An Introduction to High-Frequency Circuits and Systems

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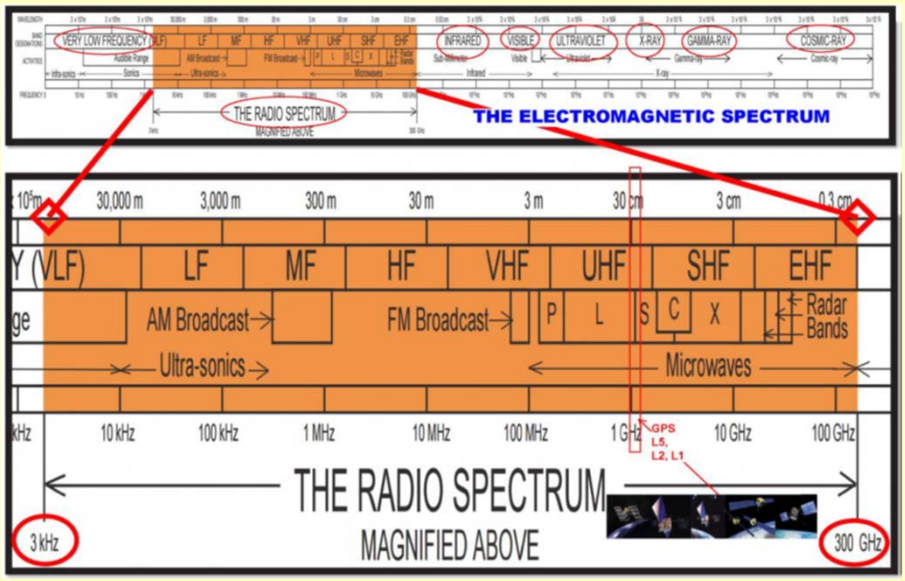
Outline

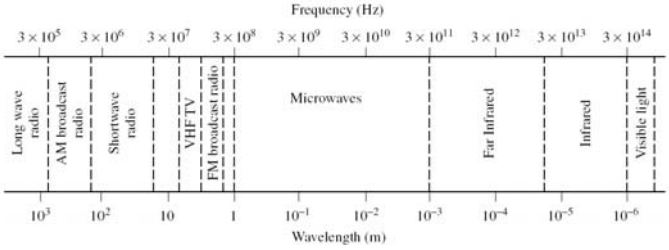
- The electromagnetic spectrum
- Review of market and technology trends
  - Semiconductors industry
  - Computers industry - signal integrity issues
  - Communication industry

Electromagnetic Spectrum



(US Department of Transportation, 2020)

Electromagnetic Spectrum (cont.)



Typical Frequencies		Approximate Band Designations	
AM broadcast band	535–1605 kHz	Medium frequency	300 kHz to 3 MHz
Short wave radio band	3–30 MHz	High frequency (HF)	3 MHz to 30 MHz
FM broadcast band	88–108 MHz	Very high frequency (VHF)	30 MHz to 300 MHz
VHF TV (2–4)	54–72 MHz	Ultra high frequency (UHF)	300 MHz to 3 GHz
VHF TV (5–6)	76–88 MHz	L band	1–2 GHz
UHF TV (7–13)	174–216 MHz	S band	2–4 GHz
UHF TV (14–83)	470–890 MHz	C band	4–8 GHz
US cellular telephone	824–849 MHz	X band	8–12 GHz
	869–894 MHz	Ku band	12–18 GHz
European GSM cellular	880–915 MHz	K band	18–26 GHz
	925–960 MHz	Ka band	26–40 GHz
GPS	1575.42 MHz	U band	40–60 GHz
	1227.60 MHz	V band	50-75 GHz
Microwave ovens	2.45 GHz	E band	60-90 GHz
US DBS	11.7–12.5 GHz	W band	75-110 GHz
US ISM bands	902–928 MHz	F band	90-140 GHz
	2.400–2.484 GHz		
	5.725–5.850 GHz		
US UWB radio	3.1–10.6 GHz		

(D. M. Pozar, Microwave Engineering, Wiley, 2005)

Practical RF and Microwave Regions

Radio frequency (RF) systems:

