

Computer Networks

Chapter 2: Physical Layer

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数据通信的理论基础

□ **Fourier Analysis:** 周期为 T 的函数 $g(t)$ 可如下表示:

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

where $f=1/T$, a_n and b_n are the sine and cosine amplitudes of the n th harmonics (terms), and c is a constant.

$$a_n = \frac{2}{T} \int_0^T g(t) \sin(2\pi nft) dt \quad b_n = \frac{2}{T} \int_0^T g(t) \cos(2\pi nft) dt \quad c = \frac{2}{T} \int_0^T g(t) dt$$



Outline

Essence: Provide the means to transmit bits from sender to receiver \Rightarrow involves a lot on how to use (analog) signals for digital information

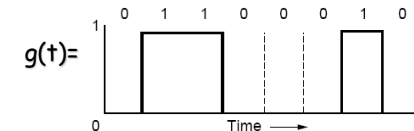
- Theoretical background: signal transmission and Fourier analysis
- Transmission media (wires and no wires)
- Modulation techniques (the actual encoding), multiplexing, and switching



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□ **Example:**

The voltage output of computer when transmitting 'b',



The Fourier analysis of this signal yields the coefficients:

$$a_n = \frac{1}{\pi n} [\cos(\pi n/4) - \cos(3\pi n/4) + \cos(6\pi n/4) - \cos(7\pi n/4)]$$

$$b_n = \frac{1}{\pi n} [\sin(3\pi n/4) - \sin(\pi n/4) + \sin(7\pi n/4) - \sin(6\pi n/4)]$$

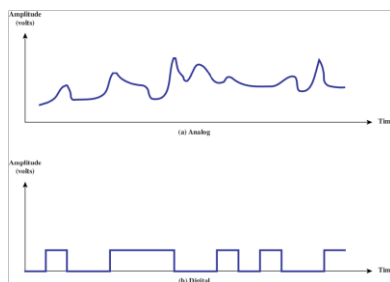
$$c = 3/4$$



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□ 这意味着什么呢?

- 传输的数字信号 可以看作是由 无限多个周期模拟信号叠加而成。



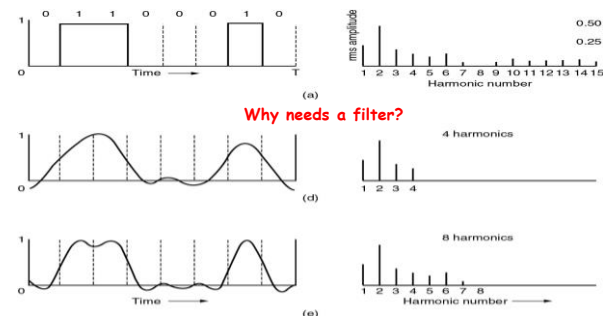
模拟信号

数字信号



Continue...

□ Th1: $a_n^2 + b_n^2$ 正比于传输相应频率分量所需能量。



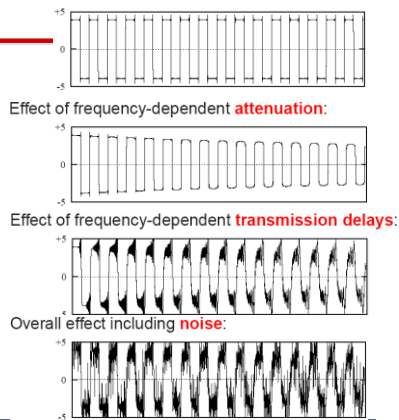
Why needs a filter?



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□ 传输介质

- 1) 不存在无损能量的传输介质, 而且不同的付立叶分量能量损耗还不一样。有信号 **衰减**。attenuation(衰减)
- 2) 不同的分量在介质中的传播速度还不一样。这会导致在接收方发生信号 **畸变**。distortion(畸变)



Continue...

□ 人为引入过滤器

比如: 电话公司过滤器频率范围0~3100 Hz.

