CHAPTER 0
WIRELESS COMMUNICATION RF/MICROWAVE/MM-WAVE CIRCUIT DESIGN & RFIC
BRIEF INTRODUCTION
無線通訊射頻/微波/毫米波電路設計簡介

Radio Frequency (RF) & Microwave (MW) Bands

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Band Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-30kHz</td>
<td>L band</td>
</tr>
<tr>
<td>30kHz – 300kHz</td>
<td>S band</td>
</tr>
<tr>
<td>300kHz – 3000kHz</td>
<td>C band</td>
</tr>
<tr>
<td>3MHz - 30MHz</td>
<td>X band</td>
</tr>
<tr>
<td>30MHz - 300MHz</td>
<td>Ku band</td>
</tr>
<tr>
<td>300MHz - 3000MHz</td>
<td>K band</td>
</tr>
<tr>
<td>1-2GHz</td>
<td>Ka band</td>
</tr>
<tr>
<td>2-4GHz</td>
<td>(Millimeter Wave 毫米波)</td>
</tr>
<tr>
<td>4-8GHz</td>
<td>mm-wave: wavelength &lt; 1cm</td>
</tr>
<tr>
<td>8-12GHz</td>
<td>1-2GHz</td>
</tr>
<tr>
<td>12-18GHz</td>
<td>2-4GHz</td>
</tr>
<tr>
<td>18-26GHz</td>
<td>4-8GHz</td>
</tr>
<tr>
<td>26-40GHz</td>
<td>8-12GHz</td>
</tr>
<tr>
<td>30-300GHz</td>
<td></td>
</tr>
</tbody>
</table>

射頻（RF：radio frequency）
● 廣義定義：無電收發機從天線下來至中頻(IF)前之電路次系統
● 狹義定義：目前無線行動通訊所用之頻率範圍由 < 3GHz 提高至 5 GHz (WLAN 802.11a) and higher to 10 GHz (UWB: ultrawide-band impulse radio communication)

微波 (MW: microwave > 4 GHz ?)
### Wireless Communication Bands

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AMPS</strong> (mobile unit)</td>
<td>824-849MHz (Tx), 869-894 MHz (Rx)</td>
</tr>
<tr>
<td><strong>European GSM</strong> (mobile unit)</td>
<td>880-915 MHz (Tx), 925-960 MHz (Rx)</td>
</tr>
<tr>
<td><strong>PCS</strong> (mobile unit)</td>
<td>1710-1785MHz (Tx)</td>
</tr>
<tr>
<td></td>
<td>1805-1880 MHz (Rx)</td>
</tr>
<tr>
<td><strong>Paging</strong></td>
<td>931-932 MHz</td>
</tr>
<tr>
<td><strong>GPS</strong></td>
<td>1227 MHz (L2)</td>
</tr>
<tr>
<td><strong>DAB</strong> (Digital Audio Broadcasting)</td>
<td>1575 MHz (L1)</td>
</tr>
<tr>
<td></td>
<td>1452~1492 MHz (L band)</td>
</tr>
<tr>
<td><strong>ISM bands</strong></td>
<td>902-928 MHz</td>
</tr>
<tr>
<td>(Bluetooth, WLAN IEEE 802.11b)</td>
<td>2.4-2.484 GHz</td>
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<tr>
<td><strong>U-NII bands</strong></td>
<td>5.15-5.35</td>
</tr>
<tr>
<td>(HiperLAN, WLAN IEEE 802.11a)</td>
<td>5.725-5.85 GHz</td>
</tr>
<tr>
<td><strong>DBS</strong> (Direct Broadcasting Satellite)</td>
<td>11.7-12.5GHz</td>
</tr>
<tr>
<td><strong>LMDS</strong> (Local Multiple Distribution System)</td>
<td>27-32GHz</td>
</tr>
<tr>
<td><strong>UWB Radio (IEEE 802.15)</strong></td>
<td>3-10GHz</td>
</tr>
<tr>
<td><strong>60-GHz mm-wave Wireless LAN</strong></td>
<td>57-64GHz</td>
</tr>
<tr>
<td><strong>77-GHz Automotive anti-collision radar</strong></td>
<td></td>
</tr>
</tbody>
</table>

