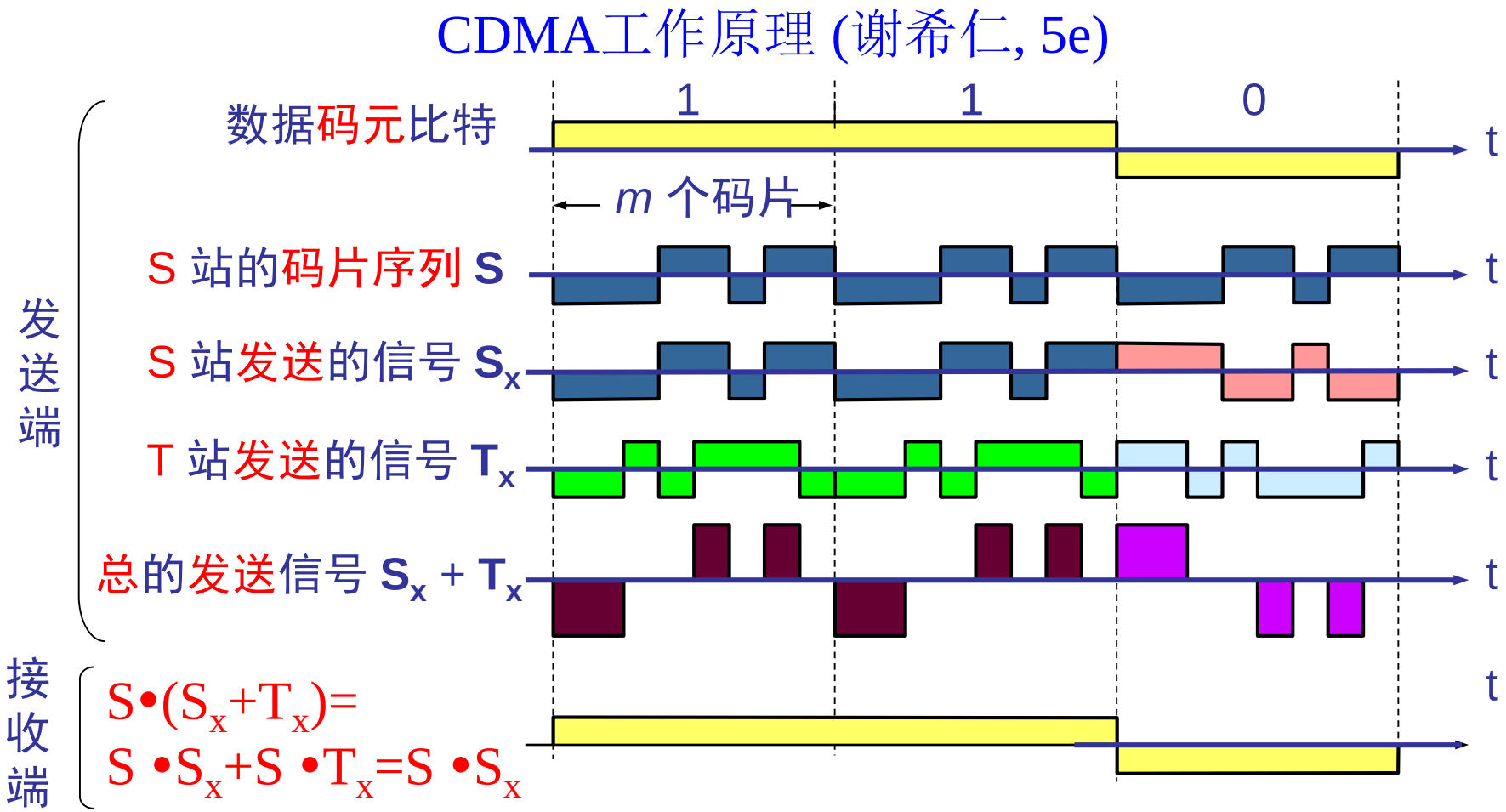
3. 6 CDM (Code Division Multiplexing)

