Electronics Circuits for Communications

Total periods: 30

Final exam: 70%

Project Assignment: 30%

Learning Resources

[1] Hoàng Đình Chiến, “Mạch Điện Tử Thông Tin”, Nhà xuất bản ĐHQG, 2004.
[2] Hoàng Đình Chiến, “Thông Tin vô tuyến – Nguyên lý và tính toán, ứng dụng”, Nhà xuất bản ĐHQG, 2008.
[3] Ulrich. L. Rohde, David. P. Newkirk, “RF/Microwave Circuit Design for Wireless Applications”, John Wiley & Sons, 2000.
[4] Steve C. Cripps, “RF Power Amplifiers for Wireless Communications”, second edition, Artech House, 2006.
[5] Jeffrey S. Beasley, Gary M.Miller, “Modern Electronic Communication”, 9th edition, Pearson, 2014.
[6] Wayne Tomachi, “Advanced Electronic Communication Systems”, Prentice Hall, 2000.
[7] J. Rogers, C. Plett, “Radio Frequency Integrated Circuit Design, Artech House”, 2003.

[8] W. A. Davis, K. Agarwal, “Radio Frequency Circuit Design”, John Wiley & Sons, 2001.

[9] F. Ellinger, “RF Integrated Circuits and Technologies”, Springer Verlag, 2008.

Chapter 1
Introduction of Communication Systems and Elements

Radio Frequency Bands

International Telecommunication Union (ITU)

Band name	Abbreviation	ITU band number	Frequency and Wavelength	Example Uses
Extremely low frequency	ELF	1	3–30 Hz 100,000–10,000 km	Communication with submarines
Super low frequency	SLF	2	30–300 Hz 10,000–1,000 km	Communication with submarines
Ultra low frequency	ULF	3	300–3,000 Hz 1,000–100 km	Submarine communication, communication within mines
Very low frequency	VLF	4	3–30 kHz 100–10 km	Navigation, time signals, submarine communication, wireless heart rate monitors, geophysics
Low frequency	LF	5	30–300 kHz 10–1 km	Navigation, time signals, AM longwave broadcasting (Europe and parts of Asia), RFID, amateur radio
Medium frequency	MF	6	300–3,000 kHz 1,000–100 m	AM (medium-wave) broadcasts, amateur radio, avalanche beacons
High frequency	HF	7	3–30 MHz 100–10 m	Shortwave broadcasts, citizens band radio, amateur radio and over-the-horizon aviation communications, RFID, over-the-horizon radar, automatic link establishment (ALE) / near-vertical incidence skywave (NVIS) radio communications, marine and mobile radio telephony
Very high frequency	VHF	8	30–300 MHz 10–1 m	FM, television broadcasts, line-of-sight ground-to-aircraft and aircraft-to-aircraft communications, land mobile and maritime mobile communications, amateur radio, weather radio
Ultra high frequency	UHF	9	300–3,000 MHz 1–0.1 m	Television broadcasts, microwave oven, microwave devices/communications, radio astronomy, mobile phones, wireless LAN, Bluetooth, ZigBee, GPS and two-way radios such as land mobile, FRS and GMRS radios, amateur radio, satellite radio, Remote control Systems, ADSB.
Super high frequency	SHF	10	3–30 GHz 100–10 mm	Radio astronomy, microwave devices/communications, wireless LAN, DSRC, most modern radars, communications satellites, cable and satellite television broadcasting, DBS, amateur radio, satellite radio.
Extremely high frequency	EHF	11	30–300 GHz 10–1 mm	Radio astronomy, high-frequency microwave radio relay, microwave remote sensing, amateur radio, directed-energy weapon, millimeter wave scanner, Wireless Lan 802.11ad.
Terahertz or Tremendously high frequency	THz or THF	12	300–3,000 GHz 1–0.1 mm	Experimental medical imaging to replace X-rays, ultrafast molecular dynamics, condensed-matter physics, terahertz time-domain spectroscopy, terahertz computing/communications, remote sensing

Radio Frequency Bands

US Institute of Electrical and Electronics Engineers (IEEE)

Band designation	Frequency range	Explanation of meaning of letters
HF	0.003 to 0.03 GHz	High Frequency[13]
VHF	0.03 to 0.3 GHz	Very High Frequency[13]
UHF	0.3 to 1 GHz	Ultra High Frequency[13]
L	1 to 2 GHz	Long wave
S	2 to 4 GHz	Short wave
C	4 to 8 GHz	Compromise between S and X
X	8 to 12 GHz	Used in World War II for fire control, X for cross (as in crosshair). Exotic.[14]
K_u	12 to 18 GHz	Kurz-under
K	18 to 27 GHz	Kurz (German for 'short')
K_a	27 to 40 GHz	Kurz-above
V	40 to 75 GHz	
W	75 to 110 GHz	W follows V in the alphabet[citation needed]
mm or G	110 to 300 GHz[note 1]	Millimeter[12]

Basic View on Modulation

Base-band signal
to be transmitted
low frequency

$e_m(t)$

$s(t)$

Sinusoidal carrier $x(t) = A_0 \cos\omega_0 t$
high frequency

Sinusoidal Carrier $x(t)$:

$$x(t) = A_0 \cdot \cos\left(\omega_0 t + \phi\right)$$

Amplitude

Frequency Phase

Angle

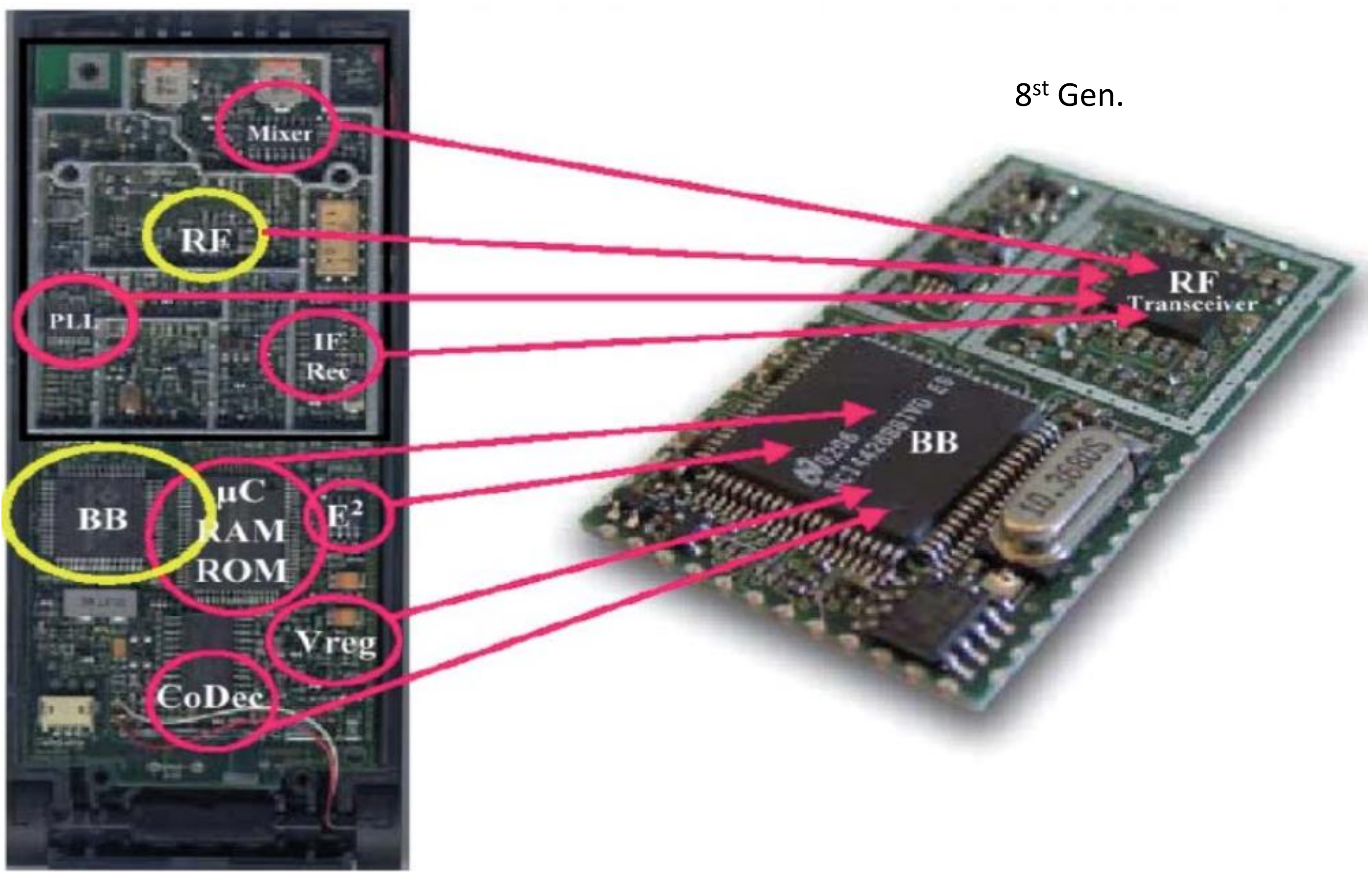
3 different parameters
available for modulation
by the base-band signal