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### Six Wireless Communication Systems

- **MegaCell**: Terrestrial fixed link
- **Satellite**: Fixed link
- **Picocell**: Fixed link
- **Macrocell**: Fixed link

### UMTS / 3G Spectrum
- **Wide Area**: > 9.6 kbps
- **Community**: > 144 kbps
- **In-Building**: > 2 Mbs

### UWB Spectrum
- **UMTS / 3G Spectrum**: ≥ 384 kbps
- **UWB**: ≥ 2 Mbs

### 60-GHz MM-wave WPAN & Wireless-HD Applications

- **60-GHz MM-wave WPAN & Wireless-HD Applications**
  - **LAN**: 60 GHz
  - **Mobile phone**: 60 GHz
  - **Notebook**: 60 GHz
  - **Obstructing wall**: 60 GHz
  - **60 GHz**: 60 GHz
  - **5 GHz**: 60 GHz

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*H.-R. Chuang, EE NCKU*
Differentiating among the profusion of current and emerging standards for wireless networking can be a challenge. Agilent has products, education, and services to help you unravel the intricacies of these complementary technologies, including the following.

WiMAX – the emerging IEEE 802.16a/d standards provide a wireless broadband connection that can replace DSL or cable modems as the medium for high speed Internet access. The range for WiMAX is 1 to 20 miles.

WLAN – the IEEE 802.11a/b/g WLAN (or Wi-Fi) standards connect multiple computers in a home or office, or at wireless hot spots, linking devices to a single Internet access point and to each other. The WLAN variants (802.11b/n/p) provide different data rates and networking schemes, generally at distances to 300 feet.

Bluetooth – the IEEE 802.15.1 standard is one of the first to provide an RF connection between two devices, allowing them to exchange information. Bluetooth lets you synchronize your computer and PDA, for example, or send a file to a printer over the air. Range is up to approximately 30 feet.

Ultra-wideband – wireless personal area networks, the IEEE 802.15.3a ultra-wideband (UWB) specification is being developed for home theater and wireless USB2 or 1394 (Firewire) applications up to 30 feet.

SiBEAM 60-GHz WirelessHD technology (2009) in home multimedia: http://www.youtube.com/user/WirelessHD#p/a/u/0/-OmniLink60 Demo: http://www.youtube.com/user/WirelessHD#p/a/u/1/9XbUL-_gG8E

60-GHz 毫米波技術應用於未來家庭網路示意圖 [see SiBeam]
**ISM Bands:** Industrial, Scientific, & Medical Bands

**U-NII Bands:** Unlicensed-National Information Infrastructure Bands

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**802.11 Wireless Local Area Network (WLAN)**

- **ISM Bands:** Industrial, Scientific, & Medical Bands
- **U-NII Bands:** Unlicensed-National Information Infrastructure Bands

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**802.11b**
- Bluetooth

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**802.11a**
2.4 GHz Bluetooth (藍芽) 短距離無線通訊系統

Overview

- What is Bluetooth?
  - A cable replacement
  - A personal ad-hoc network
  - A wireless access to data / voice networks
  - All of the above

- 操作頻率位於2.4GHz ISM (Industrial, Scientific, Medical)頻帶
- 採用FHSS（Frequency Hopping Spread Spectrum）跳頻展頻技術
- 頻道數為79或23，頻道間距爲1MHz
- 頻道跳躍率為每秒1600次
- 優點：抗干擾、抗衰退、及隨機處理等

![跳頻訊號之Waterfall頻譜](image)

2.429GHz 干擾訊號
What is a Digital Wireless System?