- 任何一个码片向量和该码片向量自己的规格化内积都是1：

$$\mathbf{S} \bullet \mathbf{S} = \frac{1}{m}\sum_{i=1}^{m} S_i S_i = \frac{1}{m}\sum_{i=1}^{m} S_i^2 = \frac{1}{m}\sum_{i=1}^{m} (\pm 1)^2 = 1$$

- 一个码片向量和该码片反码的向量的规格化内积值是–1。

3. 6 CDM (Code Division Multiplexing)



注：接收端$S•(S_x+T_x)=S•S_x+S•T_x=S•S_x$，因为$S•T_x=0$

A: 0 0 0 1 1 0 1 1
B: 0 0 1 0 1 1 1 0
C: 0 1 0 1 1 1 0 0
D: 0 1 0 0 0 0 1 0

(a)

A: (−1 −1 −1 +1 +1 −1 +1 +1)
B: (−1 −1 +1 −1 +1 +1 +1 −1)
C: (−1 +1 −1 +1 +1 +1 −1 −1)
D: (−1 +1 −1 −1 −1 −1 +1 −1)

(b)

Six examples:

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

(c)

$S_1 \bullet C = (1 +1 +1 +1 +1 +1 +1 +1)/8 = 1$
$S_2 \bullet C = (2 +0 +0 +0 +2 +2 +0 +2)/8 = 1$
$S_3 \bullet C = (0 +0 +2 +2 +0 -2 +0 -2)/8 = 0$
$S_4 \bullet C = (1 +1 +3 +3 +1 -1 +1 -1)/8 = 1$
$S_5 \bullet C = (4 +0 +2 +0 +2 +0 -2 +2)/8 = 1$
$S_6 \bullet C = (2 -2 +0 -2 +0 -2 -4 +0)/8 = -1$

(d)

Also compute as follow:
$S_2 \bullet C = (B+C) \bullet C = B \bullet C + C \bullet C = 0+1=1$

(a) Binary chip sequences for four stations (b) Bipolar chip sequences
(c) Six examples of transmissions (only one bit time) (d) Recovery of station C's signal

From Tanenbaum (4e)

第3章 Multiplexing（复用）

3.1 Introduction

3.2 FDM

3.3 TDM

3.4 Statistical TDM

3.5 ADSL

3.6 CDM (Code Division Multiplexing)

3.7 OFDM (Orthogonal Frequency Division Multiplexing)

3. 7 OFDM

3.7.1 概述

- 1966 年， Chang R W 发表论文 Synthesis of band-limited orthogonal signals for multichannel data transmission，提出在带限信道中用正交信号同时传输多路数据的原理，指出此种传输方式能保证系统中不存在符号间串扰（Inter-symbol interference，ISI）和子信道间干扰（Inter-channel interference，ICI）等问题。
- 1970年，美国申请和发明了一个专利，其思想是采用并行的数据和子信道相互重叠的频分复用来消除对高速均衡的依赖，以抵制冲激噪声和多径失真，并充分利用带宽。最初主要用于军事通信系统。

3.7 OFDM

---需求：OFDM各个子载波之间相互正交，采用FFT（Fast Fourier transform, 快速傅立叶变换）实现这种调制。

---时代及技术制约：

① 实时傅立叶变换设备的复杂度；

② 发射机和接收机振荡器的稳定性；

③ 射频功率放大器的线性要求等。

- 1971年，韦斯坦（Weistein）和艾伯特（Ebert）等人应用离散傅里叶逆/正变换（IDFT/DFT）研制了一个完整的多载波传输系统，称作正交频分复用（OFDM）系统。

