

# 无线通信系统概论(一)

池保勇 010-62795096(O)

清华大学微电子学研究所设计室

●参考书: Thomas H. Lee, 《The Design of CMOS Radio-Frequency Integrated Circuits》, § 1, § 2

●参考书: Behzad Razavi, 《RF Microelectronics》, § 1 ~ § 4

# 提要

- 射频集成电路的发展历程
- 无线通信系统组成：
  - ◆ 调制方式
  - ◆ 信道传输（眼图）
  - ◆ 复用方式（时分复用、频分复用和码分复用）
- 通信电路
  - ◆ 接收机作用及性能要求；
  - ◆ 发射机作用及性能要求；
  - ◆ 频率合成器作用及性能要求；
- 常见的无线通信系统介绍

# 无线电的发明



❑ Maxwell



❑ Marconi

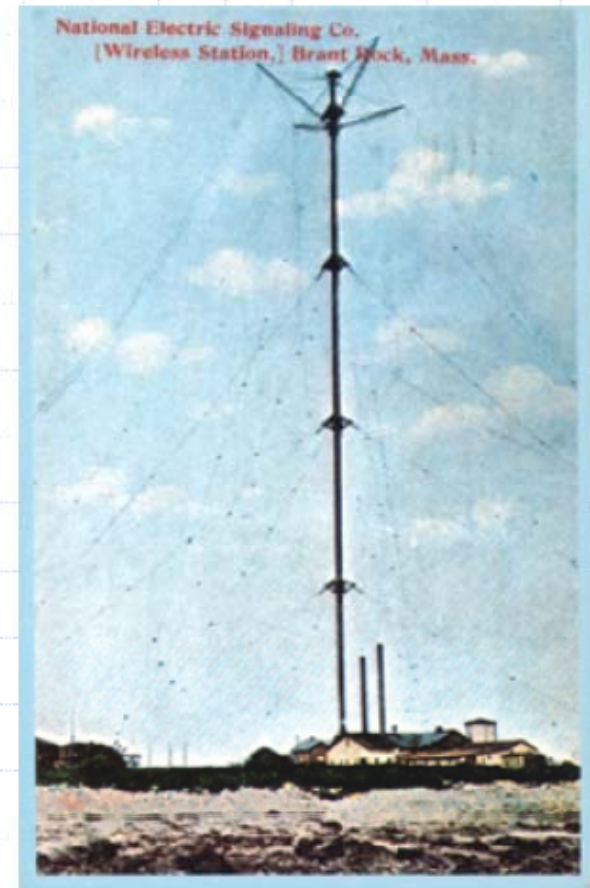


1875-1910



❑ Hertz

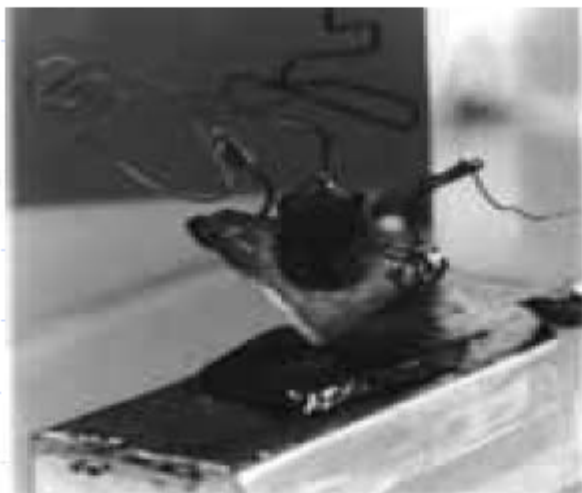
❑ The 1912 *Titanic* tragedy accelerated wireless advance



# 晶体管的发明

1947-  
1948

□ Point contact transistor



□ Amplifier



1951

□ Junction transistor



1954



# 集成电路的出现

1956  Gave birth to Silicon Valley

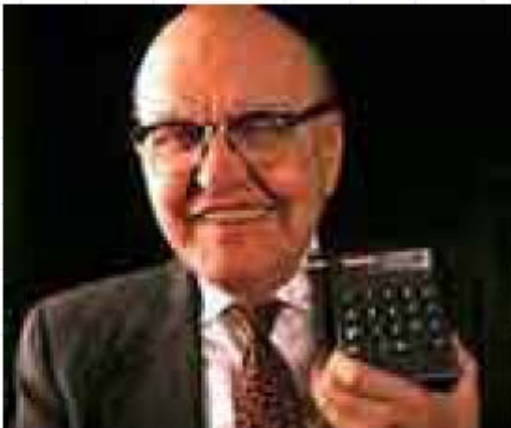


1958



TI's first IC

1967



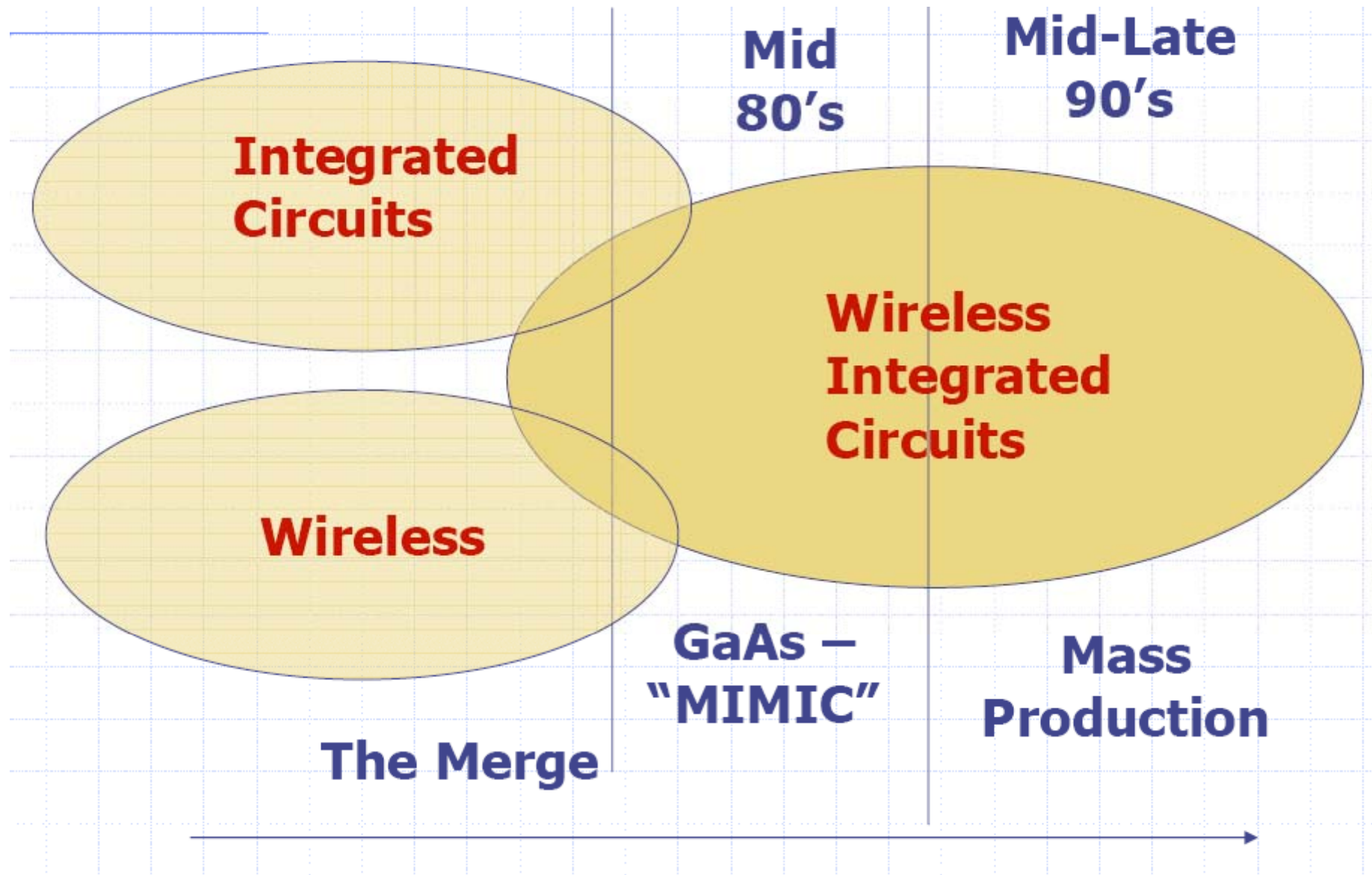
Jack Kilby and the first hand-held calculator

1968

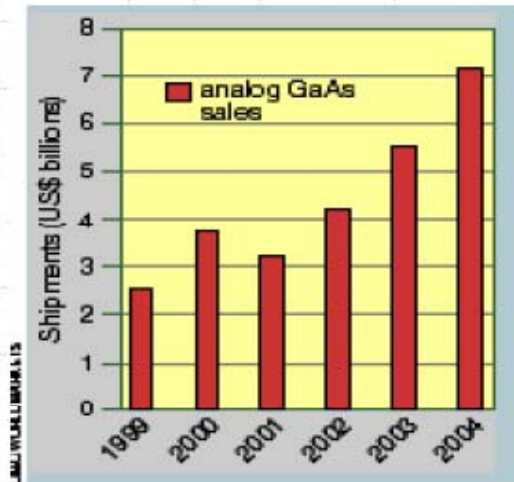
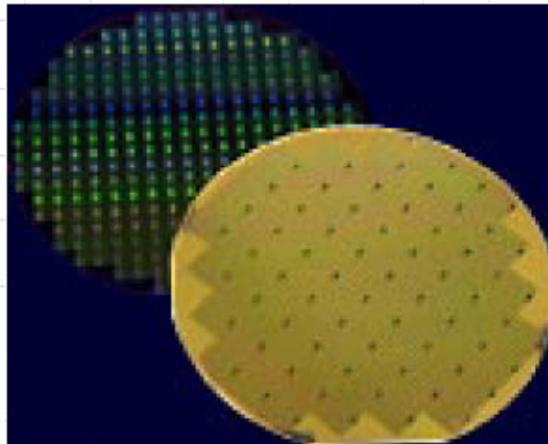
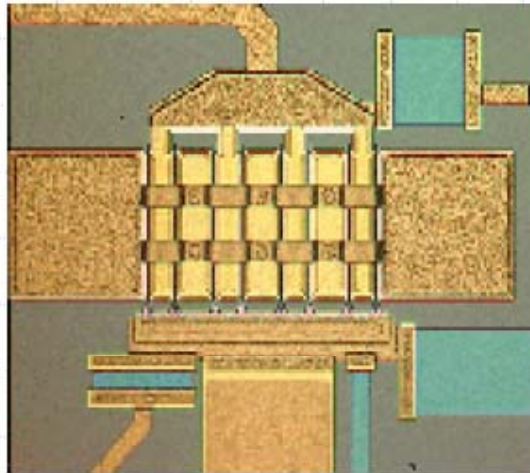
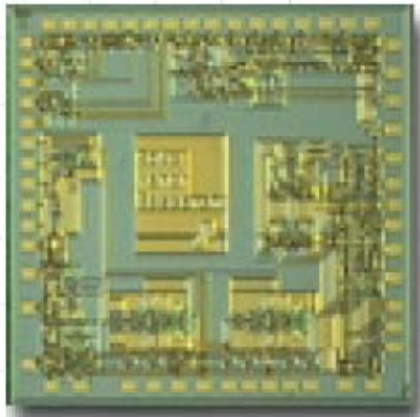




# 射频集成电路的出现



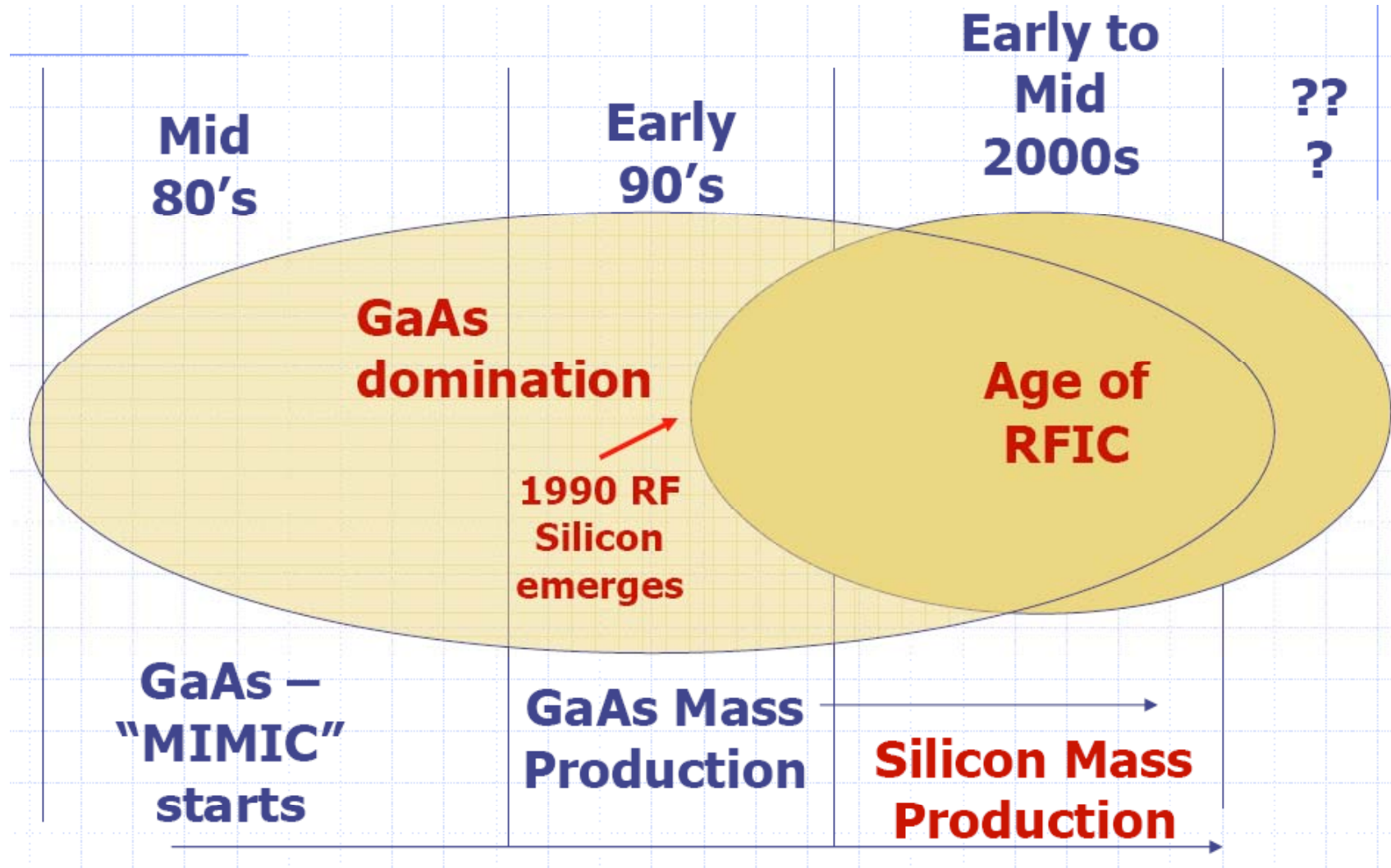
# GaAs射频集成电路 (MMIC)



Trouble ahead? Eight months ago, CIBC World Markets predicted that the total world market for analog GaAs devices would exceed \$5 billion in 2001. Now, the same firm is forecasting that total sales will actually decrease in 2001 compared to last year, signaling the first recession in the GaAs industry's history.

**Still strong sales - particularly PAs, Future cloudy**

# 射频集成电路的发展





# Why the Emergence of Silicon

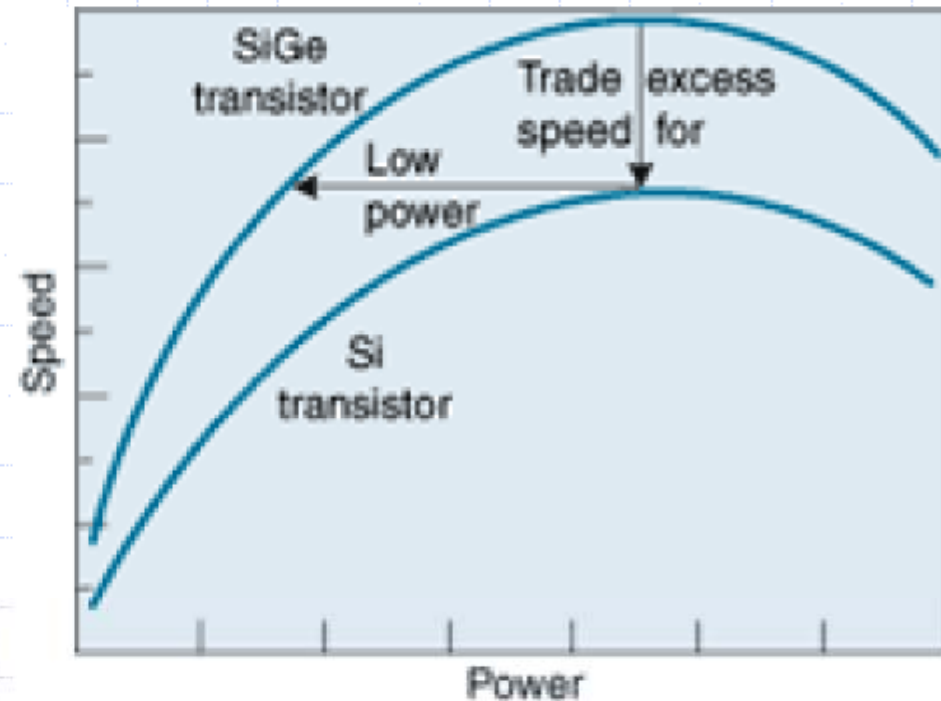
- ❑ Silicon Bipolars emerged with great performance – now good enough for RF!
- ❑ Can have digital and analog/RF on the same chip.
- ❑ RF/Analog integration easier.
- ❑ Have complementary devices (CMOS) – very useful for analog support circuits.
- ❑ Cheaper.
- ❑ More mass production available in world.
- ❑ Yields are better.
- ❑ Generally more mature and better characterized technology than GaAs.