Typical Multi-Technology RF Transceiver
**Typical Digital Radio RF Architecture**

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- **Receiver (Rx)**
  - **Receive Band**
  - **Low Noise Amp (LNA)**
  - **Frequency Synthesizer**
  - **IQ-DEMUD**
  - **Power Amp**

- **Transmitter (Tx)**
  - **Transmitting Band**
  - **Low Noise Amp (LNA)**
  - **Frequency Synthesizer**
  - **IQ-MOD**

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- **Interference signals**
- **Desired Channel**
- **Desired Signal**
- **Interference signal**
- **Downconverted Interference Signal**
  - Spread by LO phase noise
  - Contamination of desired signal

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- **Downconverted Desired Signal**
- **LO**
- **Phase Noise**
- **Harmonics**
- **Measurement Driving Power (dBm)**
- **EVM (%)**
Tx/Rx (transmitting/receiving)  
(T/R) Duplexer, Switch  
RF/IF (radio-frequency/intermediate-frequency)  
LNA (low noise amplifier)  
HPA or PA (power amplifier)  
Bandpass Filter (BPF)  
SAW (surface acoustic wave) Filter  
Mixer  
LO (local oscillator), VCO (voltage-controlled oscillator)  
Frequency Synthesizer  
IQ MOD (modulation) / DEMOD (demodulation)

<table>
<thead>
<tr>
<th>Component Symbol</th>
<th>Component Name</th>
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<tbody>
<tr>
<td><img src="image" alt="Antenna" /></td>
<td>Antenna</td>
</tr>
<tr>
<td><img src="image" alt="Amplifier" /></td>
<td>Amplifier</td>
</tr>
<tr>
<td><img src="image" alt="Mixer" /></td>
<td>Mixer</td>
</tr>
<tr>
<td><img src="image" alt="Oscillator" /></td>
<td>Oscillator</td>
</tr>
<tr>
<td><img src="image" alt="90° power divider" /></td>
<td>90° power divider</td>
</tr>
<tr>
<td><img src="image" alt="Frequency multiplier" /></td>
<td>Frequency multiplier</td>
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<tr>
<td><img src="image" alt="Frequency divider" /></td>
<td>Frequency divider</td>
</tr>
<tr>
<td><img src="image" alt="Switch" /></td>
<td>Switch</td>
</tr>
</tbody>
</table>

Diagram:
- **Antenna**
- **Bandpass filter**
- **Low noise amplifier**
- **Mixer**
- **IF filter**
- **IF amplifier**
- **Demodulator**
- **Data out**

(a) Low-pass filter  
(b) Bandpass filter  
(c) High-pass filter
Main Drivers for RF IC Design

- Cost
- Size
- Power Consumption
- System Complexity
- Time to Market

RoC

Ultimate goal: single chip CMOS RF transceiver; multi-standard; minimum external components


Microelectromechanical Components for Miniaturized Low-Power Communications

MEMS-Replaceable Transceiver Components

- A large number of off-chip high-Q components replaceable with micromachined versions; e.g., using micromachined resonators, switches, capacitors, and inductors

C. T.-C. Nguyen
Miniaturization of Transceivers

- **High-Q functionality** required by oscillators and filters cannot be realized using standard IC components; use off-chip mechanical components
- SAW, ceramic, and crystal resonators pose bottlenecks against ultimate miniaturization

Target Application: Integrated Transceivers

- Off-chip high-Q mechanical components present bottlenecks to miniaturization; replace them with micro-mechanical versions
RF Section - Design Bottleneck

- Today's mobile phones contain more than 1 million transistors
- Only a small fraction operate in the RF range – the analog front-end (AFE)
- The rest (several order of magnitude more) perform low-frequency "baseband" analog and digital signal processing (DSP)
- The RF section is the design bottleneck of the entire system
  - Multidisciplinary field
  - Complex trade-offs (see the RF design octagon)
  - Lack of design tools