- FM radio, cell phones, TV, wireless phones, GPS, etc.
- frequency range: 10 MHz to 1 GHz (approx.)
- wavelength in air: 30 m to 30 cm

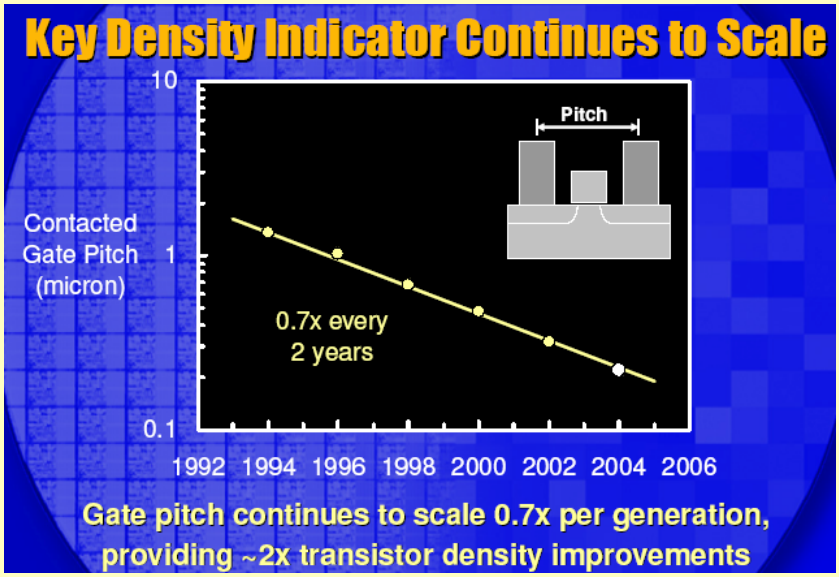
Microwave (μW) systems:

- microwave ovens, satellite circuits, radar, remote sensing, microwave antennas, ultra high-speed interconnects, etc.
- frequency range: 1 GHz to 100 GHz (approx.)
- wavelength in air: 30 cm to 3 mm

Semiconductor Industry – Technology Trends

- The use of new semiconductor and dielectric materials and manufacturing processes has been enabling faster and smaller transistors
- The minimum dimension of transistors has been continuously decreasing: 25 μm in 1960 to 32 nm in 2010 (about 200 silicon atoms); 5 nm in 2020

Decreasing Dimension of Transistors



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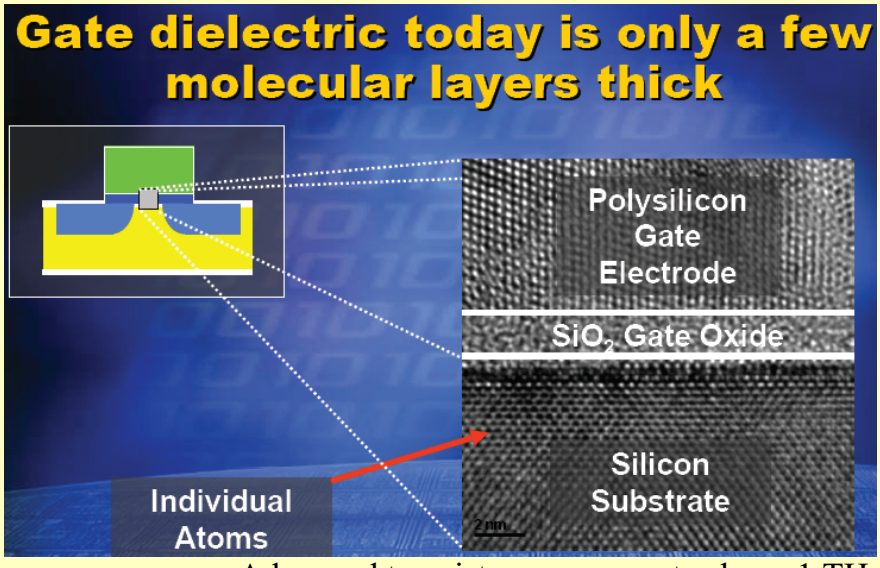
Decreasing Dimension of Transistors (cont.)