Angle modulation with
higher immunity to noise
and interference

Elements of RF Communication Systems

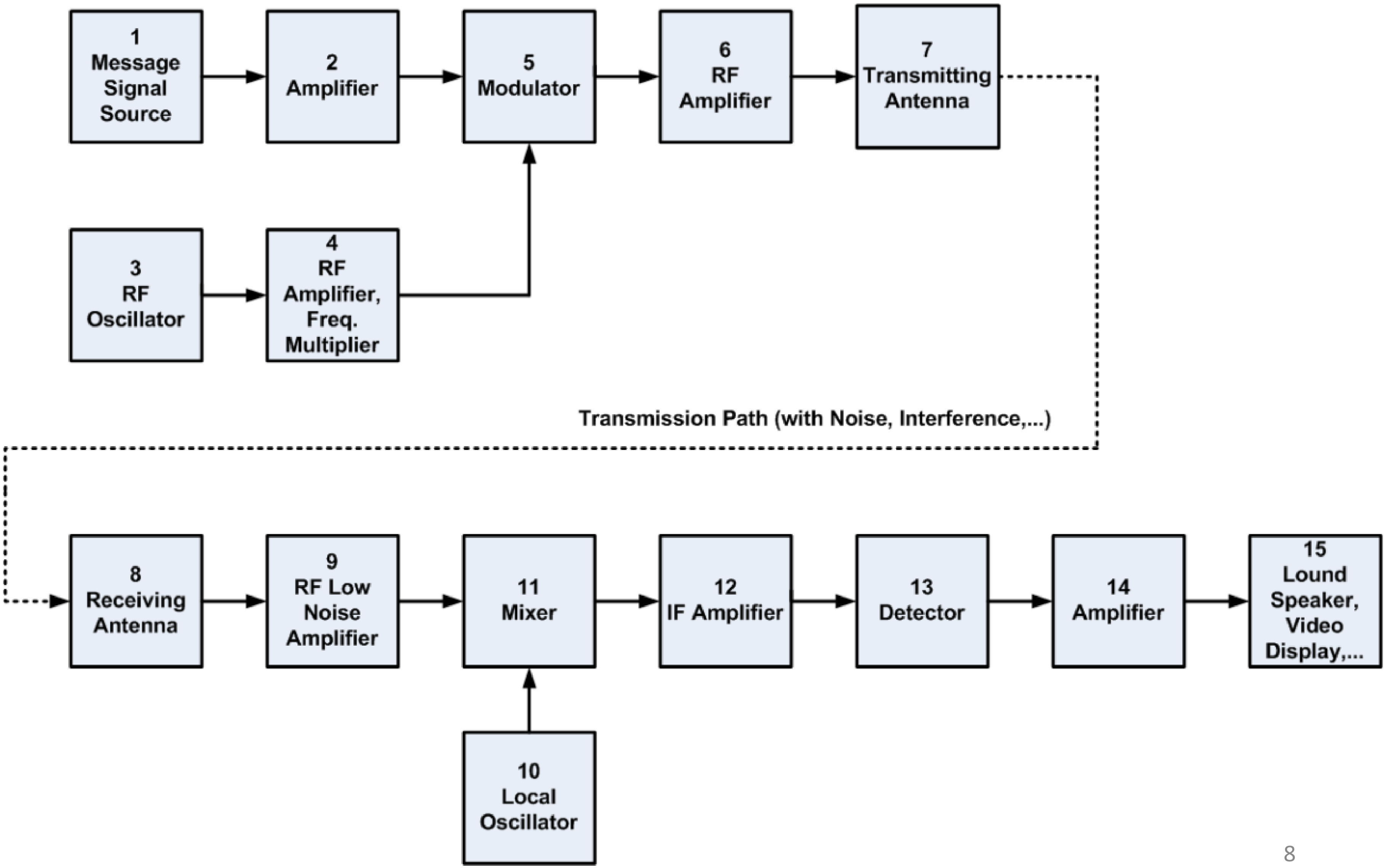
1st Gen.

8st Gen.



Example of evolution of Electronics Circuits for Communications

Elements of traditional RF Communication Systems



Elements of traditional RF Communication Systems

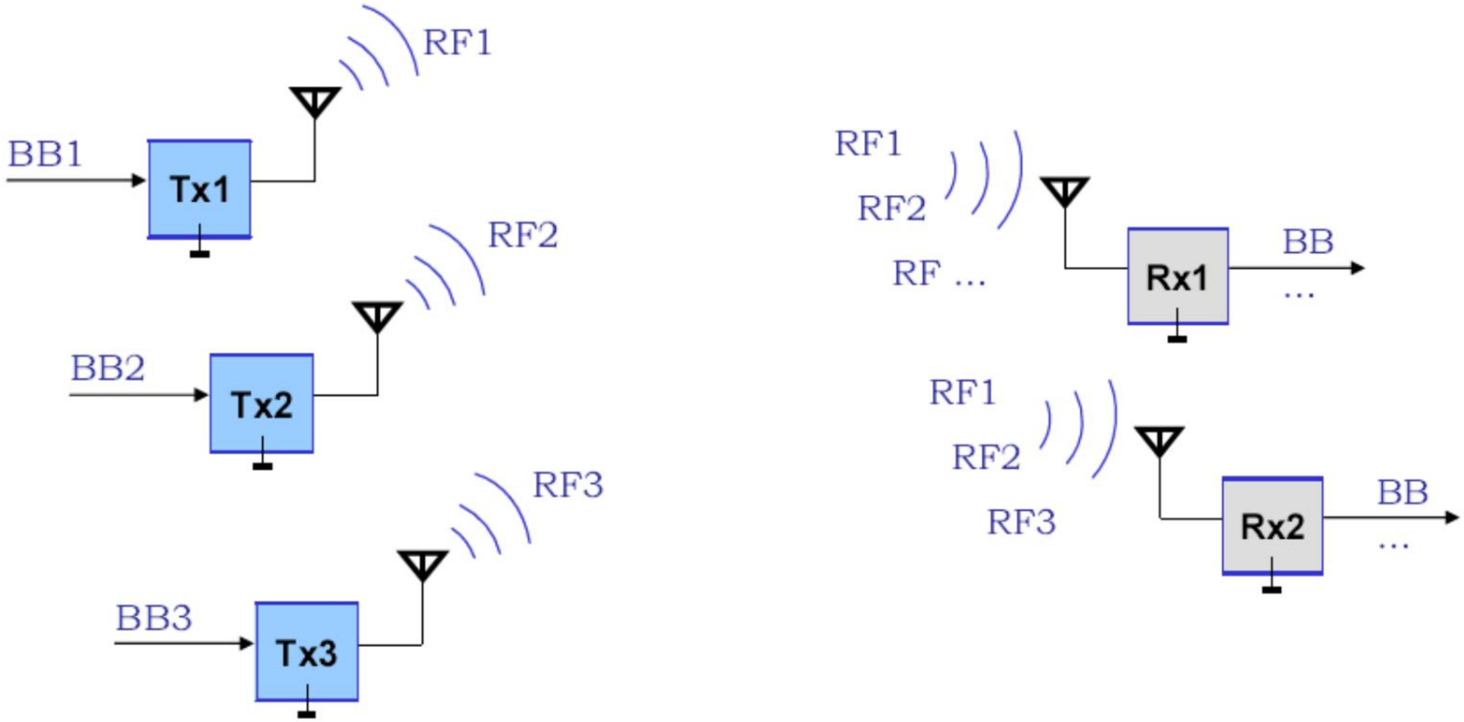
1. The source of the message, may be analogue or digital information, transformed into an electrical signal.
2. The signal is amplified and often passed through a low-pass filter to limit the bandwidth.
3. The RF oscillator establishes the carrier frequency. Frequency stability is required to keep the transmitter on its assigned frequency, the oscillator is often controlled by a quartz crystal (Chapter 7).
4. One or more amplifier (and/or frequency multiplier) stages increase the power level (and/or frequency) of the signal from the oscillator to that needed for input to the modulator.
5. The modulator combines/mixes the message signal and carrier signal (radio frequency) to produce the modulated signal (in the radio transmitting band) (Chapter 8, 9).
6. Power amplifier required after the modulator to gain the power of the transmitting signal (Chapter 3).
7. The transmitting antenna radiates the RF energy into electromagnetic waves propagating in the space and a part of this energy is toward the receiving antenna.

Elements of traditional RF Communication Systems

8. The receiving antenna may be omni-directional for general service or highly directional for point-to-point communication. Due to the path loss in the transmitting, the amplitudes at the receiving antenna port may be less than 1μV.
9. The RF low noise amplifier increases the signal power to a suitable level for the mixer because of a high degree of noise introduced in the mixer stage. This stage often includes a channel filter to reject undesired frequencies components in the channel.
10. The local oscillator in the receiver generates a signal - frequency f_{LO} that is mixed to the received signal - frequency f_{RF} to produce the signal - intermediate frequency f_{IF} that is equal to $f_{LO} – f_{RF}$ or $f_{RF} – f_{LO}$.
11. The mixer is a nonlinear device that shifts the received signal at f_{RF} to the intermediate frequency f_{IF}. The modulated message information in f_{RF} band is also shifted to the f_{IF} band.
12. The IF amplifier increases the signal to a level suitable for detection. This stage is often with good frequency selectivity at the fixed f_{IF} band (ceramic or crystal filters) to filter out undesired signals.
13. The detector or demodulator recovers the message signal from the modulated signal in f_{IF} band (Chapter 8).
14. The audio or video amplifier increases the level of the recovered message signal to a suitable level to drive a loudspeaker, a television tube, or others.
15. The output device converts the signal information back to its original physic form (sound waves, picture, etc.).