RF Design Octagon

- RF circuits must process analog signals with a wide dynamic range at high frequencies
- The trade-offs involved can be summarized in the "RF Design Octagon"
- While digital circuits directly benefit from advances in IC technologies, RF circuits do not as much
Disciplines Required in RF Design (1)

Communication Theory
Microwave Theory
Random Signals
Signal Propagation
Transceiver Architectures
Multiple Access
IC Design
RF Design
Wireless Standards
CAD Tools

- RF systems demand a good understanding of many areas that are not directly related to ICs
- It is difficult for an IC designer to acquire the necessary knowledge in a reasonable amount of time

Disciplines Required in RF Design (2)

Wireless system design has been carried out at disjoint levels of abstraction:

- **Communication theorists** – create the modulation scheme & baseband signal processing
- **RF systems experts** - plan the transceiver architecture often according to the available off-the-shelf components
- **IC designers** - develop each of the building blocks to serve as many architectures as possible
- **Manufacturers** – “glue“ the ICs and other external components together

Thus – exists a great deal of redundancy at both system and circuit level
More „concurrent engineering“ is required!
Receiver Issues

- **Sensitivity** (signal detection)
- **Quantified by:** SNR/BER, NF, distortion & intermodulation
- **Selectivity** (channel isolation by RF/IF filtering)
  - **Quantified by:** blocking performance, distortion & intermodulation, image rejection, phase noise
- **Signal processing** (amplification, down-conversion, demodulation)
  - **Quantified by:** gain, distortion & intermodulation, dynamic range, phase noise

Main receiver’s building blocks

- **Filters**
- **Amplifiers** (low noise amplifier - LNA, variable gain amplifier - VGA)
- **Mixers**
- **Voltage Controlled Oscillator (VCO)**
- **ADC**

### Sensitivity

Sensitivity is bounded by the receiver noise floor:

- **Receiver thermal noise** \((-174\, \text{dB} + 10\log(BW))\)
- **Multi-user interference noise**
- **Receiver noise figure** (own added noise)

### Selectivity

- **RF filters** suppress the noise & interference outside the receiver band
- **IF filters** suppress all but desired receiver channel
Transmitters efficiently encode information issues on carrier and amplify for transmission

- Spectrally efficient modulation
- Signal upconversion: move the signal to the desired RF carrier frequency
- Spurious and noise filtering
- Efficient signal amplification with power control to deliver wanted power to the antenna for emission

Main building blocks
- Amplifiers
- Filters
- Mixers
- VCO

In contrast to the variety of approaches for receivers, transmitter architectures are found in only a few form.

This is because issues such as noise, interference rejection, and band selectivity are more relaxed in transmitters than in receivers, the baseband signal being local generated an strong enough!

Power Amplifier / Antenna Interface (1)

- The transmitter output must pass through a duplexer filter or a TDD switch so that it can be separated from the signal received by the antenna
- Duplexer filters typically exhibit a loss of 2-3dB, dissipating 30-50% of the PA output power in the form of heat
- If the PA provides 1W of power, more than 300mW is wasted in the filter
- PA efficiency is typically 50% - the wasted 300mW power corresponding to 600mW drained from the supply! (more than the power needed by the complete transceiver)
- The TDD switch has a loss between 0.5 - 1dB, yielding higher efficiency than FDD

- Duplexer attenuation in RX band ~50dB \(\Rightarrow\) a 20V\textsubscript{pp} in a 50\textohm antenna (1W or +30dBm)
  means a leakage of 30mV\textsubscript{pp} (-26dBm) at the LNA \(\Rightarrow\) the LNA is desensitized!
Power Amplifier / Antenna Interface (2)

- Duplexer is a separate chip (matched to 50Ω) ⇒ the LNA and the PA requires 50Ω matching!

