Introduction to CMOS RF Integrated Circuits Design

II. RFIC System Overview

Outline

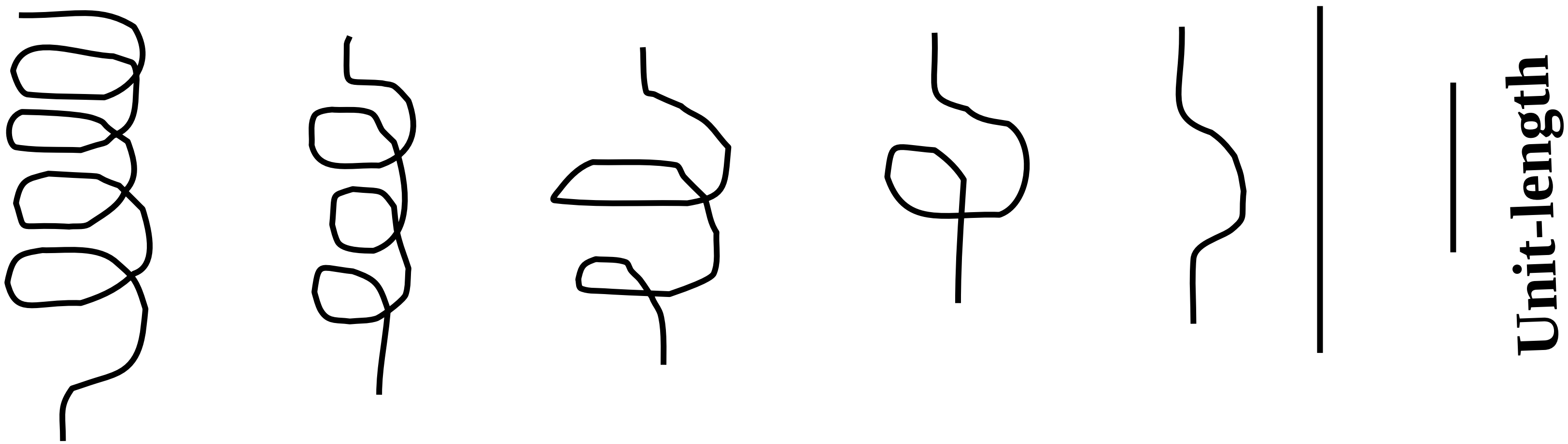
- **Introduction**
- **RF Transceiver Architectures**
- **RF System Considerations**
  - **Sensitivity and Selectivity**
  - **Noise Figure**
  - **Dynamic Range**
  - **1-dB CP and IP3**

RFIC is Analog Circuit

- KCL
- KVL
- Ohm’s Law
- Current Source
- Voltage Source
- R
- L
- C
- Wire
- Transistors

Inductors

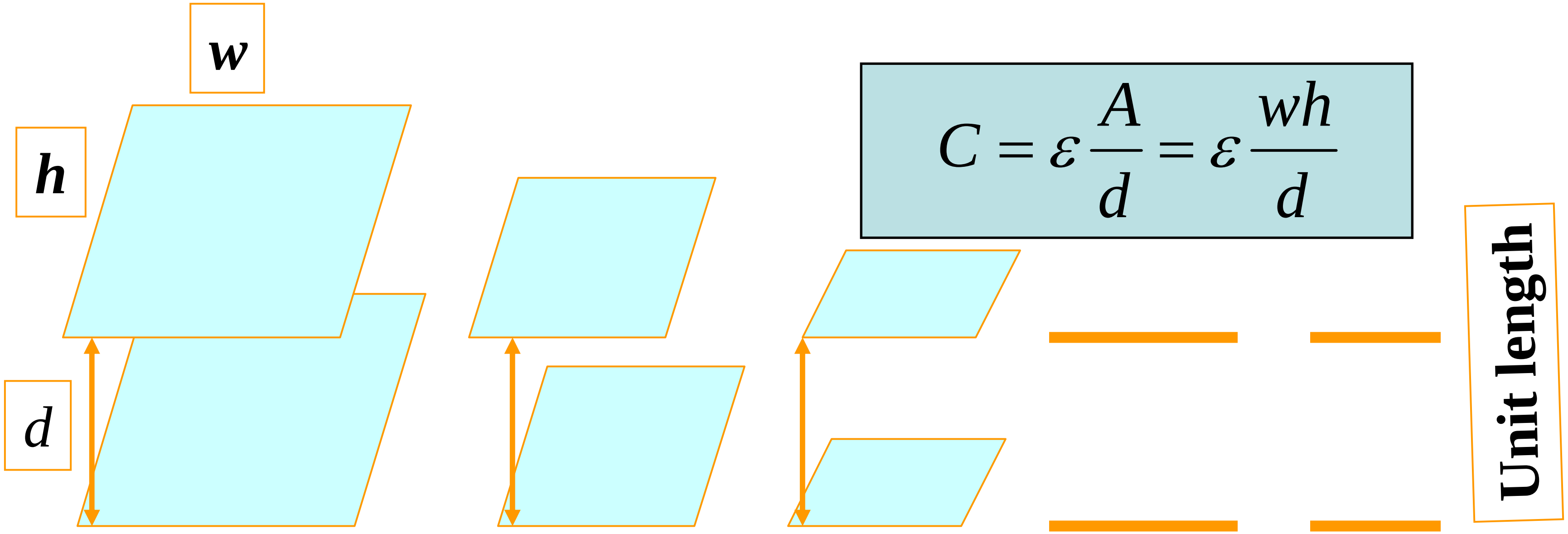
$$\omega = \frac{1}{\sqrt{LC}}$$



$$L > L_1 > L_2 > L_3 > L_4 > L_5 > L_o$$

$$f < f_1 < f_2 < f_3 < f_4 < f_5 < f_o$$

Capacitors



$$C = \varepsilon \frac{A}{d} = \varepsilon \frac{wh}{d}$$

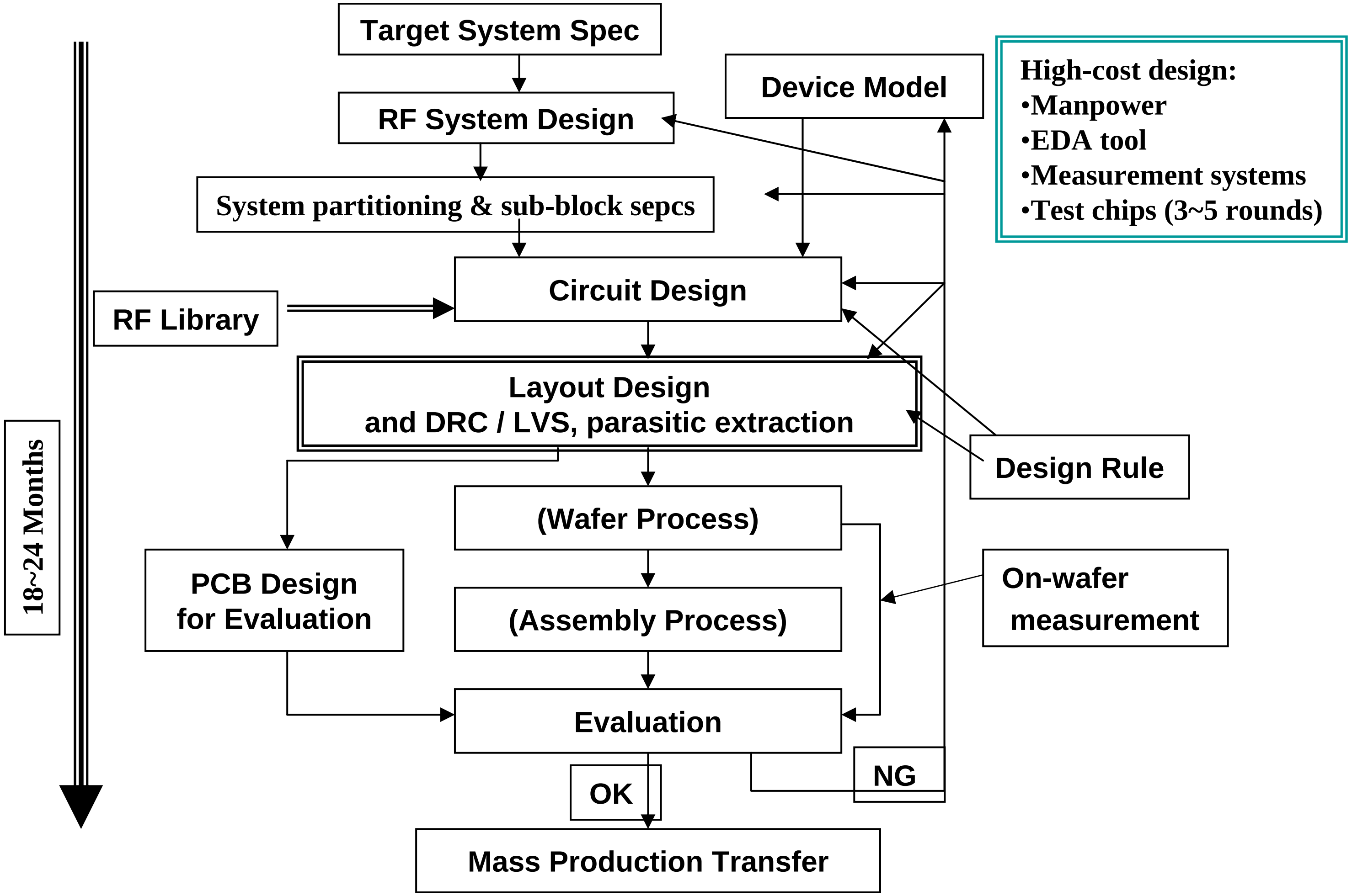
C	>	**C1**	>	**C2**	>	**C3**	>	**Co**
f	<	***f*1**	<	***f*2**	<	***f*3**	<	***f*o**

Challenges in RF IC Design

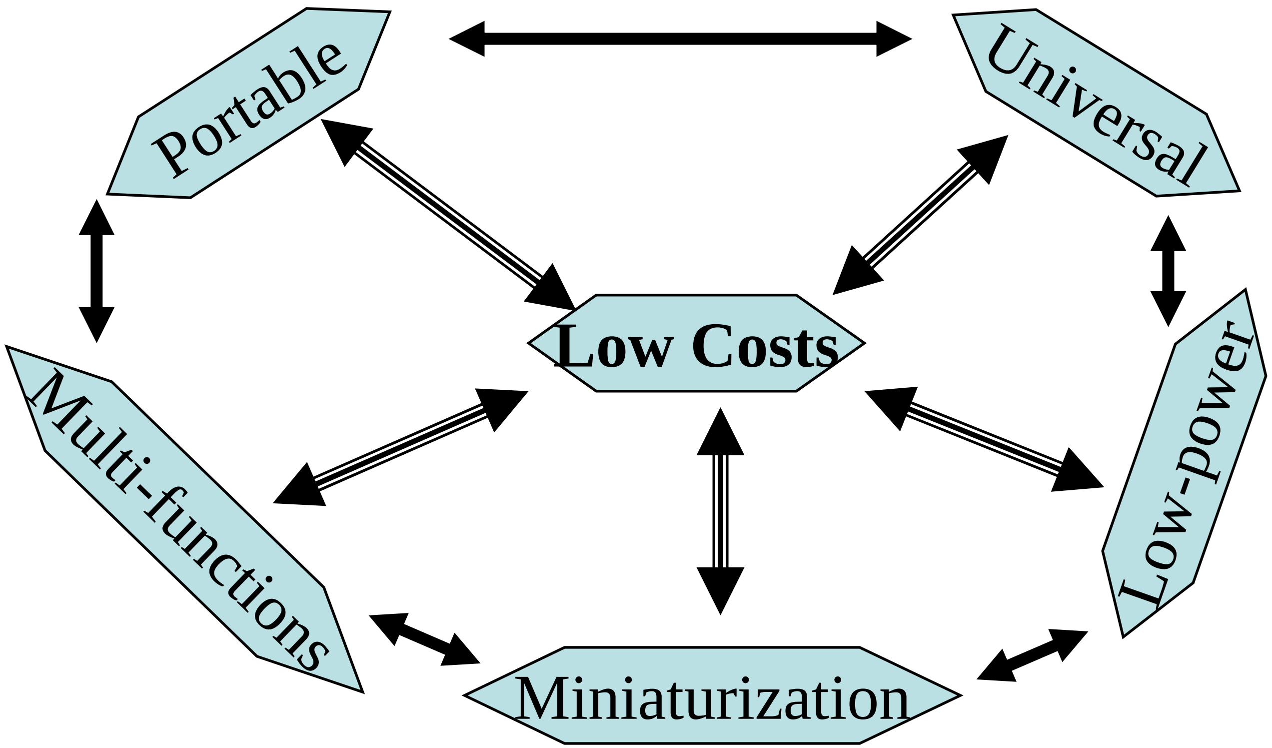
- **RF IC Designs = Device Models + Simulators + Experience**

- **RF IC Designer =**
  Analogue circuit designer (Simulation) +
  Component maker (layouts) +System designer