Problems and Solutions in Practical RF Systems

- Radio Channel Division and Multiplexing

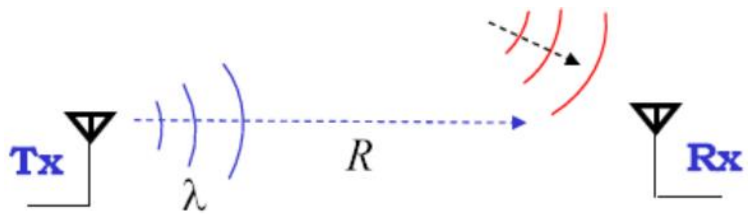


Time, Frequency, Code, Space
TDM, FDM, CDMA, Smart Antennas, MIMO

Problems and Solutions in Practical RF Systems

- Propagation Effects

Path Loss, Antenna Directivity Gain, External Noise, Interference

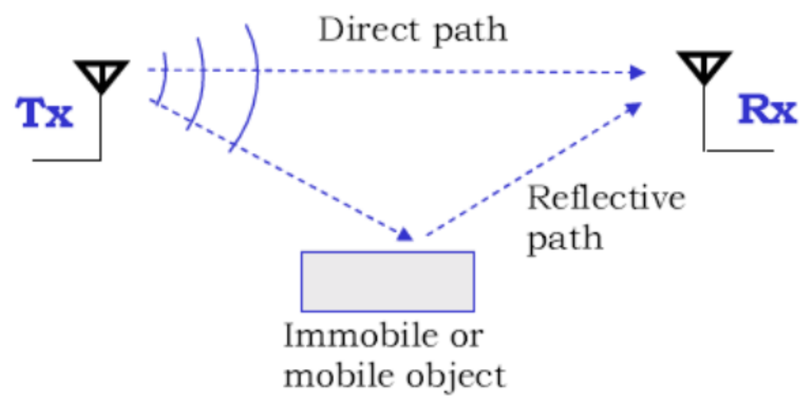


$$L_p = 20\log(4\pi R/\lambda) \quad [\mathrm{dB}]$$

$$P_{Rx} = (P_{Tx} + G_{TxAnt}) - L_p + G_{RxAnt} \quad [\mathrm{dBm}]$$

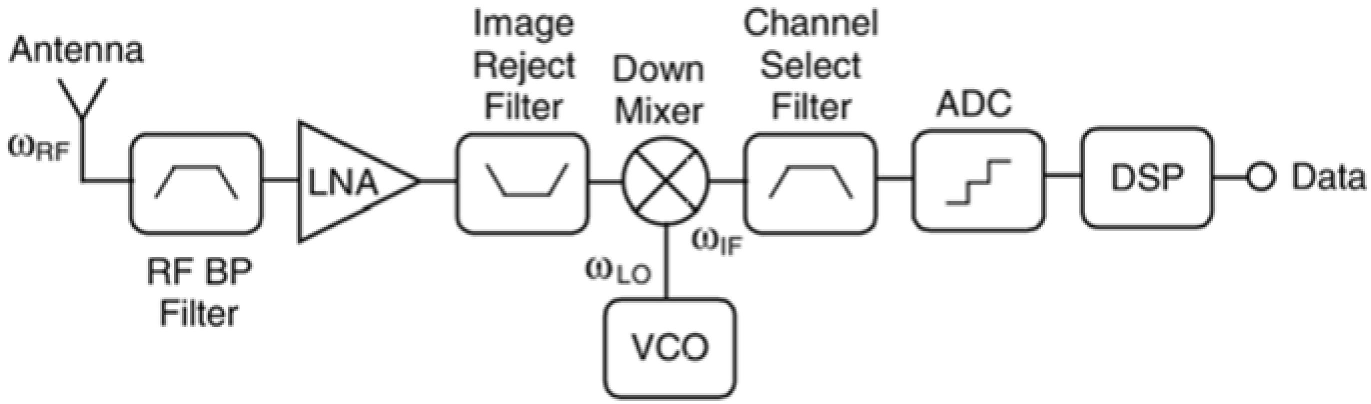
$$SNR = P_{sig}/P_{noise} \qquad SIR = P_{sig}/P_{int}$$

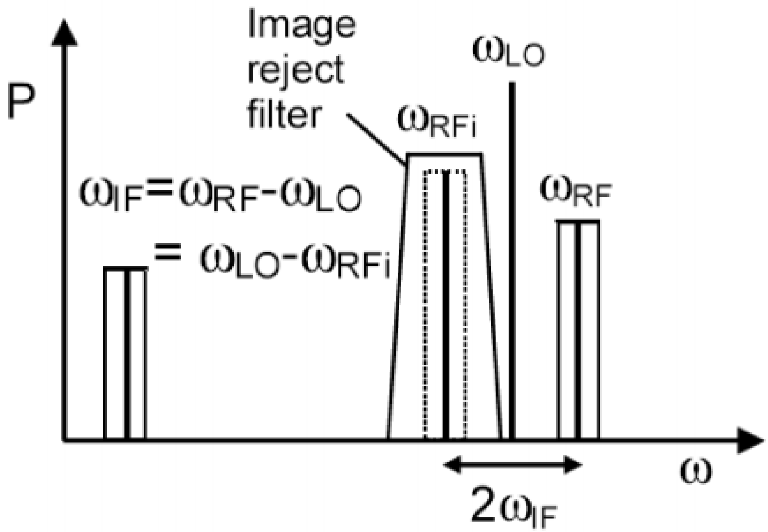
Multi-Path, Fading



Problems and Solutions in Practical RF Systems

- Image frequency and Image reject filter

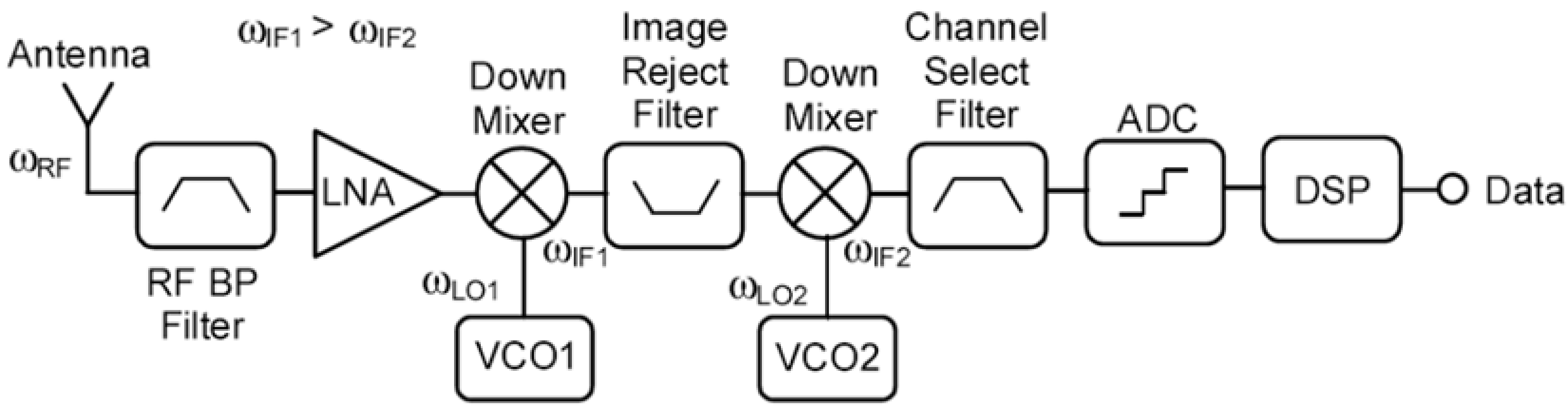




Super-heterodyne receiver
BP: Band pass,
LNA: Low Noise Amplifier,
VCO: Voltage Controlled Oscillator,
ADC: Analogue Digital Converter,
DSP: Digital Signal Processor

Problems and Solutions in Practical RF Systems

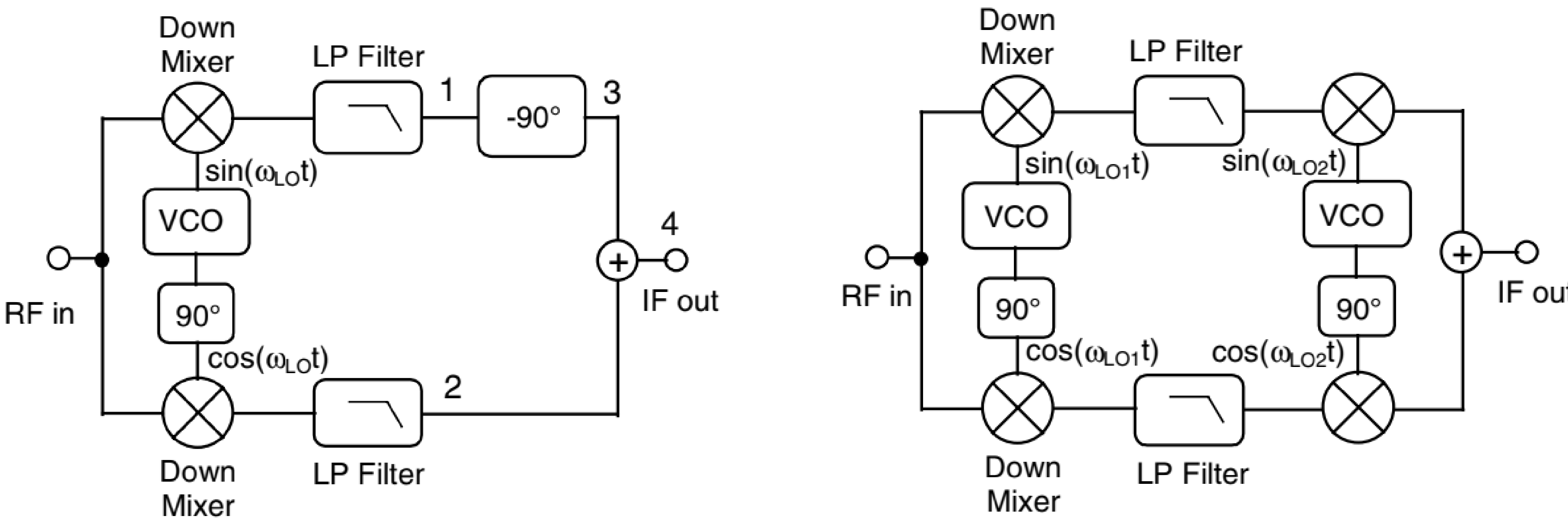
- Image frequency and Image reject filter