- Q: Linear/Non Linear Power Amplifier?
- Linear PA – max theoretical efficiency 50%
- Nonlinear PA – max theoretical efficiency 100%
- Modulation type requires linear/nonlinear PA
  - QPSK, Offset QPSK, π/4 QPSK – linear (variable amplitude modulation)
  - FSK/GMSK – nonlinear (constant amplitude modulation)

- **Microwave Integrated Circuits (MIC)**: Hybrid Microwave & RF Circuits

- **MIC** is the trend of microwave technology to replace bulky and expensive waveguide & coaxial components with small and inexpensive planar components.

- **MIC** can incorporate microstrip/strip transmission lines, discrete chip-resistors, chip-capacitors, and chip-inductors, and active devices, such as diodes and transistors.
**Monolithic RF/Microwave Integrated Circuits (RFIC/MMIC; MIMIC)**

RFIC/MMIC 是將所有的電路元件製作於單一晶片中，包括主動元件如 FETs 和被動元件如電阻、電容、電感等皆結合於單一晶片中。

The substrate of RFIC/MMIC must be **semiconductor material** to accommodate fabrication of **active devices**

- Silicon bipolar transistor (BJT) : ~10GHz (?)
- CMOS : ~10GHz => 60GHz => higher
  *See Berkeley Wireless Research Center (BWRC) OGRE (On-silicon GHz Radio Exploration): 60-GHz CMOS Radio Systems Project [http://bwrc.eecs.berkeley.edu/Research/RF/ogre_project/]*
- SiGe : ~20GHz => 60GHz => higher
- Submicron gate-length GaAs FET : up to 100GHz (?)
- GaAs HBT : up to 60GHz(?)
- PHEMT : up to 100GHz

1 GHz  2 GHz  5 GHz  10 GHz  28 GHz  77 GHz

Si  SiGe  GaAs  INP

GSM  PDC  DCS  PCS  DECT  WLAN  Bluetooth  SAT  TV  WLAN  Micro-  Wave  Links  Auto  Radar
2.4 GHz Transceiver RF Front-end

2.4-GHz ISM 頻帶數位無線通訊射頻收發模組
2.4 GHz Digital Wireless Communications Transceiver RF Front-end Module

劉先佑 (Sen-You Liu) 1997

85年十一屆龍騰碩士論文優等獎
短距無線傳輸技術 創造無障礙通訊環境
朝整合聲音/數據資料/影像傳輸服務邁進

以下數點為台灣的青少年正在啟動

RF Ch0-26

<table>
<thead>
<tr>
<th>射頻技術</th>
<th>Home RF</th>
<th>WL AN</th>
<th>IRDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>優勢</td>
<td>一、可遠距離傳輸資料，操作方便。</td>
<td>一、無線資料傳輸，操作方便。</td>
<td>一、可与光学设备搭配使用。</td>
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<tr>
<td></td>
<td>二、可传输高质量音频/视频。</td>
<td>二、可传输高质量音频/视频。</td>
<td>二、传输速率快。</td>
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<td></td>
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<td>三、可传输高质量音频/视频。</td>
<td>三、传输距离远。</td>
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<tr>
<td>匯損</td>
<td>一、易受干扰。</td>
<td>一、易受干扰。</td>
<td>一、传输距离有限。</td>
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<td></td>
<td>二、易受干扰。</td>
<td>二、易受干扰。</td>
<td>二、传输速率受限。</td>
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<td>三、易受干扰。</td>
<td>三、易受干扰。</td>
<td>三、传输距离有限。</td>
</tr>
</tbody>
</table>

Bluetooth新技術

Bluetooth技術由藍牙組織（Bluetooth Special Interest Group）於1999年推出，利用微波頻段，可進行長距離（大約10公尺）的無線通訊，但受到環境因素影響，傳輸速率僅有1MB/s。目前，Bluetooth技術已成為無線通訊的主要標準之一。
2.4 GHz Bluetooth (藍牙) RFIC/Baseband-IC模組

National Bluetooth Radio (Technology Demonstrator)

- All-In-One Radio Module
- External components integrated in Low Temperature Co-fired Ceramic (LTCC)
- Target size: 12.5 x 12.5 x 2 mm