Advanced transistors can operate above 1 THz

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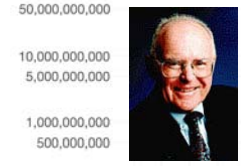
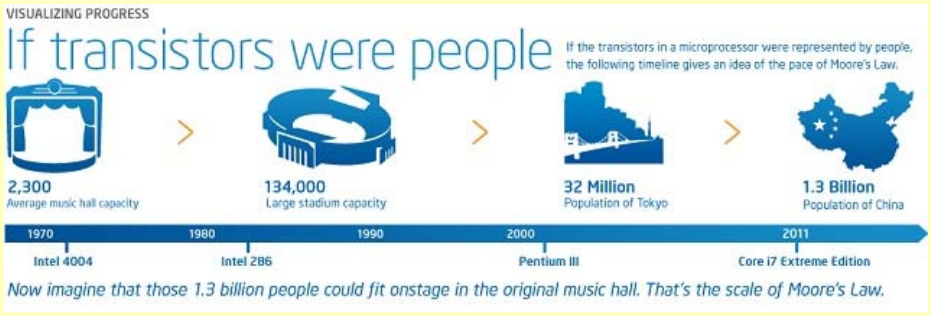
Computer Industry – Technology Trends

- The number of transistors per chip has continue to double every 1.5-2 year (Moore's law)
- CPU operating frequency has continuously increase (up to a practical limit ~ 4 GHz, due to thermal issues)
- Denser and faster buses have appeared
- Faster memories are required
- Cost of interconnects remain a small fraction (< 5%) of the system cost

Moore's Law

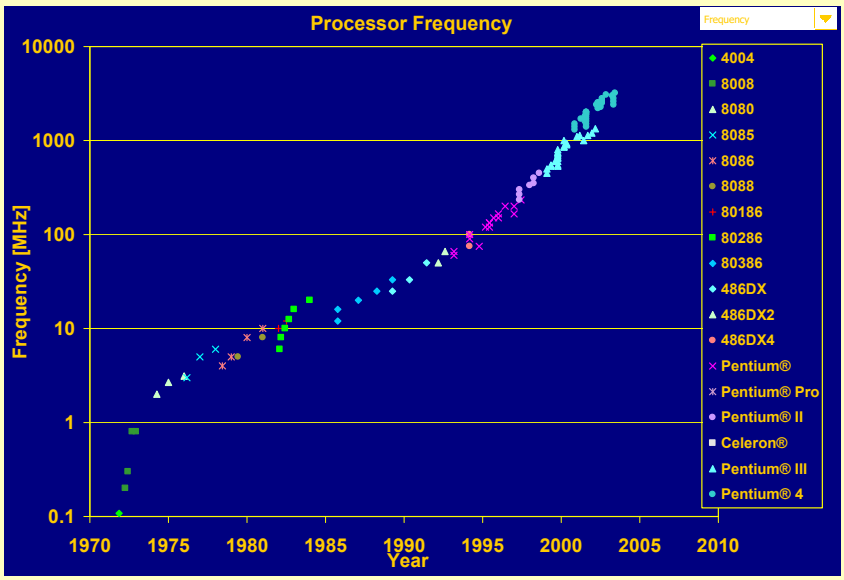


Moore's Law (cont.)



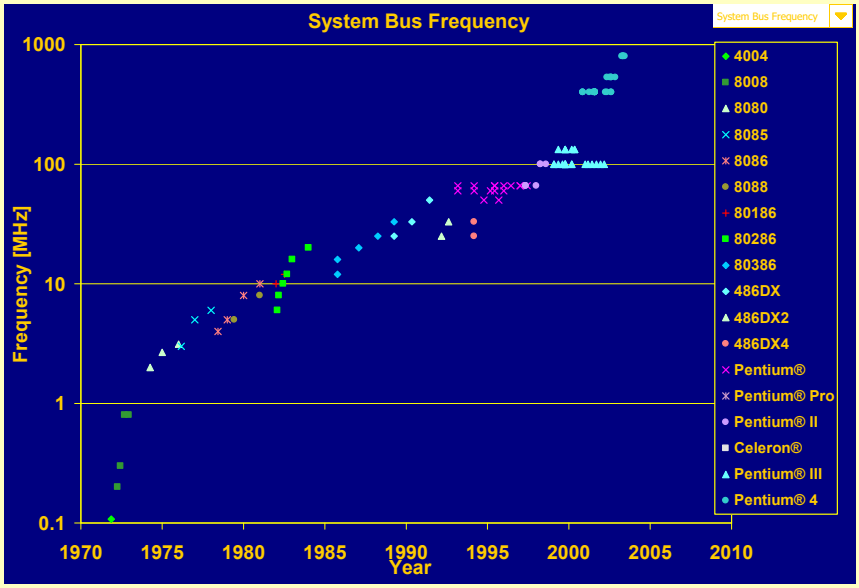
(Intel Corporation)