RFIC Development Flow

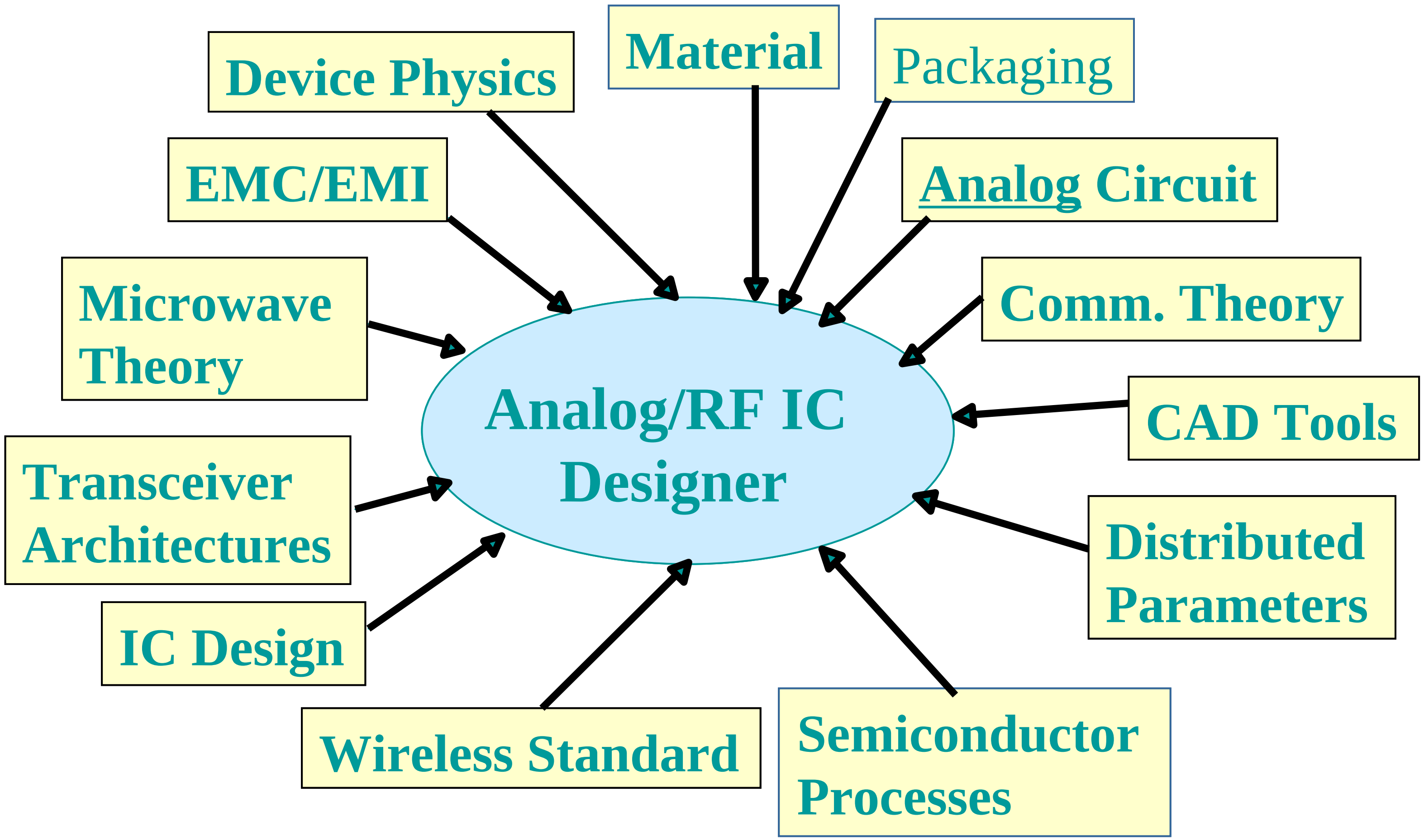


General Design Considerations

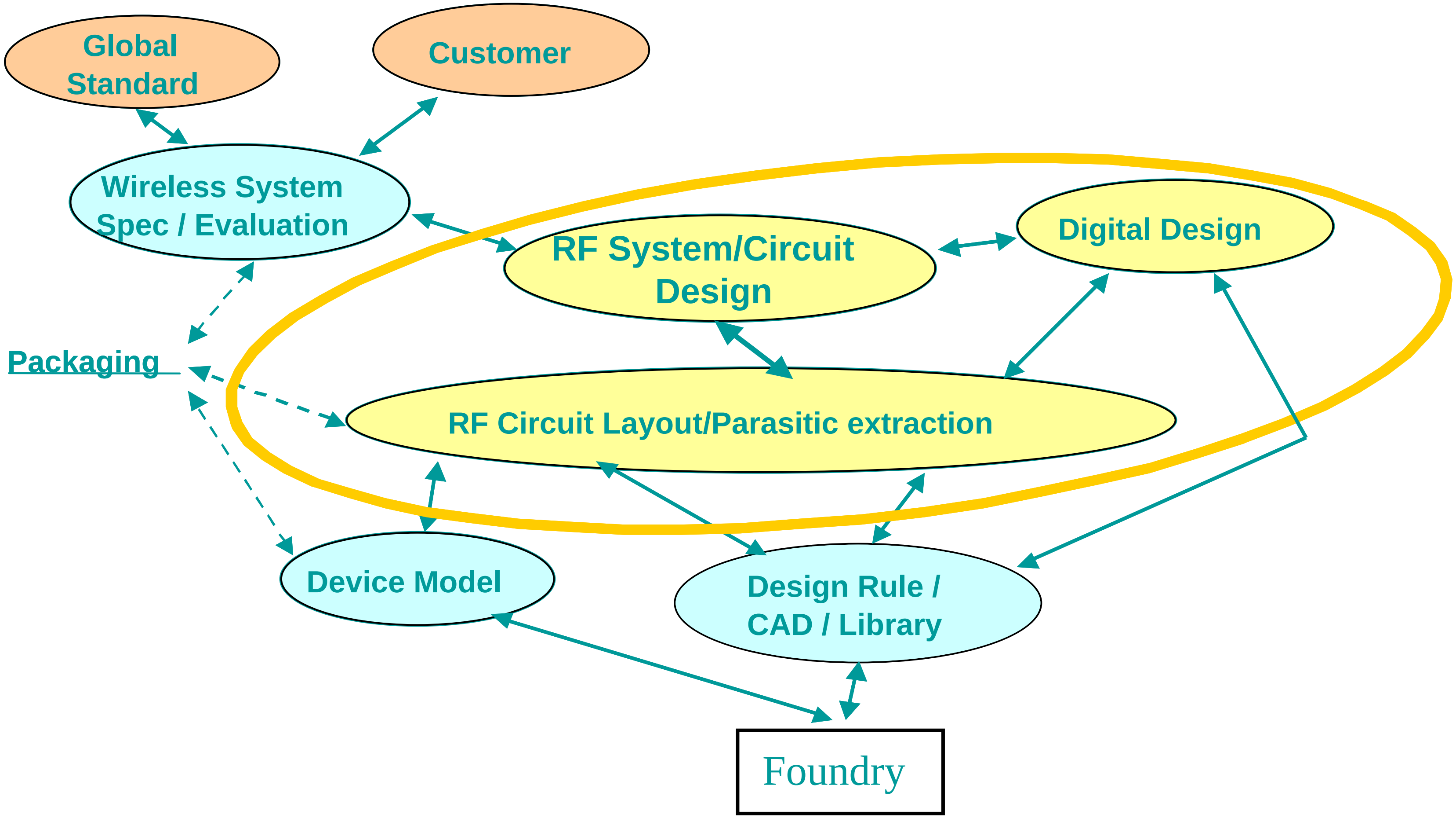


From the customers' point of view

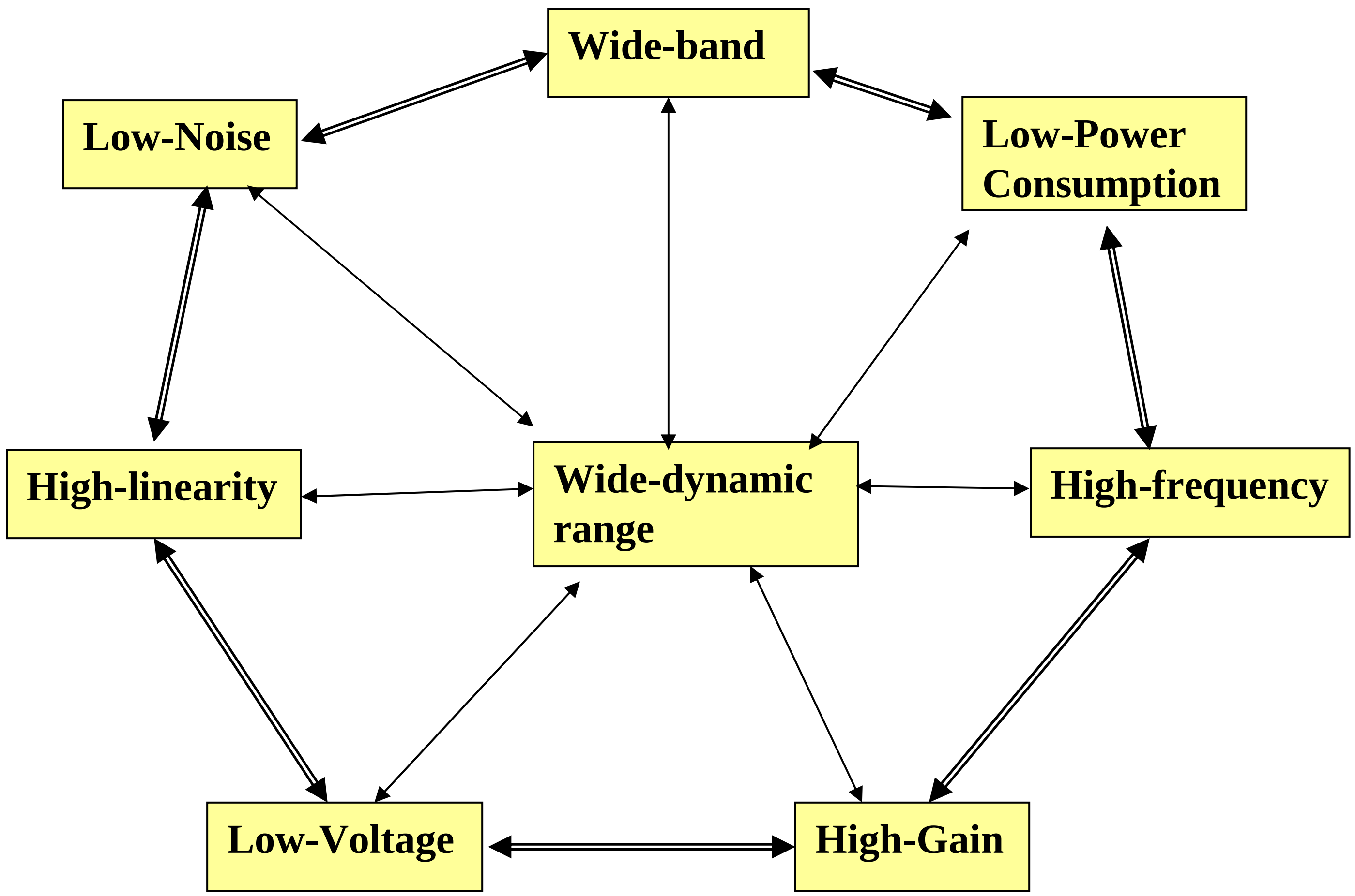
Broad-knowledge Required



Teamwork Required



Trade-Offs


Wide-band
Low-Noise
Low-Power Consumption
High-linearity
Wide-dynamic range
High-frequency
Low-Voltage
High-Gain

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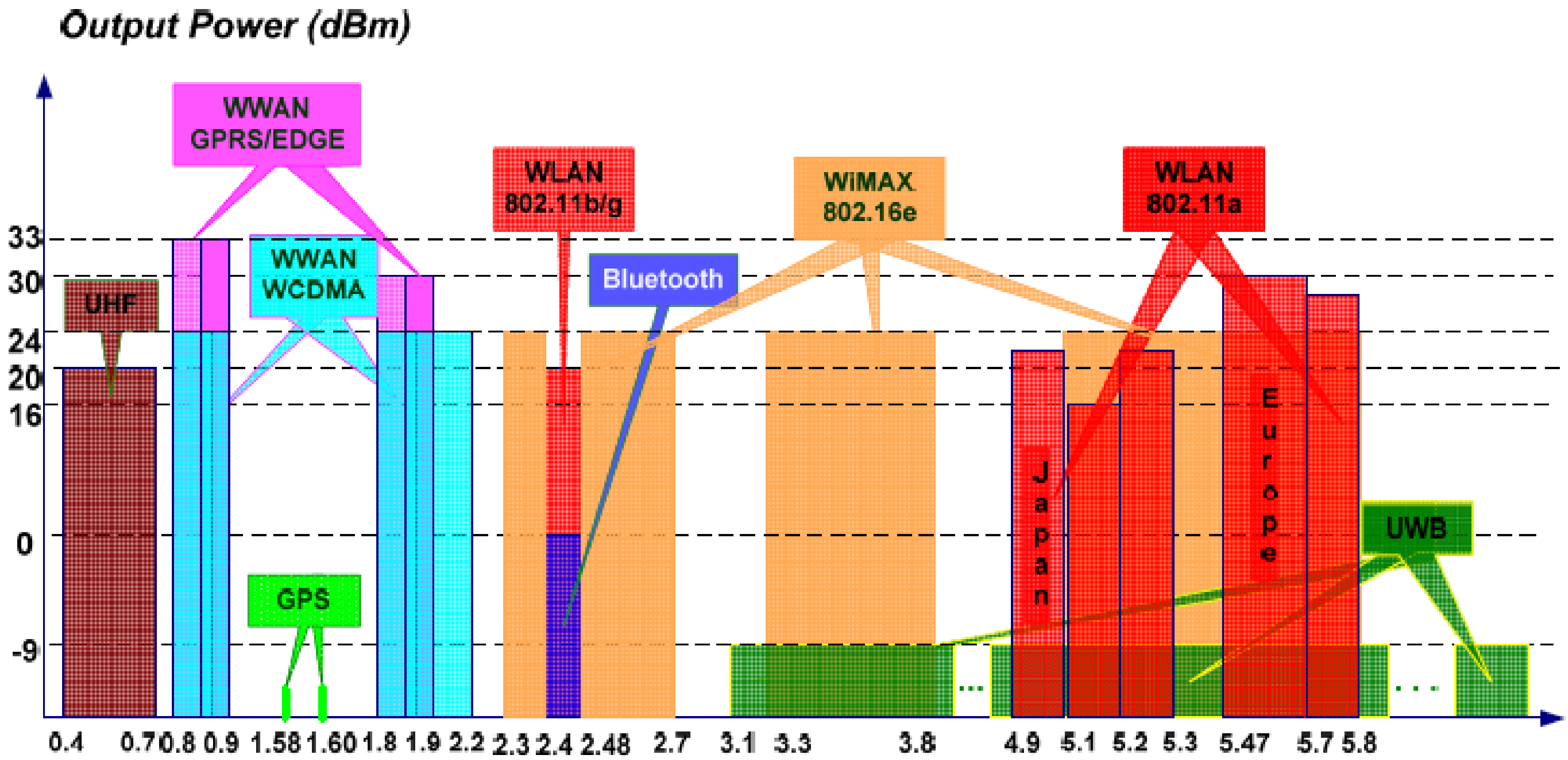
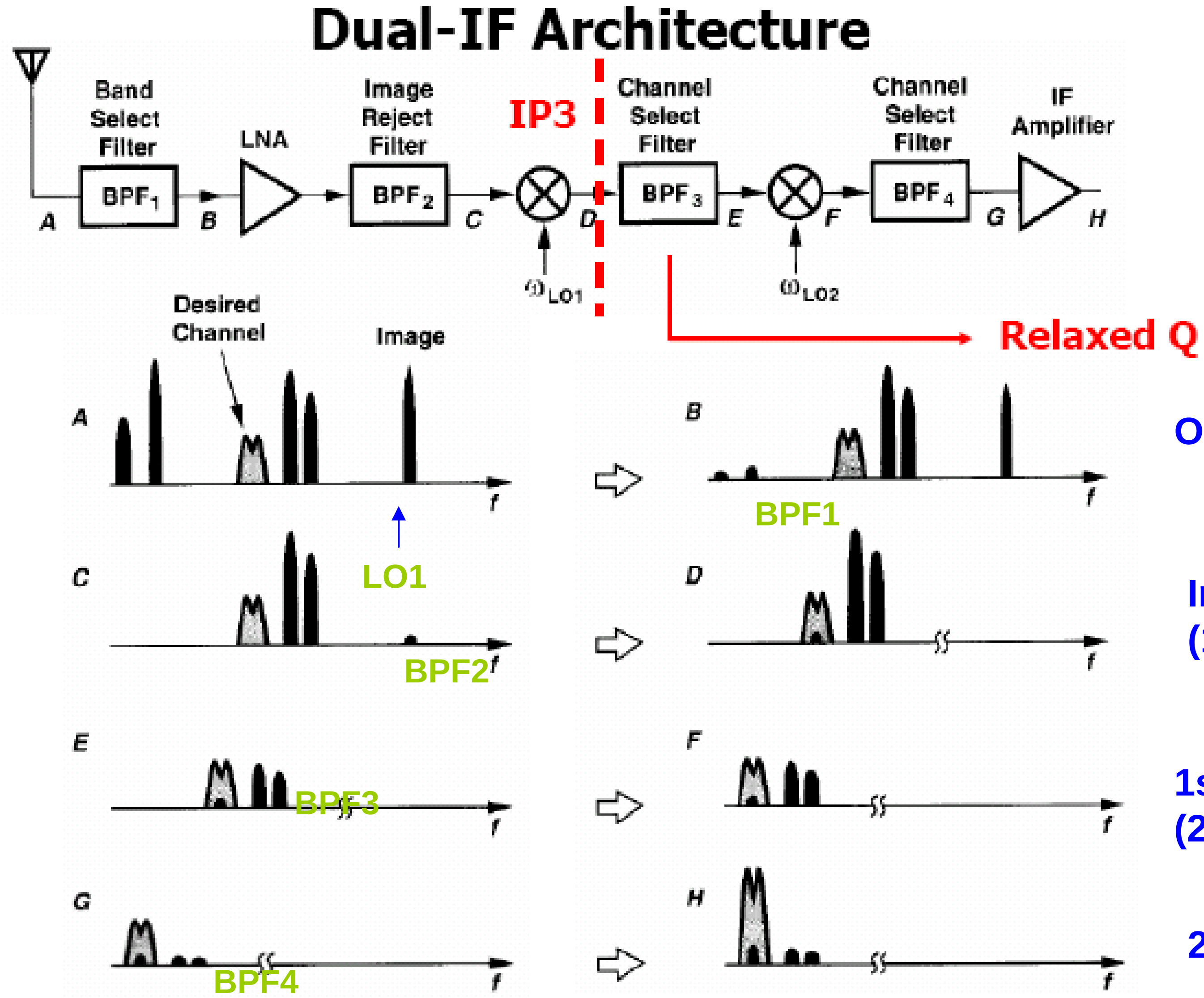
Multi-Mode Wireless



Future receivers need "Co-exist" with transmitters of different standards.
(i.e. simultaneous operation SoC/SiP)

(Super-) Heterodyne Receiver



Out-of-band rejection

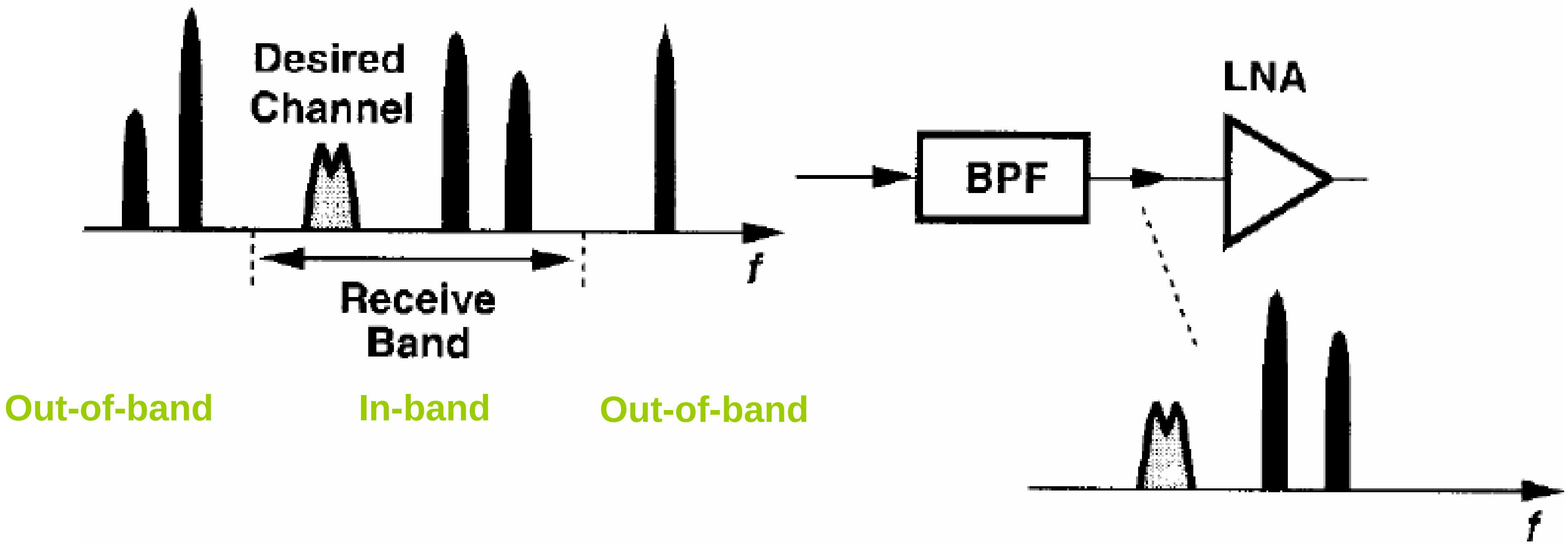
Image problem
(1st down-conversion)

1st channel selection
(2nd down-conversion)