---该系统应用IDFT/DFT方法解决了产生多个互相正交的子载波和从子载波中恢复原信号的问题，也就解决了多载波传输系统发送和接收的难题。

---同时，该系统在时域加入符号保护间隔及采用加窗技术以抵抗ISI和ICI。

3.7 OFDM

- 1980年，Peled和Ruiz提出用循环前缀（Cyclic prefix，CP）取代空信息作为系统的保护间隔，解决了多载波正交性的问题。

---只要CP的持续时间大于多径信道的冲激响应时间，各子信道之间的正交性就不会被破坏。

- 20世纪80年代，MCM（Multi-carrier modulation，多载波调制）获得突破性进展，大规模集成电路构成的数字信号处理的DSP（Digital signal process）芯片便于多载波正交调制IFFT/FFT（快速傅里叶逆/正变换）的硬件实现。
- 20世纪80年代后，Hirosaki于1981年用DFT完成了在有线信道的OFDM调整技术研究，试验成功了16QAM多路并行传送19.2kbit/s的电话线MODEM。

3.7 OFDM

- 20世纪90年代，OFDM的应用涉及到利用移动调频和单边带（SSB）信道进行高速数据通信、陆地移动通信、高速数字用户环路（HDSL）、非对称数字用户环路（ADSL）、数字音频广播(DAB)系统、数字视频广播(DVB)、高清晰度数字电视（HDTV）和陆地广播等各种通信系统。
- 1999年，IEEE 802.lla通过了5GHz的无线局域网标准，其中OFDM调制技术被采用为物理层标准，传输速率可达54Mbps。在随后的802.11b/g亦应用OFDM。
- 欧洲电信标准协会(European Telecommunications Standards Institute，ETSI，1988年创建)的宽带射频接入网的局域网标准HiperlanII也把OFDM定为它的调制标准技术。

3.7 OFDM

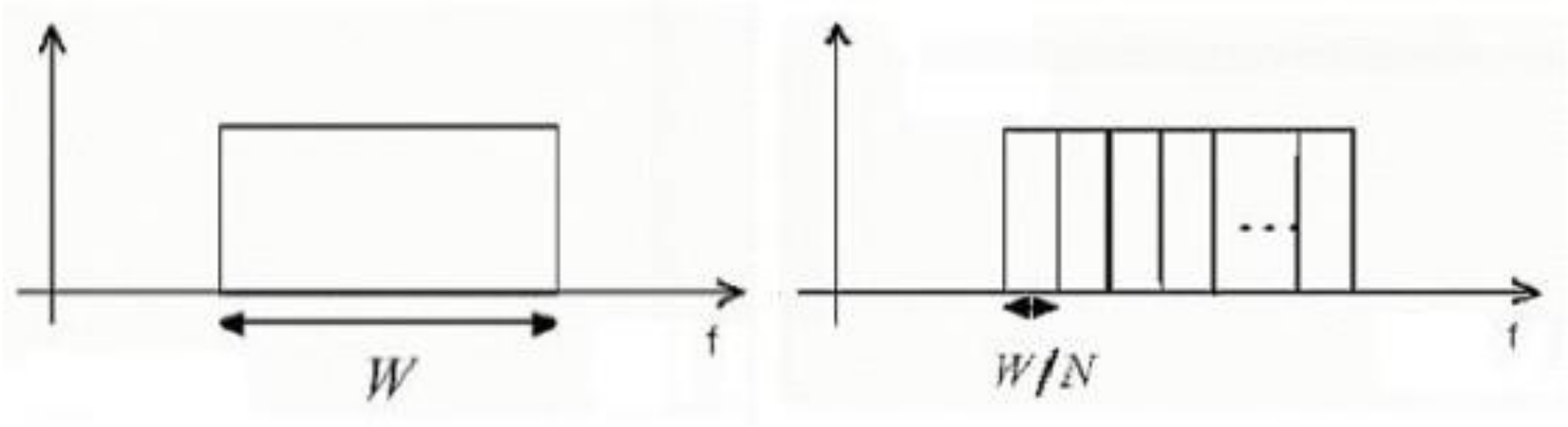
- 2002年，IEEE的802.16（WiMAX）亦采用OFDM在无线城域网（WMAN）应用的标准。
- 2006年，IEEE 802.20采用OFDM结合MIMO（Multiple-Input Multiple-Output）技术作为无线广域网（WWAN）的高速数据传输应用标准。
- 2009年批准的IEEE 802.11n采用OFDM结合MIMO，将传输速率提高到300~600Mbps。
- 国际标准化组织3GPP（3rd Generation Partnership Project）的LTE（Long Term Evolution）是3G移动通信技术向4G过渡的研究计划，同样采用OFDM及MIMO作为演进的唯一标准。实际上，2005年12月3GPP为LTE选定是下行为OFDM，上行则为SC(单载波)FDMA。
- 在无线个域网WPAN中，基于OFDM的UWB（Ultra-Wideband，超宽带）技术也将取代蓝牙。