Super-heterodyne receiver with double down-conversion

Problems and Solutions in Practical RF Systems

- Image frequency and Image reject filter



Hartley and Weaver Image reject techniques

$$v_{in}(t) = V_{RF}\cos\omega_{RF}t + V_{im}\cos\omega_{im}t \qquad \omega_{RF}>\omega_{LO}$$

$$v_1(t) = -\frac{V_{RF}}{2}\cdot\sin(\omega_{RF}-\omega_{LO})t + \frac{V_{im}}{2}\cdot\sin(\omega_{LO}-\omega_{im})t$$

$$v_2(t) = \frac{V_{RF}}{2}\cdot\cos(\omega_{RF}-\omega_{LO})t + \frac{V_{im}}{2}\cdot\cos(\omega_{LO}-\omega_{im})t$$

$$v_3(t) = \frac{V_{RF}}{2}\cdot\cos(\omega_{RF}-\omega_{LO})t - \frac{V_{im}}{2}\cdot\cos(\omega_{LO}-\omega_{im})t$$

$$v_4(t) = V_{RF}\cdot\cos(\omega_{RF}-\omega_{LO})t$$

Problems in Practical RF Systems

- Distortion

$$x(t) = A\cos(\omega t) \longrightarrow \boxed{\begin{matrix}\text{Nonlinear}\\ \text{LNA}\end{matrix}} \longrightarrow y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

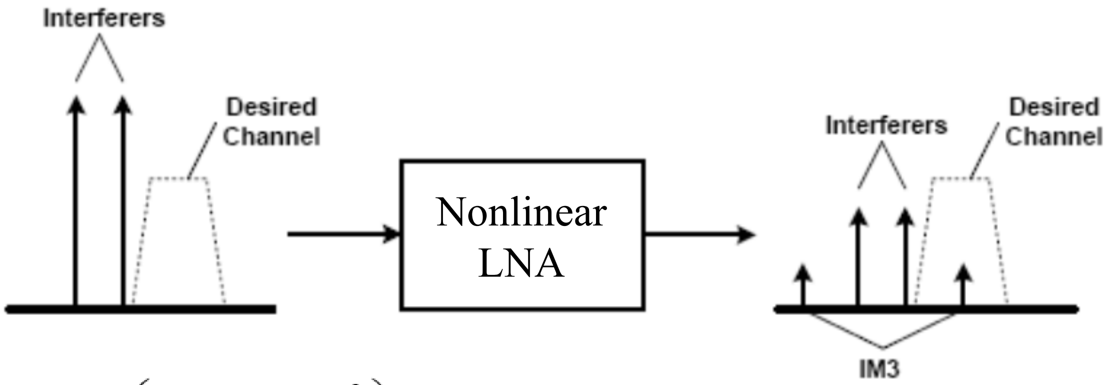
$$y(t) = \left(\alpha_0 + \frac{\alpha_2 A^2}{2}\right) + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right)\cos(\omega t) + \left(\frac{\alpha_2 A^2}{2}\right)\cos(2\omega t) + \left(\frac{\alpha_3 A^3}{4}\right)\cos(3\omega t)$$

with **fundamental** and the **higher order harmonics**

Problems in Practical RF Systems

- Intermodulation (IM)

$$x(t) = A\cos\omega_1 t + A\cos\omega_2 t,$$



Response of a Nonlinear LNA:

$$y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

$$y(t) = \left(\alpha_0 + \alpha_2 A^2\right) + \left(\alpha_1 A + \frac{9\alpha_3 A^3}{4}\right)\cos(\omega_1 t) + \left(\alpha_1 A + \frac{9\alpha_3 A^3}{4}\right)\cos(\omega_2 t) +$$

$$+\left(\frac{\alpha_2 A^2}{2}\right)\cos(2\omega_1 t) + \left(\frac{\alpha_2 A^2}{2}\right)\cos(2\omega_2 t) + \left(\alpha_2 A^2\right)\cos\left[(\omega_1 + \omega_2)t\right] +$$

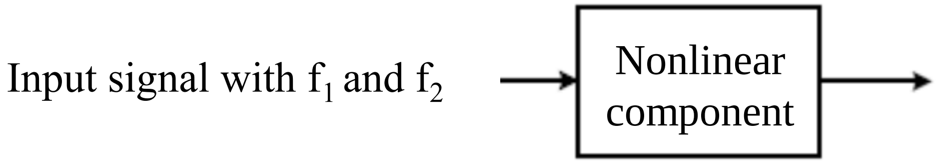
$$+\left(\alpha_2 A^2\right)\cos\left[(\omega_1 - \omega_2)t\right] + \left(\frac{3\alpha_3 A^3}{4}\right)\cos\left[(2\omega_1 - \omega_2)t\right] + \left(\frac{3\alpha_3 A^3}{4}\right)\cos\left[(2\omega_2 - \omega_1)t\right] +$$

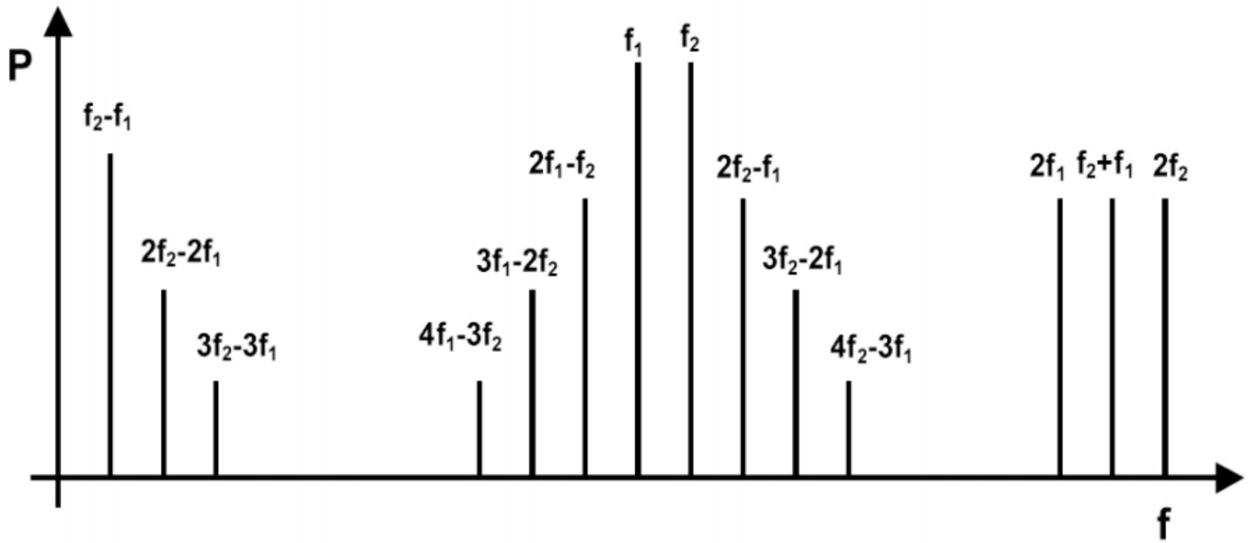
$$+\left(\frac{3\alpha_3 A^3}{4}\right)\cos\left[(2\omega_1 + \omega_2)t\right] + \left(\frac{3\alpha_3 A^3}{4}\right)\cos\left[(2\omega_2 + \omega_1)t\right] +$$

$$+\left(\frac{\alpha_3 A^3}{4}\right)\cos(3\omega_1 t) + \left(\frac{\alpha_3 A^3}{4}\right)\cos(3\omega_2 t)$$

Problems in Practical RF Systems

- Intermodulation (IM)





Metrics for RF Elements and Systems

- Signal amplitude and Power

In RF and microwave techniques, **power** is usually used to describe signals, noise level, or distortion degree with the typical unit of **decibels above 1 milliwatt** (**dBm**). Voltage and current are expressed as **peak**, **peak-to-peak**, or **root-mean-square** (**rms**).

Power in dBm, P_{dBm}, can be related to the power in watts, P_{watt}, as

$$P_{\text{dBm}} = 10 \log_{10}\left(\frac{P_{\text{watt}}}{1 \text{ mW}}\right)$$

Assuming a sinusoidal voltage waveform, P_{watt} is given by

$$P_{\text{watt}} = \frac{v_{\text{rms}}^2}{R}$$

where R is the resistance the voltage is across. Note also that v_{rms} can be related to the peak voltage v_{pp} by

$$v_{\text{rms}} = \frac{v_{\text{pp}}}{2\sqrt{2}}$$

Metrics for RF Elements and Systems

- Signal amplitude and Power

v_{pp}	v_{rms}	P_{watt} (50Ω)	P_{dBm} (50Ω)
1 nV	0.3536 nV	2.5×10^{-21}	-176
1 μV	0.3536 μV	2.5×10^{-15}	-116
1 mV	353.6 μV	2.5 nW	-56
10 mV	3.536 mV	250 nW	-36
100 mV	35.36 mV	25 μW	-16
632.4 mV	223.6 mV	1 mW	0
1V	353.6 mV	2.5 mW	+4
10V	3.536V	250 mW	+24

Metrics for RF Elements and Systems

- Total Harmonic Distortion (THD)

Harmonic distortion factors (HD_i) provide a measure for a **distortion** introduced by each harmonic for a given input signal level (using a **single tone** at a given frequency)

$$x(t) = A\cos(\omega t) \qquad y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

$$y(t) = \left(\alpha_0 + \frac{\alpha_2 A^2}{2}\right) + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right)\cos(\omega t) + \left(\frac{\alpha_2 A^2}{2}\right)\cos(2\omega t) + \left(\frac{\alpha_3 A^3}{4}\right)\cos(3\omega t)$$

HD*i* is defined as the ratio of the output signal level of the *i*-th harmonic to that of the fundamental.