CPU Operating Frequency



(H. Heck, 2005)

Denser and Faster Buses



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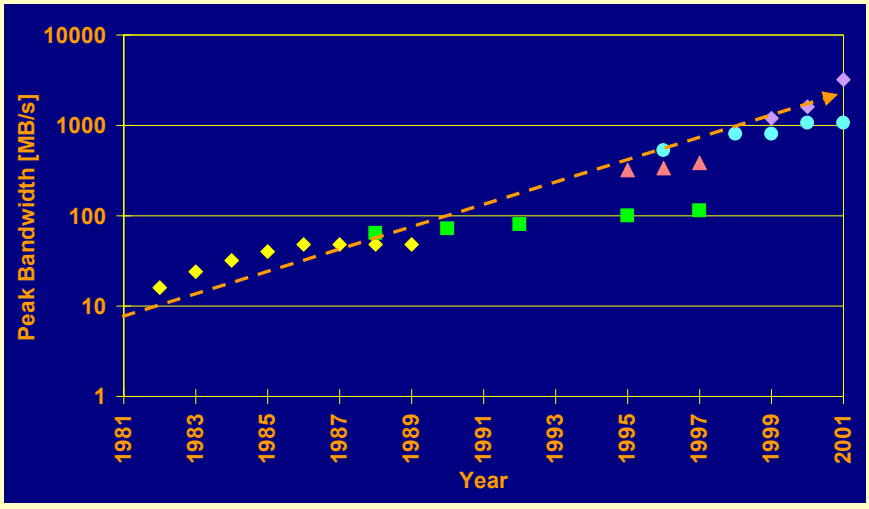
(H. Heck, 2005) 13

Faster and Denser Memories



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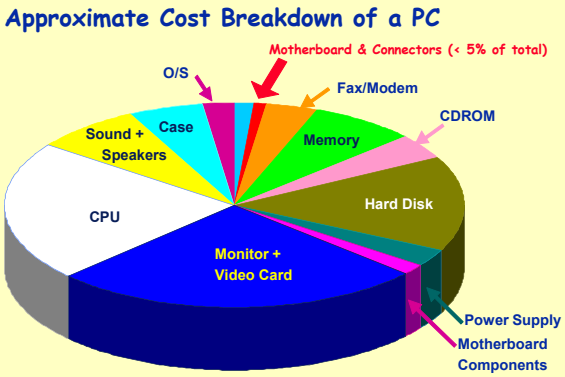
(H. Heck, 2005) 14

Cost of Interconnects

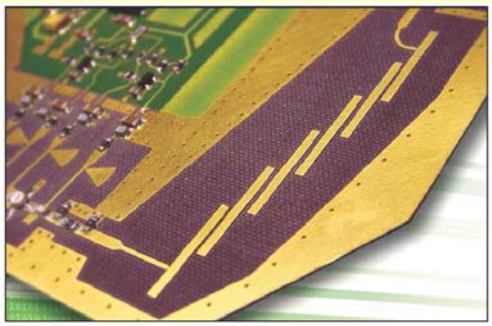
- Interconnect makes up < 5% of the system cost
  - Most technical problems can be solved with $
  - High volume PC market can't afford extra cost
- Designing Multi-GHz interconnects to fit in sub $1000 PCs is a huge challenge



(H. Heck, 2005)

Cost of Interconnects (cont.)