# Wonderful Silicon Germanium

❑ Addition of Germanium to Base improves performance:

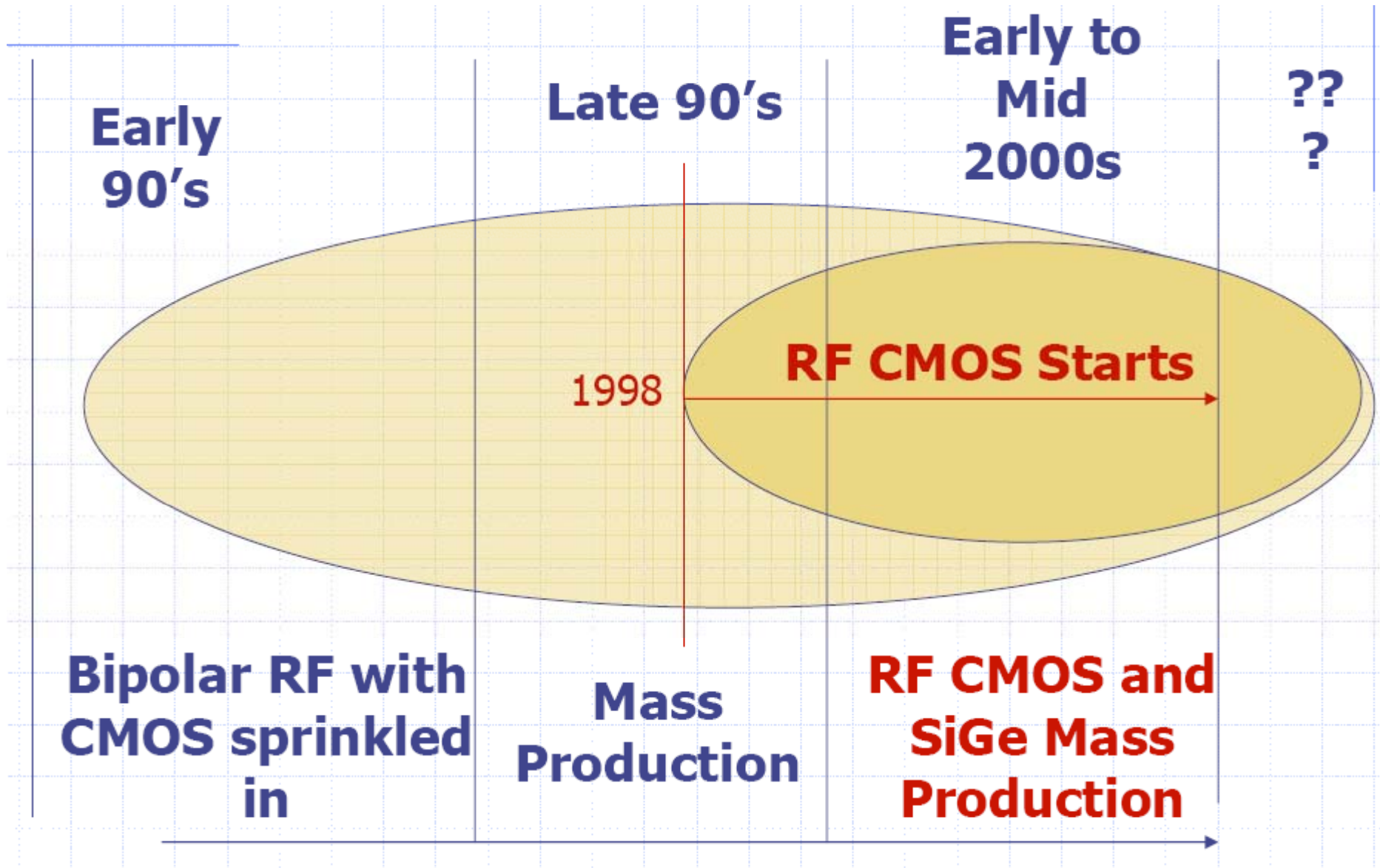
- ❑ Higher  $f_t$
- ❑ Lower Noise
- ❑ Better Early Voltage

❑ Negative: Cost more.



❑ Now performance comparable to GaAs!

# CMOS RFIC

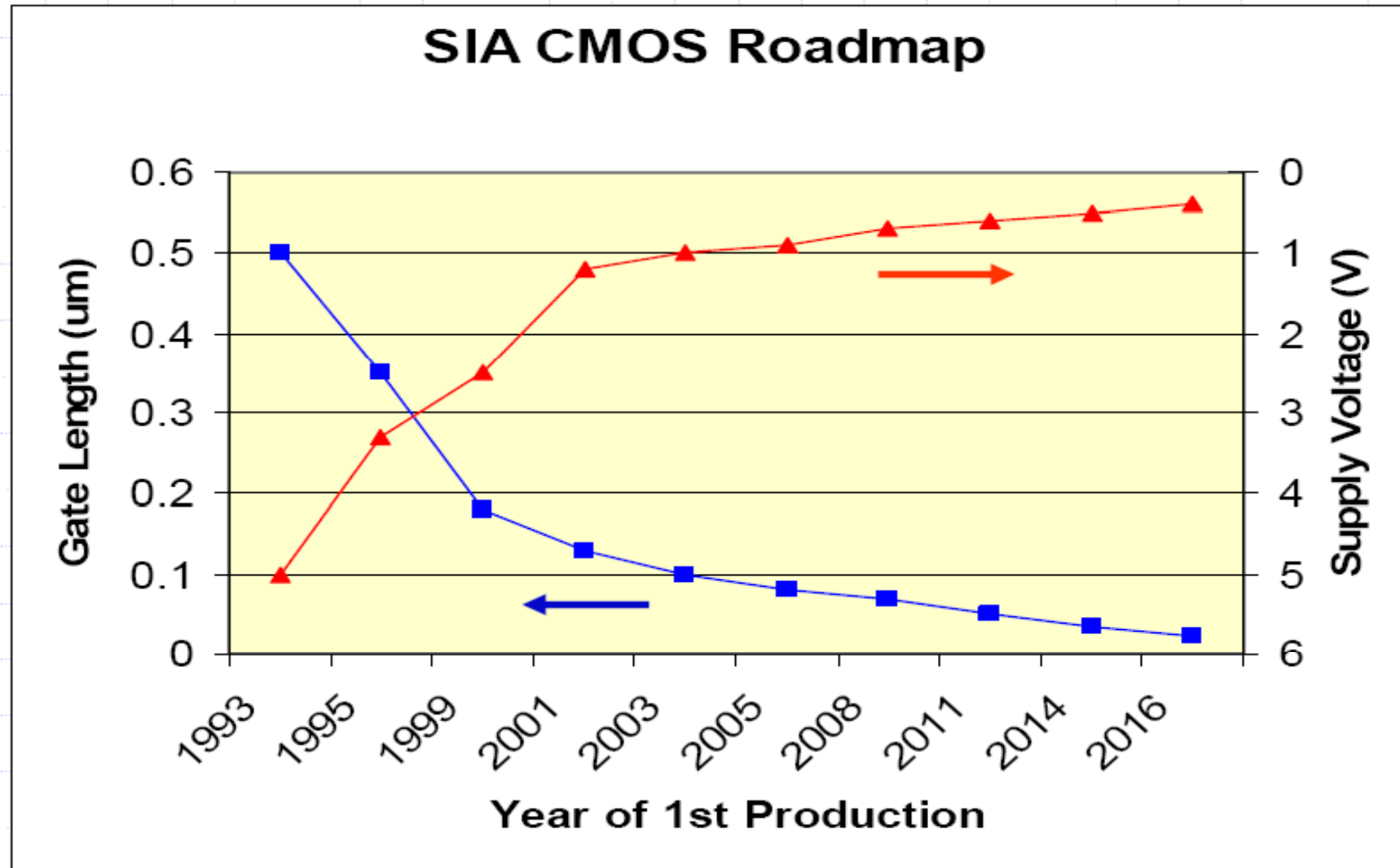


# Why RF CMOS ?

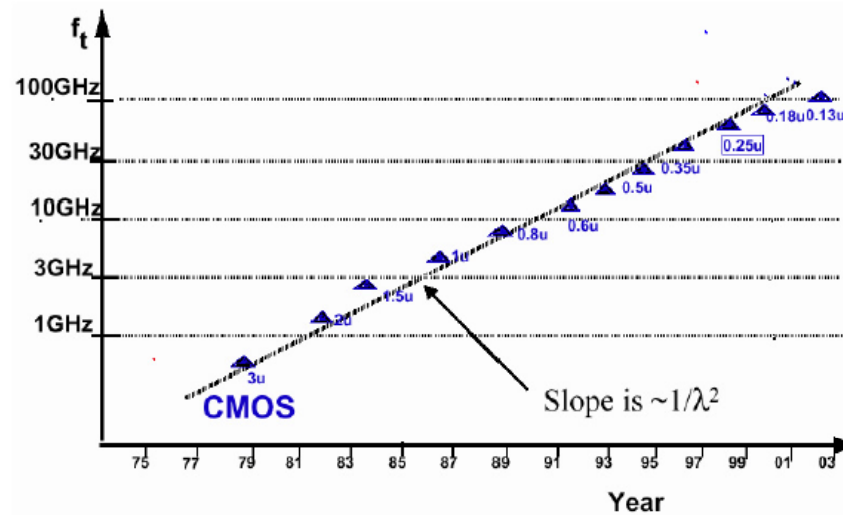
- ❑ With scaling, performance good enough for RF with latest technologies.
  - ❑ Not better than bipolars at same node.
- ❑ Cheaper than BiCMOS, arguably.
- ❑ More compatible with a larger number of foundries in the world.
- ❑ Better compatibility with digital since same devices.



# CMOS工艺技术的发展

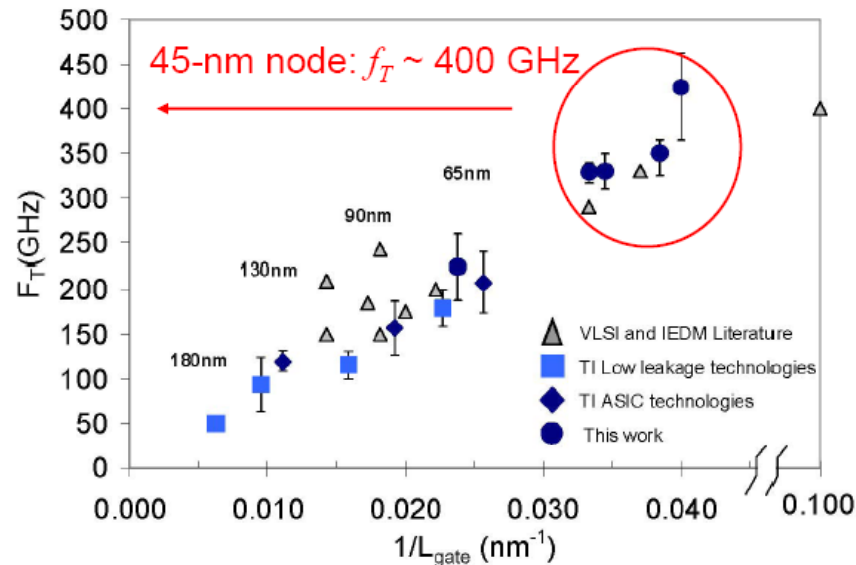


# CMOS工艺技术的发展（续）



The transition frequency,  $f_T$ , vs. the CMOS gate length

$$\omega_T = \frac{g_m}{C_{gs} + C_{gd}}$$



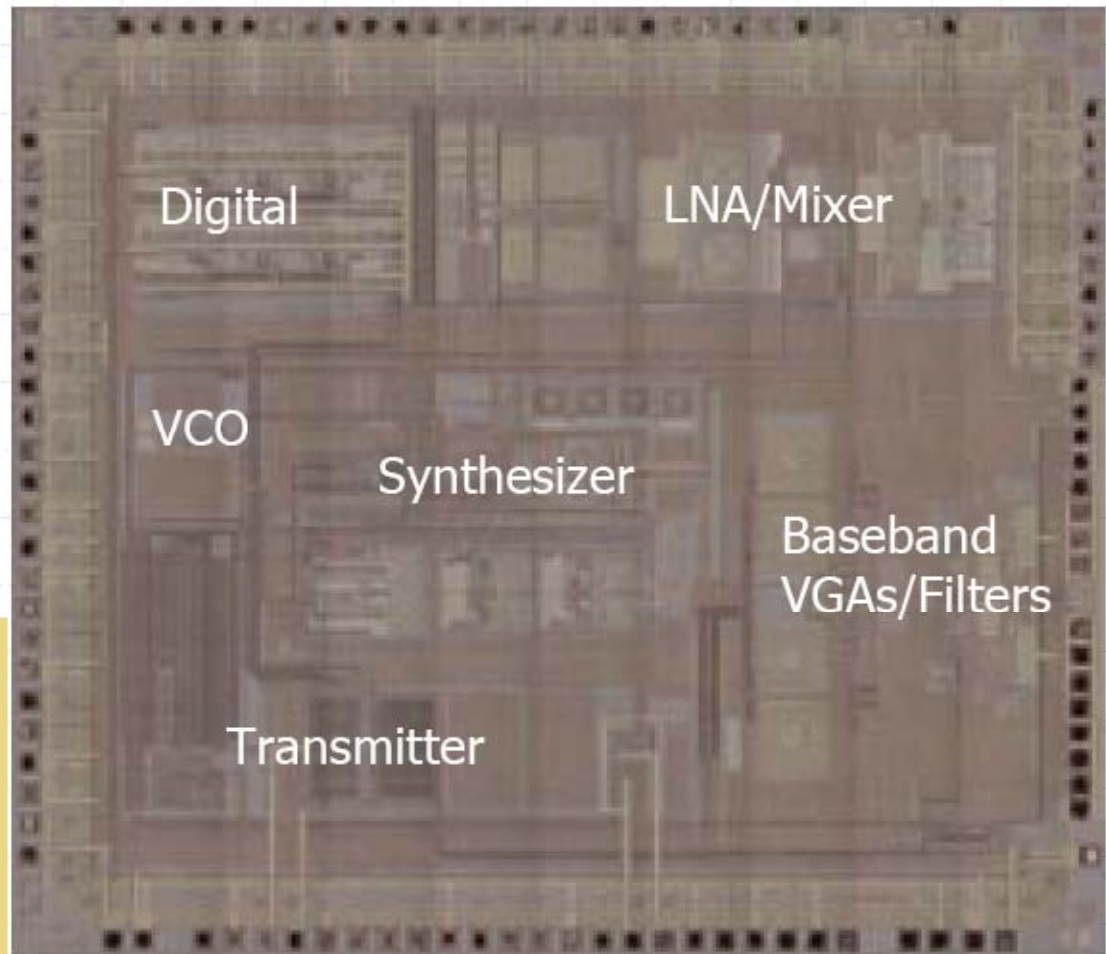
H. Stork, TI,  
*VLSI Tech '05*

# Real Examples of Silicon Chip

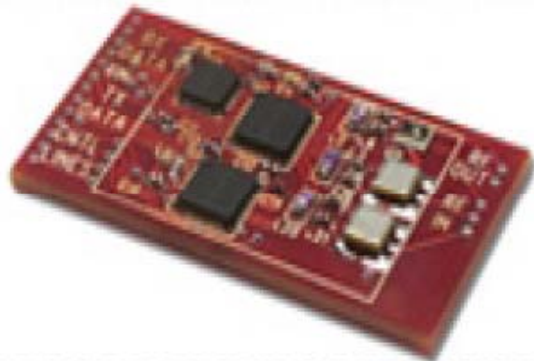
**Atheros 5GHz  
WLAN complete  
receiver – no PA**