Assuming , $\alpha_1 A \gg \frac{3\alpha_3 A^3}{4}$

$$\mathrm{HD}_2 = \frac{\alpha_2 A}{2\alpha_1} \qquad \mathrm{HD}_3 = \frac{\alpha_3 A^2}{4\alpha_1}$$

$$\mathrm{THD} = \left(\mathrm{HD}_2^2 + \mathrm{HD}_3^2 + \mathrm{HD}_4^2 + \ldots\right)^{1/2}$$

Metrics for RF Elements and Systems

▪ 1-dB Compression Point

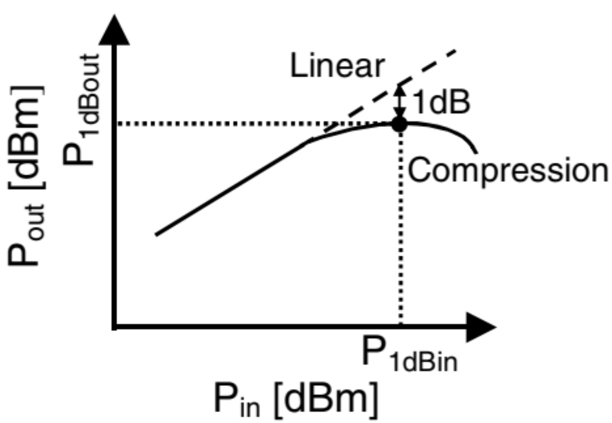
1-dB compression point is defined as **the point** where the **fundamental gain deviates** from the **ideal gain** (small signal) by **1 dB** (using a **single tone** at a given frequency)

$$x(t) = A\cos(\omega t) \qquad y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

$$y(t) = \left(\alpha_0 + \frac{\alpha_2 A^2}{2}\right) + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right)\cos(\omega t) + \left(\frac{\alpha_2 A^2}{2}\right)\cos(2\omega t) + \left(\frac{\alpha_3 A^3}{4}\right)\cos(3\omega t)$$

$$20\log\left(\alpha_1 A_{1-dB} + \frac{3\alpha_3 A_{1-dB}^3}{4}\right) = 20\log\left(\alpha_1 A_{1-dB}\right) - 1 = 20\log\left(0.89125\alpha_1 A_{1-dB}\right)$$

(Note that 20 log 0.89125= -1dB, |1-0.89125| = 0.10875)

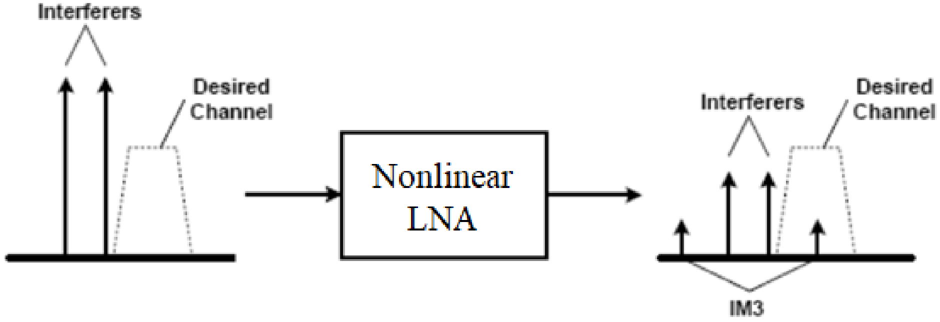


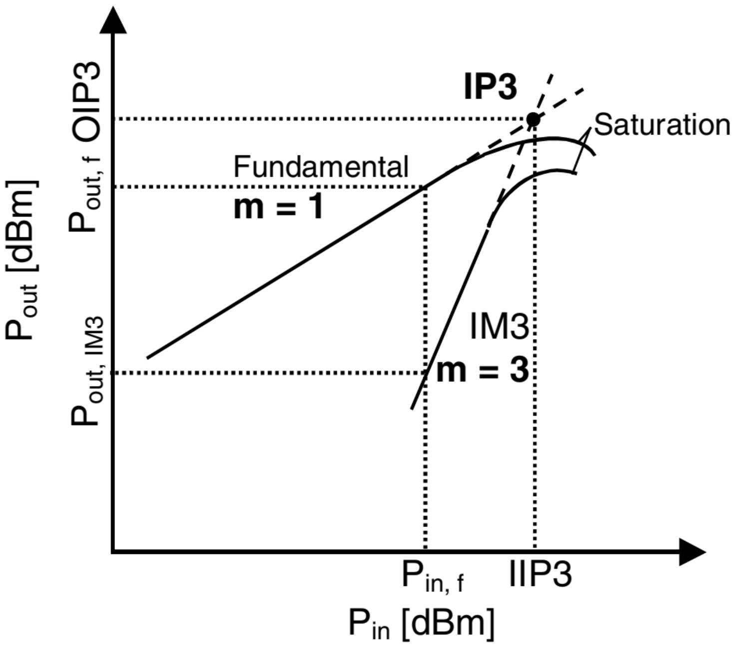
$$\Rightarrow \qquad A_{1-dB}^2 = 0.10875\frac{4}{3}\frac{|\alpha_1|}{|\alpha_3|} = k\frac{|\alpha_1|}{|\alpha_3|}$$

Metrics for RF Elements and Systems

- Third-order Intercept Point (IP_3)

IP_3 point is defined as the **intercept point** of the **fundamental component** with **third-order intermodulation component** (using **dual tone**)



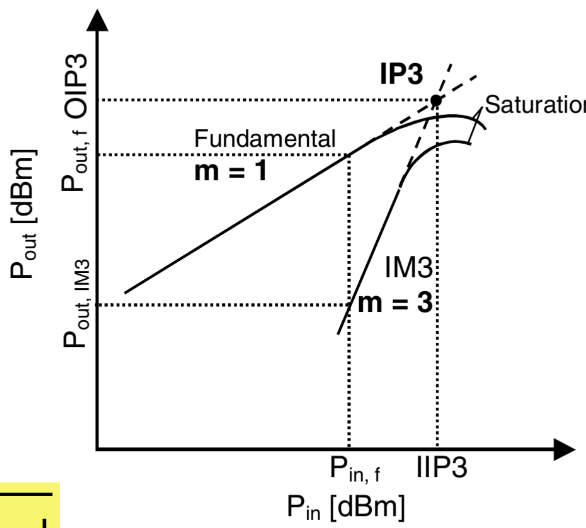


Metrics for RF Elements and Systems

- Third-order Intercept Point (IP_3)

$$x(t) = A\cos\omega_1 t + A\cos\omega_2 t, \qquad y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

$$\begin{aligned} y(t) = &\left(\alpha_0 + \alpha_2 A^2\right) + \left(\alpha_1 A + \frac{9\alpha_3 A^3}{4}\right)\cos(\omega_1 t) + \left(\alpha_1 A + \frac{9\alpha_3 A^3}{4}\right)\cos(\omega_2 t) + \\ &+ \left(\frac{\alpha_2 A^2}{2}\right)\cos(2\omega_1 t) + \left(\frac{\alpha_2 A^2}{2}\right)\cos(2\omega_2 t) + \left(\alpha_2 A^2\right)\cos\left[(\omega_1 + \omega_2)t\right] + \\ &+ \left(\alpha_2 A^2\right)\cos\left[(\omega_1 - \omega_2)t\right] + \left(\frac{3\alpha_3 A^3}{4}\right)\cos\left[(2\omega_1 - \omega_2)t\right] + \left(\frac{3\alpha_3 A^3}{4}\right)\cos\left[(2\omega_2 - \omega_1)t\right] + \\ &+ \left(\frac{3\alpha_3 A^3}{4}\right)\cos\left[(2\omega_1 + \omega_2)t\right] + \left(\frac{3\alpha_3 A^3}{4}\right)\cos\left[(2\omega_2 + \omega_1)t\right] + \\ &+ \left(\frac{\alpha_3 A^3}{4}\right)\cos(3\omega_1 t) + \left(\frac{\alpha_3 A^3}{4}\right)\cos(3\omega_2 t) \end{aligned}$$



$$\alpha_1 A_{IIP_3} \cong \frac{3\alpha_3 A_{IIP_3}^3}{4} \qquad \Rightarrow A_{IIP_3} \cong \sqrt{\frac{4}{3}\frac{|\alpha_1|}{|\alpha_3|}}$$

- Third-order Intermodulation Distortion (IM_3)

$$IM_3 \cong \frac{3}{4}\frac{|\alpha_3|}{|\alpha_1|}A^2$$

Note that $\dfrac{A_{IIP3}^2}{A_{1-dB}^2} = 9.195 \quad \Rightarrow \quad A_{IIP3}(dB) \cong A_{1-dB}(dB) + 10$