2nd channel selection

*Razavi

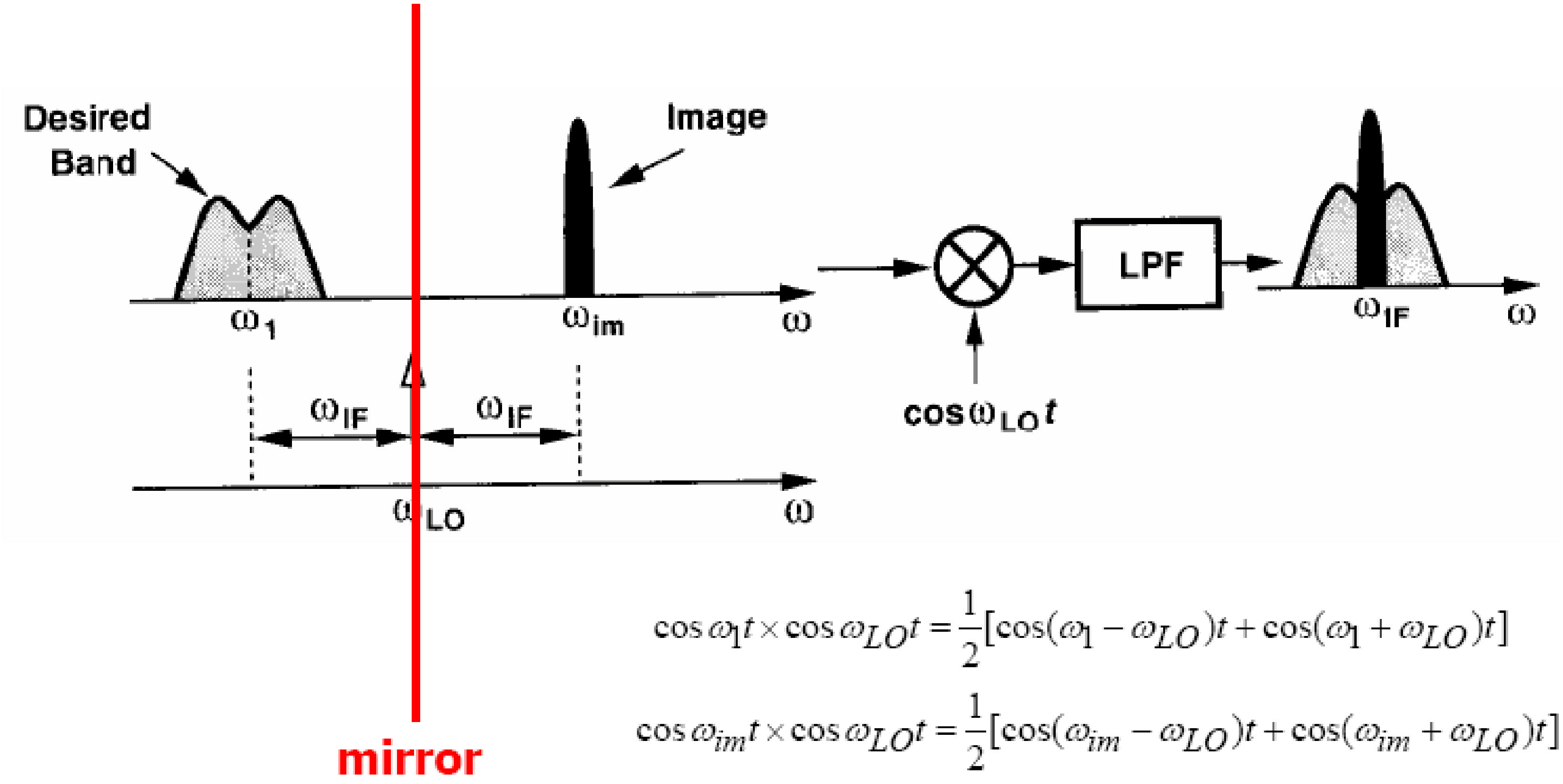
Out-of-band Interference Rejection (Band Selection)



Band: the entire spectrum in which users of a standard can use.
Examples: GSM downlink 935-960 MHz, FM 88-108 MHz

Channel: a portion in the band that one user occupies.
Examples: GSM/FM channel bandwidth=200kHz

Image Problem in Heterodyne System

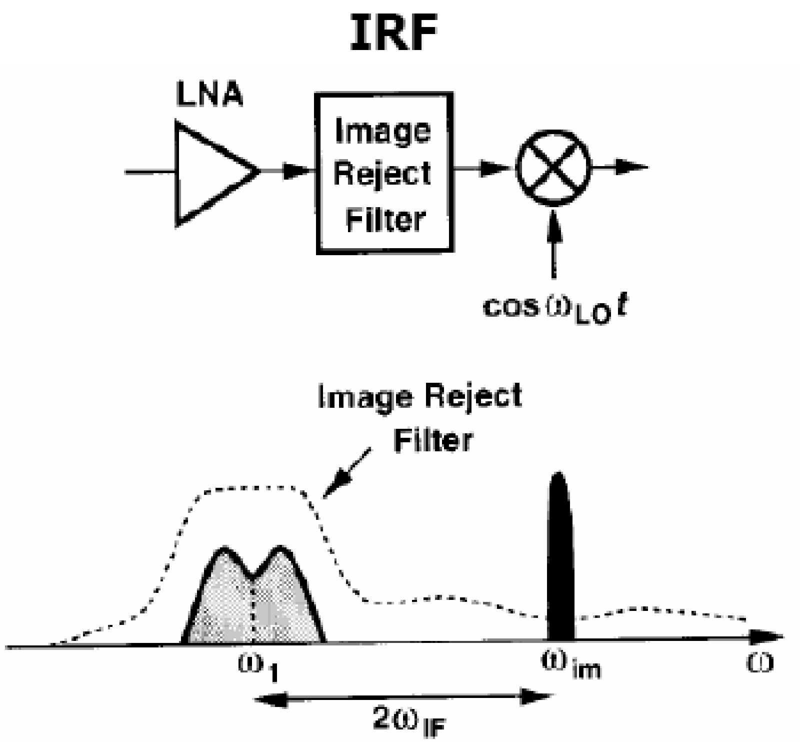


$$\cos\omega_1 t \times \cos\omega_{LO} t = \frac{1}{2}[\cos(\omega_1 - \omega_{LO})t + \cos(\omega_1 + \omega_{LO})t]$$

$$\cos\omega_{im} t \times \cos\omega_{LO} t = \frac{1}{2}[\cos(\omega_{im} - \omega_{LO})t + \cos(\omega_{im} + \omega_{LO})t]$$

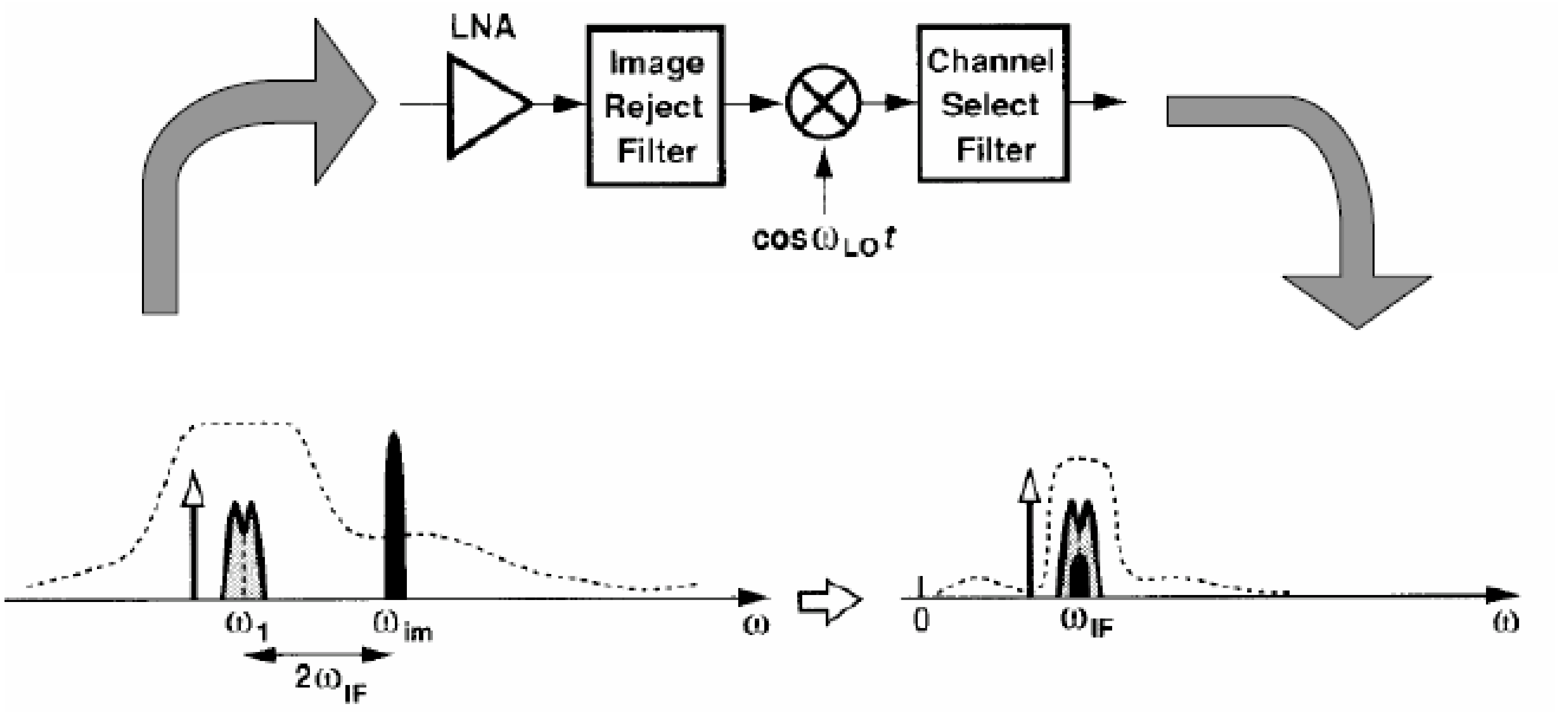
$$\omega_{LO} - \omega_1 = \omega_{IF} = \omega_{im} - \omega_{LO}$$

Image Rejection by Filter



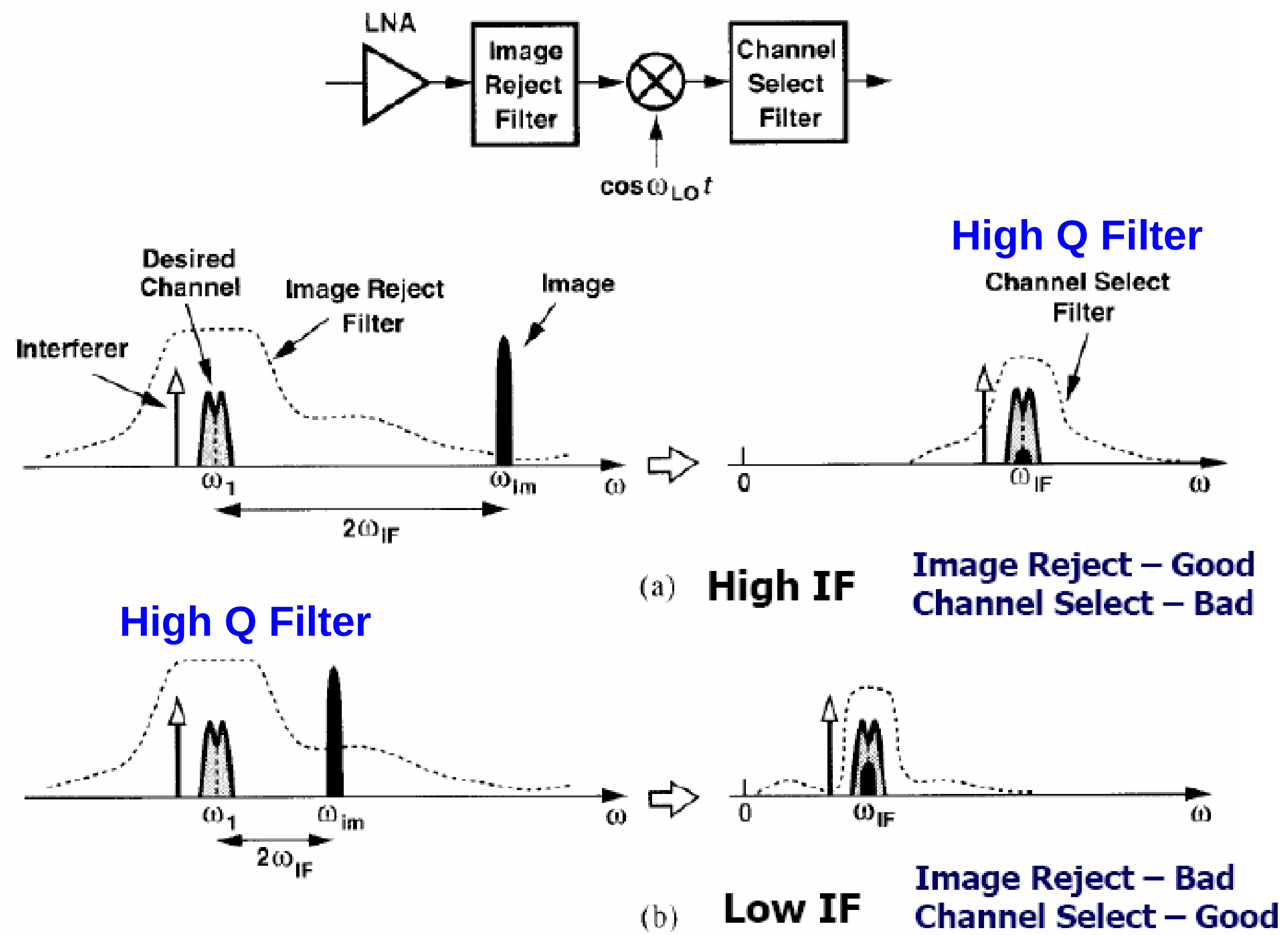
- IRF also rejects large output noise of LNA.
- An alternative is to use Image Reject Receiver

Channel Selection Filter



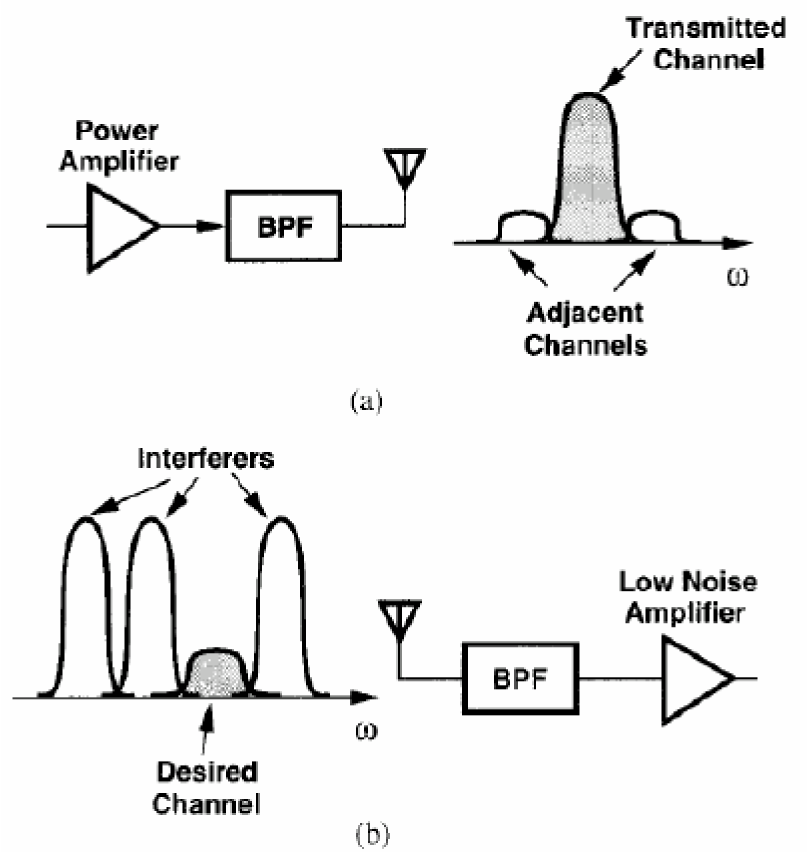
Important: IP3 is not an issue after channel select filter.

Image Rejection and Channel Selection



In-band Interference (1)