**0.25um CMOS  
technology only**

**Highly Integrated,  
Compact. Note  
Number of I/O,  
and mixed digital  
/analog stuff**



# Really Real World Silicon



Silicon Laboratories:  
Raising CMOS  
to the Power of RF

**Above: Silicon  
Labs 2G Cellular  
"Aero" Module**

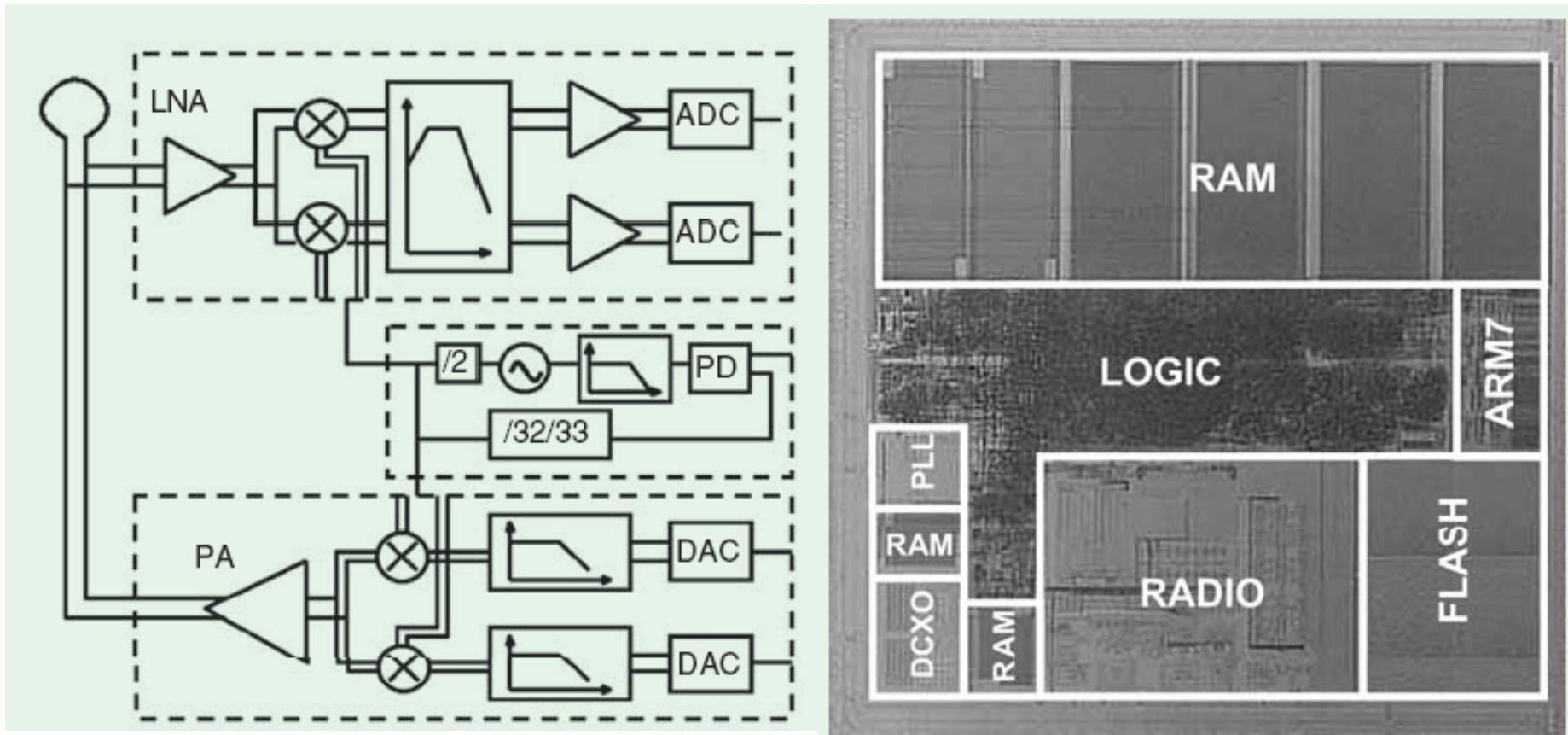
**Right: Huntech  
BT Complete  
Module with  
Single Chip Radio**





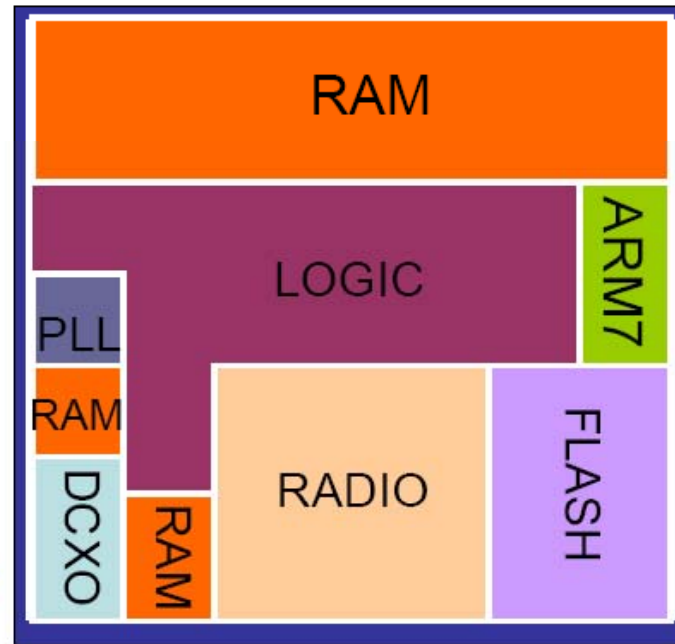
# Really Real World Silicon

- Bluetooth: Alcatel

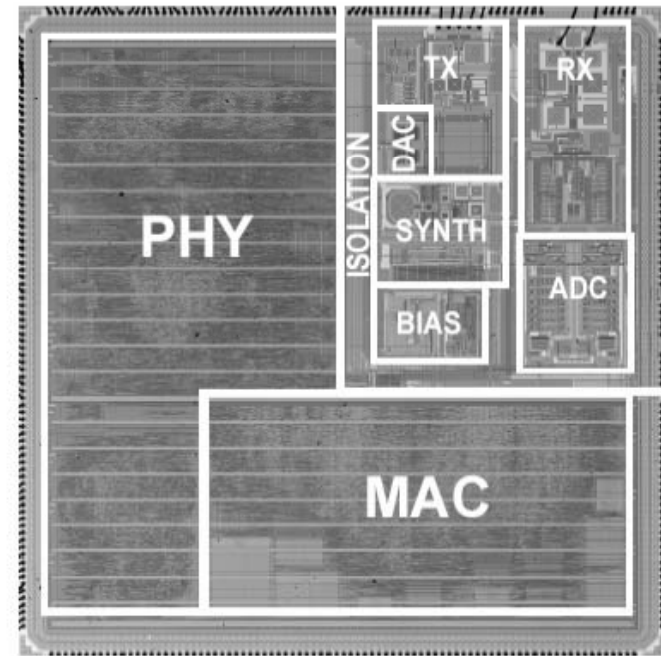


# Really Real World Silicon

DCXO:  
digitally-  
compensated  
crystal  
oscillator



A bluetooth wireless transceiver SOC  
Alcatel, ISSCC'01

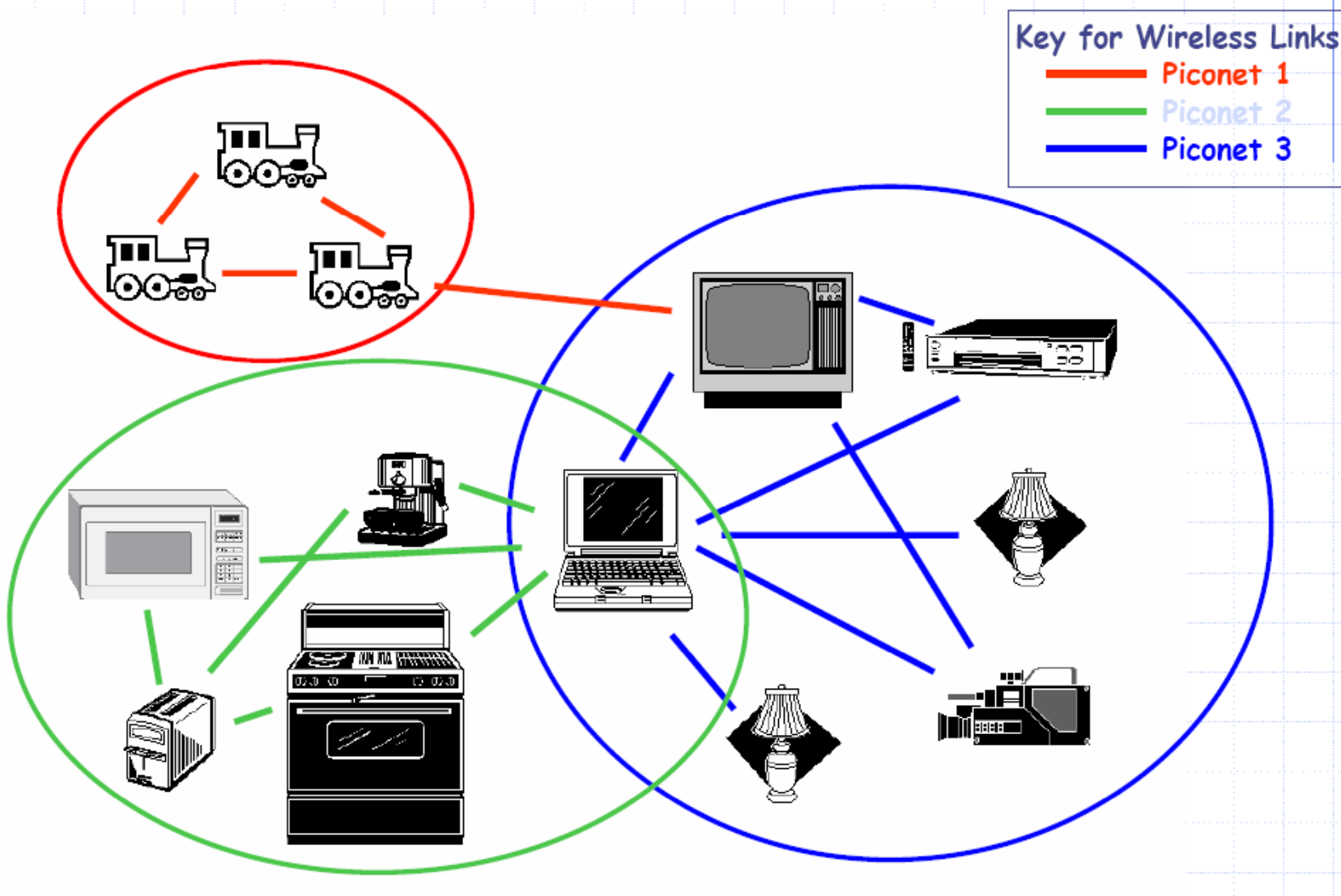


An 802.11g WLAN SOC  
Atheros Communications, ISSCC'05

# Commercial Applications

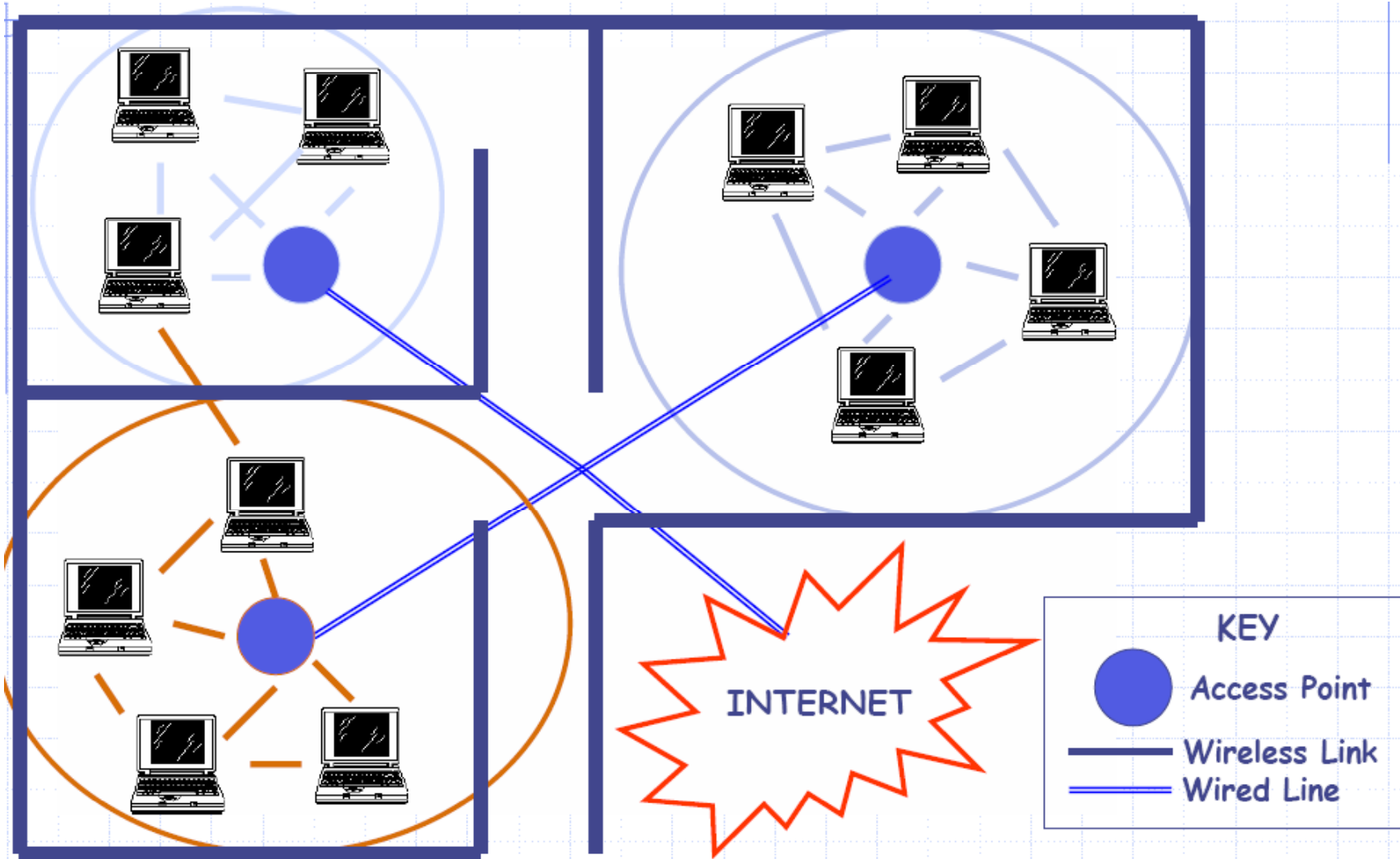
- ❑ Pagers.
  - ❑ 1<sup>st</sup> Application - Just about dead now.
- ❑ Cellular
  - ❑ 1G, 2G, 2.5G, 3G.
- ❑ Wireless Networking:
  - ❑ Bluetooth.
  - ❑ Zigbee.
  - ❑ WLAN.
  - ❑ WMAN.
- ❑ **Wireless is transforming our society, and Silicon is the technology to ride the wave!**