- 这个范围足够满足语音通信的需要,
- 并且能提高全系统资源的利用率(介质频分通信)

Def. 通常, 0~ f_c 频率的 the **amplitudes** of harmonics 是不会改变的, 0~ f_c was called the **bandwidth**. 实际上带宽被定义成0到能还有一半能量通过的频率处。

- 带宽是介质的固有属性, 取决于材料、粗细和长度。
- 3100Hz 也称为语音级线路带宽。
 - 假设发送8位时间为 $T=8/b$ 秒, 因此1次谐波频率 $b/8\text{Hz}$
 - 这意味着通过的最大谐波号约是 $3000T=3000*8/b$. $//nf=3000 \rightarrow n=3000T$



数据传输速度和介质带宽的关系

Bps	T (msec)	First harmonic (Hz)	# Harmonics sent
300	26.67	37.5	80
600	13.33	75	40
1200	6.67	150	20
2400	3.33	300	10
4800	1.67	600	5
9600	0.83	1200	2
19200	0.42	2400	1
38400	0.21	4800	0

Assumption: We are using a simple encoding technique based on the fact that the line supports only two signal values.

Observation: Most telephone carriers cut off the highest frequency at 3000 Hz \Rightarrow we can never transmit at a higher speed than 9600 bps.



□ 问题:

可以无限制的去提高介质数据传输率?



Continue...

Improvement: If there are four signal values available, we could encode 2 bits at a time:

00 \rightarrow 0 volt 01 \rightarrow 2 volt
10 \rightarrow 4 volt 11 \rightarrow 6 volt

The number changes in a signal per second is called the **baud**.

Example 2: A 2400 bauds line (modem) can make a bit rate of 9600 bps provided it uses 16 (2^4) signal values:

S	bits	S	bits	S	bits	S	bits
0	0000	4	0100	8	1000	12	1100
1	0001	5	0101	9	1001	13	1101
2	0010	6	0110	10	1010	14	1110
3	0011	7	0111	11	1011	15	1111



Nyquist and Shannon

Nyquist showed that if the cut-off frequency is H Hz, the filtered signal can be reconstructed by making $2H$ samples. No more, no less. **Consequence:**

maximum transmission rate = $2H \log_2 V$ bps

(where V is the number of signal values)

Shannon showed that a *noisy* channel with a signal-to-noise ration S/R , has a limit with respect to the bit rate:

maximum transmission rate = $H \log_2(1 + S/R)$ bps

Example: A telephone line with $H = 3000$ and $10 \log_{10}(S/R) = 30$ dB, can do no better than 30 kbps, no matter how you do your encoding (excluding compression).

56kbps modem?



Continue...

- **56kbps modems** use a 8000 baud line (4000Hz) with 8 bits per sample (1 bit is reserved for control purpose)

// $H \log_2(1+S/R)$, 减少一个本地回路, R降低一半

- **ADSL** uses up to 224 4-kHz channels, With 15 bits/ baud and 4000 baud, the downstream bandwidth would be 13.4 Mbps (more details later on)



铜线(1/2)

- **Twisted pair**: 两根绝缘铜线, twisted like a DNA string (reduces electrical inference). Often, twisted pairs go by the bundle. Comparable to telephone wiring at home.



(a) Category 3 UTP(16MHz)



(b) Category 5 UTP(100MHz)

- Further distinction between shielded (STP) and unshielded (UTP) versions, but the shielded ones used to be primarily used only with IBM installations; now also for local networks (Cat 7, 600MHz)



传输介质 -- 磁带

- Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway
 - Take a standard videotape that can carry about 7GB of data.
 - A box of 50*50*50cm can hold about 1000 tapes, which corresponds to 7000GB.
 - Sending such a box can be done within 24 hours, worldwide.

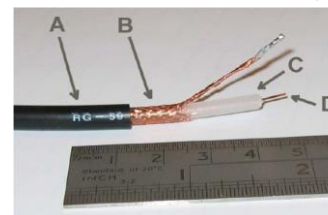
We've got a transmission rate of 648 Mbps!