3. 7 OFDM

3.7.2 基本原理

1. 多载波调制MCM

多载波调制的思想是将高速数据分为多路并行的低速数据，并搬移到多个子载波上，这样某时刻的衰落或干扰只给部分子信道带来影响，其抗多径干扰能力远强于单载波系统。



单载波与多载波系统频谱示意图

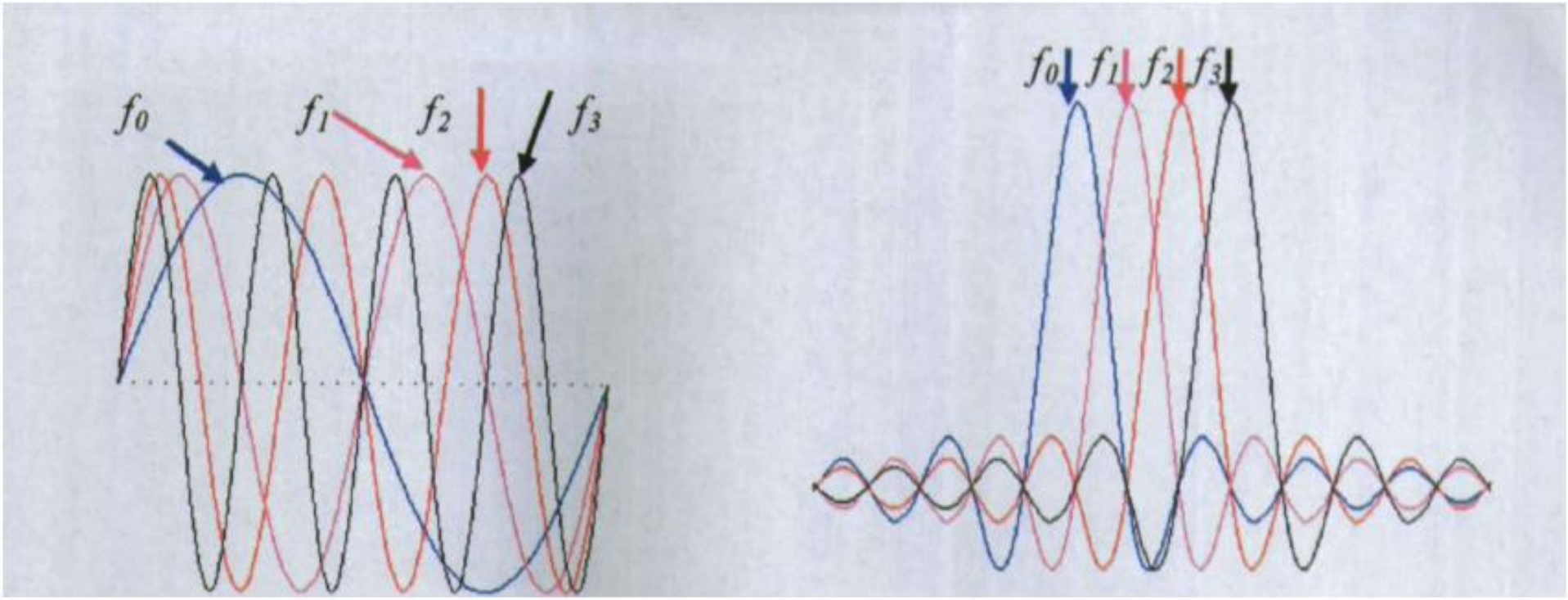
3. 7 OFDM

2. OFDM基本思想

OFDM是MCM技术中的一种，其基本原理就是把高速的数据流通过串并变换，分配到传输速率相对较低的若干个子信道中进行传输。

OFDM技术是一种子载波相互混叠的MCM，具有更高的频谱利用率。频域重叠的子载波，在时域是相互正交的，在接收端能够被分离出来。

3. 7 OFDM



（a） 各子载波（时域）示意图

（b）各子载波（频域）示意图

OFDM技术中的子载波

引自：伶学俭, 罗涛. OFDM移动通信技术原理与应用[M]. 人民邮电出版社, 2003.