# WPAN Example Network

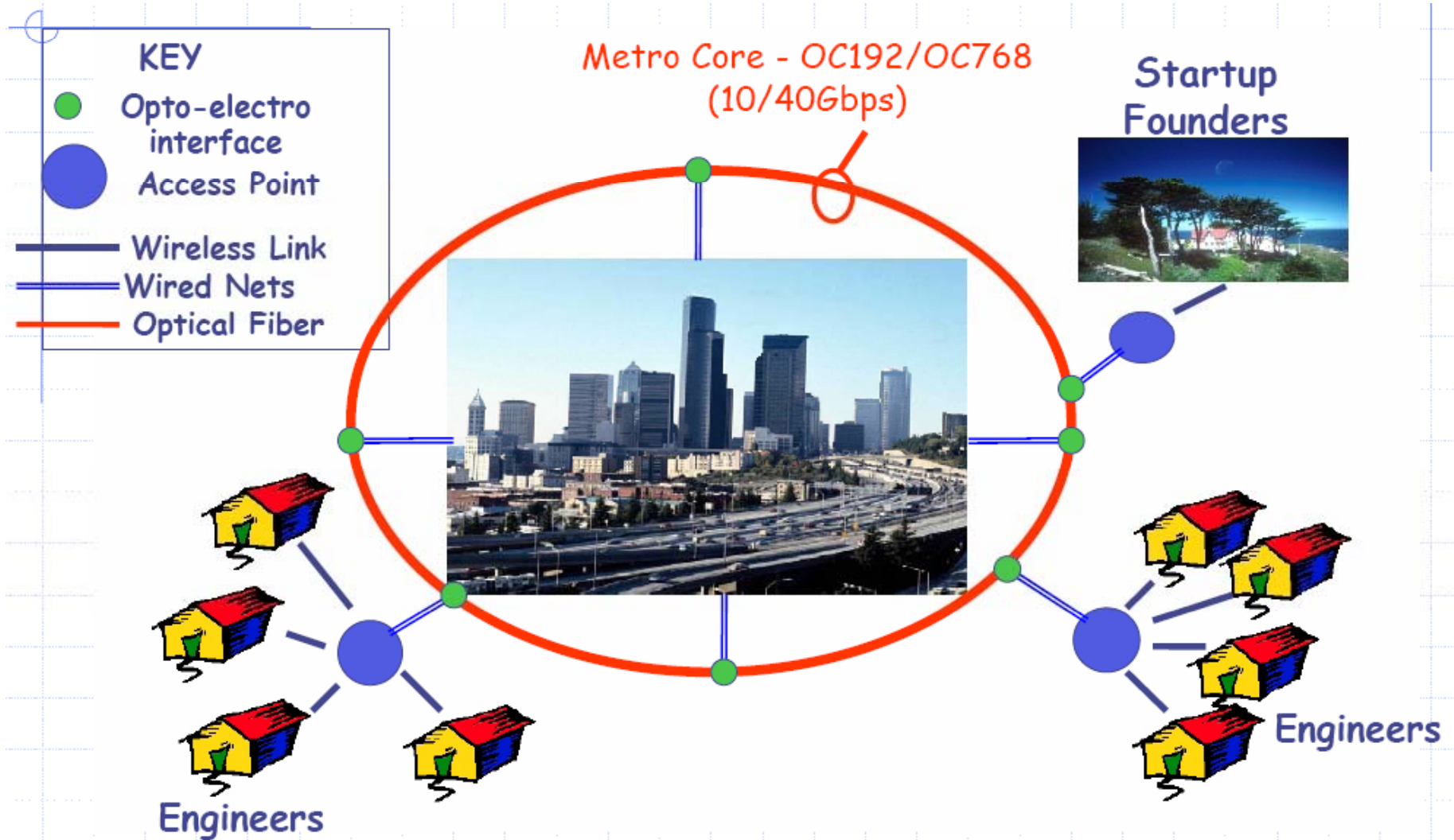




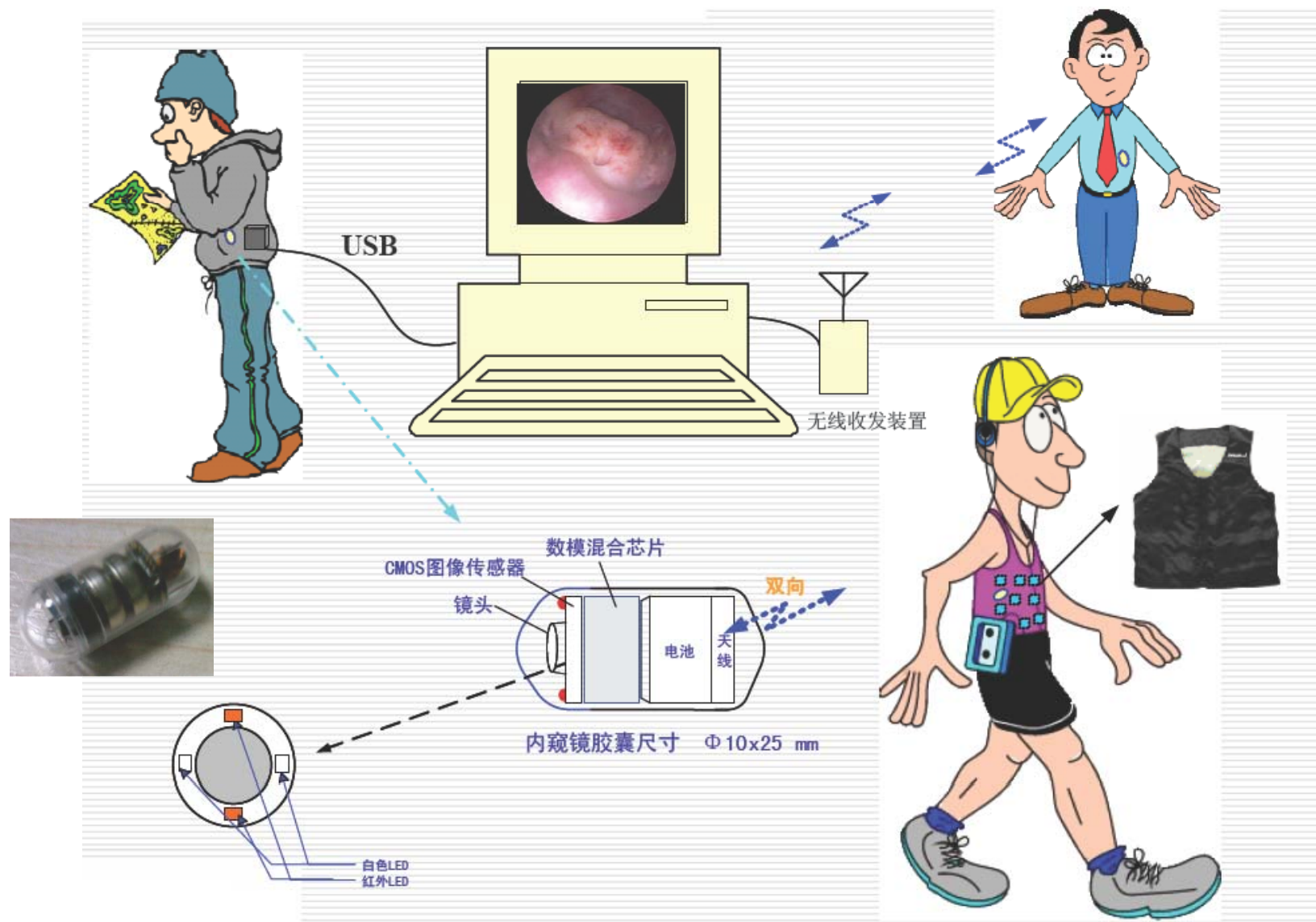
# WLAN Example Network



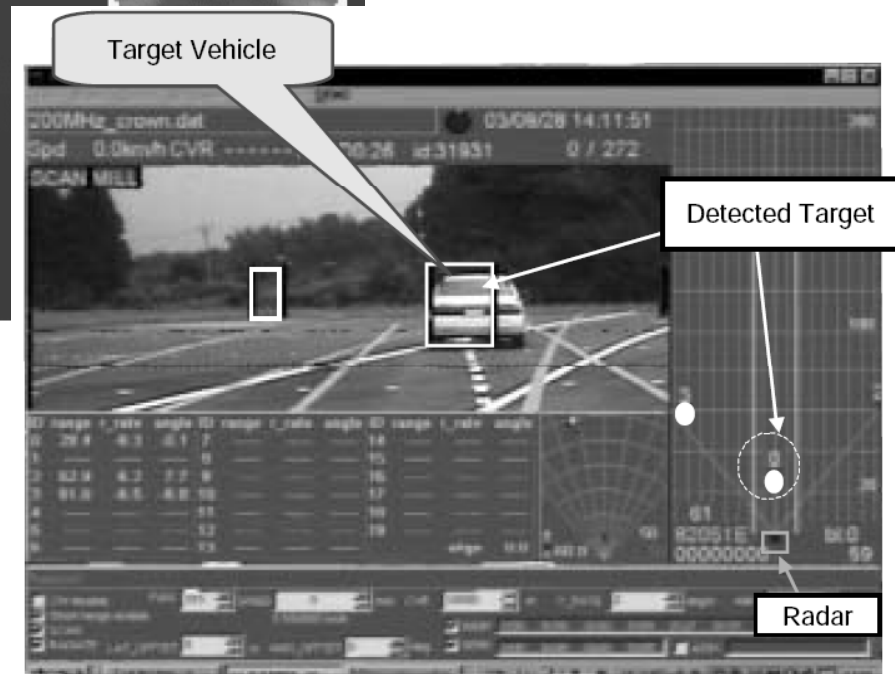
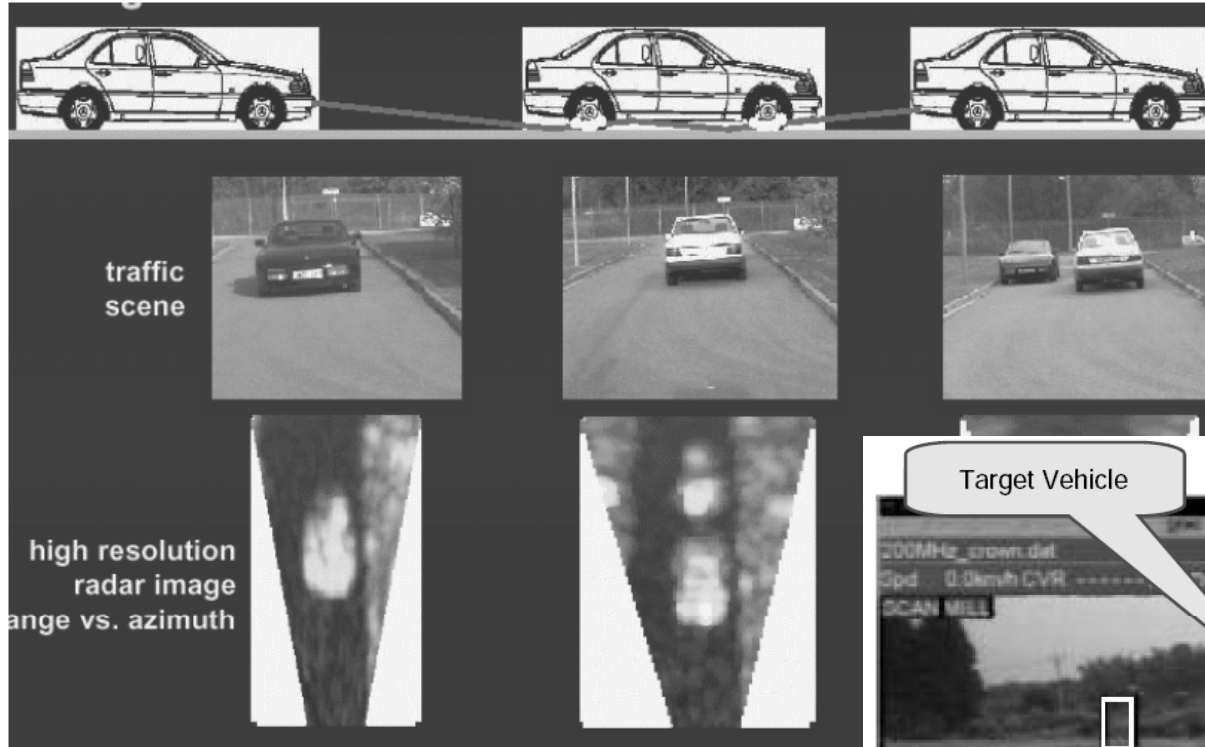
# WMAN Example Network



# 双向数字化无线内窥镜系统设计



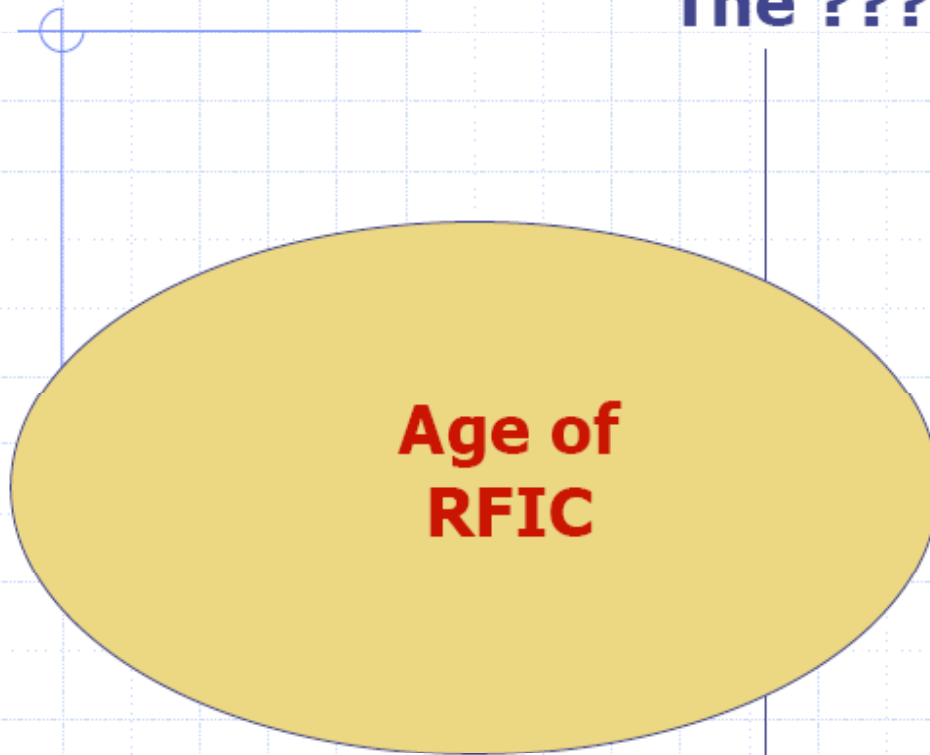
# 汽车雷达系统 (24GHz、77GHz)



# The Future

❑ Silicon chip TX/RX with integrated antennas and filters now available!

The ???



## ???? Possible Trends

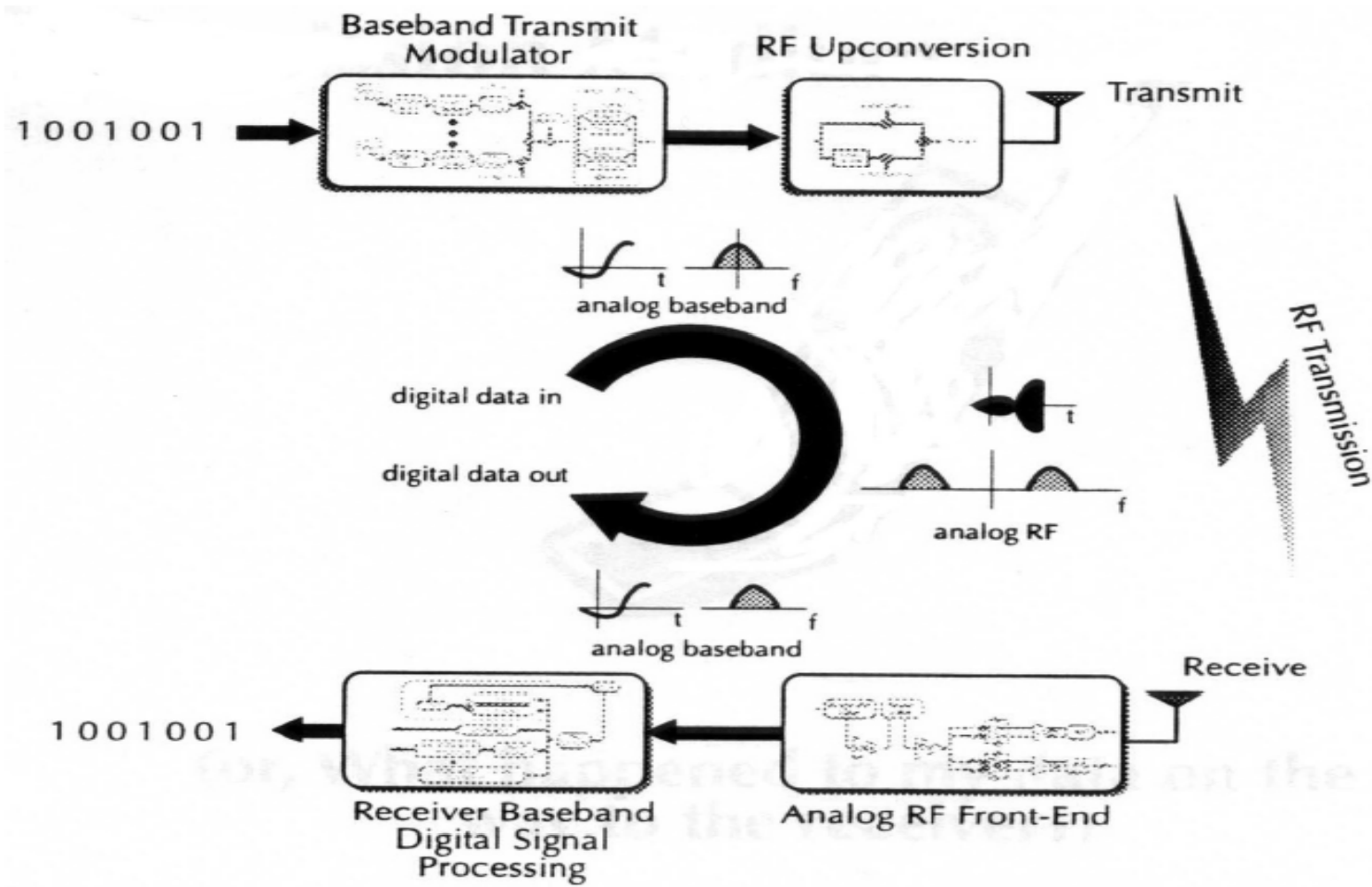
1. More integration – on chip PA, Single chip Transceivers.
2. More digital pushed into RF – software defined radio.
3. Next technology node in future – New flavor of Silicon, for example Silicon Carbide.
4. Extinction of Bipolars