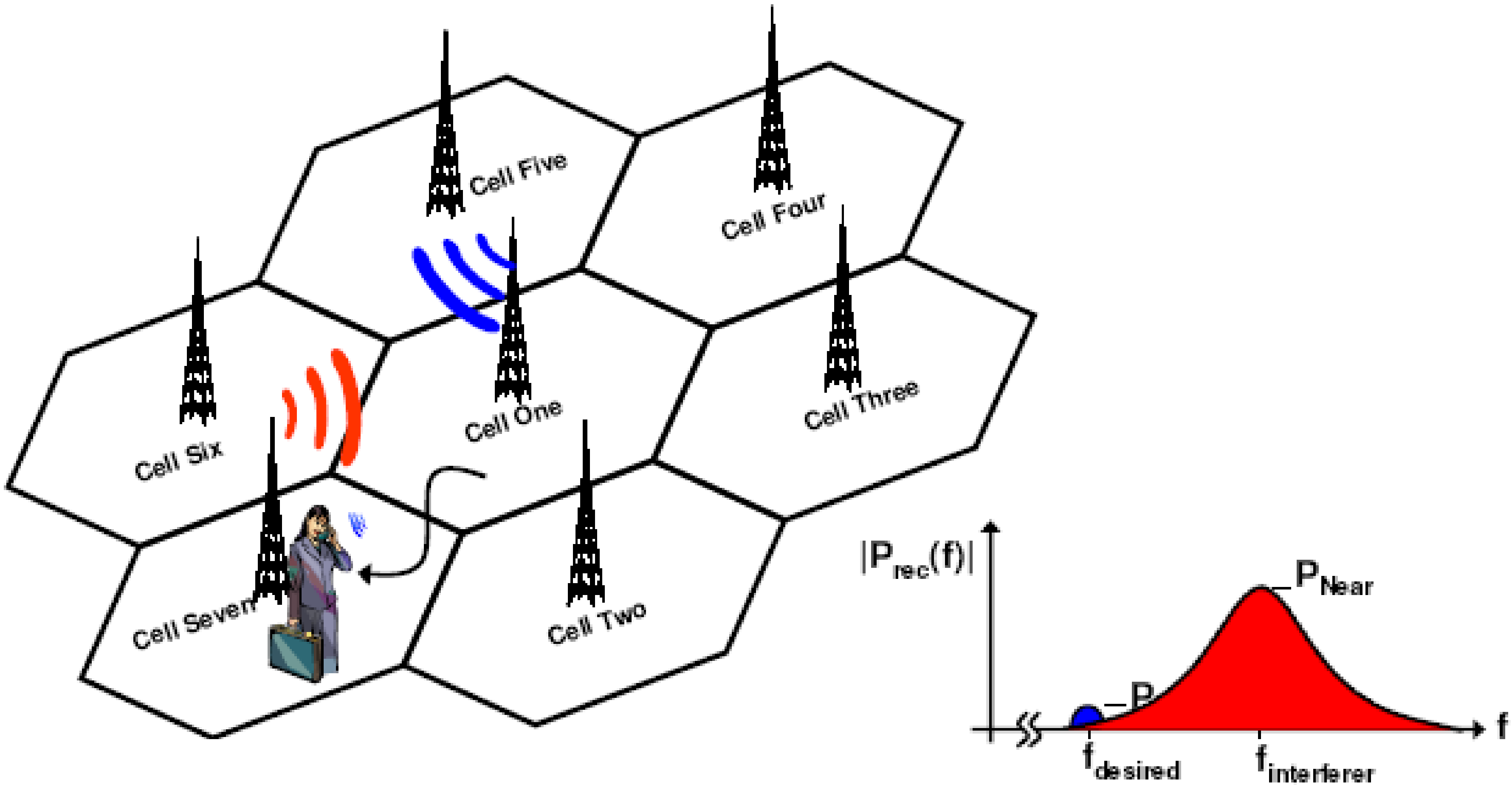
Transmitter



Receiver

- **Where do those interferers come from?**

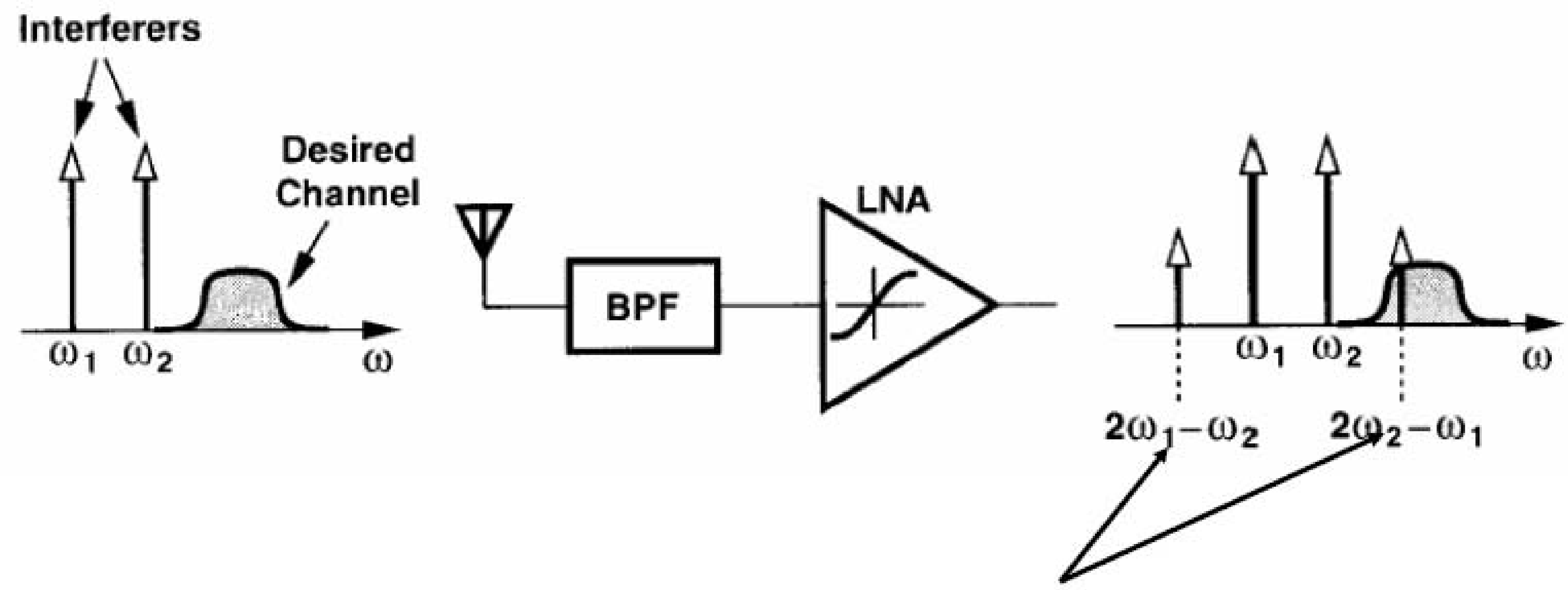
In-band Interference (2)



Near-Far Problem Comes from Wandering into Adjacent Cells

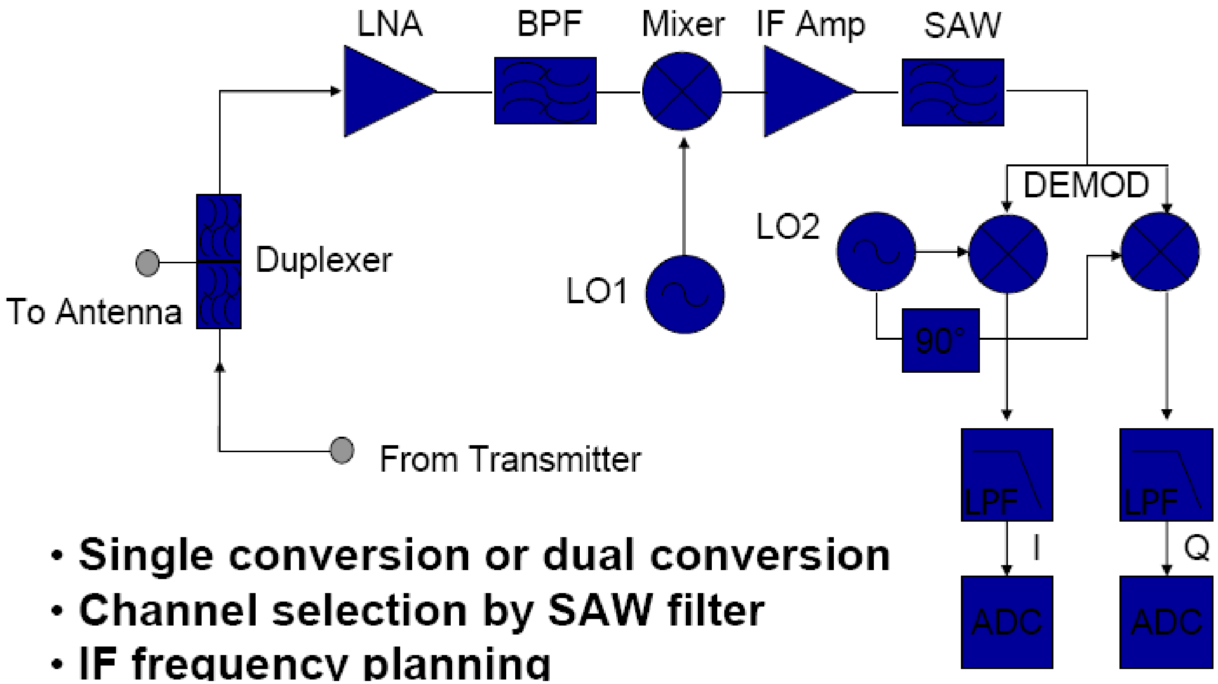
In-band Interference (3)

How does Non-linear Amplifier (IMD3) affect the signal?



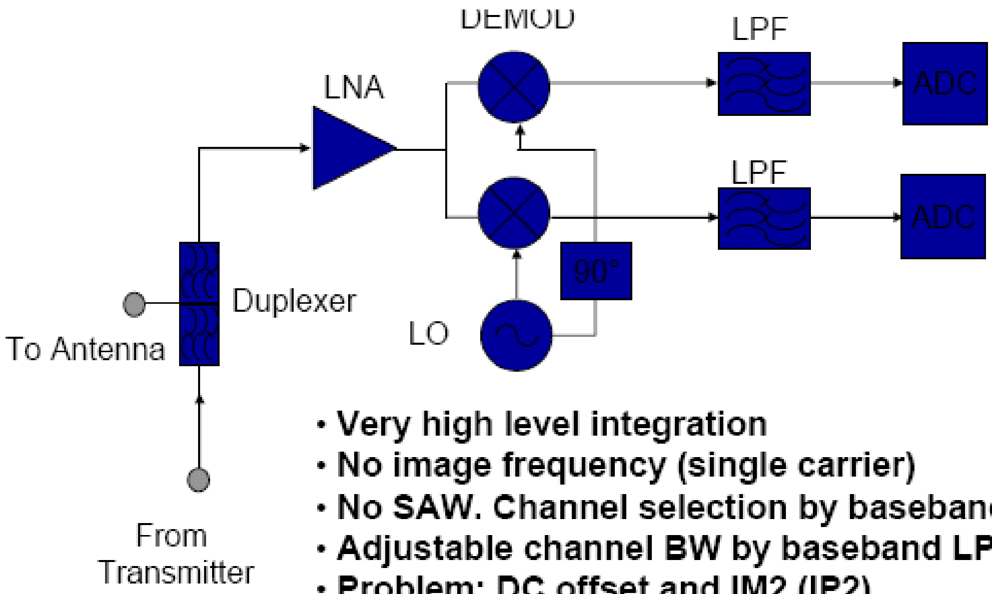
3rd-order intermodulation products

Receiver : Heterodyne



- Advantages
  - (High Selectivity) Relaxation of linearity requirements due to the use of IF SAW BPF
  - (High Sensitivity) Less DC-offset impairment, Easier I/Q match at lower frequencies
- Disadvantages
  - Bulky off-chip RF/IF SAW BPFs
  - A good frequency plan is essential
  - Image problem
  - "Half-IF" spurious response at lower IF frequencies
  - Need at least two LO sources
  - Integration level is low due to filter

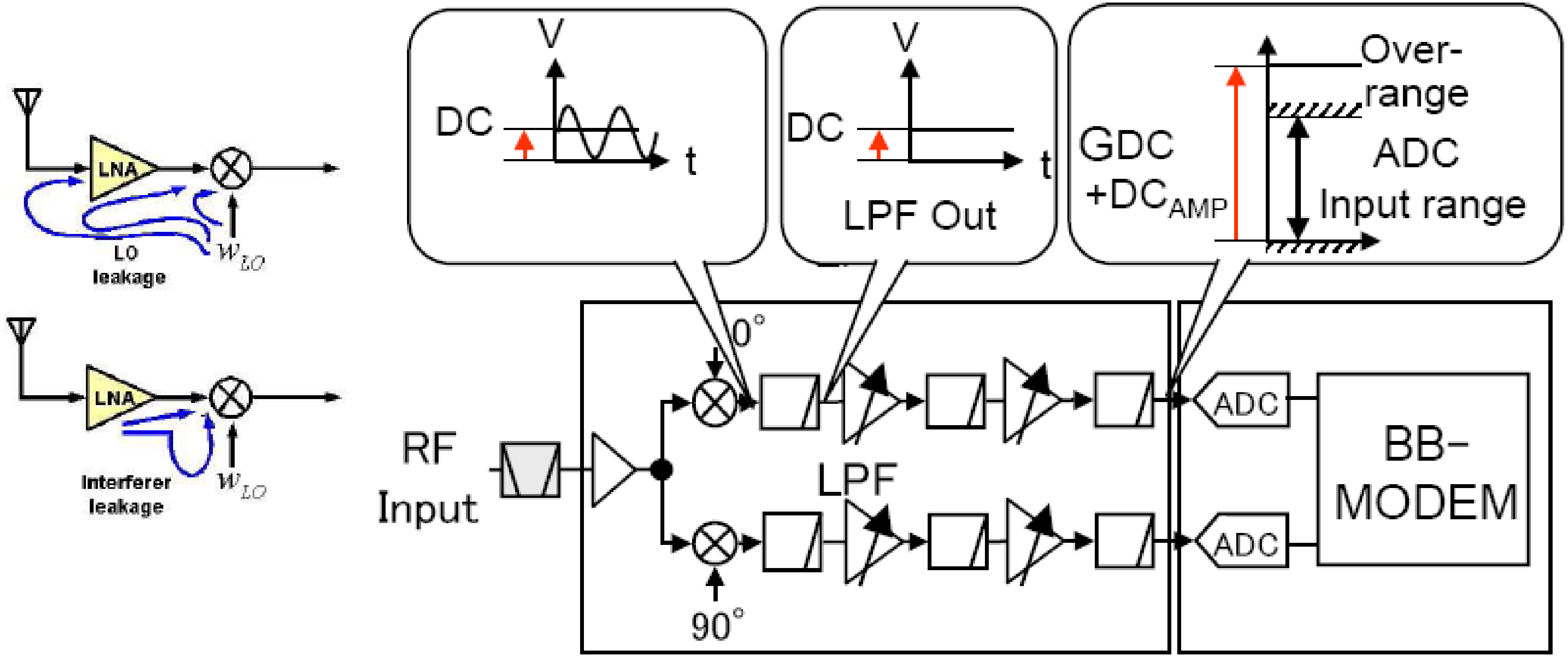
Receiver : Direct-Conversion (Zero-IF)

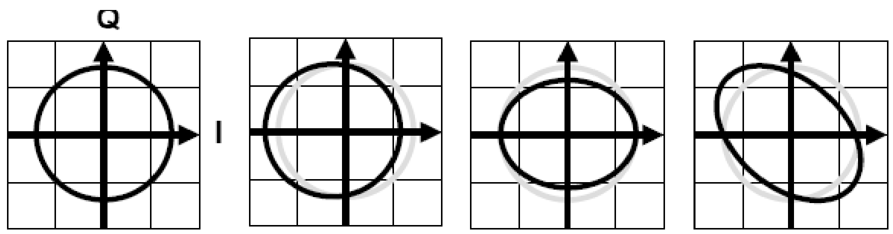


- Very high level integration
- No image frequency (single carrier)
- No SAW. Channel selection by baseband LPF
- Adjustable channel BW by baseband LPF
- Problem: DC offset and IM2 (IP2)
- Problem: 1/f noise (CMOS)
- LO pulling by in-band interferer (injection locking)
- AC coupling can be used in broadband system

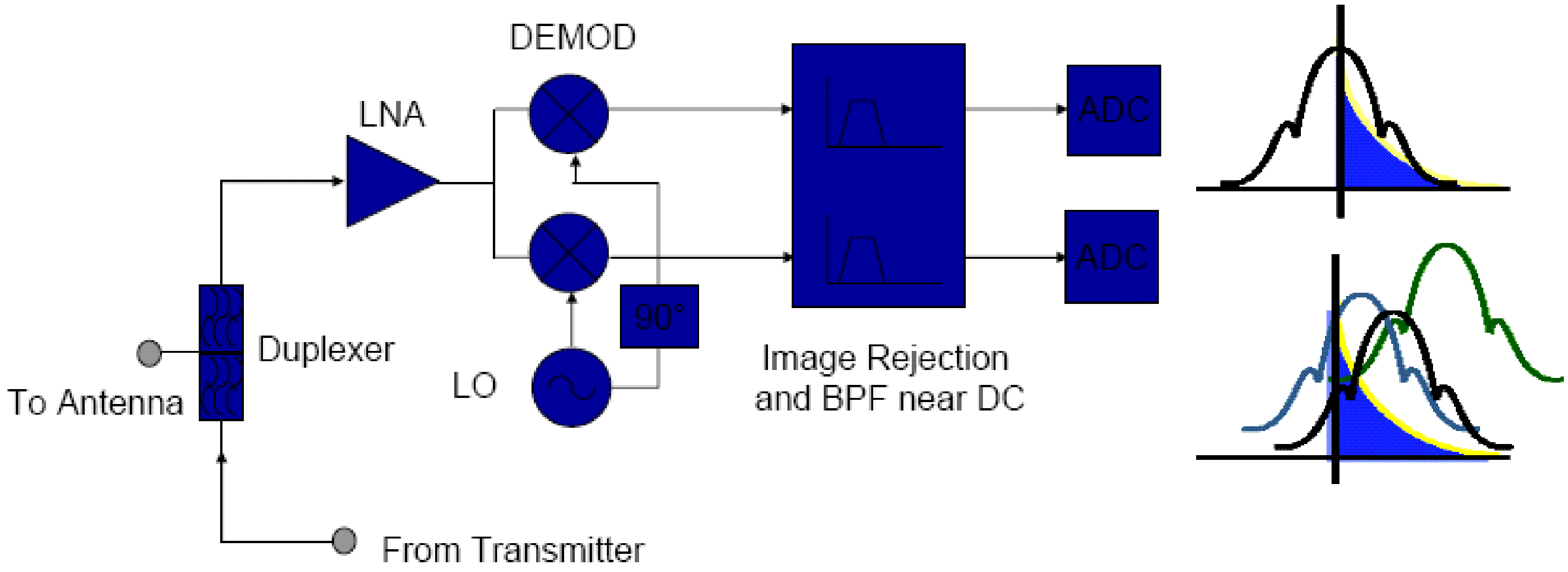
- **Advantages**
  - **No Image or "half-IF" issues**
  - **High level integration and lower cost (No IF filters)**
- **Disadvantages**
  - **DC offset problems are extremely challenging (IM2/IP2)**
  - **LO leakage re-radiation (LO pulling)**
  - **1/f noise (CMOS) can substantially corrupt the D/C signal**
  - **Even-order distortion of great concert**
  - **More difficult I/Q match at RF frequencies**

DC offset


LNA
LO
leakage
w_{LO}
Interferer
leakage
DC
V
t
LPF Out
GDC
+DC$_{AMP}$
Over-
range
ADC
Input range
RF
Input
0°
90°
LPF
ADC
BB-
MODEM