- FR4 has been the standard choice for PCBs in the last four decades
- Other dielectrics have better performance: polyethylene (PE), polytetrafluoroethylene (PTFE)
- PTFE-based laminates can cost up to US$100 per squared foot
- FR4 is < US$2/sq ft



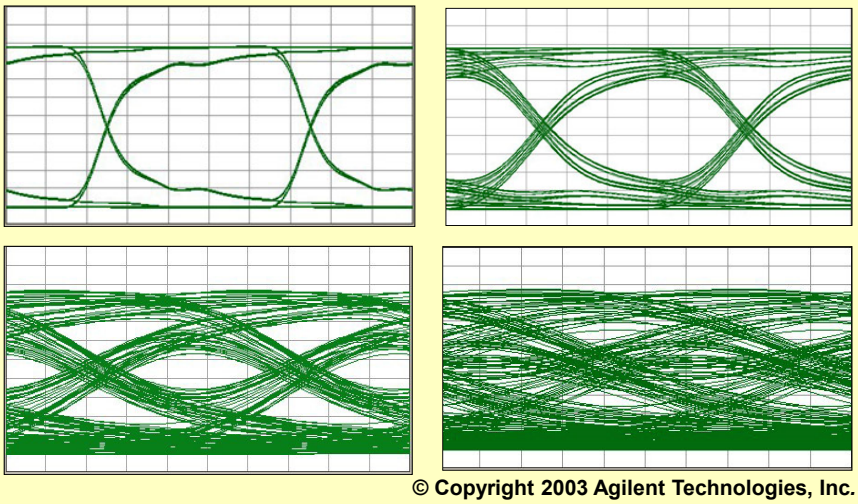
(D. Reed, 2003)

High-Speed Digital Design

- Physical design becomes crucial: connectors, backplanes, packages, PCB structures, material properties, etc.
- Analog techniques (**analog electronics, RF and microwave engineering**) are used to solve most signal integrity problems

High-Speed Digital Design (cont.)

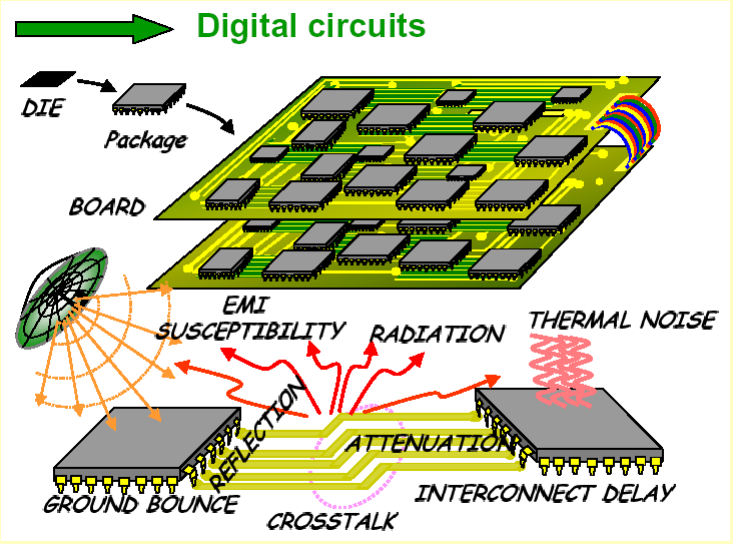
Eye Diagrams (for a 25-inch channel)



What is Signal Integrity (SI)?

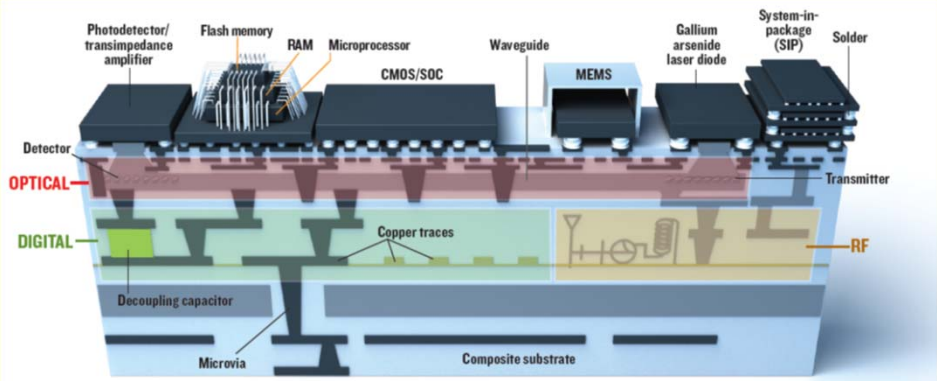
- It is an engineering practice that aims at ensuring reliable high-speed data transmission and reception, without polluting the electromagnetic spectrum and without damaging any device
- SI effectively combines concepts and techniques from the following disciplines:
  - microwave and RF engineering
  - electromagnetics
  - physical design
  - analog electronics
  - communications, and
  - digital design