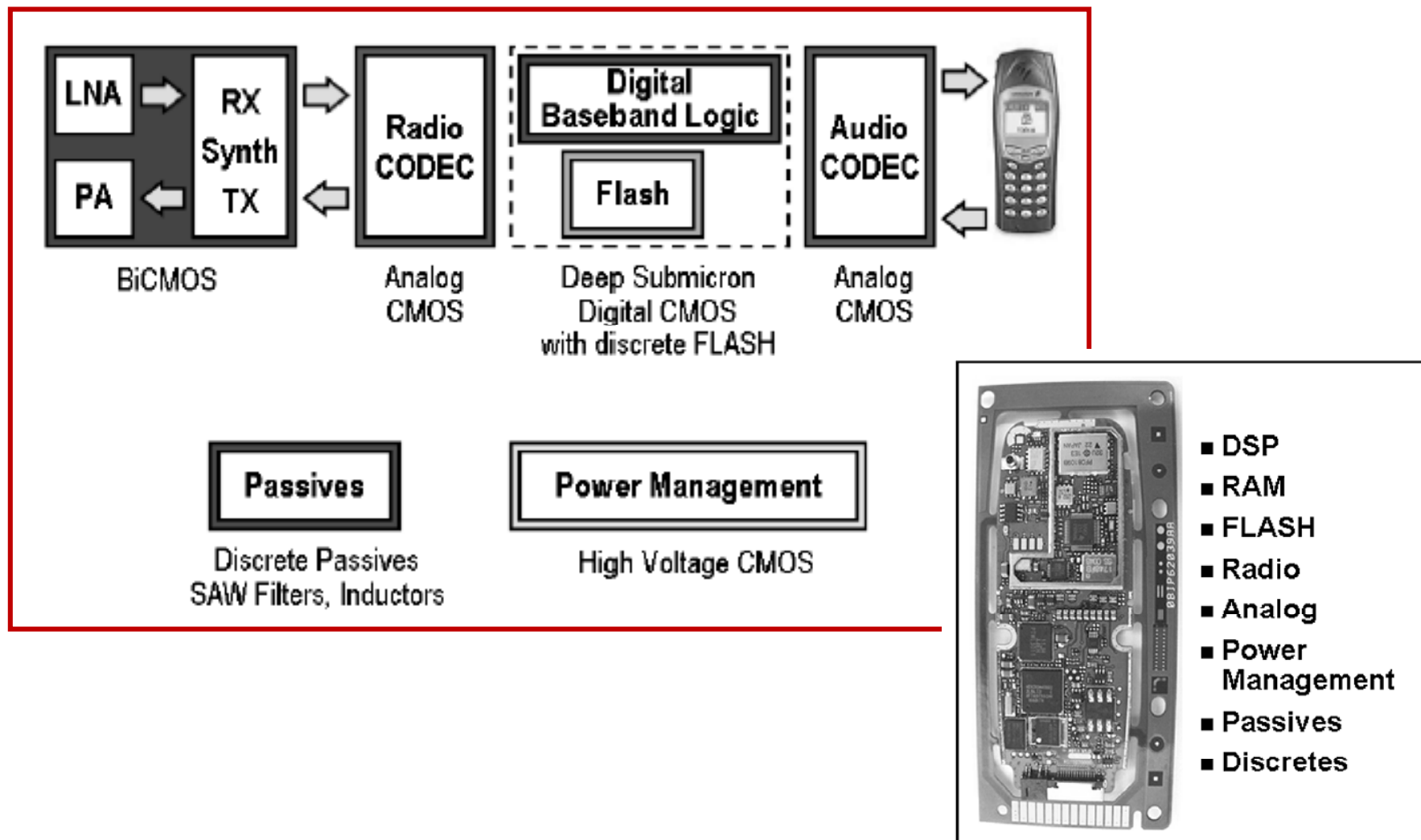
# 提要

- 射频集成电路的发展历程
- 无线通信系统组成：
  - ◆ 调制方式
  - ◆ 信道传输（眼图）
  - ◆ 复用方式（时分复用、频分复用和码分复用）
- 通信电路
  - ◆ 接收机作用及性能要求；
  - ◆ 发射机作用及性能要求；
  - ◆ 频率合成器作用及性能要求；
- 常见的无线通信系统介绍

# 无线通信系统的组成



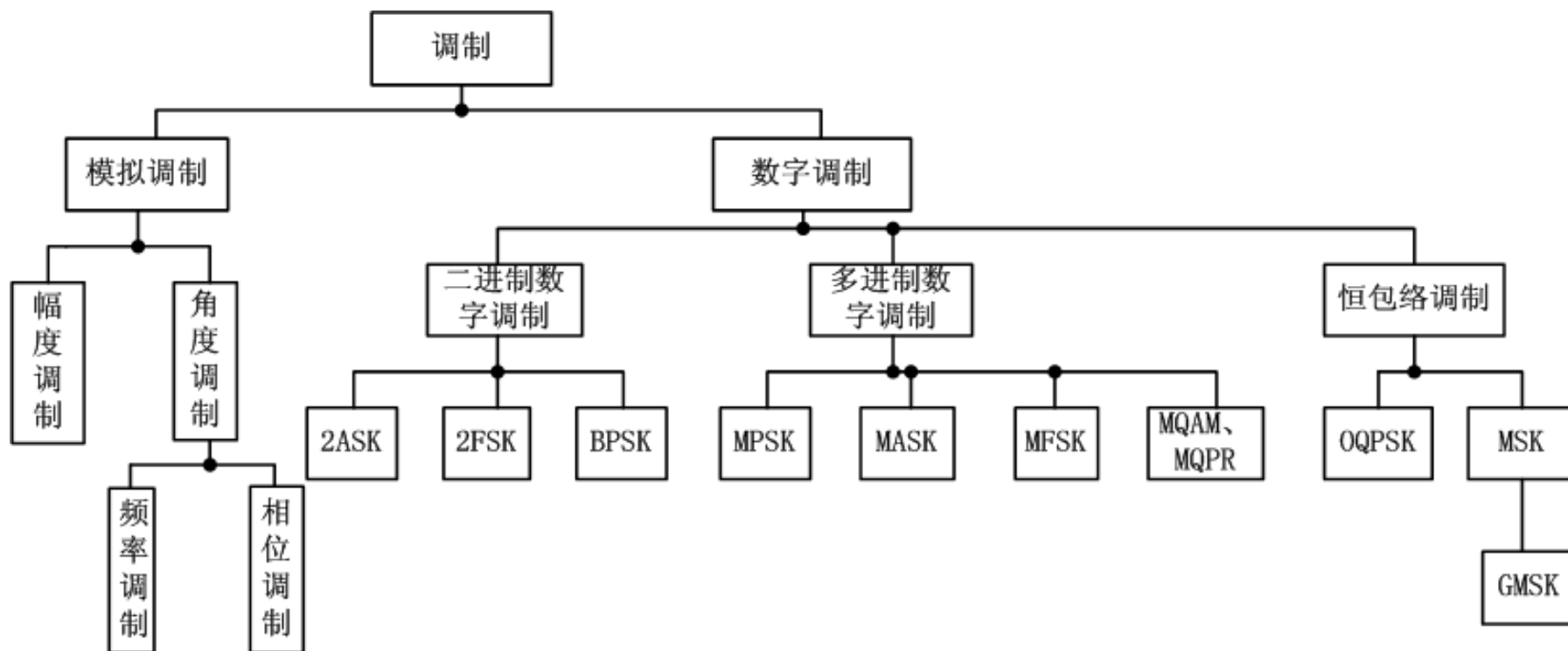
# 射频电路在无线通信系统中的位置



# 调制和解调

- 调制是使消息载体的某些特性随消息变化的过程，其作用是把消息置入消息载体，以便于传输和处理
- 解调:调制的逆过程，从消息载体中还原出原来的消息
  - 载波:用来传送消息的载体
  - 调制信号:代表欲传送消息的信号
  - 已调信号:经调制后的信号
- 载波可以是正弦波、脉冲波和光波等
- 所欲传送的消息可以是话音、图象或其它物理量——模拟信号，也可以是数据、电报和编码信号等——数字信号
- 调制是一种非线性过程。载波被调制后将产生新的频率分量，通常它们分布在载波频率的两边，并占有一定的频带

# 调制的方式和分类



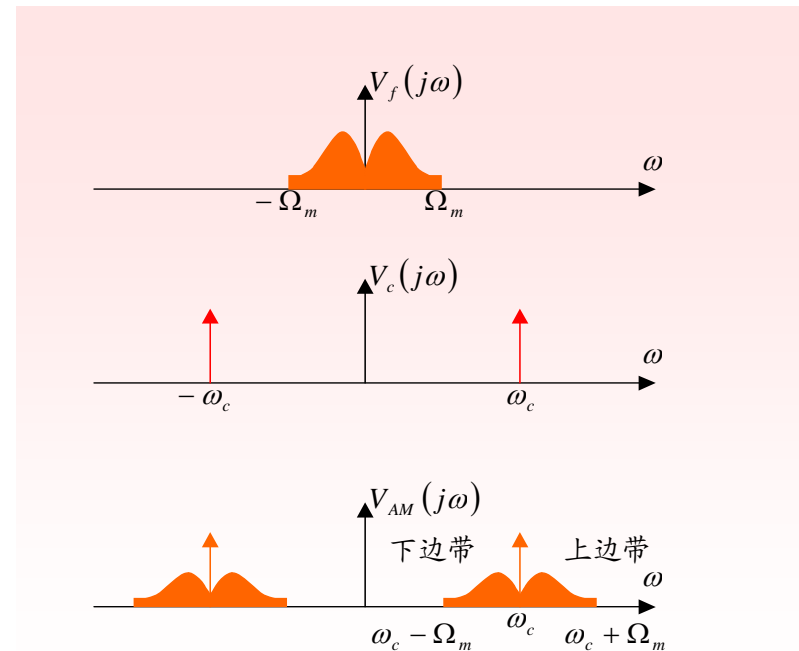
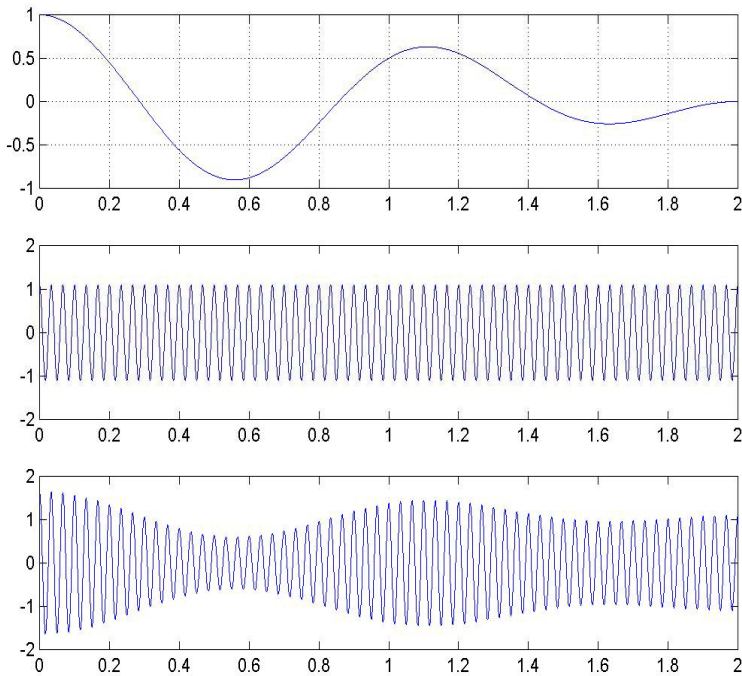


# 幅度调制

- 载波的幅度随调制信号的变化规律而变化，而其角频率和初相位均为常数

调幅指数

$$v_{AM}(t) = (V_{cm} + V_{\Omega m} \cos \Omega t) \cos \omega_c t = V_{cm} (1 + m_A \cos \Omega t) \cos \omega_c t$$
$$= V_{cm} \cos \omega_c t + m_A V_{cm} \cos \Omega t \cos \omega_c t$$



调制深度

$$\%MOD = \frac{V_{PEAK} - V_{MIN}}{V_{PEAK} + V_{MIN}} \times 100$$

## 调幅波信号的功率（单位电阻上）分配关系

$$v_{AM}(t) = V_{cm} \cos \omega_c t + \frac{1}{2} m_A V_{cm} \cos(\omega_c + \Omega) t + \frac{1}{2} m_A V_{cm} \cos(\omega_c - \Omega) t$$

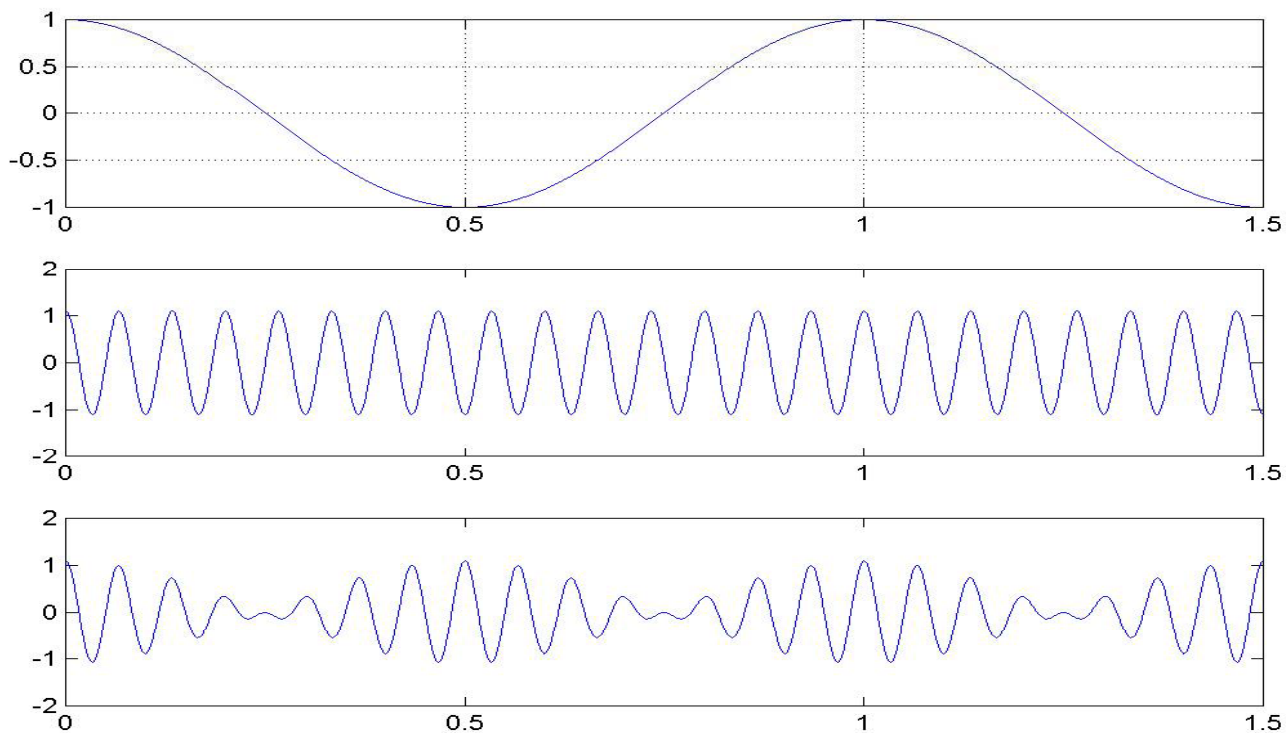
载波占有功率为：
$$P_c = \frac{1}{2} V_{cm}^2$$

边带（两个）所占有的功率为：
$$P_s = \frac{(m_A V_{cm})^2}{4} = \frac{m_A^2}{2} P_c$$

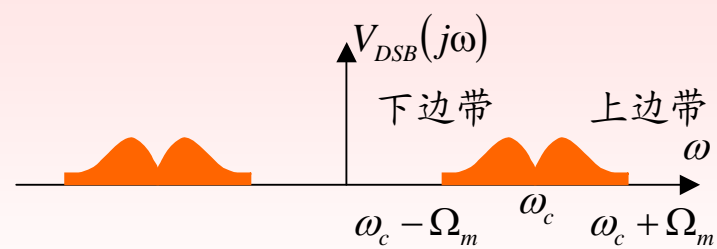
调幅波所具有的总功率为：
$$P_{AM} = P_c + P_s = \left(1 + \frac{m_A^2}{2}\right) P_c$$

# 调幅小结

- 已调信号的幅度随调制信号而变化，信号幅度的包络反映了调制信号的规律，只要能取出这个包络信号就可实现解调
- 调幅波的频谱由两部分组成。一部分是未调载波的频谱，另一部分是分别平移至载波两旁的调制信号的频谱
- 频带宽度：标准调幅信号所占的频带宽度是调制信号频带宽度的两倍。但从传递信息的角度看，标准调幅信号所占的频带宽度中有一半是多余的，因此，这种调幅方式在频率资源利用上是有缺点的
- 调幅波所具有的总功率：载波占有功率和边带所占有的功率之和。在调幅波中，欲传送的信息包含在边带内，载波分量并不包含欲传送的信息。而它所占有的功率却为总功率的一半以上。因此，从有效地利用发射机功率的角度考虑，标准幅度调制是有缺点的

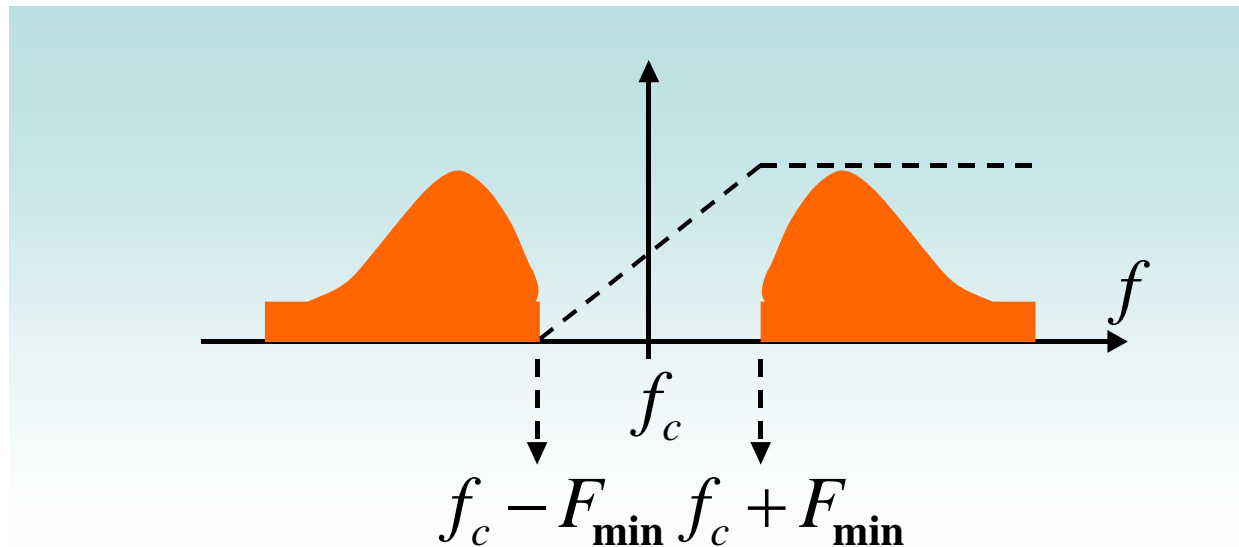


# 抑制载波调幅



# 单边带调幅

- 只传送一个边带的调幅信号称为单边调幅，可以选择上边带也可以采用下边带
- 可充分利用发射机的功率又节省占有频带。信息传输的角度是最佳调幅方式。但是实现这种调幅方式的调制和解调技术比较复杂