3. 7 OFDM

图中给出的是一个OFDM符号内包括4个子载波的例子。

每个子载波在一个符号周期内都包含整数倍个周期，而且每个相邻子载波之间相差1个周期。这一特性可以在数学上证明子载波之间的正交性。

---正交性可从频域角度来理解。

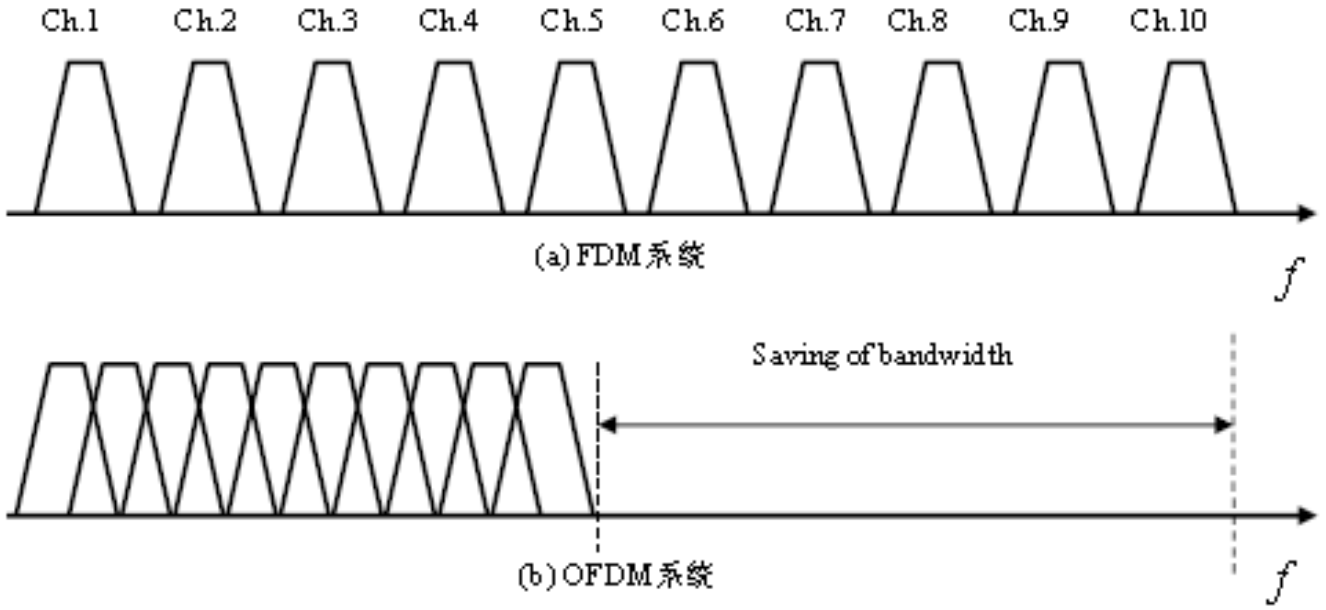
图(b)所示，各个子载波的sin函数频谱相互叠加。在每一个子载波频率的最大值处，所有其他子信道的频谱值恰好为零。因此，可以从多个相互叠加的子信道符号频谱中提取出每个子信道符号，而不会受到其他子信道的干扰，避免了ICI的出现。