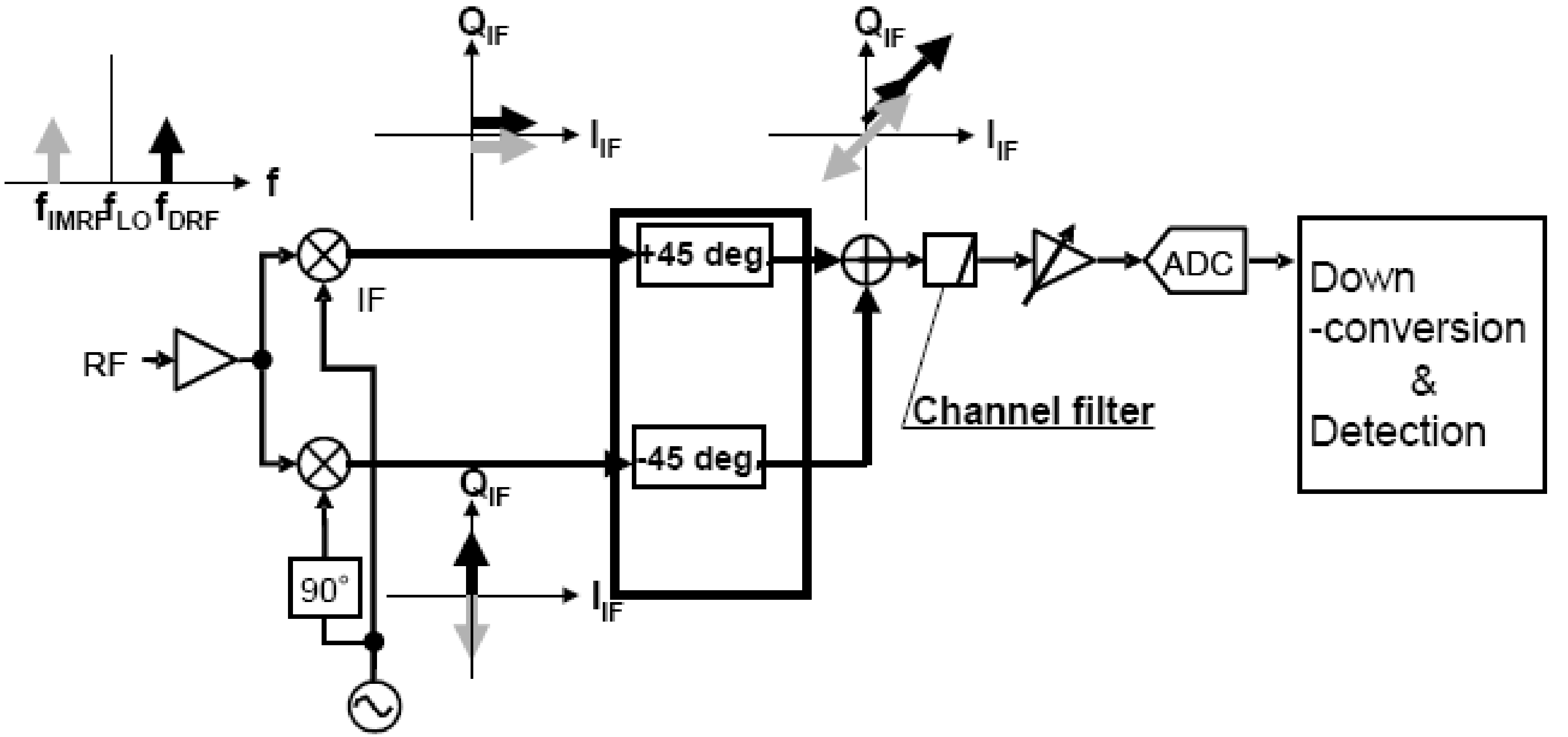

Q
I
Original
DC offset
Amplitude
Error
Phase
Error

Receiver : Low-IF



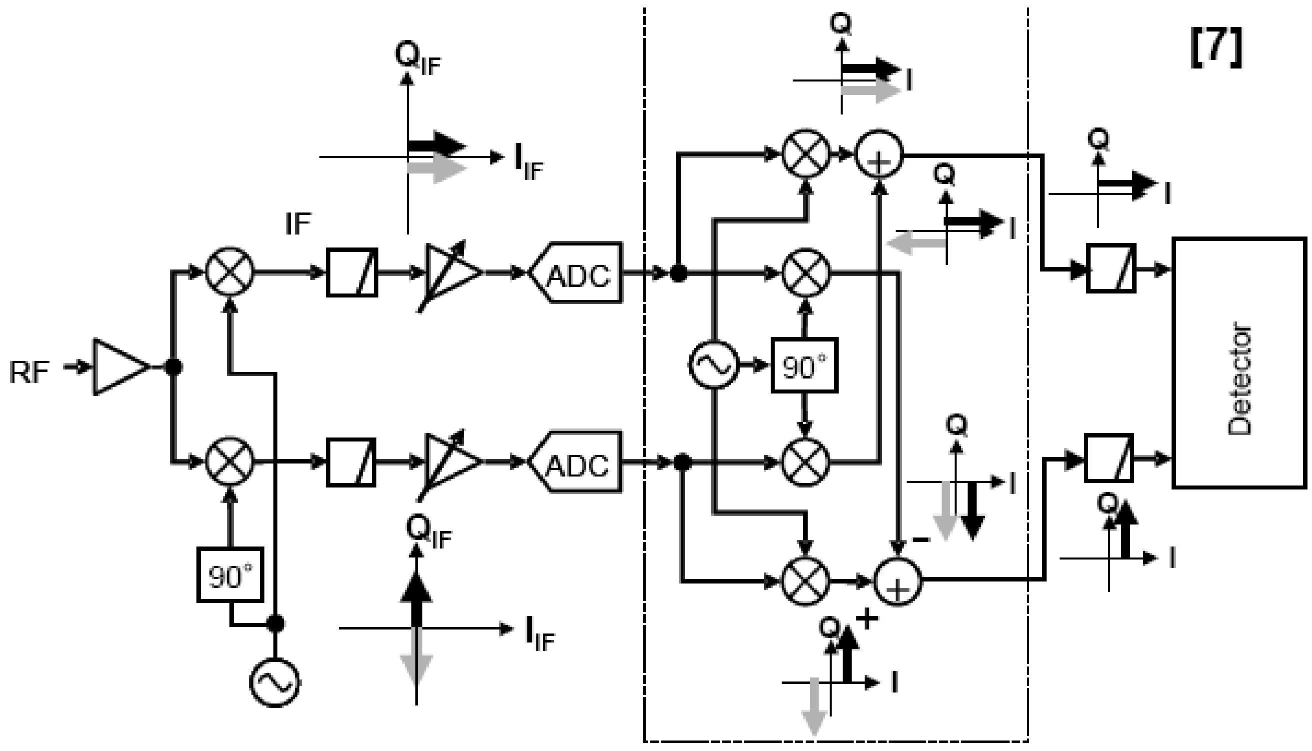
- **Advantages**
  - **Integration of channel filters is possible**
  - **Less susceptible to 1/f noise and DC offsets (AC coupling)**
  - **Low-frequency IM2 product can be easily blocked.**
- **Disadvantages**
  - **Image is still a problem, which entails precise I/Q match**
  - **Complex signal processing is essential to obtain necessary selectivity**

Receiver: Image Rejection Low-IF



- **To achieve 30dB Image rejection**
  - **IQ amplitude imbalance is less than 0.5dB**
  - **IQ phase imbalance is less than 3.5 degree**

Receiver: Image Rejection Low-IF (Digital)



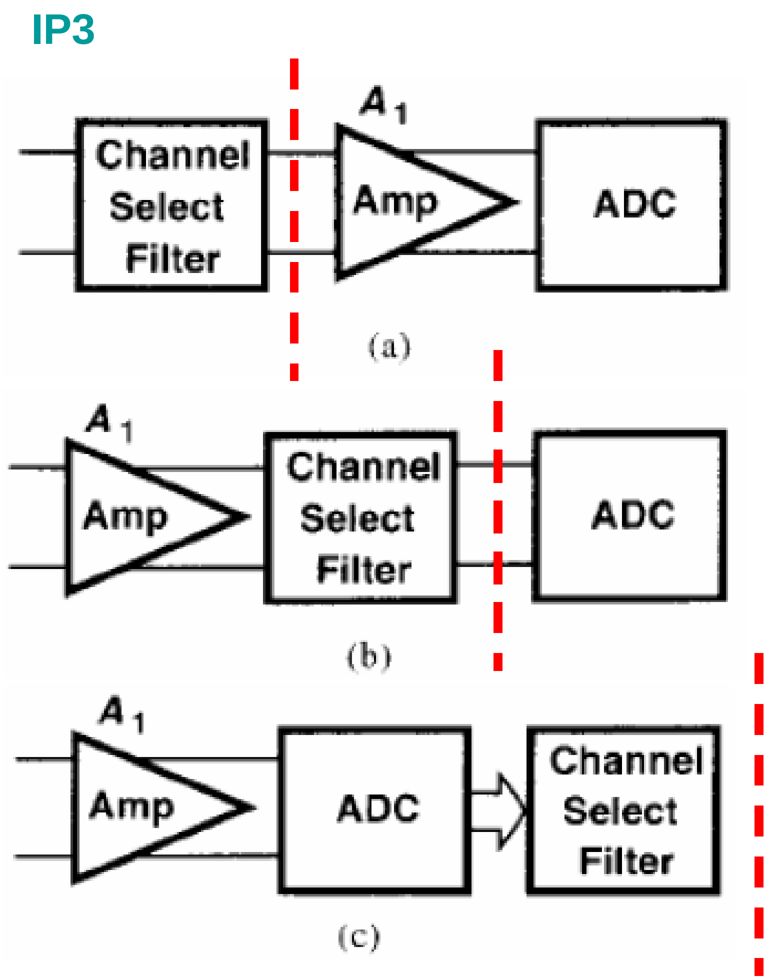
- **Advantages**
  - **Digital signal process avoids the problem of I/Q mismatch**
  - **Less susceptible to process variations**
- **Disadvantages**
  - **ADC performance is a great concern**

Zero-IF Receiver Channel Selection

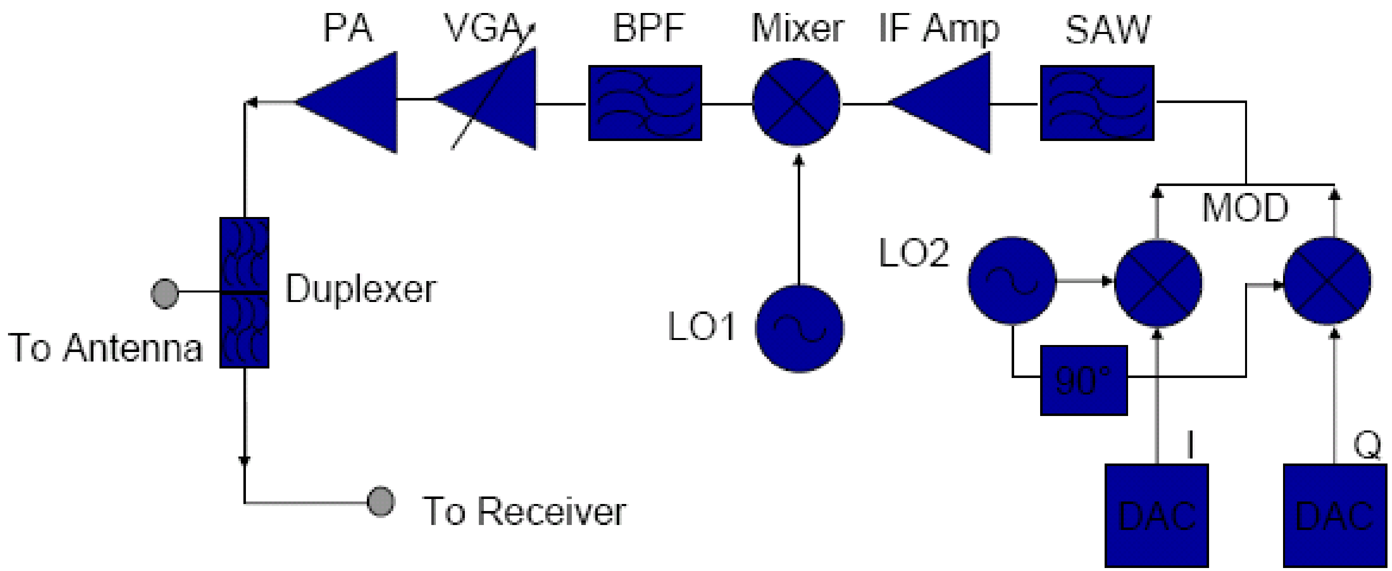
LPF: linear & low noise
Amp: can be nonlinear

LPF: noise not critical
Amp: linear & low noise

Filtering in digital domain
ADC: high linearity

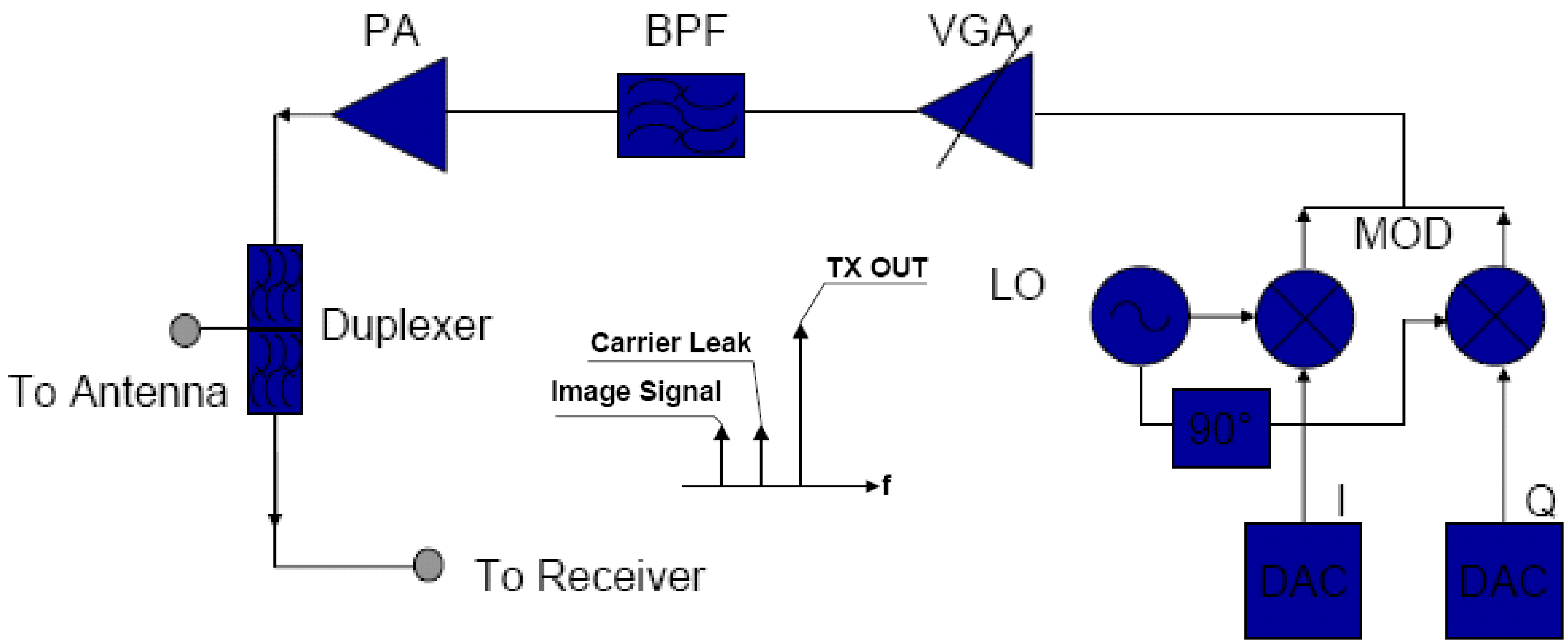


Transmitter : Heterodyne



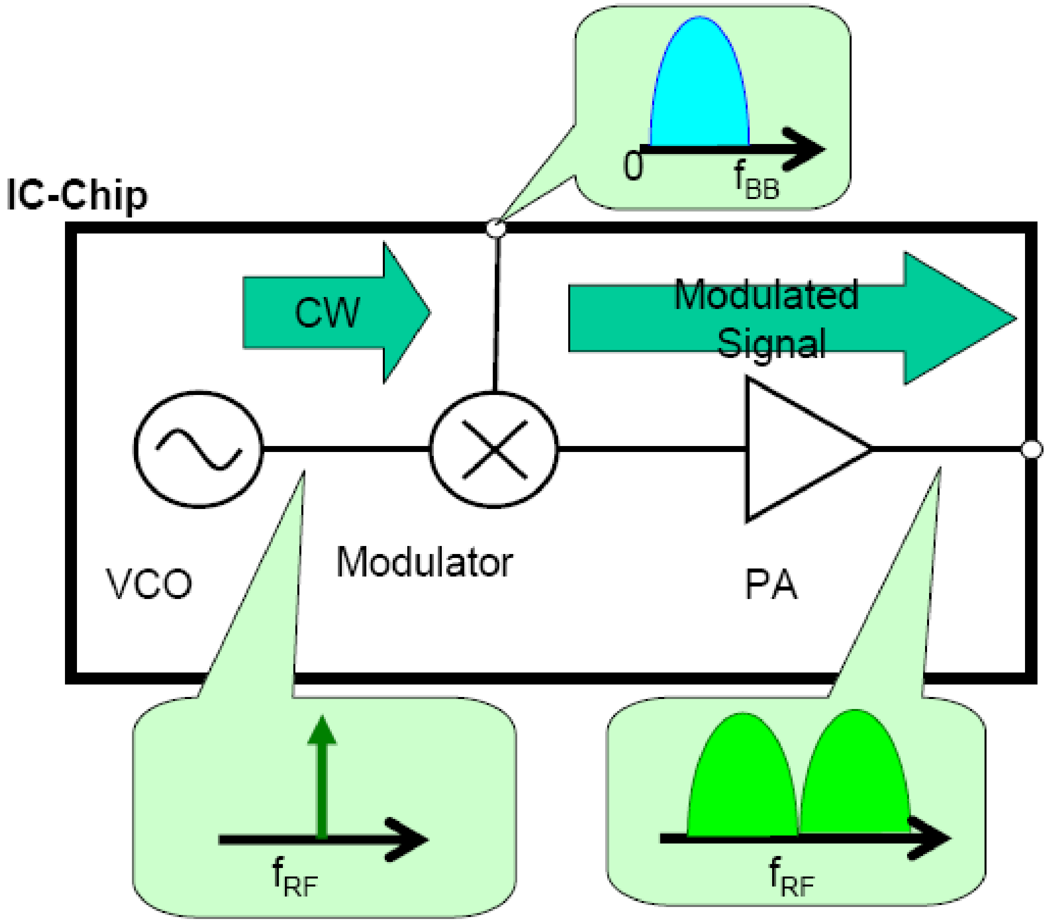
- SAW filter cleans up modulator noise
- Need two LO sources