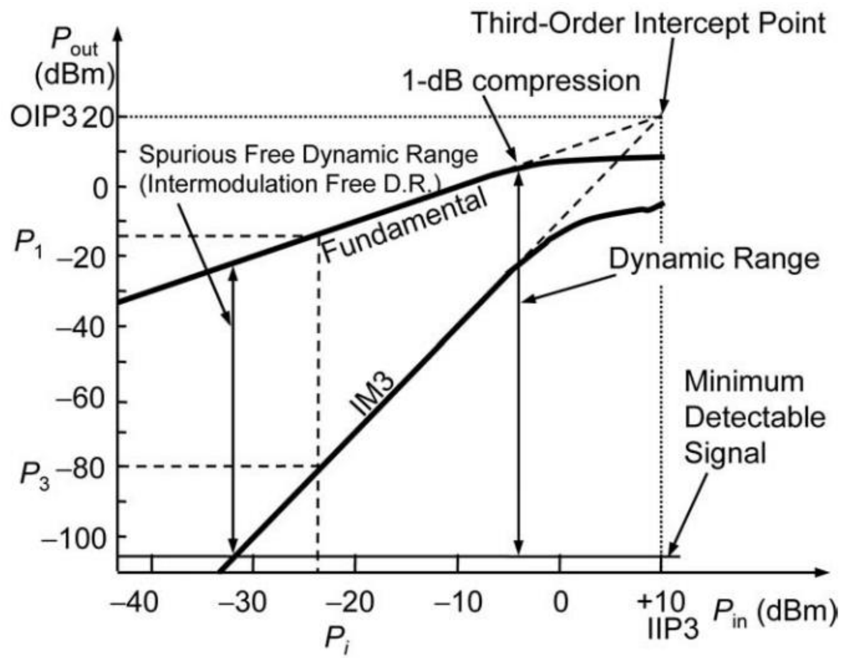
Metrics for RF Elements and Systems

- Dynamic Range

➢ **Linearity** determines **how large** a signal a receiver can handle

➢ **Noise** determines **how small** a signal a receiver can handle

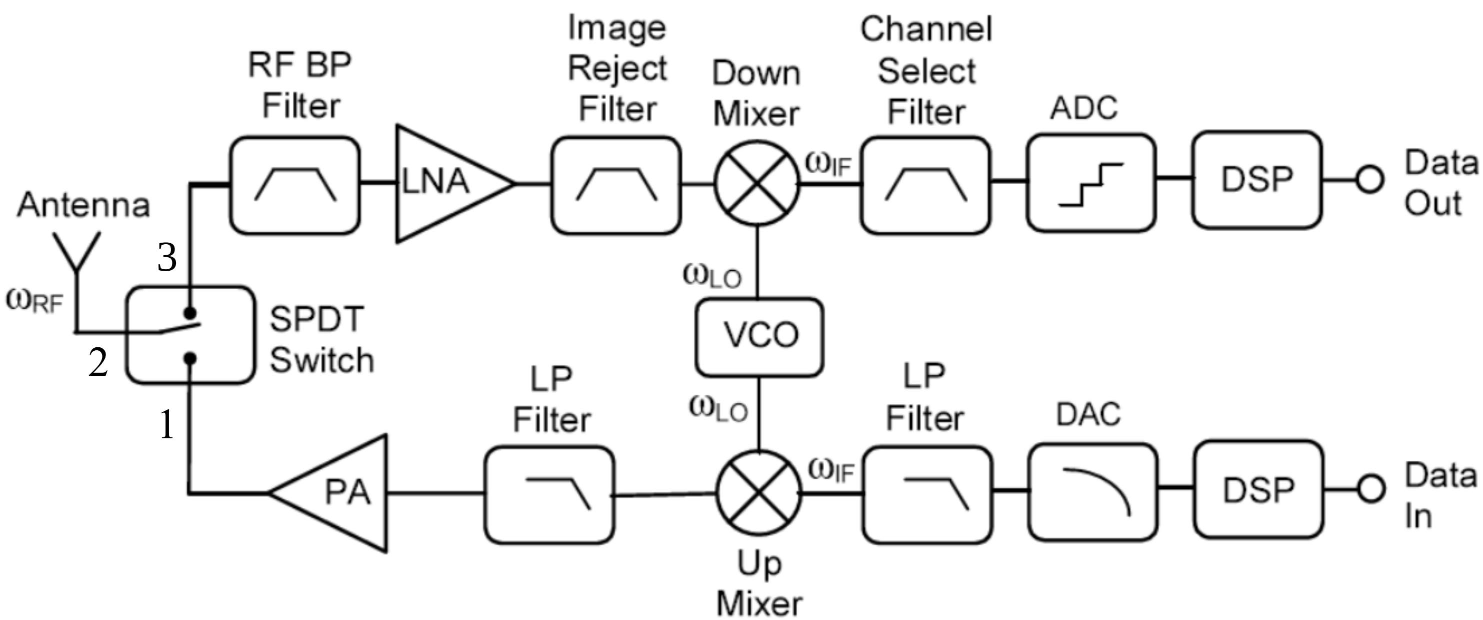
1. **Dynamic Range**: the minimum detectable signal to the 1-dB compression point
2. **Intermodulation Free Dynamic Range**



Modern RF Transceiver Architectures

A **Transceiver** consists of a **trans**mitter and a re**ceiver**

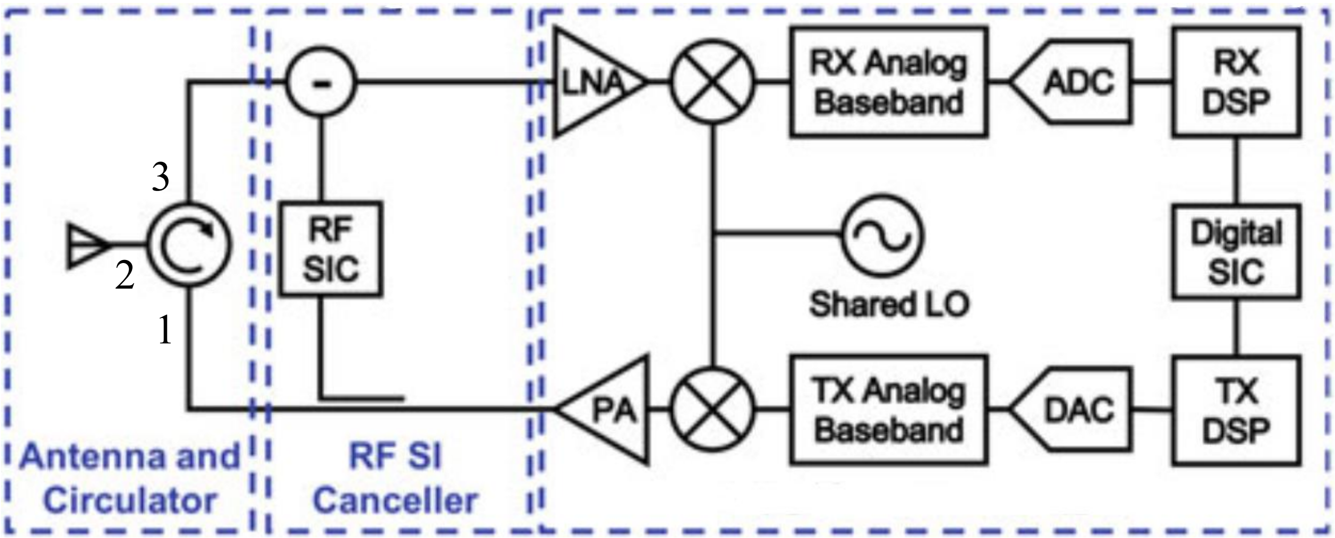
Example of **Half Duplex** Super-**Heterodyne** Transceiver



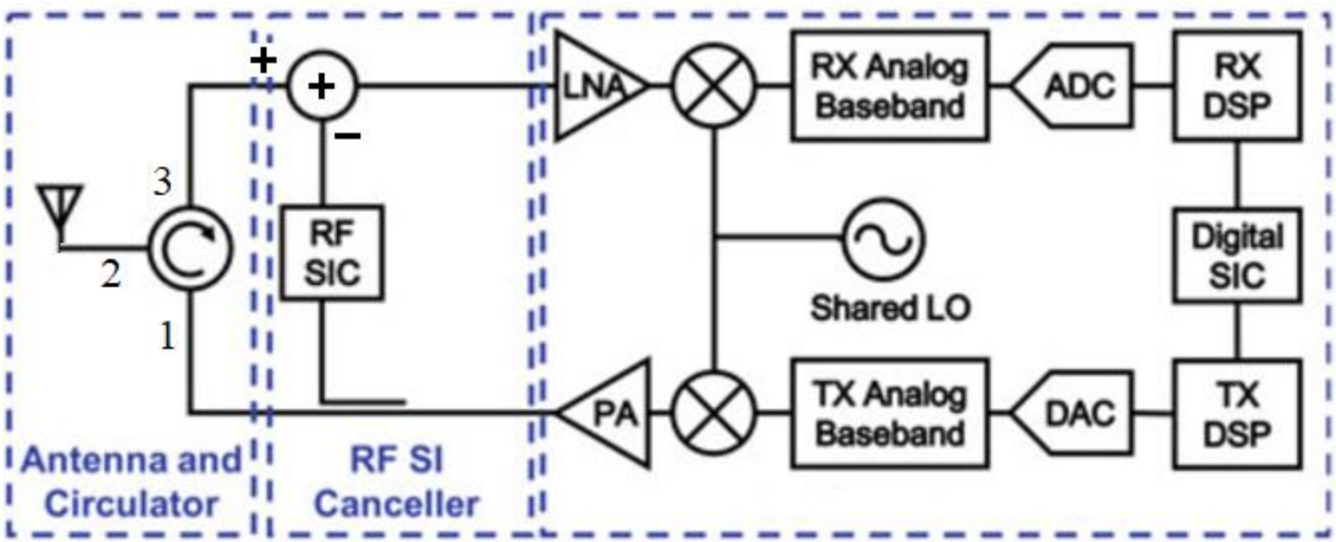
(SPDT: Single Pole Double Throw)

Modern RF Transceiver Architectures

Full Duplex Transceiver with **Circulator** and **Self-Interference Canceller**



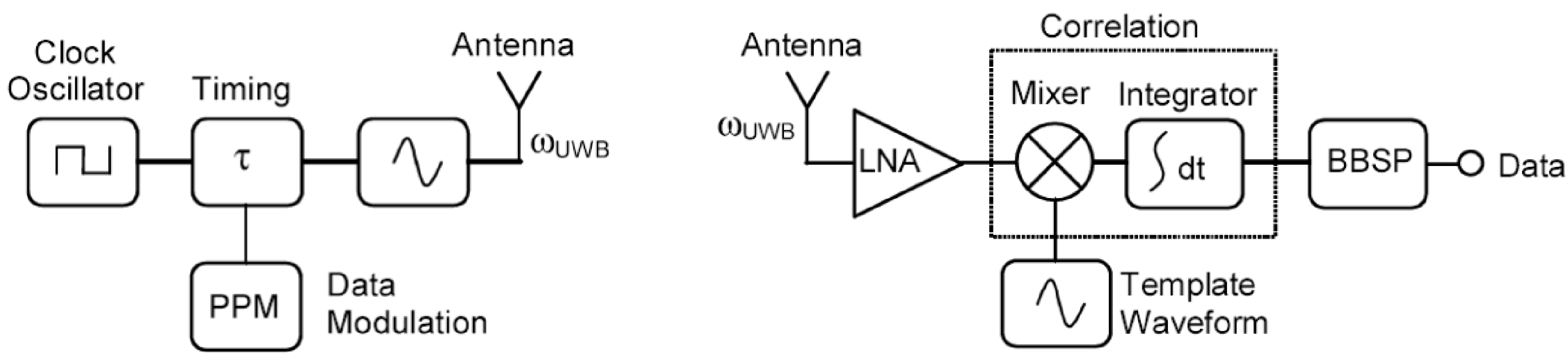
SIC: Self-Interference Canceller
LO: Local Oscillator