3. 7 OFDM

3. 传统FDM与OFDM

传统FDM：多个互不重叠的子频带，且相邻子带间留有保护频带；接收端需要复杂的滤波器组来分离不同子信道的信号。

OFDM：多个子频带相互间1/2重叠，频谱利用率比传统FDM系统提高近一倍；OFDM系统用FFT即可实现多个子载波信号的解调，无需复杂的滤波器组。



3. 7 OFDM

3.7.3 OFDM信号模型

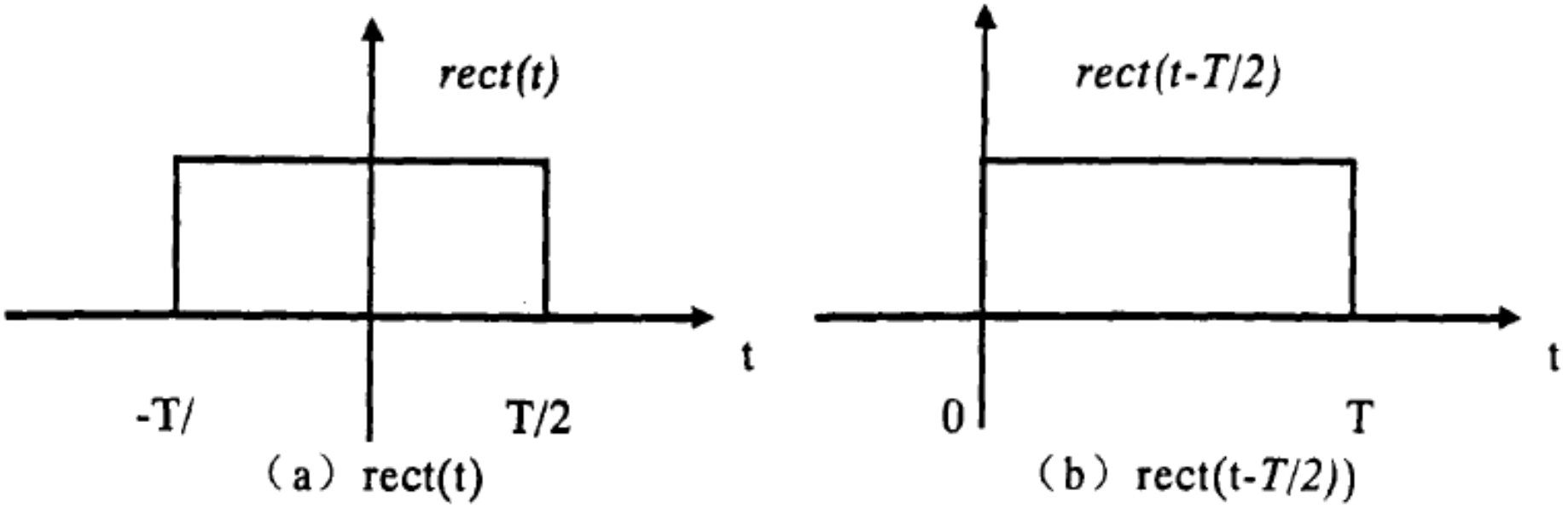
一个OFDM符号之内包括多个经过调制的子载波的合成信号，其中每个子载波都可以受到相移键控(PSK)或者正交幅度调制(QAM)符号的调制。

假设：N为子信道的个数，T表示OFDM符号的宽度（若基带信号$d_0,d_1,\ldots d_{N-1}$的时间间隔为T/N，则OFDM符号的宽度为T），d_i (i=0,1,…N-1)是分配给每个子信道的数据符号，f_0是第0个子载波的载波频率，rect(t)=1，$|t|\le T/2$，则从t=0开始的OFDM符号表示为：

$$s(t)=\sum_{i=0}^{N-1} d_i rect(t-\frac{T}{2})\cos[2\pi(f_0+\frac{i}{T})t],0\le t\le T$$

3. 7 OFDM

rect函数是矩形函数，其波形如下图：



3. 7 OFDM

根据欧拉公式： $e^{j\omega t} = \cos\omega t + j\sin\omega t$

则 $\cos\omega t = \mathrm{Re}[e^{j\omega t}]$

其中，Re[]表示取实部，则从t=0开始的OFDM符号可以表示为:

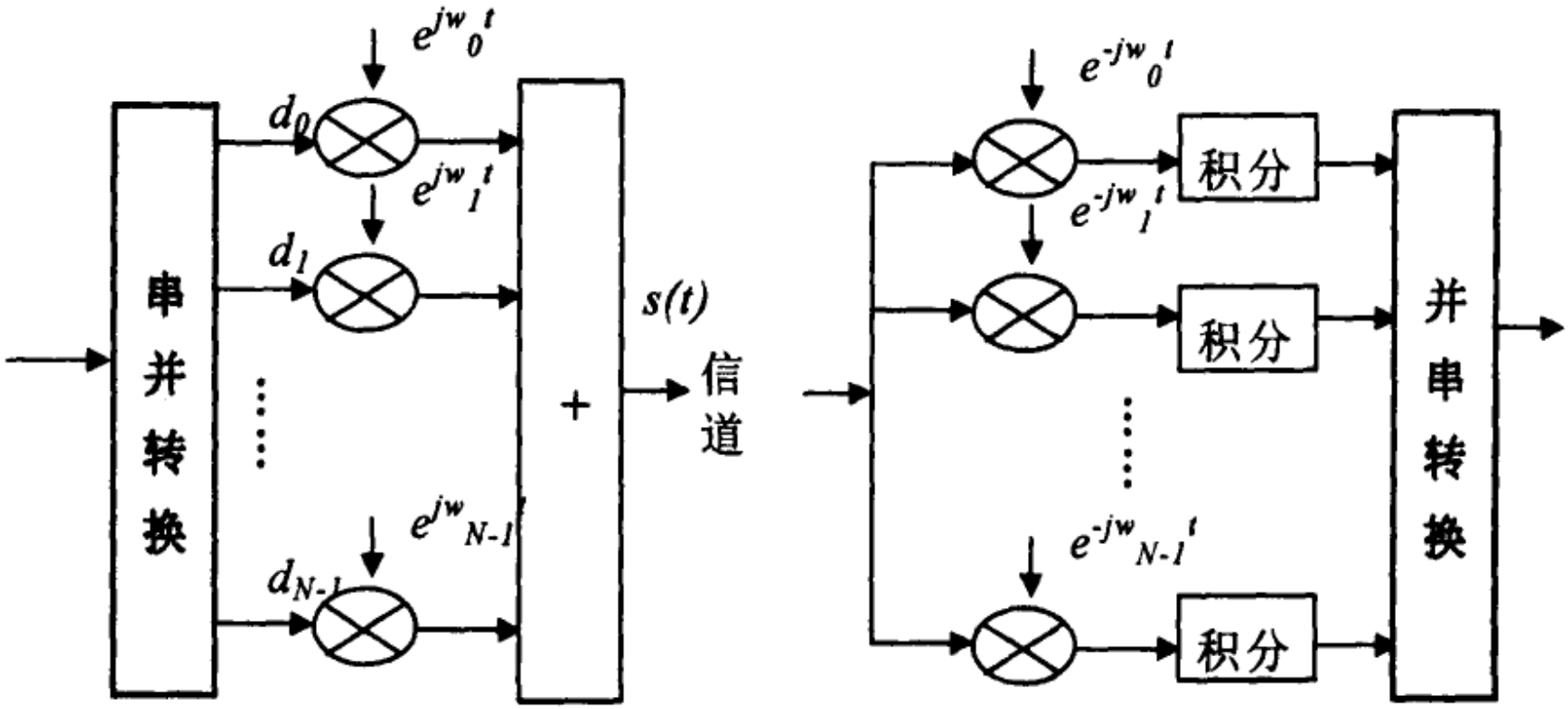
$$s(t) = \mathrm{Re}[\sum_{i=0}^{N-1} d_i rect(t-\frac{T}{2}) e^{j2\pi(f_0+\frac{i}{T})t}], 0 \le t \le T$$

$$s(t) = 0, t\text{取其它值}$$

令： $\omega_i = 2\pi f_i,\ f_i = f_0 + \dfrac{i}{T}$

则有以下OFDM系统信号模型图：

3. 7 OFDM



OFDM信号模型图

引自：汪裕民. OFDM关键技术与应用[M]. 机械工业出版社, 2007.