Transmitter: Direct Conversion

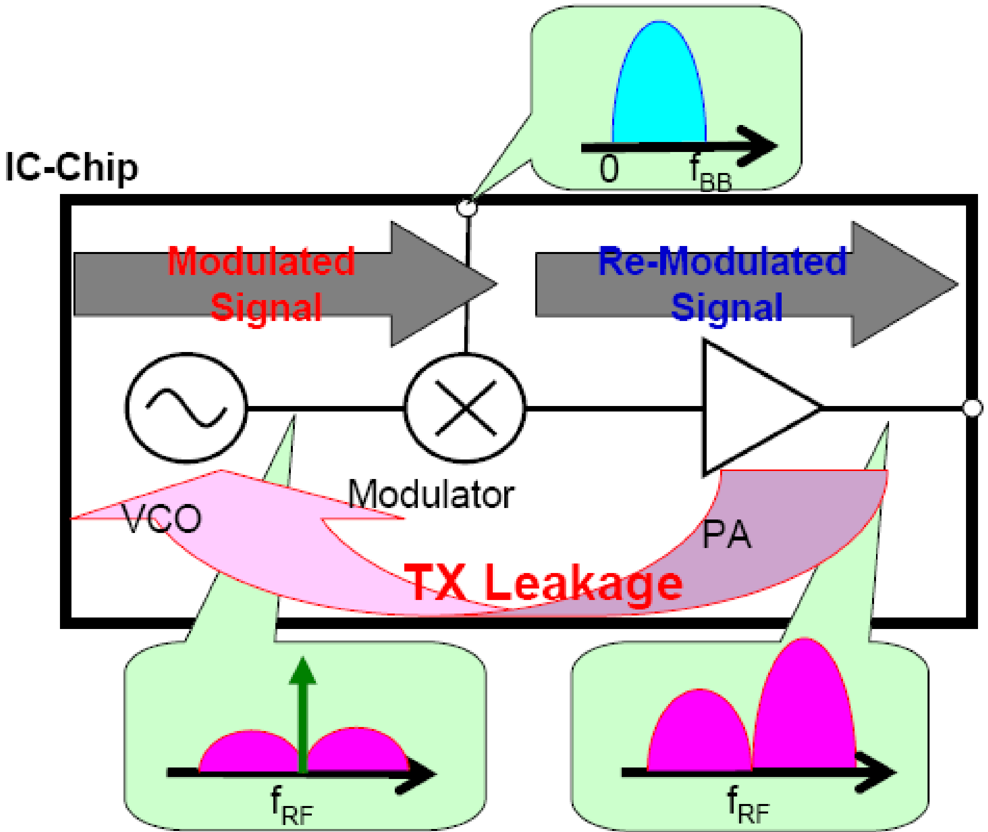


- No SAW filter
- High level integration - only one LO needed
- Modulator noise floor must be low enough
- LO pulling

No interference



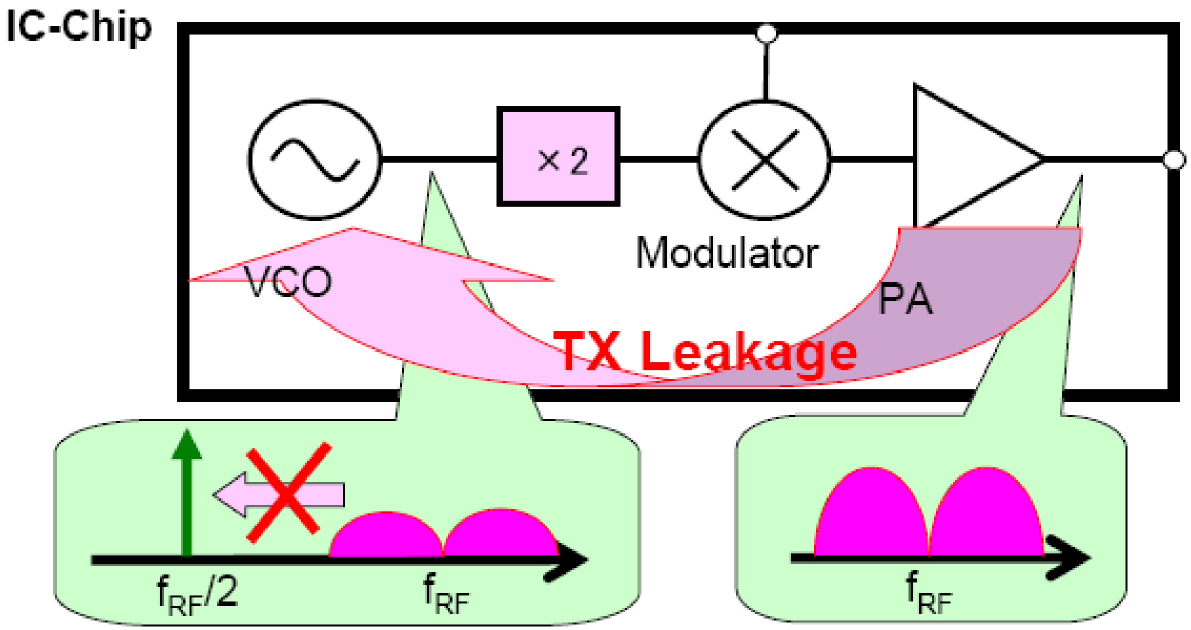
With Interference (LO Pulling)



USB/LSB imbalance of output spectrum occurs!
-> Degradation of TX signal !

Indirect VCO Frequency (Sub-harmonic LO)

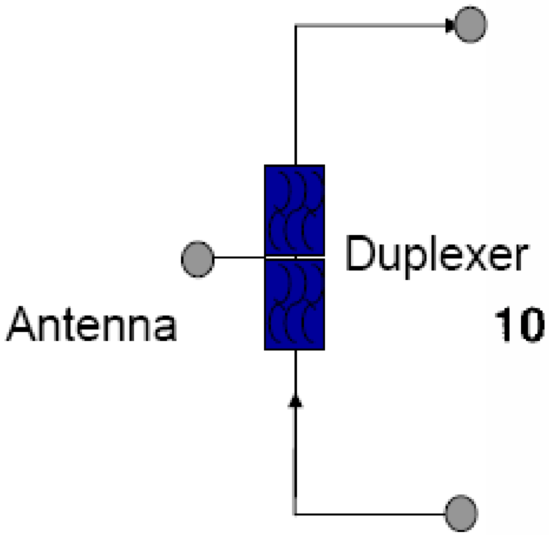
- Change VCO freq. from RF(TX) freq.
  (fLO= 1/2 x fRF or 2 x fRF)

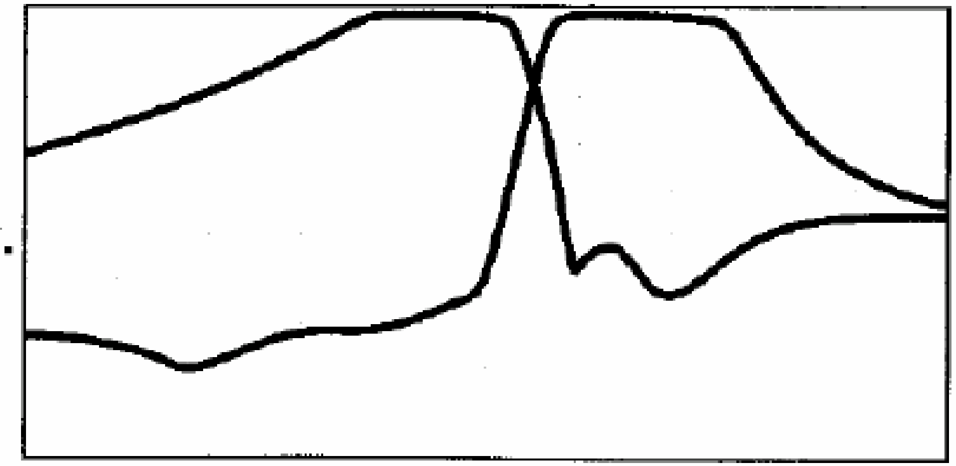


- Or using sub-harmonic modulator or mixer

Leaked TX signal does not affect on VCO's signal directly.

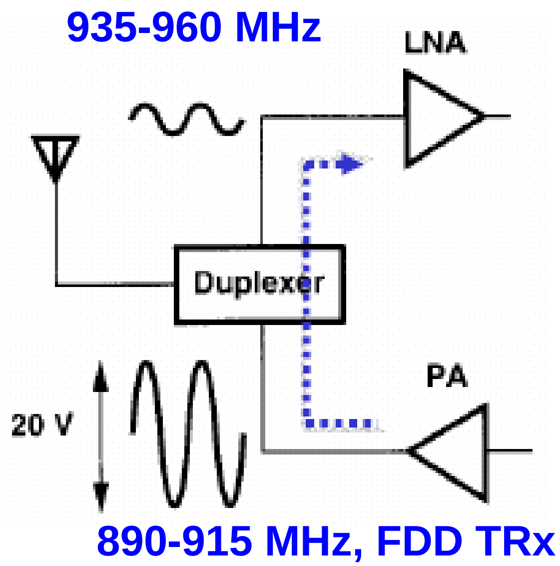
Duplexer Freq. Response

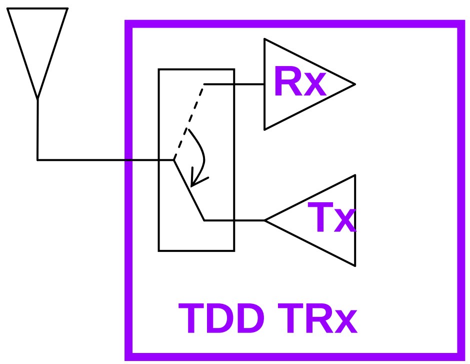




PA Leakage to Rx

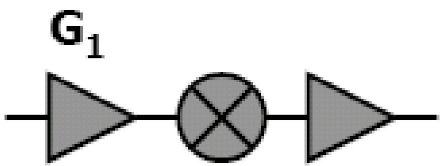
? W
? dBw
? dBm





- Affects the sensitivity – desensitization.
- Problem in FDD with high power transmitter.

Gain Compression
→ G_1 ↓
→ NF_{total} ↑



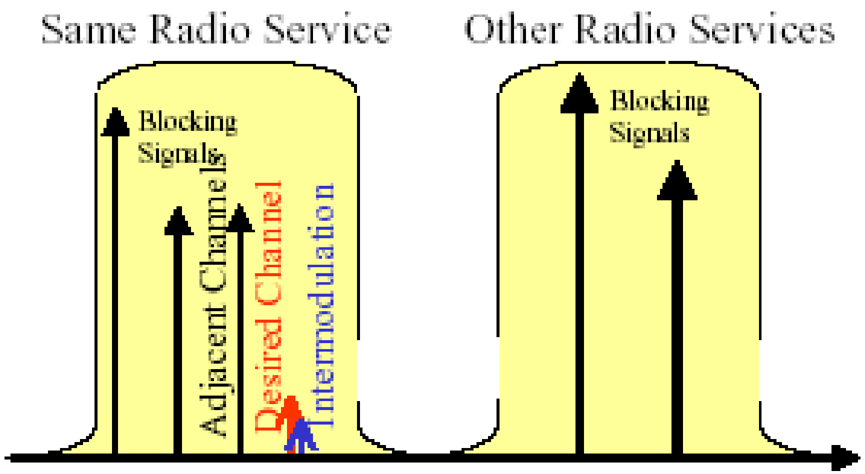
Desensitization Through Compression

Compression Point Is a Measure for the Receiver's Ability to Receive Weak Signals in the Presence of Strong Out-of-Band Interferers.

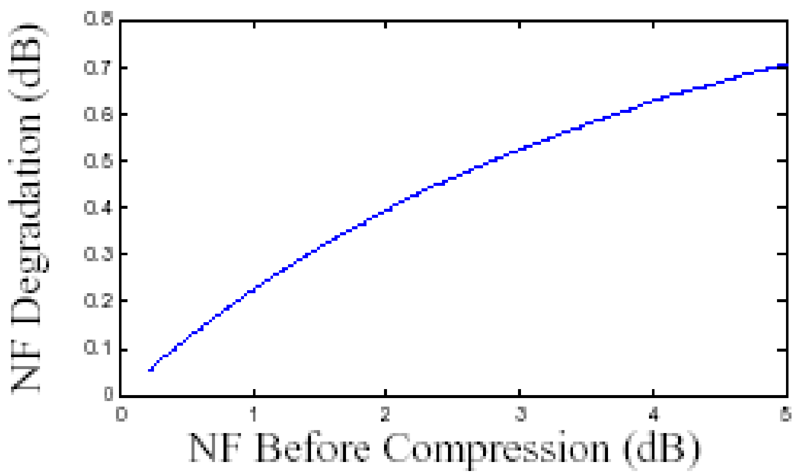
The Interferers Cause the R_x Gain to Compress. Receiver NF Degrades as a Result.

Receiver Sensitivity Therefore Degrades by Up to the Amount of Gain Compression

Interferer Power and Crest-Factor Together Determine the Amount of Gain Compression



Degradation of NF by 1dB Gain Compression



TRx Architecture Selection

RX,TX systems in mobile wireless applications

	GSM	EDGE	Bluetooth	WCDMA	CDMA	W-LAN	UWB
RX	Direct Conv. [1-6] Low-IF [7-11] Sampling [12-15]		Low-IF [39,40] Sampling [41]	Direct Conv. [43-47]	Direct Conv. [50]	Direct Conv. [54-61] Sliding IF [51-53]	Direct Conv. [63-65]
TX	O-PLL [16-21] $\Delta\Sigma$ [22-28] Direct Conv. [29] DCO [31,32]	Polar (closed) [32,33] Polar (open) [34-38] Direct Conv.	$\Delta\Sigma$ DCO Direct Mod. [39,40] Low-IF [42]	Direct Conv. [49] 2-Step Conv. [48]	Direct onv.	Direct Conv. [54-62] Sliding IF [51-53]	Direct Conv. [63-65]

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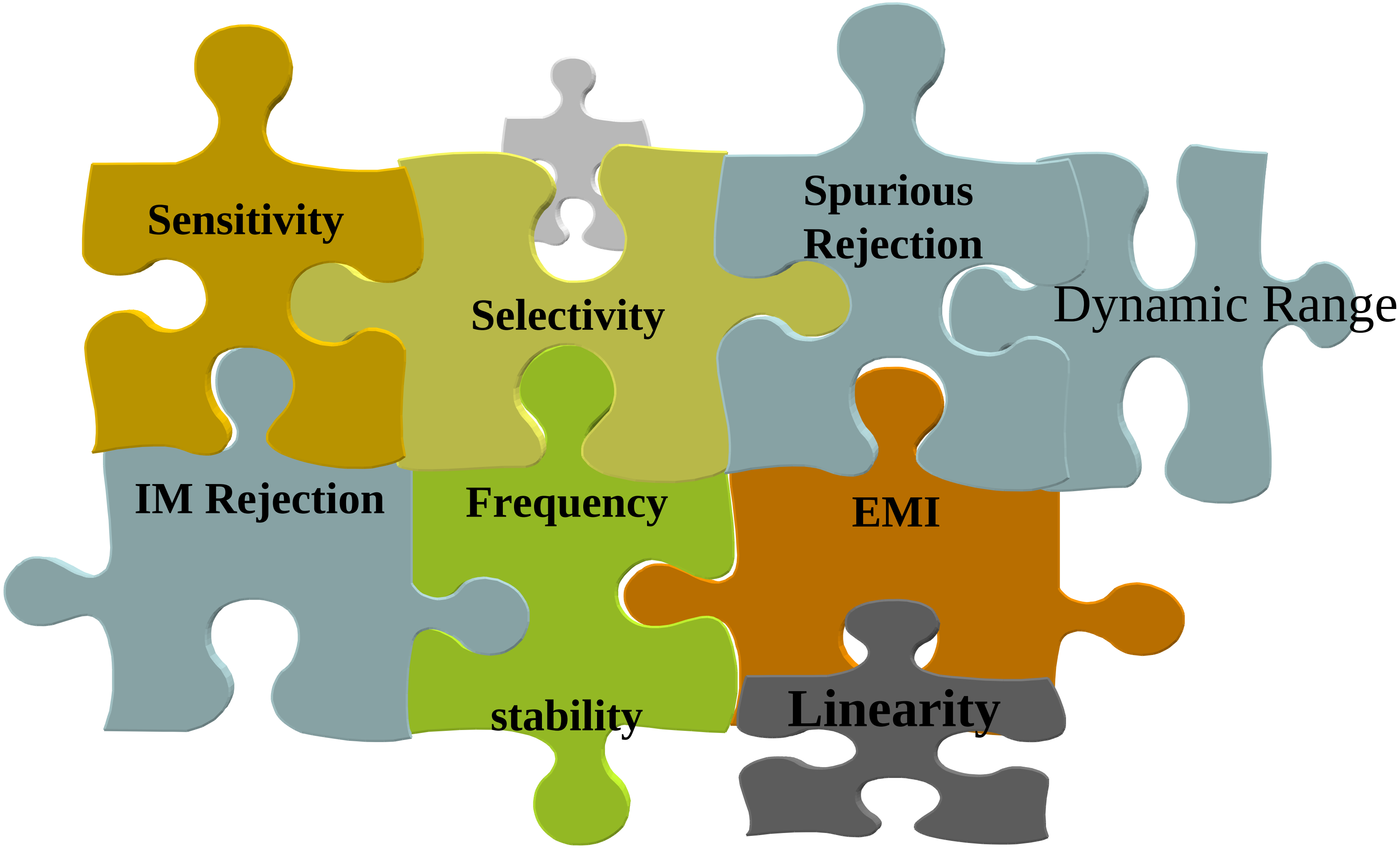
System Considerations



Sensitivity

- RF Receiver sensitivity: quantifies the ability to respond to a weak signal.
- Defined as the minimum detectable signal power level, satisfying the requirement of the specified signal-to-noise ratio (SNR) for an analog receiver and bit-error-rate (BER) for a digital receiver.