+
+
−
3
2
1
RF
SIC
LNA
PA
RX Analog
Baseband
TX Analog
Baseband
ADC
DAC
RX
DSP
TX
DSP
Digital
SIC
Shared LO
Antenna and
Circulator
RF SI
Canceller

Modern RF Transceiver Architectures

Impulse Radio Transmitter and Receiver

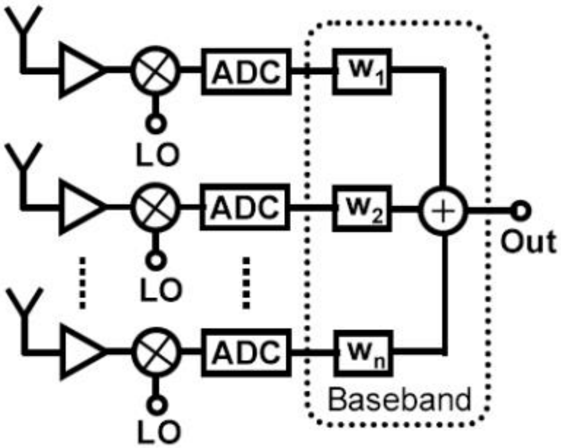


PPM: Pulse Position Modulation
BBSP: Baseband Signal Processing

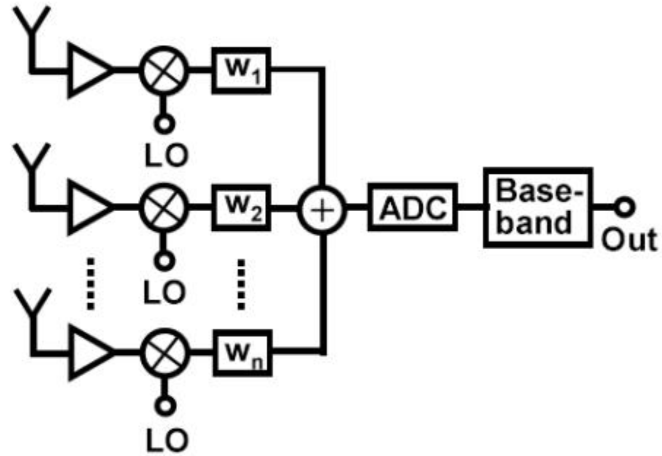
Impulse based radios for **short range, low power and high speed** applications.
UWB (Ultra-Wideband) standards have already been published by the FCC (Federal Communications Commission - US) employing impulse transmission within a frequency band between **3.1 GHz** and **10.6 GHz**.

Modern RF Transceiver Architectures

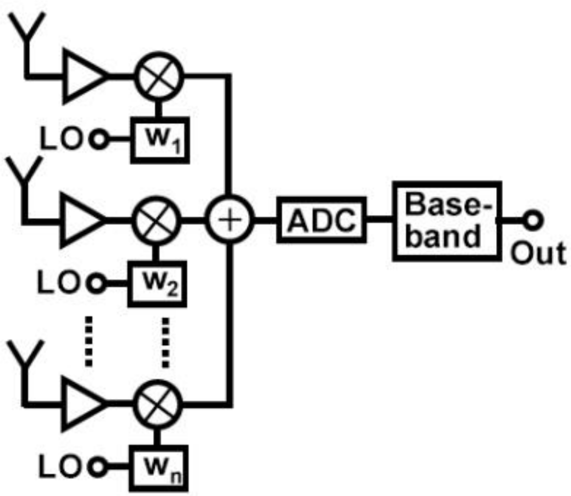
Smart Antenna, **MIMO** Transceivers



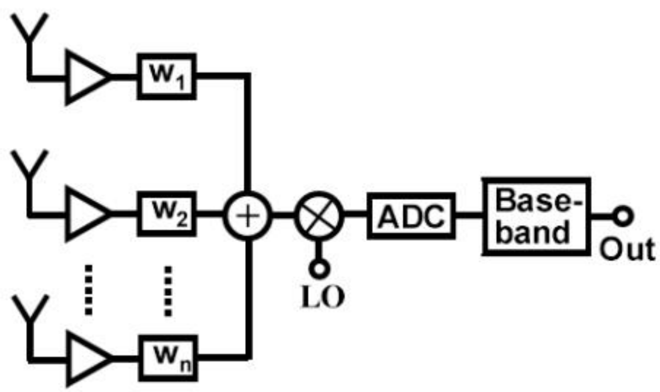
a.) Adaptive BB Combining



b.) Adaptive IF Combining

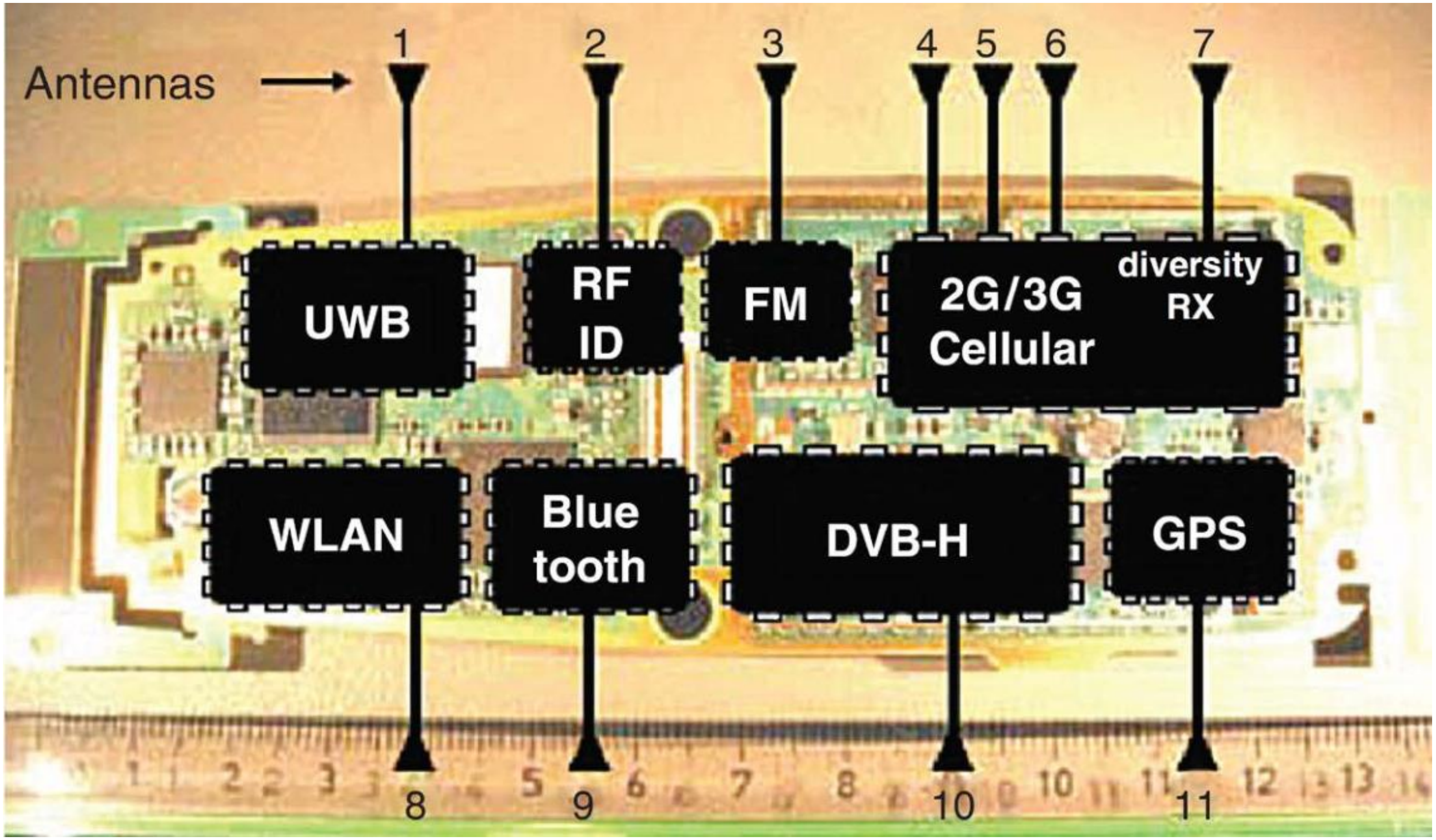


c.) Adaptive LO Combining



d.) Adaptive RF Combining

Software-Defined Radios (SDR)