Question: What is overlooked in this reasoning?



铜线(2/2)

- **Coaxial cable**: like the one you use for your TV Set:



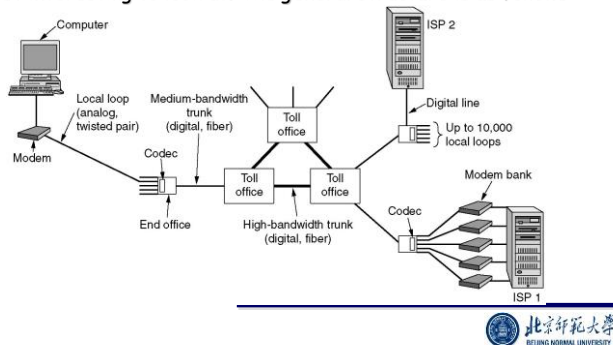
D=Copper core
C=insulating material
B=Braided outer conductor
A=Protective plastic covering

- Coax is better than twisted pair **when you need more bandwidth** (in that it has better shielding, up to 1GHz), mainly used in MAN and Cable TV, but is now rapidly being replaced with fiber.



The local loop (本地回路)

- Observation: when it comes the telephone system, from a networking perspective the local loop (a.k.a. the **last mile**) is the most interesting to look at. The general structure is as follows:



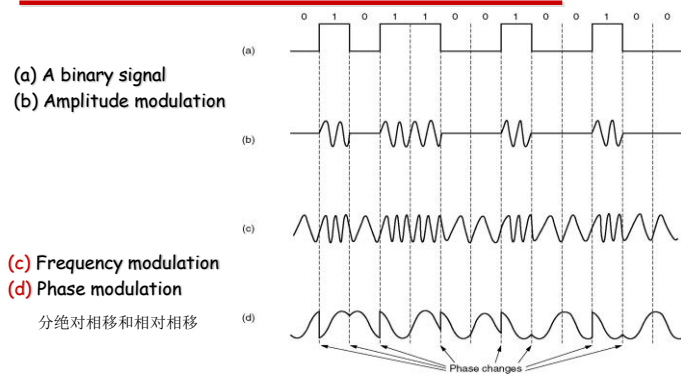
调制技术(1/5)

- Problem: How can we encode our signals when we can effectively use only a single frequency (or better: small frequency range) ?

Answer: Apply modulation techniques:

- Change the **amplitude** (strength) of the signal: changing amplitude means a binary 1, constant amplitude a binary 0.
- Use different **frequencies** to encode your bits (these frequencies can be put "on top" of your base frequency).
- Change the **phase** of the wave (cf. sine and cosine) to do signal encoding.

调制技术(2/5)



调制技术(3/5)

一些概念

- 实践中,大多数Modem采样频率2400Hz,焦点在于:每次采样如何表达更多的位信息.
- 每秒钟采样的次数用波特(Baud)计量
- 在一个波特中,发送的是一个码元
- 一个码元可编码m位数据
- 数据传输速率就是波特率的m倍

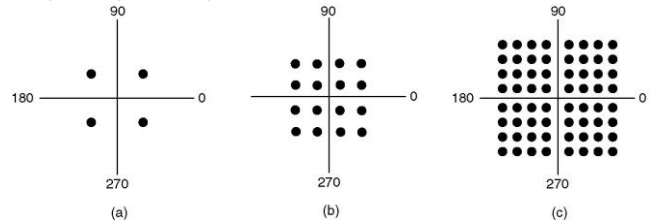
- 组合几种调制技术, 以便在每个波特中传输尽可能多的位

- 描述工具: 星座图



调制技术(4/5)