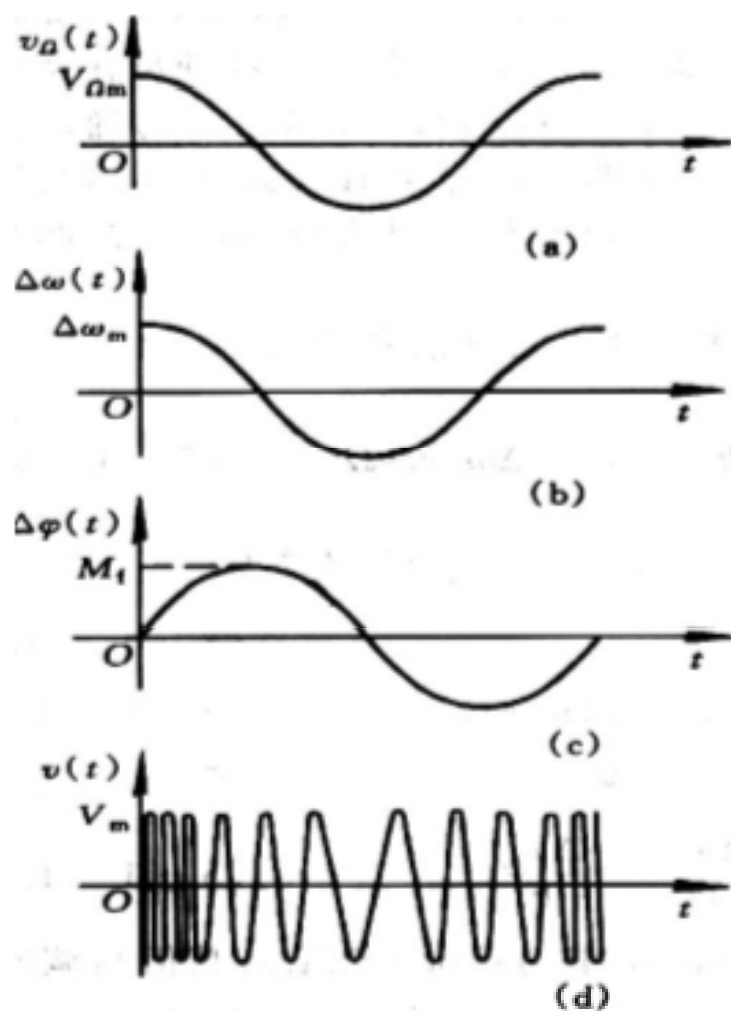
# 角度调制

- 正弦波的瞬时频率或瞬时相位随调制信号变化的调制方式，统称为角度调制（**Angular Modulation**）

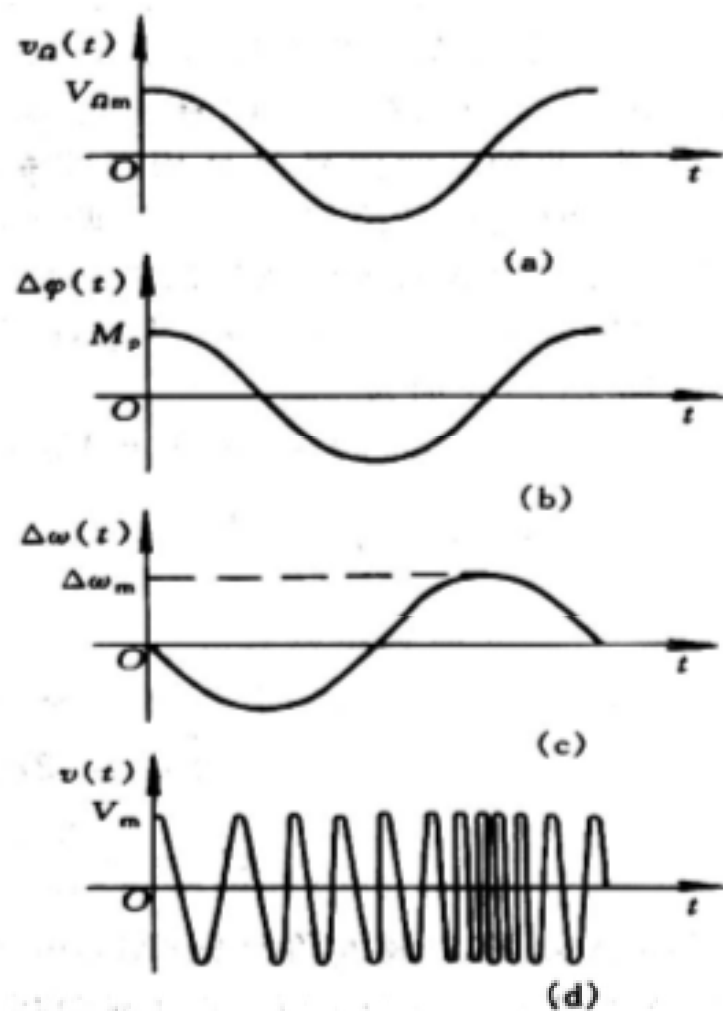
$$v_c(t) = V_{cm} \cos(\omega t + \theta) = V_{cm} \cos \phi(t)$$

- 频率调制（**Frequency Modulation**, 简称为**FM**）：正弦波的瞬时频率随调制信号线性变化称为频率调制
- 相位调制（**Phase Modulation**, 简称为**PM**）：正弦波的瞬时相位随调制信号线性变化，称为相位调制
- 由于频率调制与相位调制都表现为载波信号的总相角受到调变,故统称为角度调制。但已调波的振幅恒定不变。
- 角度调制与解调均属频谱非线性变换电路

## 单音调制的调频信号



## 单音调制的调相信号



## 调角波的数学表示式、频移和相移和调制指数

假定未调载波表示为：

$$v_c(t) = V_{cm} \cos(\omega_c t + \theta) = V_{cm} \cos[\phi(t)]$$

假定调制信号为一单频余弦波，并表示为：

$$v_f(t) = V_{\Omega m} \cos \Omega t$$

载波频率

■ 调频波的瞬时角频率为：

$$\omega_F(t) = \omega_c + K_F v_f(t) = \omega_c + \Delta\omega_m \cos\Omega t$$

最大频偏或简称频偏

$$\Delta\omega_m = K_F V_{\Omega m}$$

$$|\Delta\omega_F(t)|_{\max} = \omega_F(t) - \omega_c = K_F |v_f(t)|_{\max} = K_F V_{\Omega m}$$

# 调角波的数学表示式、频移和相移和调制指数（续1）

- 调频波的瞬时相位为：

$$\begin{aligned}\phi_F(t) &= \int_0^t \omega_F(\lambda) d\lambda + \theta_0 = \int_0^t [\omega_c + K_F v_f(\lambda)] d\lambda + \theta_0 \\ &= \omega_c t + K_F \int_0^t v_f(\lambda) d\lambda + \theta_0 = \omega_c t + \Delta\phi_F(t) + \theta_0\end{aligned}$$

- 调频波的调制指数

$$m_F = \left| \Delta\phi_F(t) \right|_{\max} = K_F \left| \int_0^{\lambda} v_f(\lambda) d\lambda \right|_{\max} = \frac{K_F V_{\Omega m}}{\Omega} = \frac{\Delta\omega_m}{\Omega} = \frac{\Delta f_m}{F}$$

## 调角波的数学表示式、频移和相移和调制指数（续2）

$$\begin{aligned}v_{FM}(t) &= V_{cm} \cos[\phi_F(t)] = V_{cm} \cos\left[\int_0^t \omega_F(\lambda) d\lambda + \theta_0\right] \\&= V_{cm} \cos\left[\omega_c t + K_F \int_0^t v_f(\lambda) d\lambda + \theta_0\right] \\&= V_{cm} \cos\left[\omega_c t + \frac{K_F V_{\Omega m}}{\Omega} \sin \Omega t + \theta_0\right] \\&= V_{cm} \cos[\omega_c t + m_F \sin \Omega t + \theta_0]\end{aligned}$$

### 主要性质有：

- 瞬时频率按调制信号的规律变化。瞬时相位按调制信号的时间积分值规律变化
- 调制信号的振幅决定频偏，调制信号的频率决定频率变化周期
- 调频波的幅度为常数
- 调频波的调制指数可大于1，而且通常应用于大于1的情况
- 调制指数与频偏成正比，与调制频率成反比



# 调角波的数学表示式、频移和相移和调制指数（续3）

## ■ 对于调相波

$$\phi_p(t) = \omega_c t + K_p v_f(t) + \theta_0$$

▼ 调相波的瞬时相位为：

$$= \omega_c t + \Delta\phi_p(t) + \theta_0$$

▼ 调相波的调制指数  $m_P$  —— 最大附加相移：

$$m_P = \left| \Delta\phi_P(t) \right|_{\max} = K_P \left| v_f(t) \right|_{\max} = K_P V_{\Omega m}$$

▼ 调相波的瞬时角频率为：

$$\omega_p(t) = \frac{d\phi_p(t)}{dt} = \frac{d[\omega_c t + K_P v_f(t)]}{dt} = \omega_c + K_P \frac{dv_f(t)}{dt} = \omega_c + \Delta\omega_p(t)$$

▼ 单频余弦调制  
时调相波的数学  
表示式：

$$\begin{aligned} v_{PM}(t) &= V_{cm} \cos[\phi_p(t)] \\ &= V_{cm} \cos[\omega_c t + K_p v_f(t) + \theta_0] \\ &= V_{cm} \cos[\omega_c t + K_P V_{\Omega m} \cos \Omega t + \theta_0] \\ &= V_{cm} \cos[\omega_c t + m_P \cos \Omega t + \theta_0] \end{aligned}$$

# 调角波的数学表示式、频移和相移和调制指数（续4）

调频波和调相波的主要参数

	频率调制	相位调制
瞬时角频率	$\omega_F(t) = \omega_c + K_F v_f(t)$	$\omega_p(t) = \omega_c + K_p dv_f(t) / dt$
附加相位	$\theta_F(t) = K_F \int_0^t v_f(\lambda) d\lambda$	$\theta_p(t) = K_p v_f(t)$
全相角	$\phi_F(t) = \omega_c t + K_F \int_0^t v_f(\lambda) d\lambda + \theta_0$	$\phi_p(t) = \omega_c t + K_p v_f(t) + \theta_0$
已调信号	$v_{FM}(t) = V_{cm} \cos[\phi_F(t)]$	$v_{PM}(t) = V_{cm} \cos[\phi_p(t)]$

# 频率调制信号的频谱

假定调制信号为一单频余弦波，并表示为：

$$v_f(t) = V_{\Omega m} \cos \Omega t$$

调频波的表示式为：

$$v_{FM}(t) = \cos[\omega_c t + m_F \sin \Omega t]$$

下面分析单频余弦信号调制下，调频波的频谱。

$$v_{FM}(t) = \cos \omega_c t \cos(m_F \sin \Omega t) - \sin \omega_c t \sin(m_F \sin \Omega t)$$

$$v_{FM}(t) = J_0(m_F) \cos \omega_c t + J_1(m_F) [\cos(\omega_c + \Omega)t - \cos(\omega_c - \Omega)t]$$

$$+ J_2(m_F) [\cos(\omega_c + 2\Omega)t + \cos(\omega_c - 2\Omega)t]$$

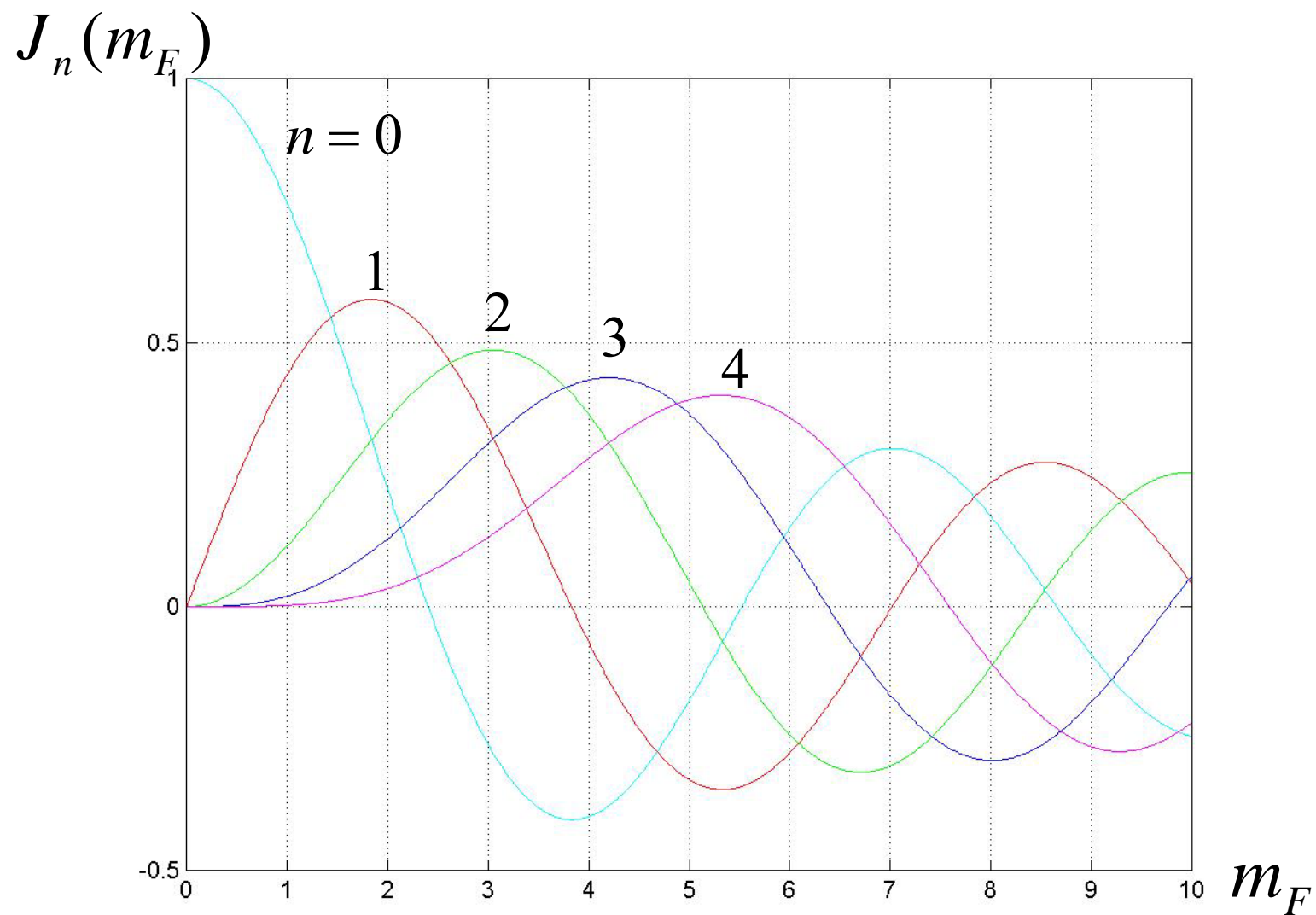
$$+ J_3(m_F) [\cos(\omega_c + 3\Omega)t - \cos(\omega_c - 3\Omega)t]$$

+ ...