SI Problems Appear at Different Levels



(M. Nakhla, 2004)

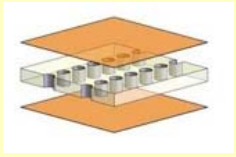
Systems on Packages (SOP)



MANY IN ONE: This is an illustration of a system-on-package test bed that combines three types of circuits in its dielectric layers: an optical circuit—with waveguide and detector just beneath the surface; RF thin-film components—resistors, inductors, and antennas, embedded within the package; and digital thin-film components—low-loss dielectrics, low-resistance conductors, and decoupling capacitors—at the bottom. In addition, a variety of bare and packaged devices, including flash memory, microprocessor, system-on-chip (SOC), the optical circuit's gallium arsenide laser diode, MEMS, and system-in-package (SIP) devices can be attached to the top layer. Global interconnections on the surface connect the top devices to the layers, which are deposited on a thin but stiff inorganic composite substrate.

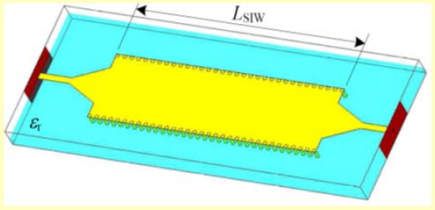
New Paradigms for High-Speed Interconnects

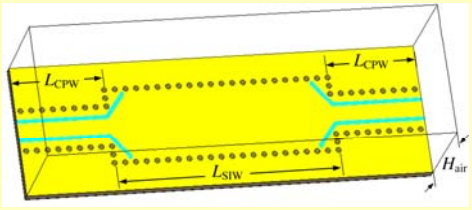
Substrate Integrated Waveguides (SIW)



(K. Wu, 2001)

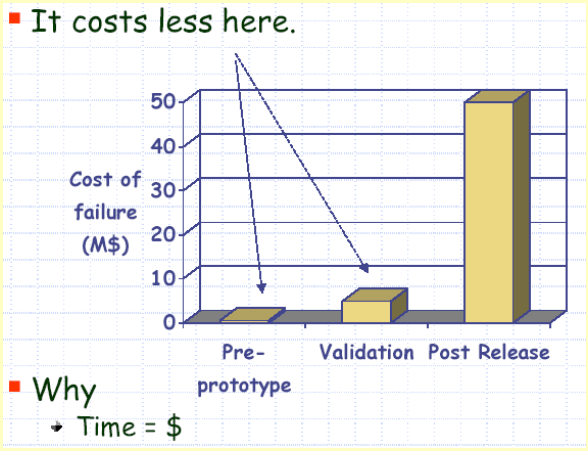
(J.J. Simpson, 2006)





Effective Signal Integrity Practices

- Correcting signal integrity problems after the hardware has been created can be extremely complicated and costly



(R. Mellitz, 2003)

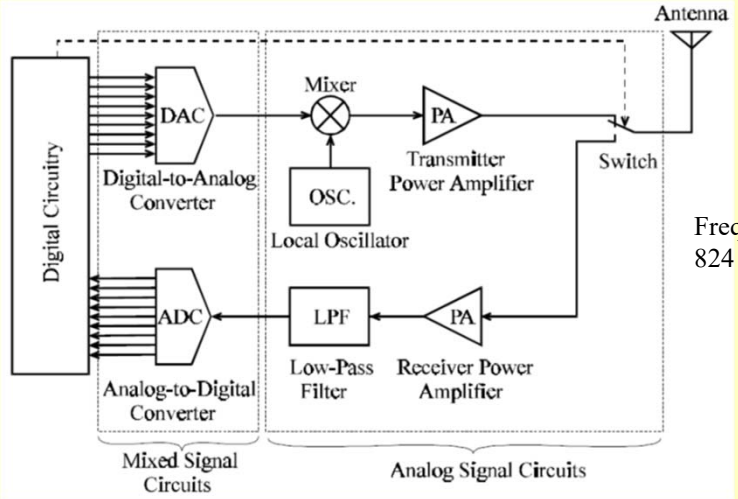
Communications Industry Drive

An extremely fast growth has been consistently occurring in:

- Cellular phone service
- Direct Broadcast Satellite (DBS) television
- Wireless Local Area Networks (WLAN)
- Global Positioning Satellite (GPS) service
- Radio Frequency Identification (RFID) systems
- The Internet of Things (IoT) and Internet of Space (IoS)

In early 1980's a marketing firm hired by AT&T forecasted less than 900,000 cell phone users in USA by the year 2000. In 1998, the number of subscribers in USA was over 6 millions *(D.M. Pozar, 2001)*

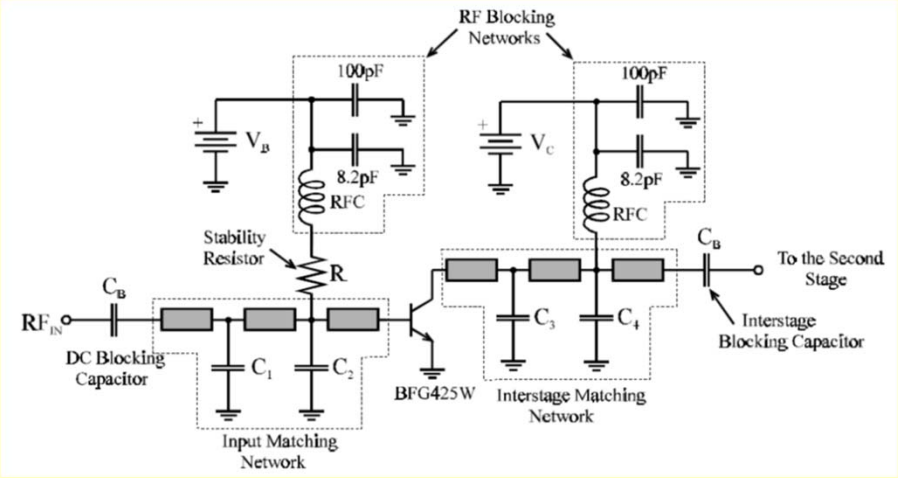
Cell Phone Transceiver



Frequency range:
824 MHz – 1.9GHz

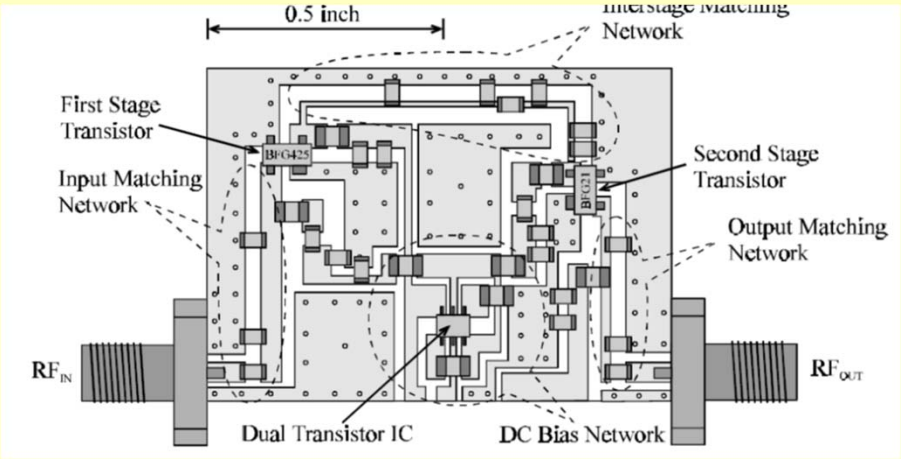
(R. Ludwig and P. Bretchko, RF Circuit Design, Prentice Hall, 2000)

RF Power Amplifier Equivalent Circuit



(R. Ludwig and P. Bretchko, RF Circuit Design, Prentice Hall, 2000)

Two-stage RF Power Amplifier Implementation



(R. Ludwig and P. Bretchko, RF Circuit Design, Prentice Hall, 2000)

Bandstop Microstrip Filter