- QPSK, QAM-16, QAM-64



正交相移键控：4种相移，
每个码元2位→4800bps

正交振幅调制（QAM）：
3种振幅12种相移，每个
码元4位→9600bps

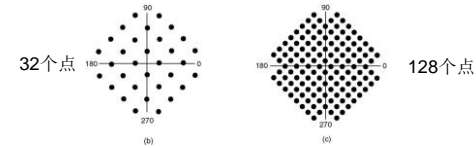
每个码元6位→14.4kbps

- 星座中的点越多，干扰引起传输错误的可能性越大



调制技术(5/5)

- V.32 for 9600 bps. V.32 bis for 14,400 bps 带1位奇偶校验位



- V.34: 12个数据位，28.8kbps; V.34 bis: 14个数据位，33.6kbps

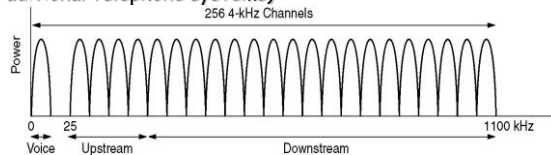
- 香农modem限制35kbps，56kbps modem何来？

- 减少一个本地回路，S/N增大，最大速率可以增加一倍→70kbps
- 为什么不是70kbps，而是56kbps？
- 在美国，电话信道带宽4kHz，采样8000波特，每次采样的位数是8，1位用于控制，所以56kbps。
- 标准名为：V.90（33.6kbps上行，56kbps下行）
- V.92（48kbps上行，56下行kbps）



Asymmetric DSL(1/3)

- Essence: considering that the local loop has a 1.1MHz spectrum, we can divide the spectrum into 256 4kHz channels (like in traditional telephone systems):

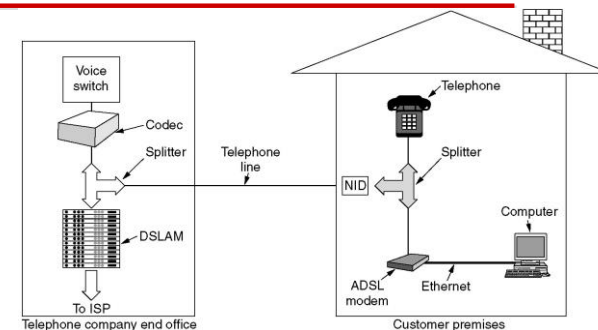


使用离散多信道调制技术（DMT）的ADSL频谱划分方案

- Note: it is up to the provider to decide how it will arrange its channels. Different combinations are possible.
- 每条信道使用QAM（正交振幅调制）调制方案，但采样频率4000Hz



Asymmetric DSL(2/3)

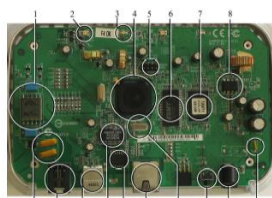


NID	Network Interface Device
DSLAM	DSL Access Multiplexer

A typical ADSL equipment configuration.



Asymmetric DSL(3/3)



ADSL Modem

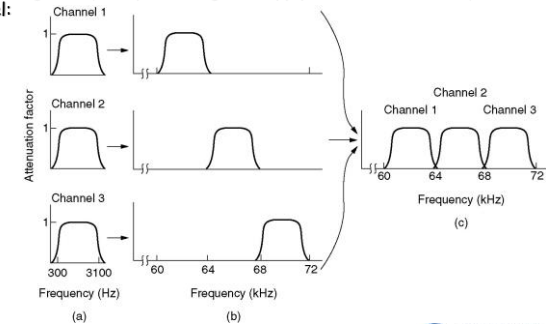
DSLAM

- | | |
|--------------------|-------------------|
| 4: CPU | 5: JTAG interface |
| 6: 8 Mb RAM | 7: Flash memory |
| 13: Ethernet port | 16: USB port |
| 17: Telephone port | |