dBm

$$\text{dBm} = 10\log(\text{mW}) = 10\log(\text{W}) + 30\text{dB}$$

Boltzmann constant *k* = 1.3806503 $\times$ 10^{-23} JK^{-1}
Room temp=300K

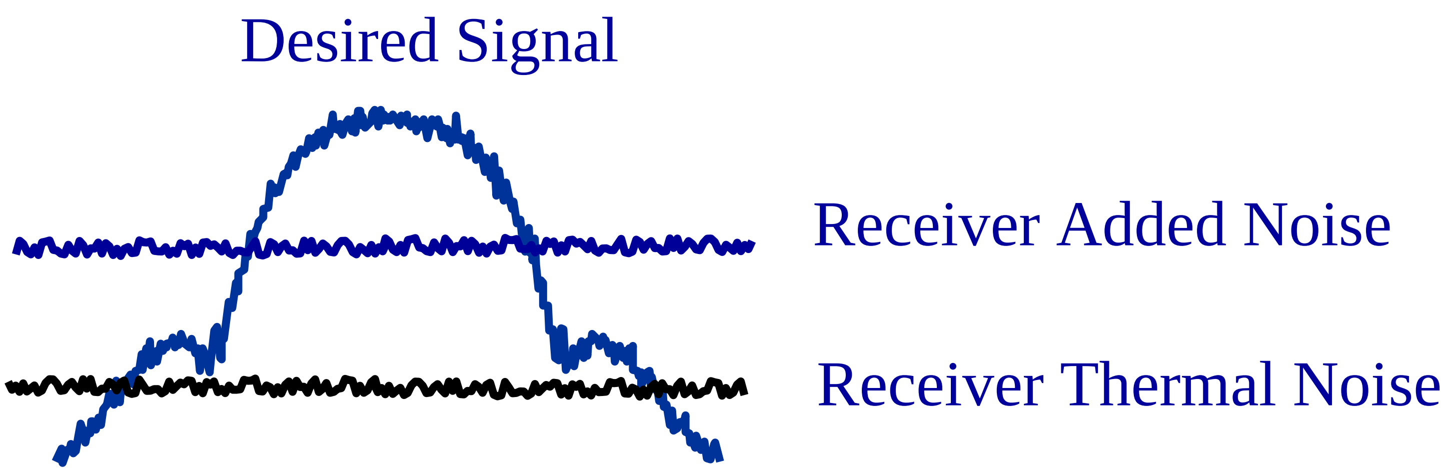
$$\text{kT} = 1.38 \times 10^{-23} \times 300\text{W/Hz} = -173.83 dBm / Hz$$

Equations

$$Noise\ Floor = P_{nf}\,(\text{dBm}) = kTB(\text{dBm}) + F_{receiver}\,(\text{dB})$$

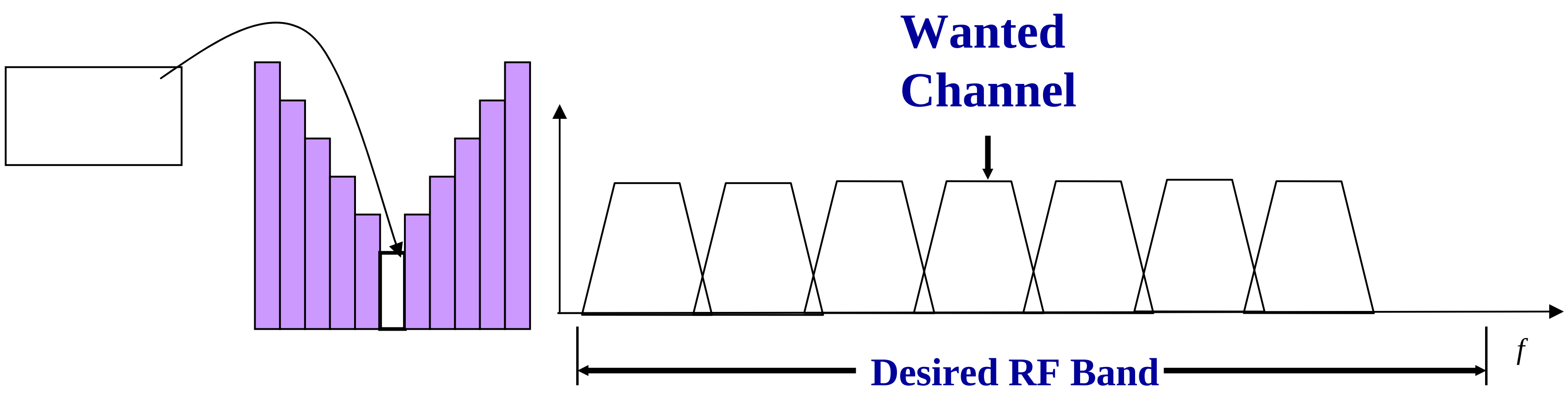
$$Sensitvity = P_{in,\min}\,(\text{dBm}) = kTB(\text{dBm}) + F_{receiver}\,(\text{dB}) + SNR_{\min}\,(\text{dB})$$

$$= -174 dBm/Hz + 10\log \text{B} + F_{receiver} + SNR_{\min}$$



Selectivity

The ability to reject unwanted signals on adjacent channels (channel selectivity) and/or the outside of the wanted band (band selectivity). 70 to 90 dB rejections are normally required



Band selectivity

Channel selectivity

Spurs and Intermodulation

Spurious Response Rejection

The ability to reject undesired channels to reduce the interference. Rejection of 70dB to 100 dB is usually required for wireless communications;

Intermodulation (IM) Rejection

The receiver has the tendency to generate its own on-channel interference from one or more RF signals due to the nonlinearity of the receiver. These interference signals are called IM products. Greater than 70 dB rejection is desirable

Others

Frequency Stability

Stable frequency operation is important in order to capture the desired frequency channel. PLL/synthesizers are commonly employed to obtain an accurately controlled LO frequency.

EMI: Electromagnetic Interference

From one part to another part within an RF front-end receiver or from interconnects as well as the silicon substrates

Noise Figure

- **Signal-to-noise ratio (SNR): ratio of the signal power to the total noise power**

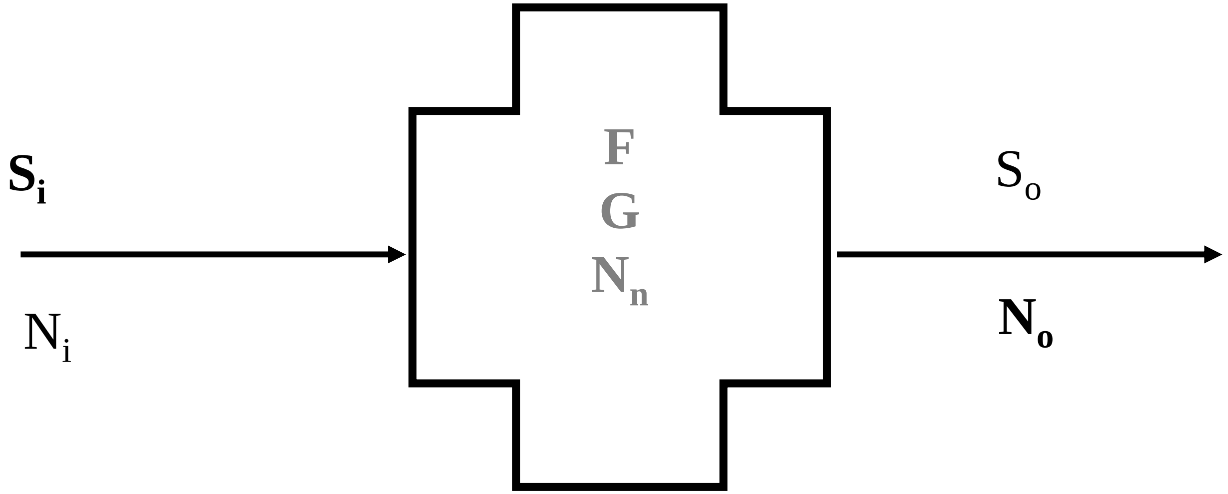
$$\mathrm{SNR} = \frac{\text{wanted signal power}}{\text{unwanted noise power}}$$

- **Noise figure is a figure of merit quantitatively specifying how noisy a system/component is. The noise factor F is defined for the two-port network:**

$$F = \frac{\mathrm{SNR}|_{\text{in put}}}{\mathrm{SNR}|_{\text{out put}}} = \frac{S_i / N_i}{S_o / N_o}$$

NF=10log(F) (dB)

Noise Figure—cont.

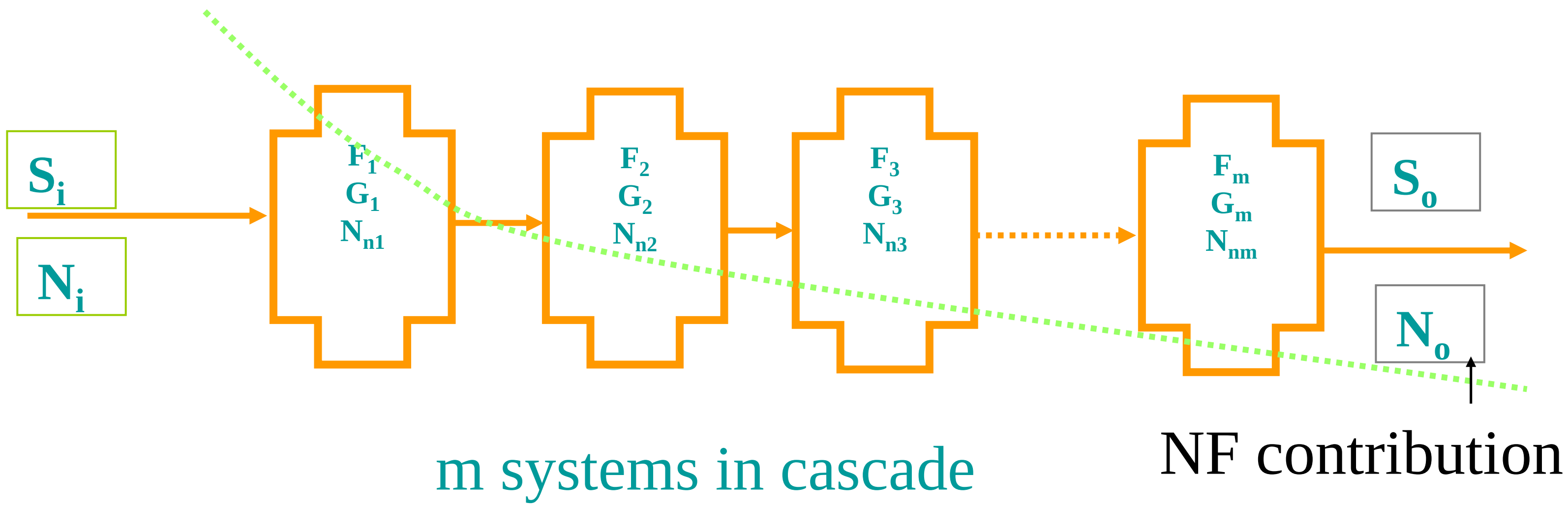


Two-port system with power gain G, added noise power N_n and the noise factor F

$$S_o = GS_i \qquad N_o = GN_i + N_n \ \text{(W)}$$

$$F = \frac{S_i / N_i}{GS_i / N_o} = \frac{N_o}{GN_i} = 1 + \frac{N_n}{GN_i} \qquad N_o = FGN_i$$

Cascaded Noise Figure



Friis equation:

$$F_{\text{total}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_m - 1}{G_1 G_2 G_3 \cdots G_{m-1}}$$

Dynamic Range

$$P_{\text{in}} = P_{\text{out}} - G \quad (\text{dB})$$

- **For an RF system, operation is normally in a region where the output power is linearly proportional to the input power, while the coefficient is the desired power gain. This region is called as the *dynamic range* (DR).**
- **DR is the rang between the maximum power level that the system is still in linear region to the minimum detectable signal (MDS) power level**
  - **The range could be specified in terms of input power or output power.**
  - **Higher DR is desirable**

Nonlinear Effects

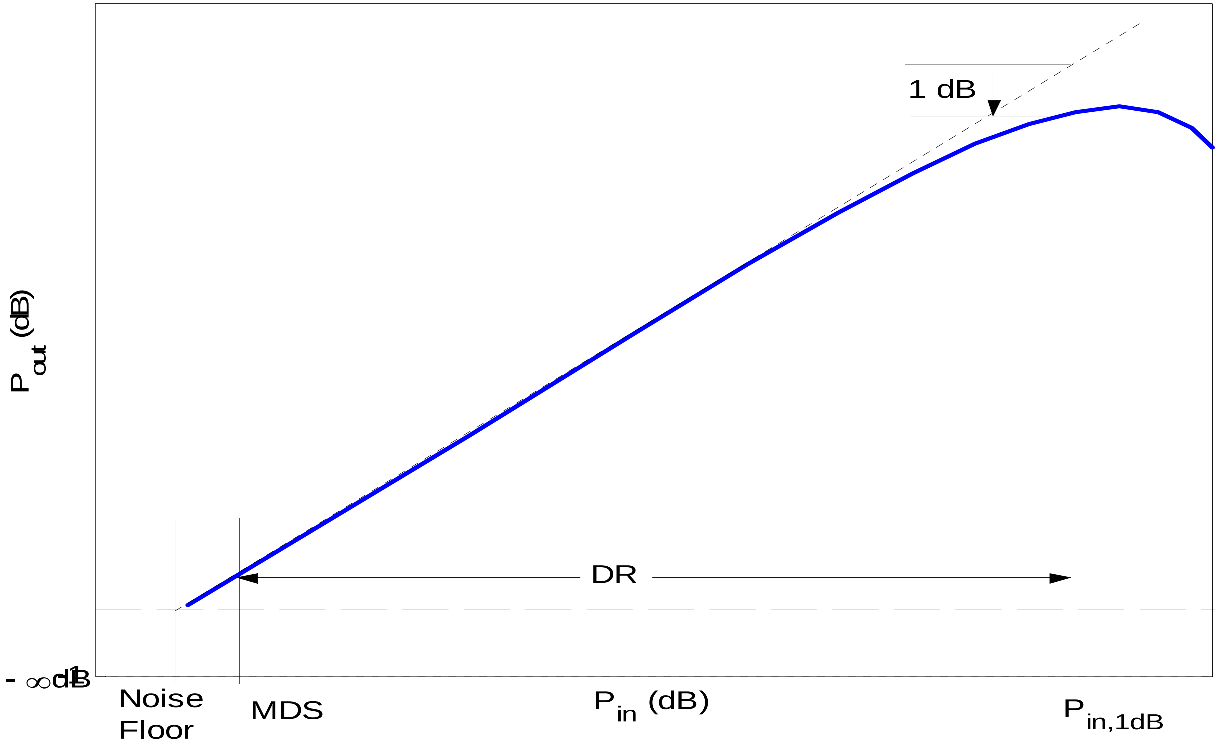
It is desired that no matter how high the input signal power is, the output power will be the linearly amplified input signal. Nonlinearities often exist in practical systems and lead to interesting phenomena, those phenomena limit the linear operating range of a system. For simplicity, the output – input relationship can be approximately modelled as (Taylor Series expansion):

$$y(t) \approx a_o + a_1 x(t) + a_2 x^2(t) + a_3 x^3(t)$$

y(t) is the output and *x(t)* is the input signal. a_o is the DC component, a_1 the gain, a_2 and a_3 (less than zero) the coefficients of the second and third-order nonlinear terms.

1-dB Compression Point

$$P_{in,1\text{-}dB} = P_{out,1\text{-}dB} - G + 1\ \text{dB} \qquad \text{DR} = P_{\text{in,1dB}} - \text{MDS} \qquad (\text{dB})$$



Gain-compression of a realistic RF system

1-dB Compression Point: Equations

$$y(t) = a_o + a_1(A_o \cos\omega_o t + A_1 \cos\omega_1 t + A_2 \cos\omega_2 t)$$
$$+ a_2(A_o \cos\omega_o t + A_1 \cos\omega_1 t + A_2 \cos\omega_2 t)^2$$
$$+ a_3(A_o \cos\omega_o t + A_1 \cos\omega_1 t + A_2 \cos\omega_2 t)^3$$

Fundamental components:

$$\{a_1 + a_3[\frac{3A_0^2}{4} + \frac{3}{2}(A_1^2 + A_2^2)]\}A_0 \cos\omega_0 t +$$
$$+\{a_1 + a_3[\frac{3A_1^2}{4} + \frac{3}{2}(A_0^2 + A_2^2)]\}A_1 \cos\omega_1 t +$$
$$+\{a_1 + a_3[\frac{3A_2^2}{4} + \frac{3}{2}(A_1^2 + A_0^2)]\}A_2 \cos\omega_2 t$$

1-dB CP

If ω_0 is the desired signal then the gain will be , a decreasing gain because of $a_3<0$. If the unwanted signal strengths A_1 and A_2 are so strong, the gain of the wanted signal drops to 1 or lower when:

$$A_1^2 + A_2^2 \geq \frac{2}{3}\frac{a_1 - 1}{|a_3|} - \frac{1}{2}A_0^2$$

Now the wanted signal is "blocked" by the unwanted strong signal, because the wanted signal cannot be amplified by the RF section. Many RF sections in wireless applications must be able to withstand blocking signals 60 to 70 dB stronger than the wanted signal

1dB CP vs a3

The 1-dB compression point can be obtained from three-tone for the wanted channel as (assuming 3 input tones are at the same power):

$$20\log(a_1 A_{1-dB}) - 20\log(a_1 A_{1-dB} - |a_3|\frac{15}{4}A_{1-dB}^3) = 1 \quad \text{(dB)}$$

Or

$$|a_3| = 0.029\frac{a_1}{A_{1-dB}^2} \quad \text{or} \quad A_{1-dB} = \sqrt{0.029\frac{a_1}{|a_3|}}$$

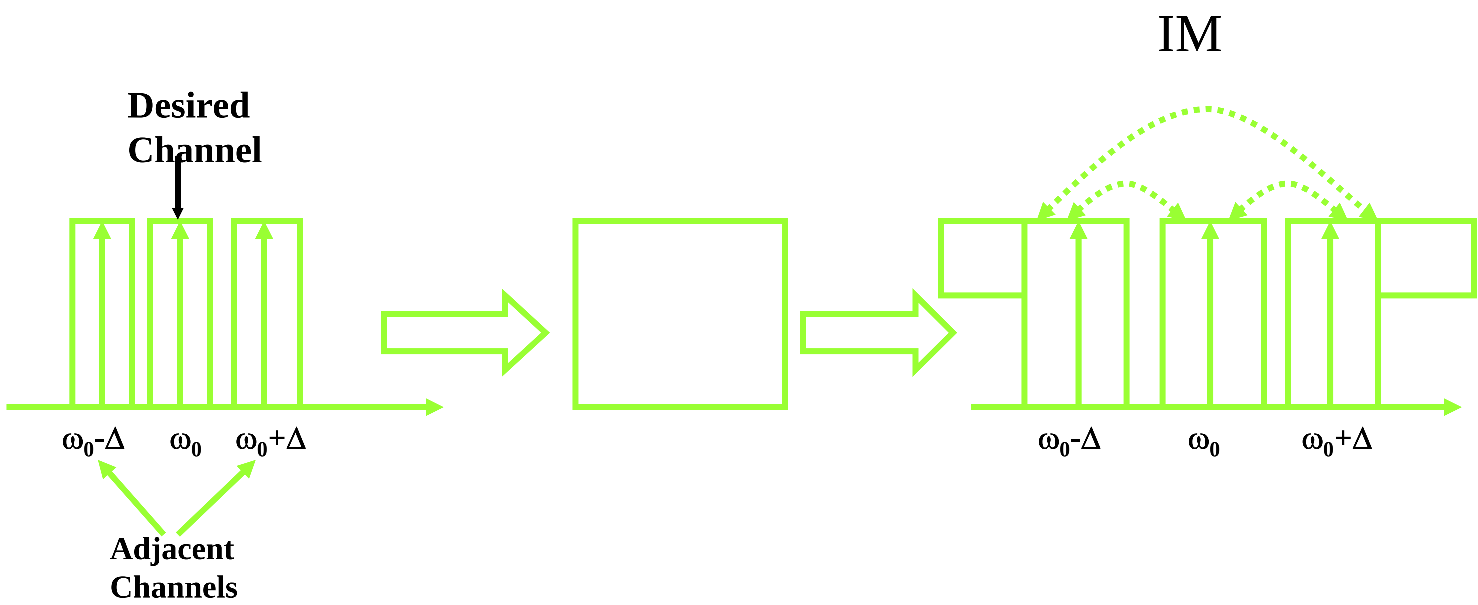
Thus, from the measured linear gain a_1 and the input level at the 1-dB compression point, one can calculate the nonlinear coefficient $|a_3|$

Intermodulation

Intermodulation or intermodulation distortion (IMD), or intermod for short, is the result of two or more signals of different frequencies being mixed together, forming additional signals at frequencies that are not, in general, at harmonic frequencies (integer multiples) of either.