$$= \sum_{n=-\infty}^{\infty} J_n(m_F) \cos(\omega_c + n\Omega)t$$

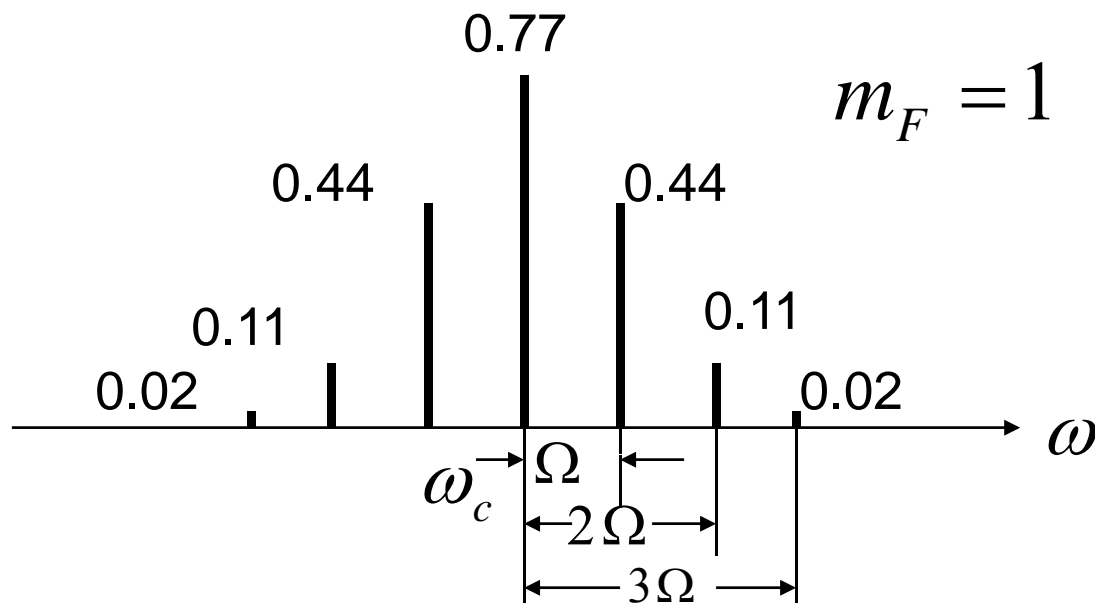
贝赛尔函数

## 频率调制信号的频谱（续2）



# 调频波的频谱特点

- 包含载波频率分量（但是幅度小于1，与  $m_F$  有关。）；还包含无穷多个旁频分量；
  - 各旁频分量之间的距离是调制信号角频率  $\Omega$ ；
  - 各频率分量的幅度由贝塞尔函数  $J_n(m_F)$  决定；
- 频率调制不是将信号的频谱在频率轴上平移,而是将信号各频率分量进行非线性变换。因此，频率调制是一种非线性过程，又称为非线性调制
- 各频率分量间的功率分配。因为调频波是一个等幅波，所以它的总功率为常数，不随调制指数的变化而变化，并且等于未调载波的功率。调制后，已调波出现许多频率分量，这个总功率就分配到各分量。随  $m_F$  的不同，各频率分量之间功率分配的数值不同



# 调频波的频带

- 1、调频波所占的带宽，理论上说是无穷宽的，因为它包含有无穷多个频率分量。
- 2、但实际上，在调制指数一定时，超过某一阶数的贝塞尔函数的值已经相当小，其影响可以忽略，这时则可认为调频波所具有的频带宽度是近似有限的。

$$J_n(m_F) \approx 0 \quad n > m_F + 1$$

- 3、调频波的频带宽度有两种近似：

忽略了小于0.01的分量：  
(集中99%以上的功率)

$$BW_{0.01} \approx 2(m_F + \sqrt{m_F} + 1)F$$

忽略了小于0.1的分量：

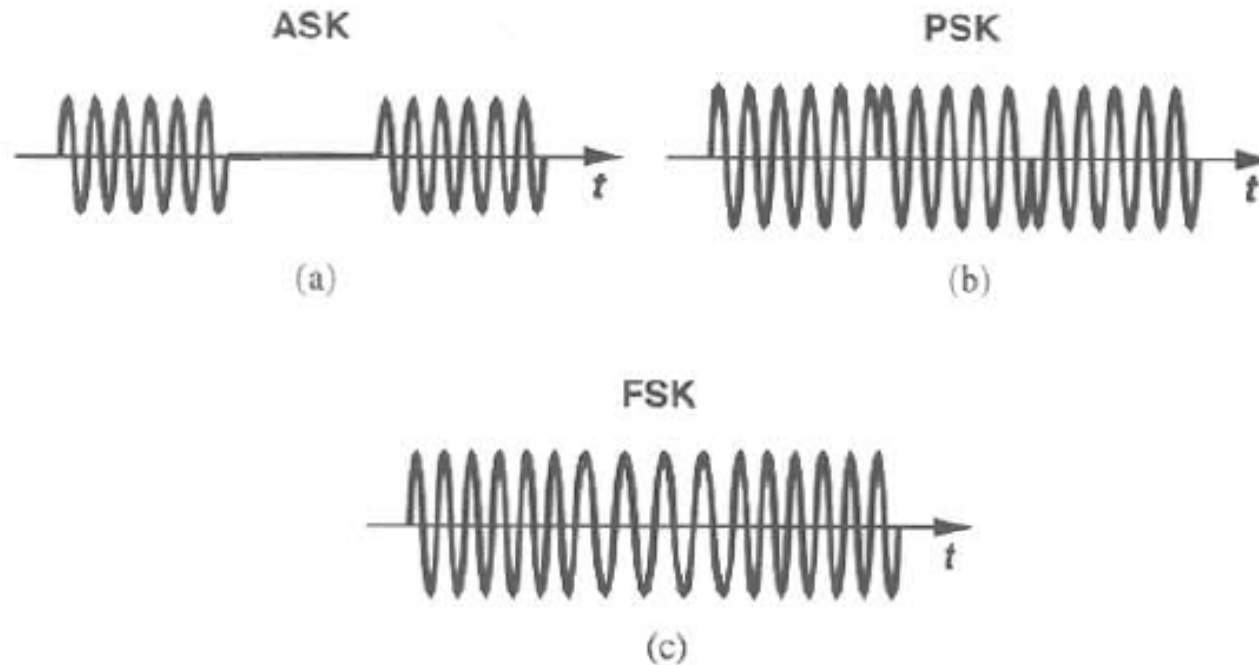
$$BW_{0.1} \approx 2(m_F + 1)F = 2(\Delta f_m + F)$$

卡森 (Carson) 公式



# 数字调制

- 数字调制：用数字信号对载波进行调制，使数字信号能在带通信道中进行传输的一种调制形式
- 调制方式：幅度键控、频移键控、相移键控



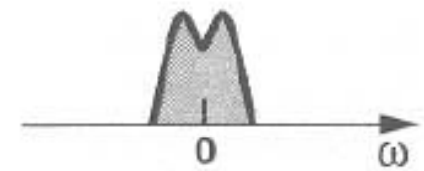
# 衡量调制方式性能的参数

- **信号质量**: 在传输信道存在衰减、干扰以及噪声的情况下, 接收机恢复出来信号的信号的质量
  - ◆ **BER (Bit Error Rate)**: Average number of erroneous bits observed at the output of the detector divided by the total number of bits received in a unit time
- **Power Efficiency**: Ability of a modulation technique to preserve the fidelity of digital message at low power level
  - ◆ Signal energy per bit to noise power spectral density ( $E_b/N_0$ ) required at the receiver input for a certain probability of error
- **Spectral Efficiency**: Ability of a modulation scheme to accommodate data within a limited bandwidth, dependent on the data rate
  - ◆ Throughput data rate per Hertz
  - ◆ Upper bound( Shannon's channel coding theorem)

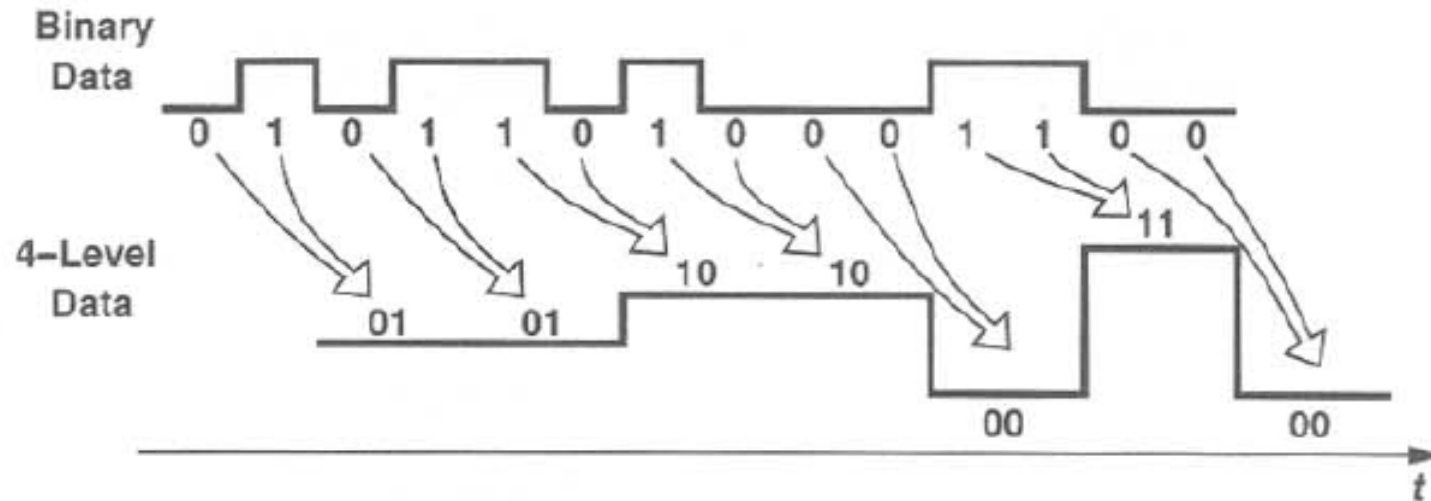
$$\eta_{B_{\max}} = \frac{C}{B} = \log_2 \left( 1 + \frac{S}{N} \right)$$

# Basic Concepts

- **Baseband Signal:** Defined as one whose spectrum is nonzero in the vicinity of  $\omega=0$  and negligible elsewhere

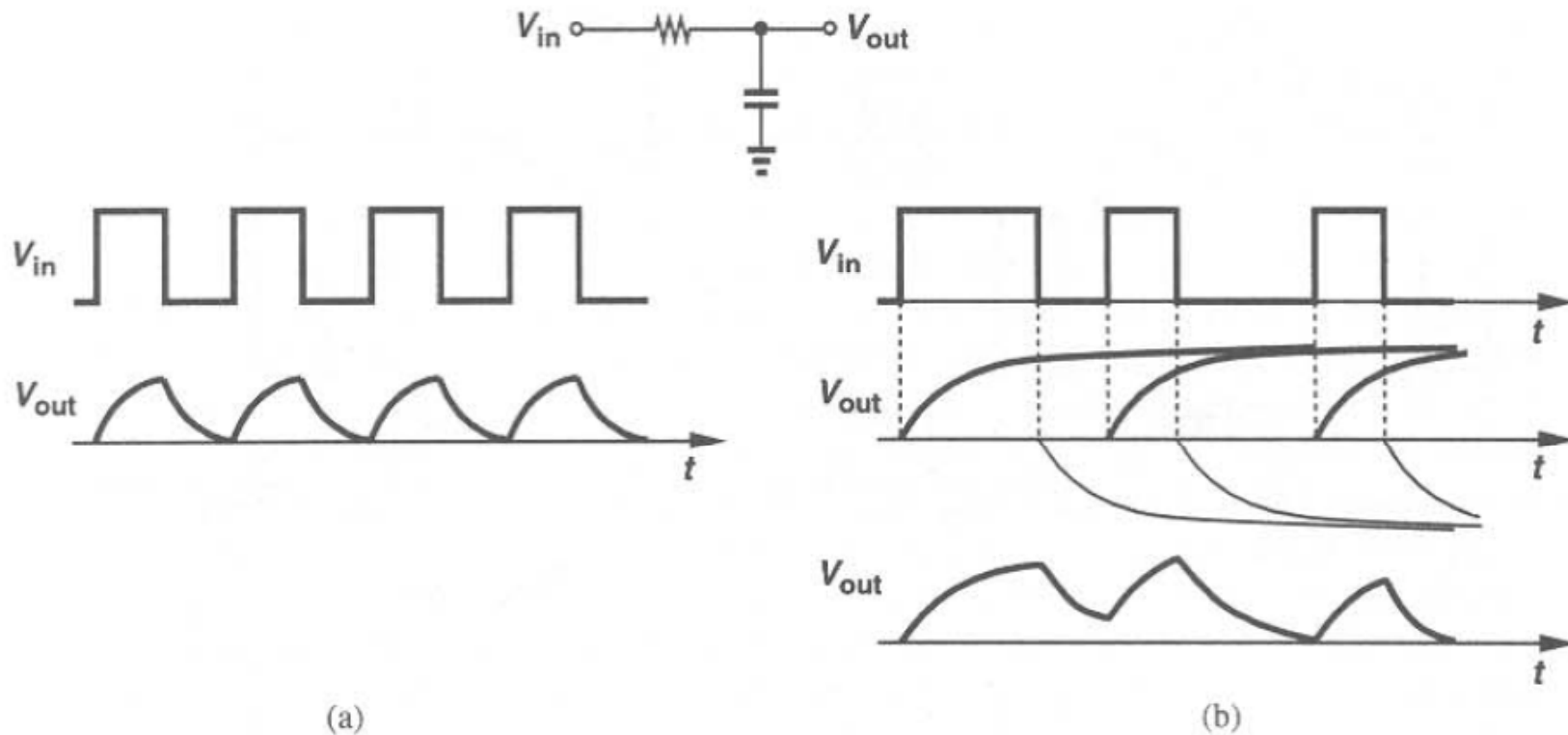


- 数字基带编码:



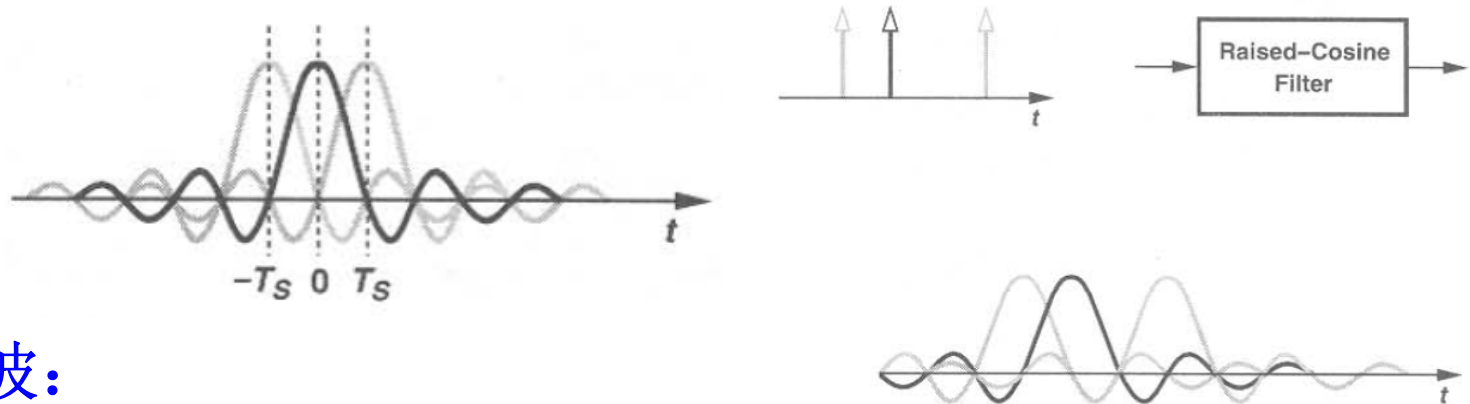
# ISI

- **ISI (Intersymbol Interference):** Each bit level is corrupted by decaying tails created by previous bits due to limited channel bandwidth



# ISI的解决办法

- 奈奎斯特第一准则：如果信号经传输后整个波形发生了变化，但只要其特定点的抽样值保持不变，那么用再次抽样的方法，仍然可以准确无误的恢复原始信号，因为信息完全携带在抽样幅度值上



- 升余弦滤波：
- 均衡：一个实际的基带传输系统不可能完全满足理想的波形传输无失真条件，因而串绕几乎是不可避免的。当串绕造成严重影响时，必须对整个系统的传递函数进行校正，使其接近无失真传输条件
  - ◆ 频率均衡：补偿整个系统的幅频和相频特性
  - ◆ 时域均衡：直接校正系统的冲激响应

# 眼图

- The eye diagram provides visual information that can be useful in the evaluation and troubleshooting of digital transmission systems
- The eye diagram is an oscilloscope display of a digital signal, repetitively sampled to get a good representation of its behavior