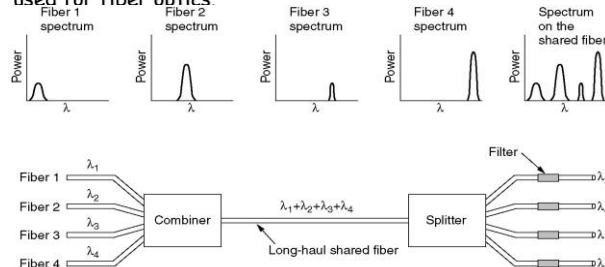
复用 Multiplexing: FDM

- **Problem:** considering that the bandwidth of a channel can be huge, wouldn't it be possible to divide the channel into sub-channels?
- **Frequency Division Multiplexing:** Divide the available bandwidth into channels through frequency filtering, and apply modulation techniques per channel:



复用 Multiplexing: WDM*

- **Wavelength Division Multiplexing:** actually the same as FDM, but used for fiber optics

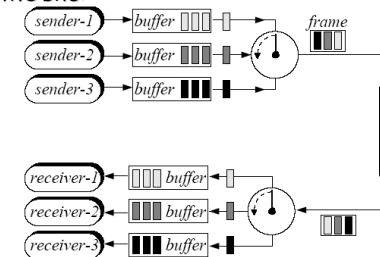


- **Observation:** light waves have their own frequency range; they are simply combined and separated using standard (de)fraction properties.



复用 Multiplexing: TDM (1/4)

- **Time Division multiplexing:** simply merge/split streams of digital data into a new stream. Data is handled in **frames**-a fixed series of consecutive bits:

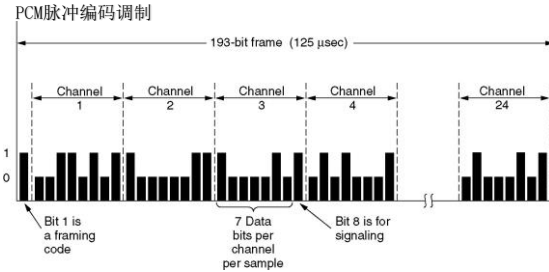


- **Observation:** this is full-digital solution in contrast to FDM and WDM (完全数字化的复用线路方案)



复用 Multiplexing: TDM(2/4)

- Example: the T1 system samples at 8000Hz, and encodes each sample as a 7-bit number (i.e. 128 different values). With some extra control bits, we merge samples into 193-bit frames, every 125usec.



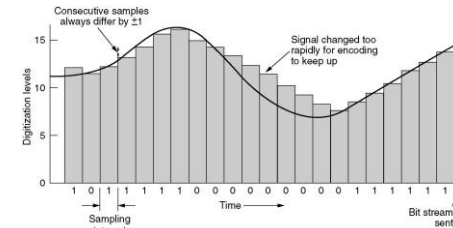
- Observation: T1 supports a total of 1.544Mbps



复用 Multiplexing: TDM (3/4)

- 压缩方法：减少每条信道所需要的位数

- 差分PCM: 传输前后采样值之差，5位足够，无需7位。
- 增量调制: ± 1 较前一采样是高了，还是低了。1位。

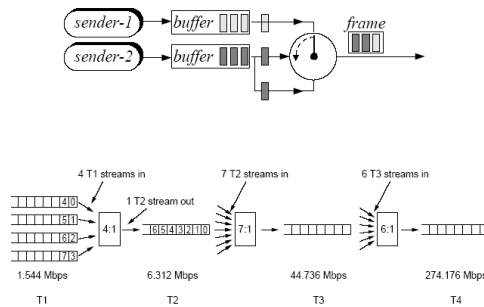


- 预测编码: 对实际与预测的差值编码



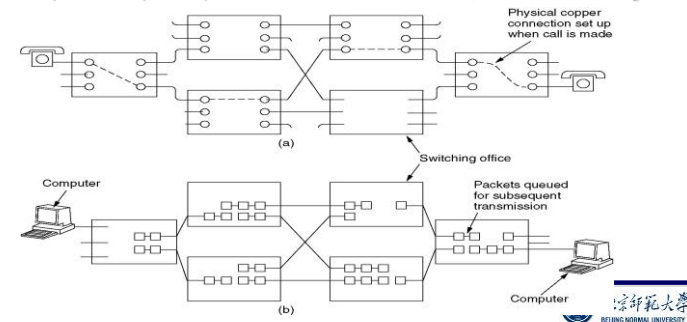
复用 Multiplexing: TDM (4/4)