3. 7 OFDM

通常采用复等效基带信号来描述OFDM的输出信号，则有：

$$s(t)=\mathrm{Re}[\sum_{i=0}^{N-1}d_i rect(t-\frac{T}{2})e^{j2\pi\frac{i}{T}t}],0\le t\le T$$

$$s(t)=0,t\text{取其它值}$$

3. 7 OFDM

3.7.4 快速傅立叶变换在OFDM系统中的应用

OFDM复等效基带信号可以采用离散傅立叶逆变换(IDFT)来实现。

对前述的OFDM符号$s(t)$以T/N的速率进行抽样，即令$t=kT/N(k=0, 1\ldots N-1)$，可以得到:

$$s(k)=s(kT/N)=\sum_{t=0}^{N-1} d_i e^{j\frac{2\pi tk}{N}},0\le k\le N-1$$

对照下面的离散傅立叶反变换(IDFT)的公式:

$$x(n)=\frac{1}{N}\sum_{k=0}^{N-1} x(k)e^{j\frac{2\pi nk}{N}},0\le n\le N-1$$

可以看出，$s(k)$等效为对d_i进行IDFT运算。

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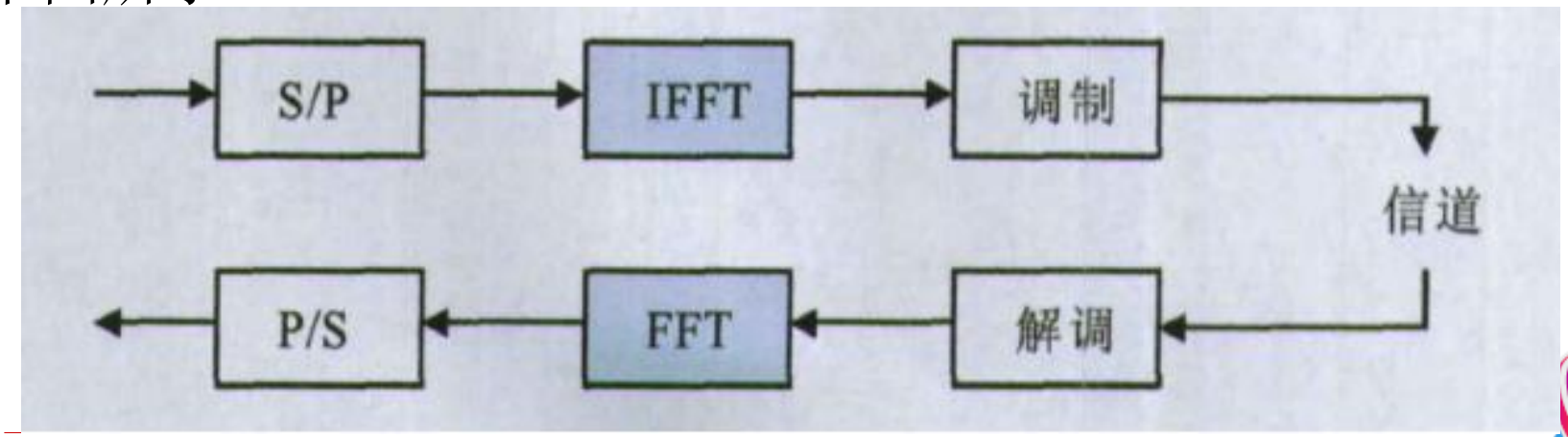
同样，在接收端，为恢复出原始的数据符号d_i，可以对$s(k)$进行逆变化，即离散傅立叶变换(DFT)得到：

$$d_i = \sum_{k=0}^{N-1} s(k) e^{-j\frac{2\pi ik}{N}}, 0 \le k \le N-1, 0 \le i \le N-1$$

在OFDM系统的实际应用中，可以采用更加方便快捷的快速傅立叶变换(IFFT/FFT)来实现系统的正交调制解调。OFDM系统框图如下图所示。



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