Intermodulation should not be confused with general harmonic distortion. Intermodulation specifically creates non-harmonic tones ("off-key" notes, in the audio case) due to unwanted mixing of closely spaced frequencies.

IMD in a 3-Tone Case



Intermodulation Equations for 3-Tone Case

$$y(t) = \{1 - \frac{|a_3|}{a_1}[\frac{3A_0^2}{4} + \frac{3}{2}(A_1^2 + A_2^2 + A_1 A_2)]\} a_1 A_0 \cos\omega_0 t +$$

$$\{1 - \frac{|a_3|}{a_1}[\frac{3(A_0^2 \frac{A_2}{A_1} + A_1^2)}{4} + \frac{3}{2}(A_0^2 + A_2^2)]\} a_1 A_1 \cos(\omega_0 - \Delta)t +$$

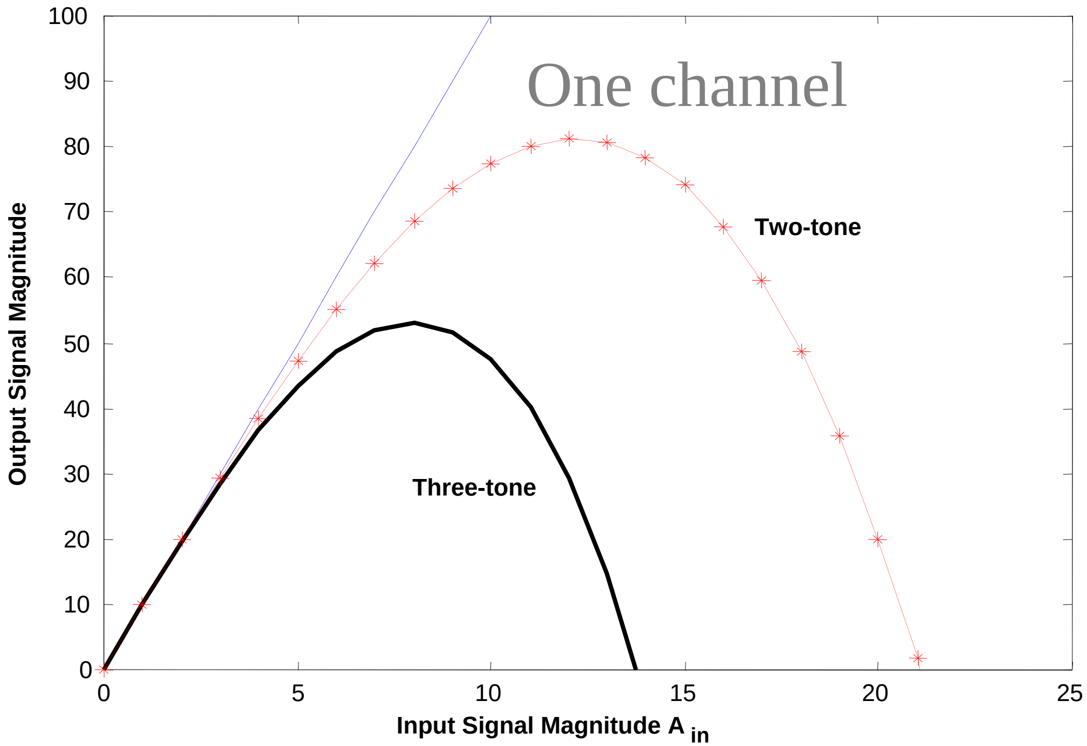
$$+\{1 - \frac{|a_3|}{a_1}[\frac{3(A_0^2 \frac{A_1}{A_2} + A_2^2)}{4} + \frac{3}{2}(A_0^2 + A_1^2)]\} a_1 A_2 \cos(\omega_0 + \Delta)t +$$

$$+ a_3 \frac{3A_0}{2}\{[\frac{1}{2}A_1^2 + A_1 A_2]\cos(\omega_0 - 2\Delta)t + [\frac{1}{2}A_2^2 + A_1 A_2]\cos(\omega_0 + 2\Delta)t\} +$$

$$+ a_3 \frac{3}{4} A_1 A_2 \{A_1 \cos(\omega_0 - 3\Delta)t + A_2 \cos(\omega_0 + 3\Delta)t\} + \text{others}$$

There are IM effects between any two channels

Intermodulation Examples



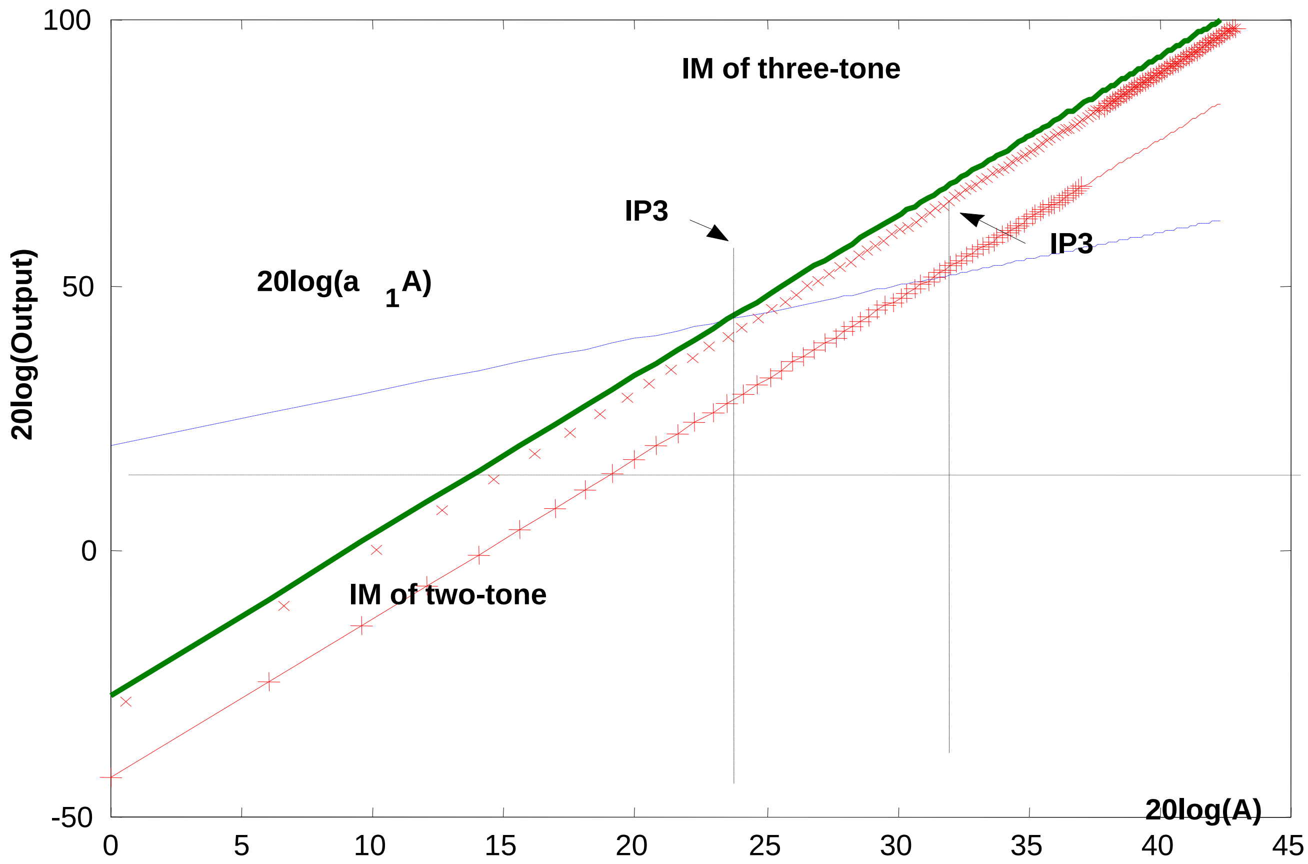
The output signal vs. the input signal amplitude for the three-tone and the two-tone tests, respectively

Intercept Point (IP)

The intercept point is obtained graphically by plotting the output power versus the input power both on logarithmic scales (e.g., dB). Two curves are drawn; one for the linearly amplified signal at an input tone frequency, one for a nonlinear product. On a logarithmic scale, the function *xn* translates into a straight line with slope of *n*. Therefore, the linearly amplified signal will exhibit a slope of 1. A third-order nonlinear product will increase by 3 dB in power when the input power is raised by 1 dB.

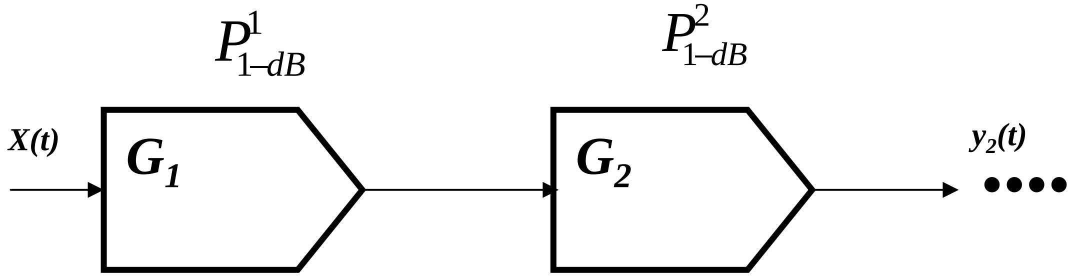
The intercept point is a purely mathematical concept, and does not correspond to a practically occurring physical power level. In many cases, it lies beyond the damage threshold of the device.

IP3 Plots



100
50
0
-50
20log(Output)
IM of three-tone
IP3
IP3
20log(a 1A)
IM of two-tone
20log(A)
0
5
10
15
20
25
30
35
40
45

Nonlinear Effects of Cascaded RF Systems



P_{1-dB}^{1} and IP_3^1

$$\frac{1}{P_{IP3}} = \frac{1}{P_{IP3,1}} + \frac{G_1}{P_{IP3,2}} + \frac{G_1G_2}{P_{IP3,3}} + \cdots$$

$$\frac{1}{P_{1dB}} = \frac{1}{P_{1dB,1}} + \frac{G_1}{P_{1dB,2}} + \frac{G_1G_2}{P_{1dB,3}} + \frac{G_1G_2G_3}{P_{1dB,4}} + \cdots$$

$$P_{IP3}\,|_{\mathrm{dBm}} = P_{IP3,N}\,|_{\mathrm{dBm}} - \sum_{i=1}^{N-1} G_i\,|_{\mathrm{dBm}} - 10\log[1 + P_{IP3,N} \sum_{i=1}^{N-1} \frac{1}{P_{IP3,i}} \frac{1}{\prod_{j=1}^{N-i} G_j}]$$

Trade-off between NF & IP3

Higher gains → lower NF → lower IP3

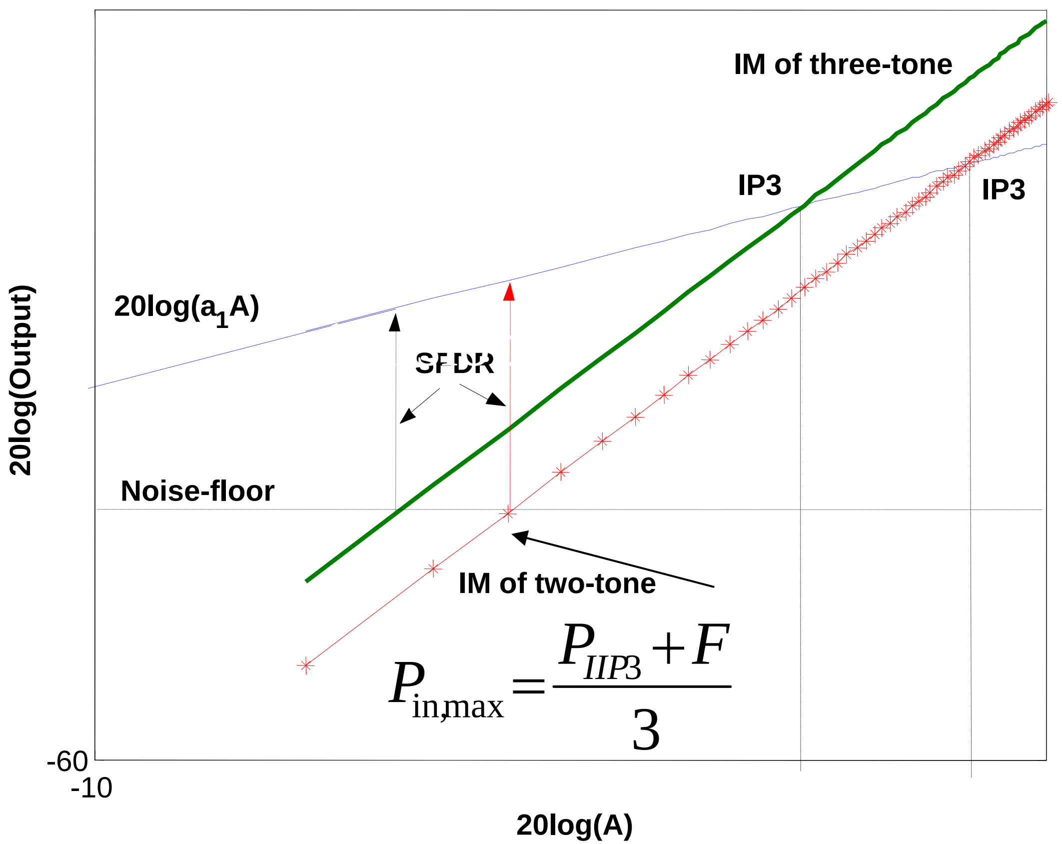
$$\frac{1}{P_{1dB}} = \frac{1}{P_{1dB,1}} + \frac{G_1}{P_{1dB,2}} + \frac{G_1 G_2}{P_{1dB,3}} + \frac{G_1 G_2 G_3}{P_{1dB,4}} + \cdots$$

$$\frac{1}{P_{IP3}} = \frac{1}{P_{IP3,1}} + \frac{G_1}{P_{IP3,2}} + \frac{G_1 G_2}{P_{IP3,3}} + \cdots$$

$$P_{IP3}\big|_{\text{dBm}} = P_{IP3,N}\big|_{\text{dBm}} - \sum_{i=1}^{N-1} G_i\big|_{\text{dBm}} - 10\log\Big[1 + P_{IP3,N}\sum_{i=1}^{N-1}\frac{1}{P_{IP3,i}}\frac{1}{\prod_{j=1}^{N-i} G_j}\Big]$$

$$F_{\text{total}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_m - 1}{G_1 G_2 G_3 \cdots G_{m-1}}$$

Spurious-Free Dynamic Range



$$P_{in,max} = \frac{P_{IIP3} + F}{3}$$

characterizes a receiver with more than one signal applied to the input

Spurious-Free Dynamic Range

$$P_{IIP3} = P_{\text{in}} + \frac{P_{\text{out}} - P_{\text{IM,out}}}{2} \qquad P_{\text{in}} = \frac{2P_{IIP3} + P_{\text{IM,in}}}{3}$$

The maximum input level for which the IM products become Equal to the noise floor:

$$P_{\text{in,max}} = \frac{P_{IIP3} + F}{3}, \qquad F = -174\text{dBm} + NF + 10\log B$$

$$SFDR = \frac{2P_{\text{IIP3}} + F}{3} - (F + SNR_{\text{min}}) = \frac{2(P_{\text{IIP3}} - F)}{3} - SNR_{\text{min}}$$

E.g. if a receiver with NF=9dB, P_{IIP3}=-15dBm, and B=200kHz SNR_{min}=12dB, then, SFDR≈53dB.

The SFDR represents the maximum relative level of interferers that a receiver can tolerate while producing an acceptable signal quality from a small input level.

Total System IIP3

Transfer all input intercept points to system input, subtracting gains and adding losses decibel for decibel
Convert intercept points to powers (dBm to mW). We have IP1, IP2, …. IPN for N elements
Assuming all input intercepts points are independent and uncorrelated, add powers in "parallel":
Convert IIP3 from power (mW) to dBm.

$$IIP3 = \left(\frac{1}{IP_1} + \frac{1}{IP_2} + \frac{1}{IP_3} + \cdots \frac{1}{IP_N}\right)^{-1} \qquad \text{(mW)}$$