- Observation: TDM also makes it easy to offer individual senders higher bandwidth, by simply putting more data into a frame, or to combine several trunks into higher-bandwidth trunks:



交换 Switching(1/2)

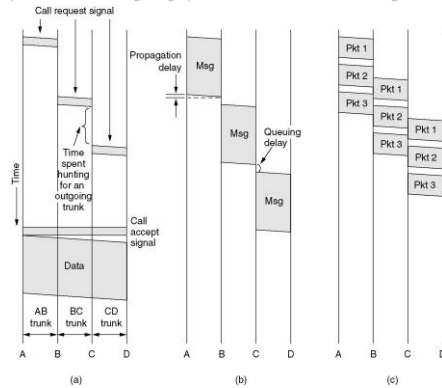
- Circuit switching: make a true physical connection from sender to receiver. This is what happens in traditional telephone systems.
- Packet switching: (1) split any data into small packets, (2) route those packets separately from sender to receiver, and (3) assemble them again.



交换 Switching (2/2)

- Variation: **message switching** - a message is completely received at a router, stored, and then put into an outgoing queue for further routing.

- (a) Circuit switching
(b) Message switching
(c) Packet switching



交换 Switching: Comparision

Item	Circuit-switched	Packet-switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
Is a switch crash fatal	Yes	No
Bandwidth available	Fixed	Dynamic
When can congestion occur	At setup time	On every packet
Potentially wasted bandwidth	Yes	No
Store-and-forward transmission	No	Yes
Transparency	Yes	No
Charging	Per minute	Per packet



CDMA(1/2, 码分多路访问)

- Code Division Multiple Access allows transmissions to be interleaved, but avoids interference. Note that this means inherently no message collision.
- Principle: assign a **chip sequence** to a station, which is just an m-bit code. Make sure that all chip sequences are pairwise orthogonal:
- Rewrite a binary 0 as -1, and a binary 1 as +1
 - Send a 1 bit as your chip sequence, and a 0 bit as the inverse
 - Just transmit your bits when a new bit time slot starts → the **chip sequences** (possibly inversed 补码) are just added.
 - Getting the original value means taking the **inner product** of the original chip sequence with the signal sent.



CDMA(2/2, 码分多路访问)

(a) 4个移动点的chip sequence
 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

(b) 时间片序列的双极表示
 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)

(c) 6个传输例子
 --1-- C
 -11-- B+C
 10-- A+B
 101-- A+B+C
 1111 A+B+C+D
 1101 A+B+C+D

(d) 接收方恢复C的信号过程
 $S_1 \cdot C = (1 + 1 + 1 + 1 + 1 + 1 + 1 + 1)/8 = 1$
 $S_2 \cdot C = (2 + 0 + 0 + 0 + 2 + 2 + 0 + 2)/8 = 1$
 $S_3 \cdot C = (0 + 0 + 2 + 2 + 0 - 2 + 0 - 2)/8 = 0$
 $S_4 \cdot C = (1 + 1 + 3 + 3 + 1 - 1 + 1 - 1)/8 = 1$
 $S_5 \cdot C = (4 + 0 + 2 + 0 + 2 + 0 - 2 + 2)/8 = 1$
 $S_6 \cdot C = (2 - 2 + 0 - 2 + 0 - 2 - 4 + 0)/8 = -1$

AMPS & GSM: 频段 → 信道 → 时槽

CDMA:

- 1、在整个频段范围内发送信号
- 2、利用编码技术分离叠加信号