Figure 1. Transition Pattern 011

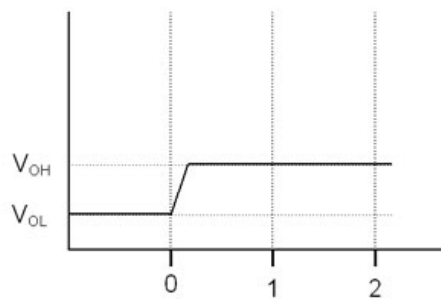


Figure 2. Transition Pattern 001

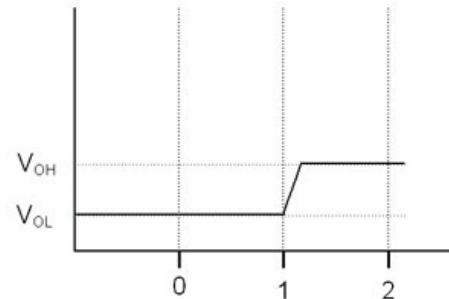


Figure 3. Transition Pattern 100

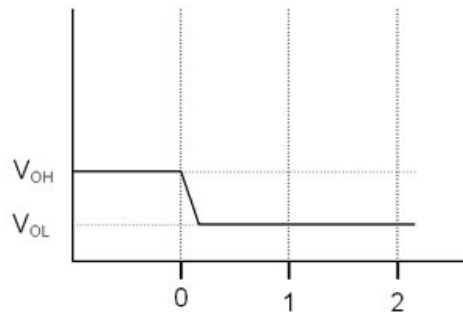


Figure 4. Transition Pattern 110

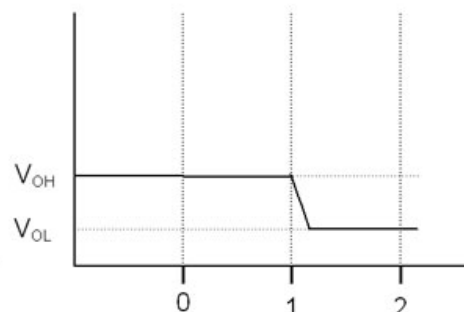
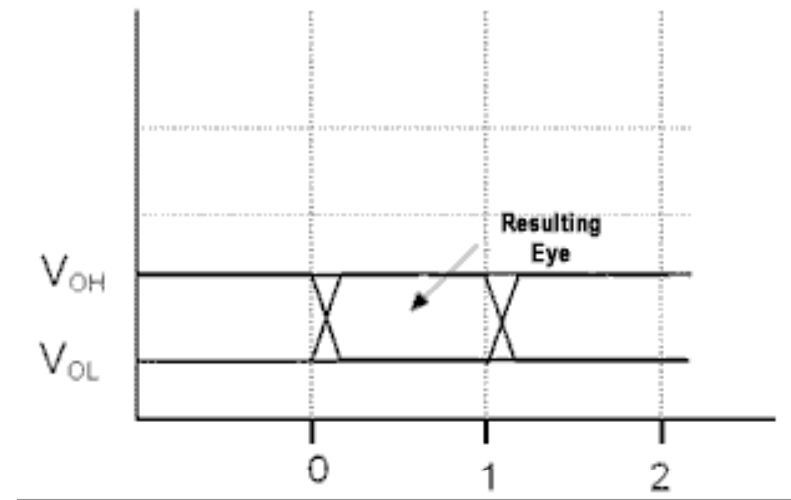
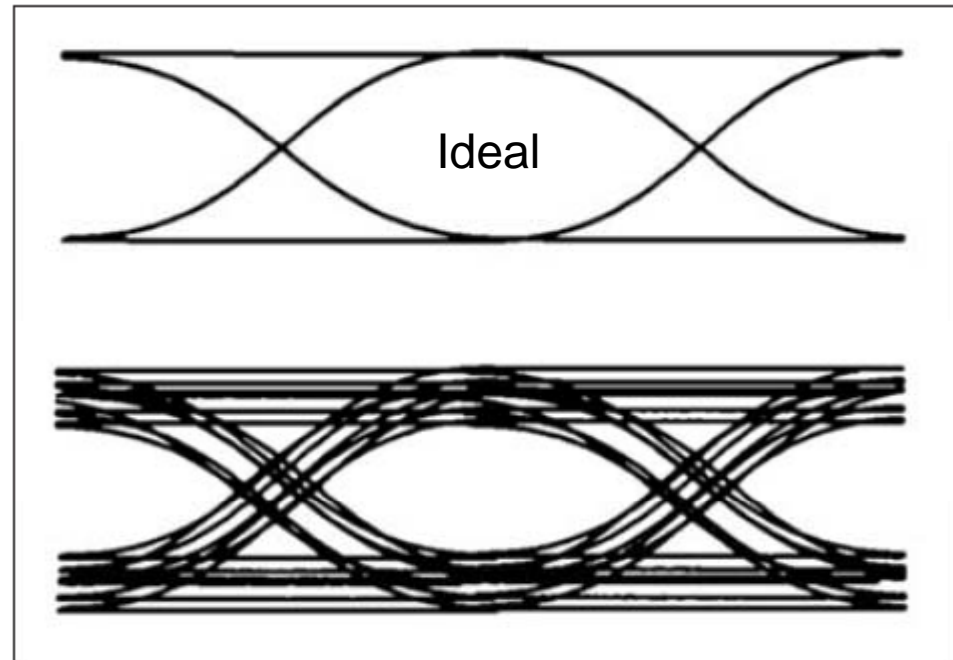
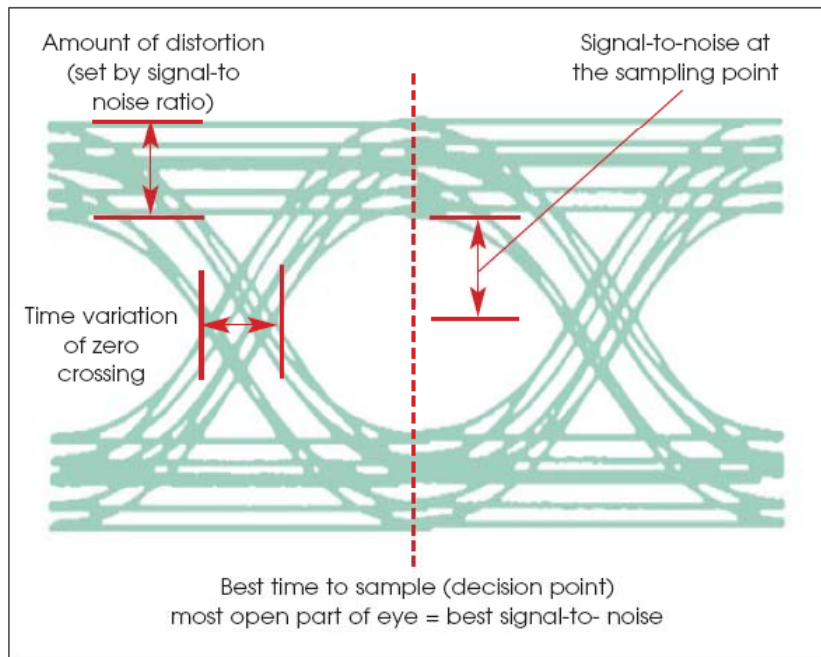


Figure 5. Sample Eye Diagram





# 眼图 (续)



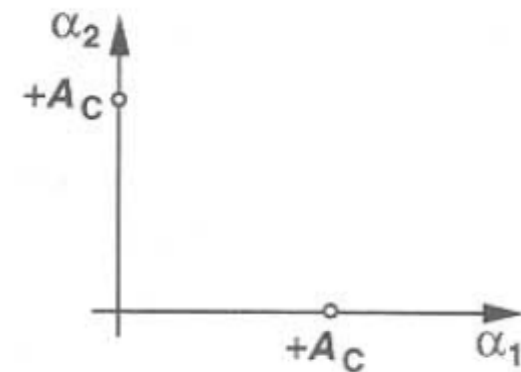
**Amplitude (noise) and phase (timing) errors**

# Constellations

- **Signal Constellations: Representing a waveform as a linear combination of “basis functions”, ignore the basis functions and plot all possible values of the vector in cartesian coordinates.**

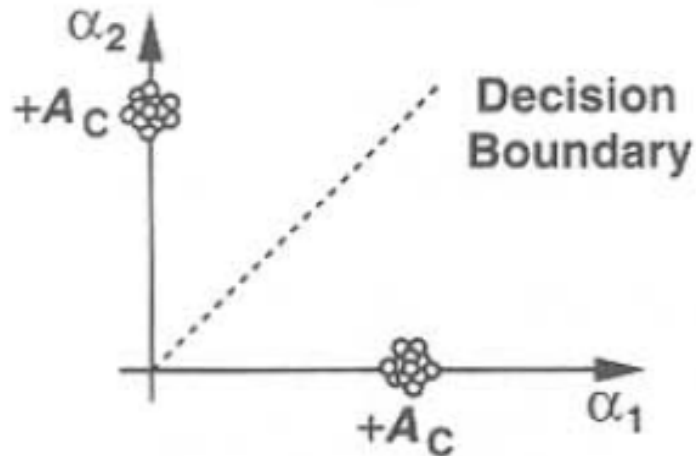
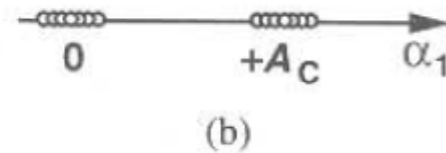
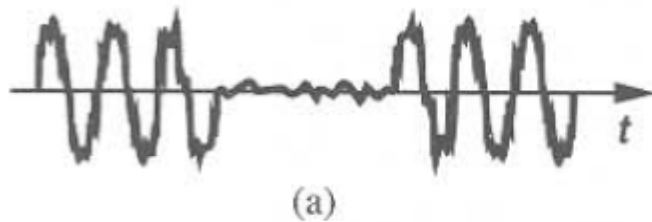
$$\begin{aligned}x_{FSK}(t) &= A_c \cos \omega_1 t, & \text{if } b_n = 0, \\ &= A_c \cos \omega_2 t, & \text{if } b_n = 1.\end{aligned}$$

$$\begin{aligned}x_{FSK}(t) &= \alpha_1 \phi_1(t) + \alpha_2 \phi_2(t) \\ &= [\alpha_1 \ \alpha_2] \cdot [\phi_1(t) \ \phi_2(t)],\end{aligned}$$



# Noise and Constellation

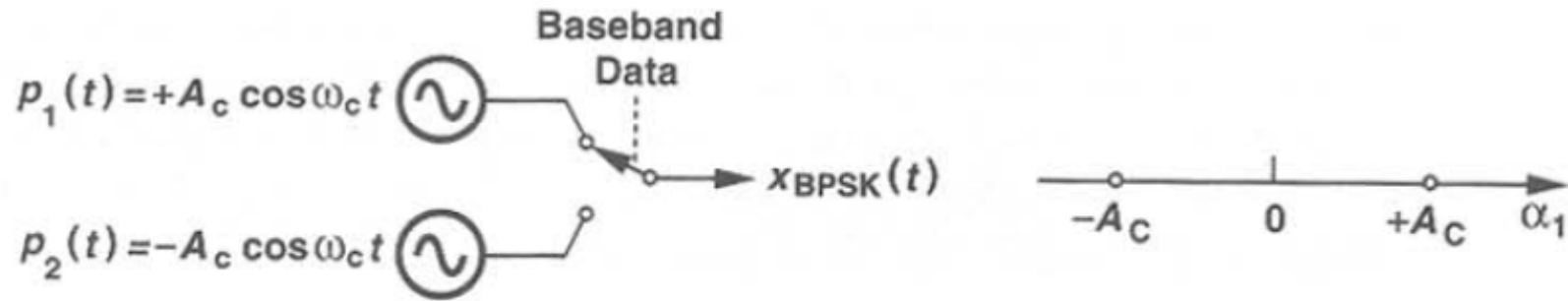
$$\text{ASK: } x_{ASK}(t) = A_c \cos \omega_c t, \quad \text{if } b_n = 1, \\ = 0, \quad \text{if } b_n = 0.$$



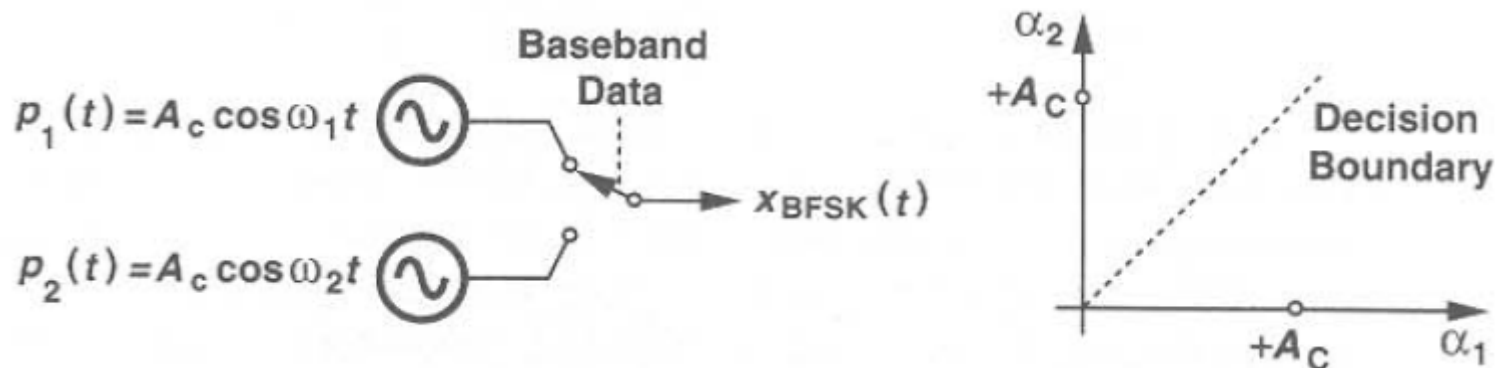
FSK

# 常见的数字调制

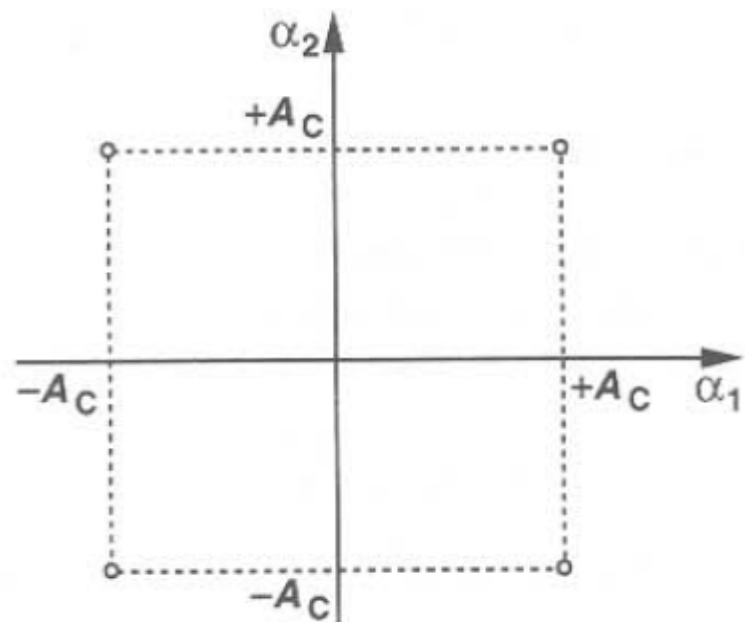
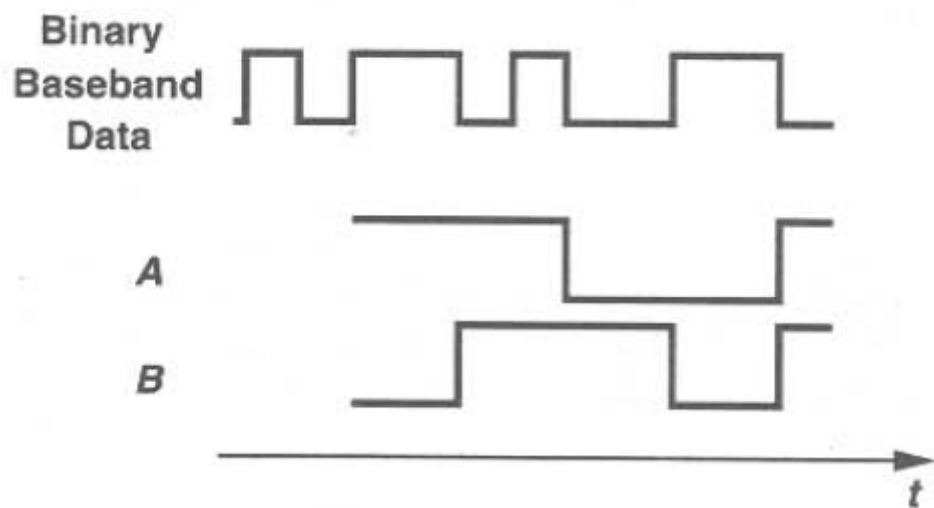
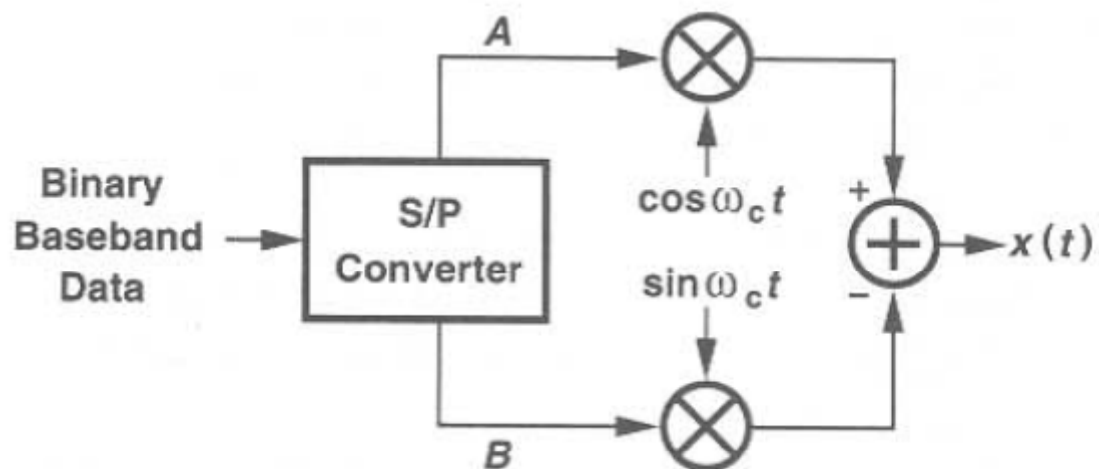
- **BPSK: the binary baseband data selects one of two opposite phases of the carrier**



- **BFSK: the binary baseband data selects one of two carrier frequencies with equal amplitudes**



# 正交调制



# MSK & GMSK