Multi-mode handset featuring separate radios

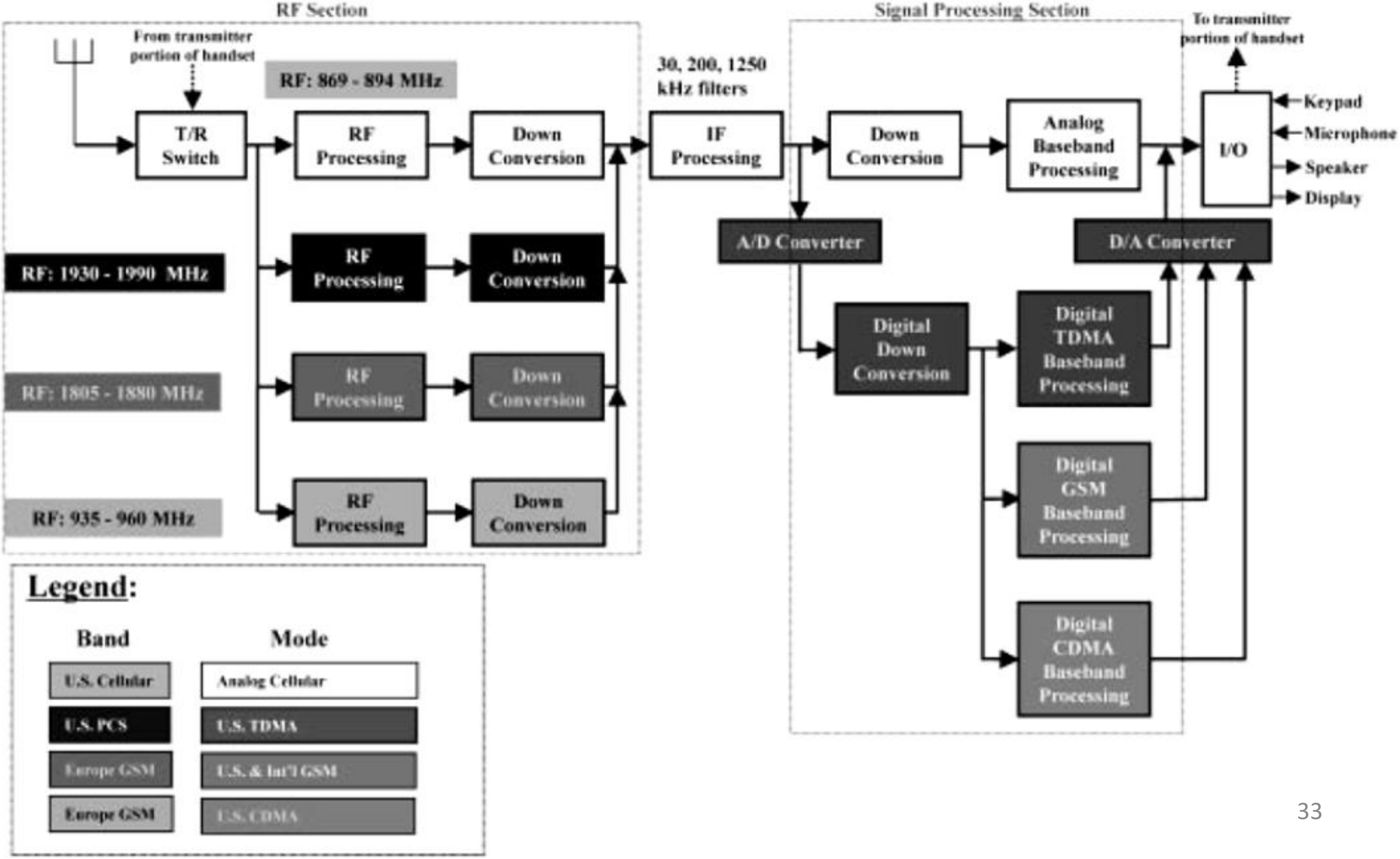
Software-Defined Radios (SDR)

- SDR is a radio communication technology that is based on **software defined wireless communication protocols instead of hardwired implementations**. In other words, frequency band, air interface protocol and functionality can be upgraded with software download and update instead of a complete hardware replacement. SDR provides an efficient and secure solution to the problems of building multi-mode, multi-band and multifunctional wireless communication devices.
- A SDR is capable of being **re-programmed or reconfigured** to operate with **different waveforms and protocols** through **dynamic loading** of new waveforms and protocols. These waveforms and protocols can contain a number of different parts, including modulation techniques, security and performance characteristics defined in software as part of the waveform itself.

Source: http://focus.ti.com/docs/solution/folders/print/357.html

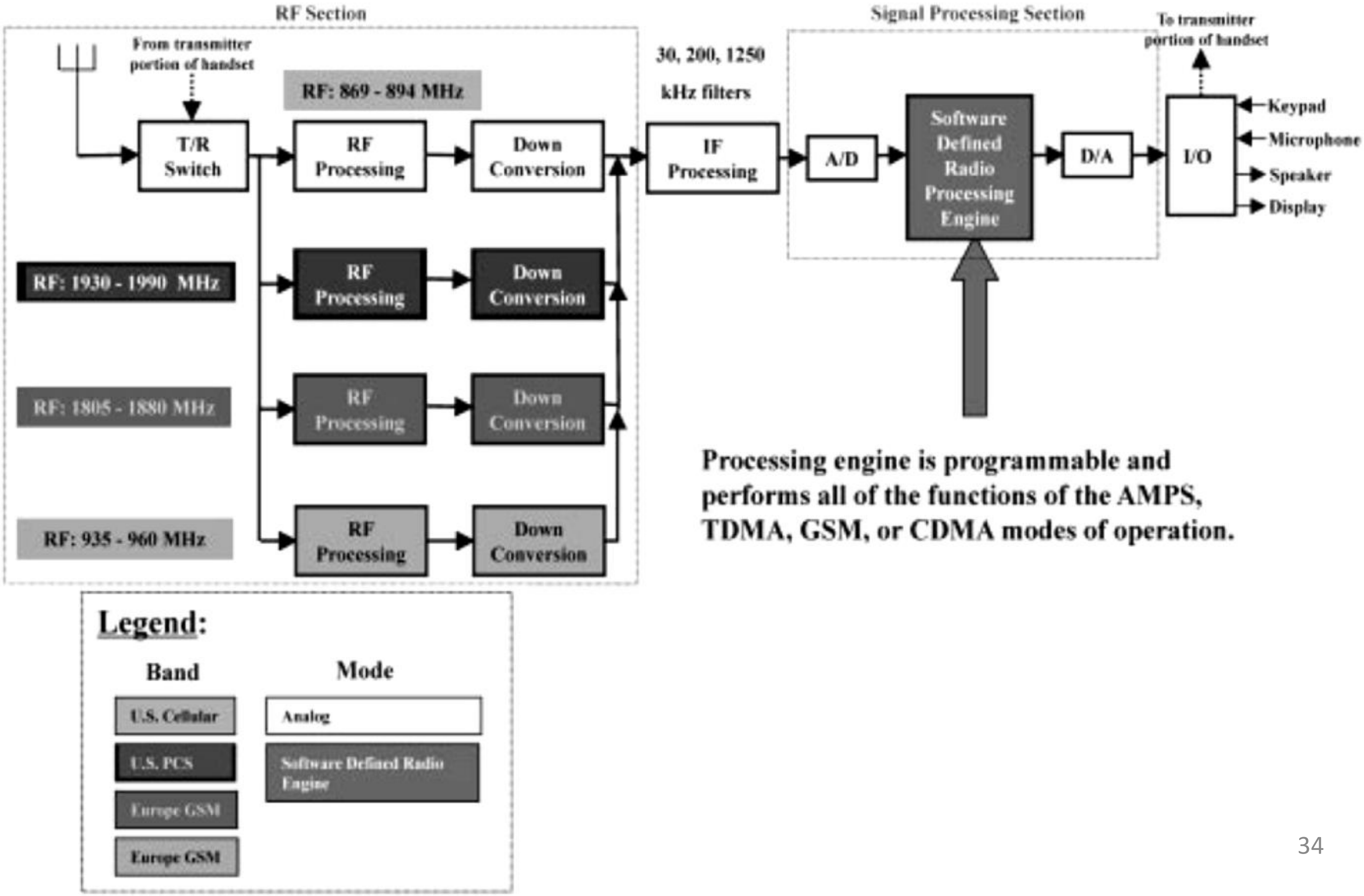
Software-Defined Radios (SDR)

- SDR Evolution – stage 2: Quadruple-band (800, 900,1800, and 1900 MHz), quadruple-mode (AMPS, TDMA, GSM, CDMA), multi-band, multi-mode handset.



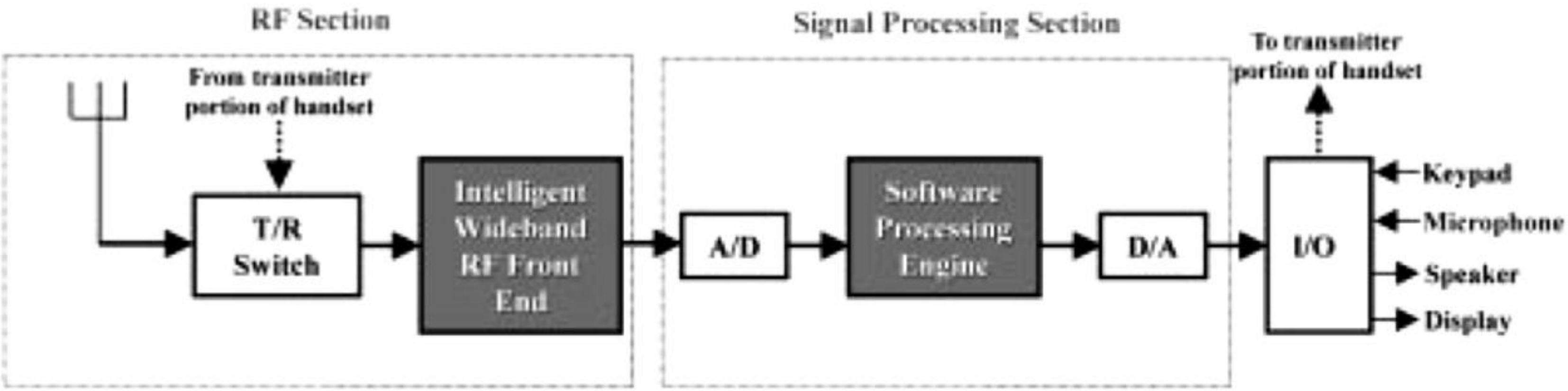
Software-Defined Radios (SDR)

- SDR Evolution – stage 3: **A/D, D/A** and signal **processing chips** at that stage **had the capacity** to perform **IF** and **baseband** processing.



Software-Defined Radios (SDR)

- SDR Evolution – stage 4: Current and Future products.



- System on Chip