EE4011

Transceiver Architectures

From Superhet

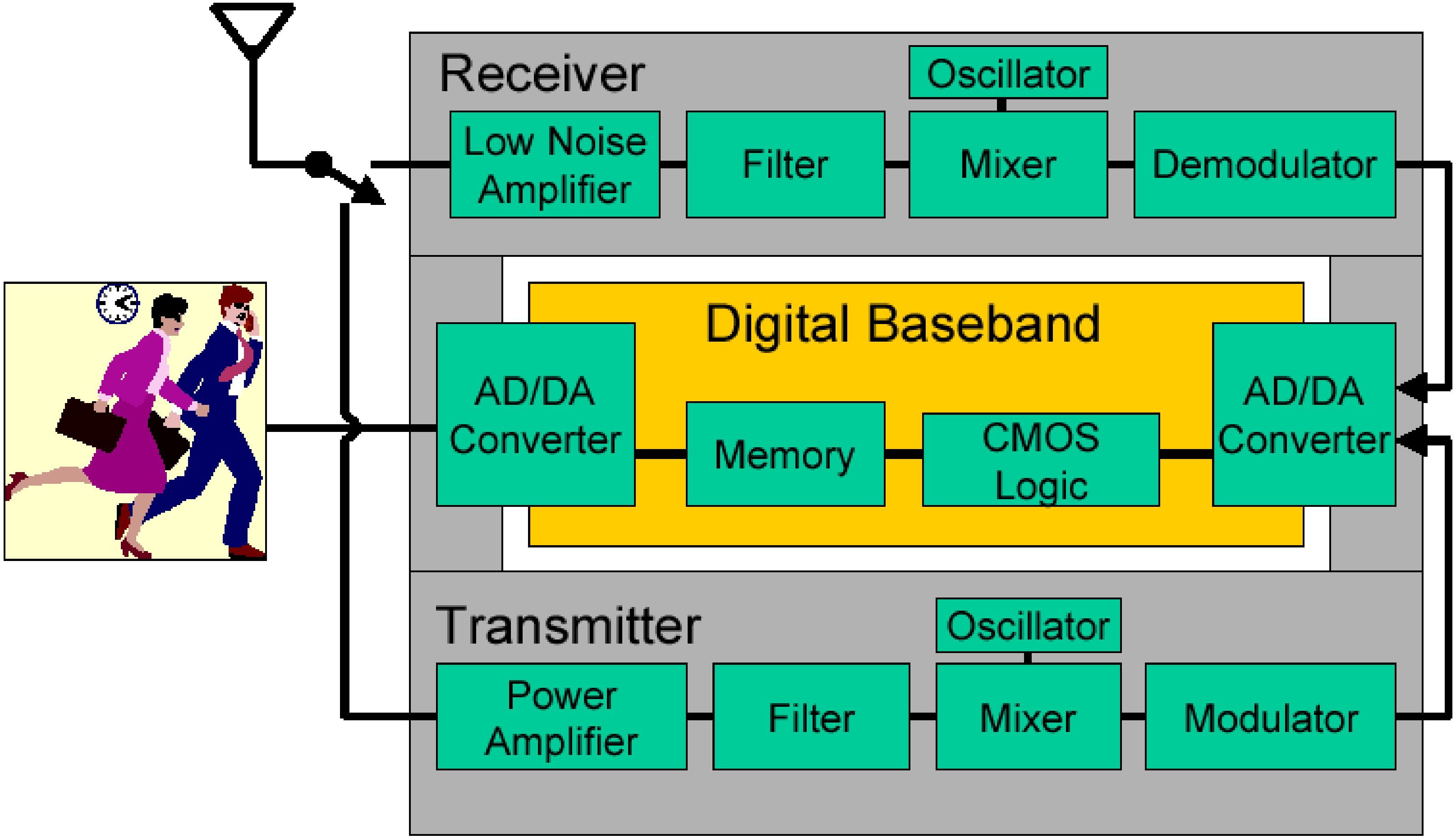
to

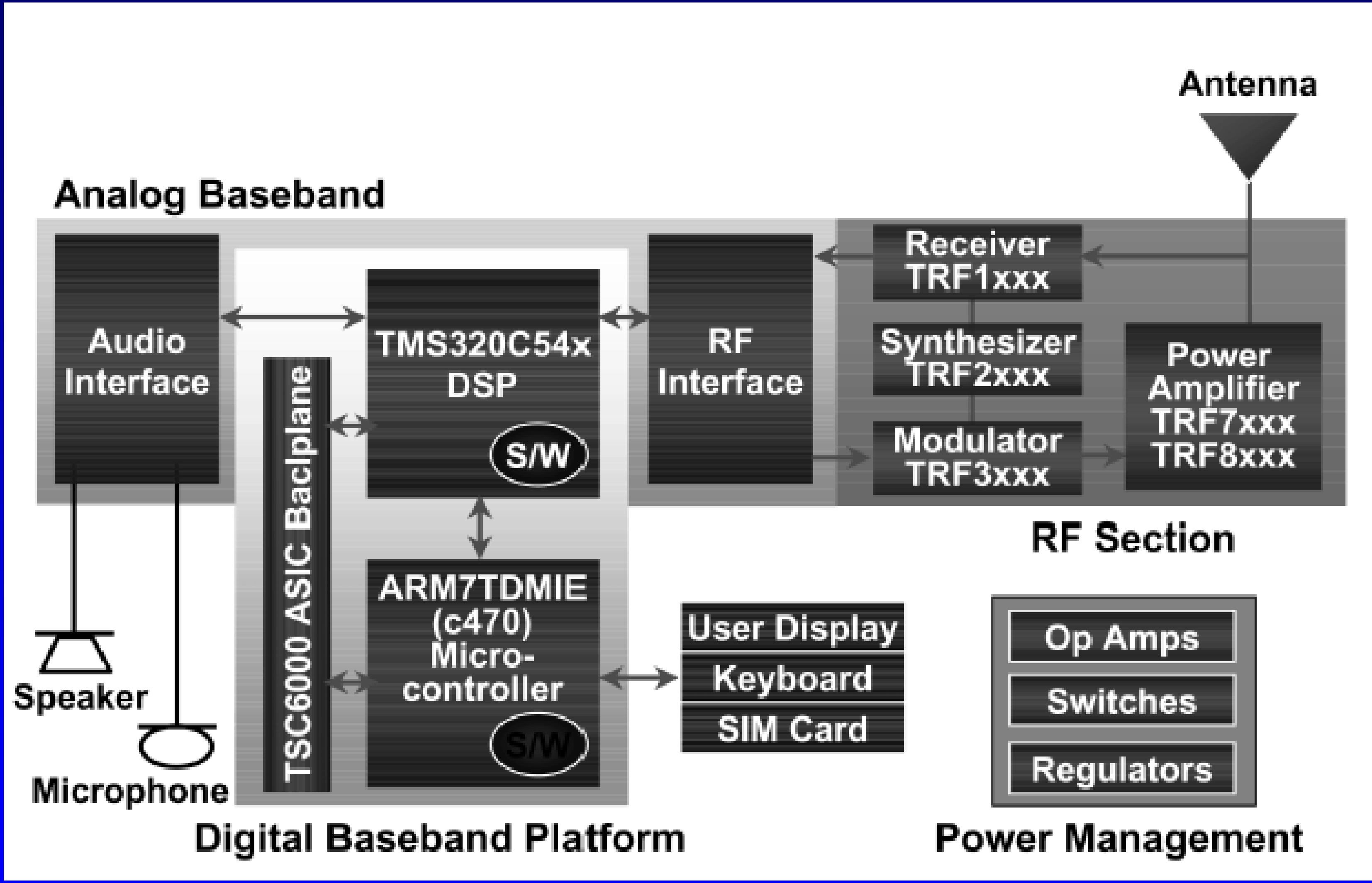
Direct Conversion

Transceivers

- Transmitter + Receiver (eg mobile phone)
- Common Antenna
- Functionally separate - but increasingly interdependent
- Level of integration increasing
- => "System on a Chip" SOC

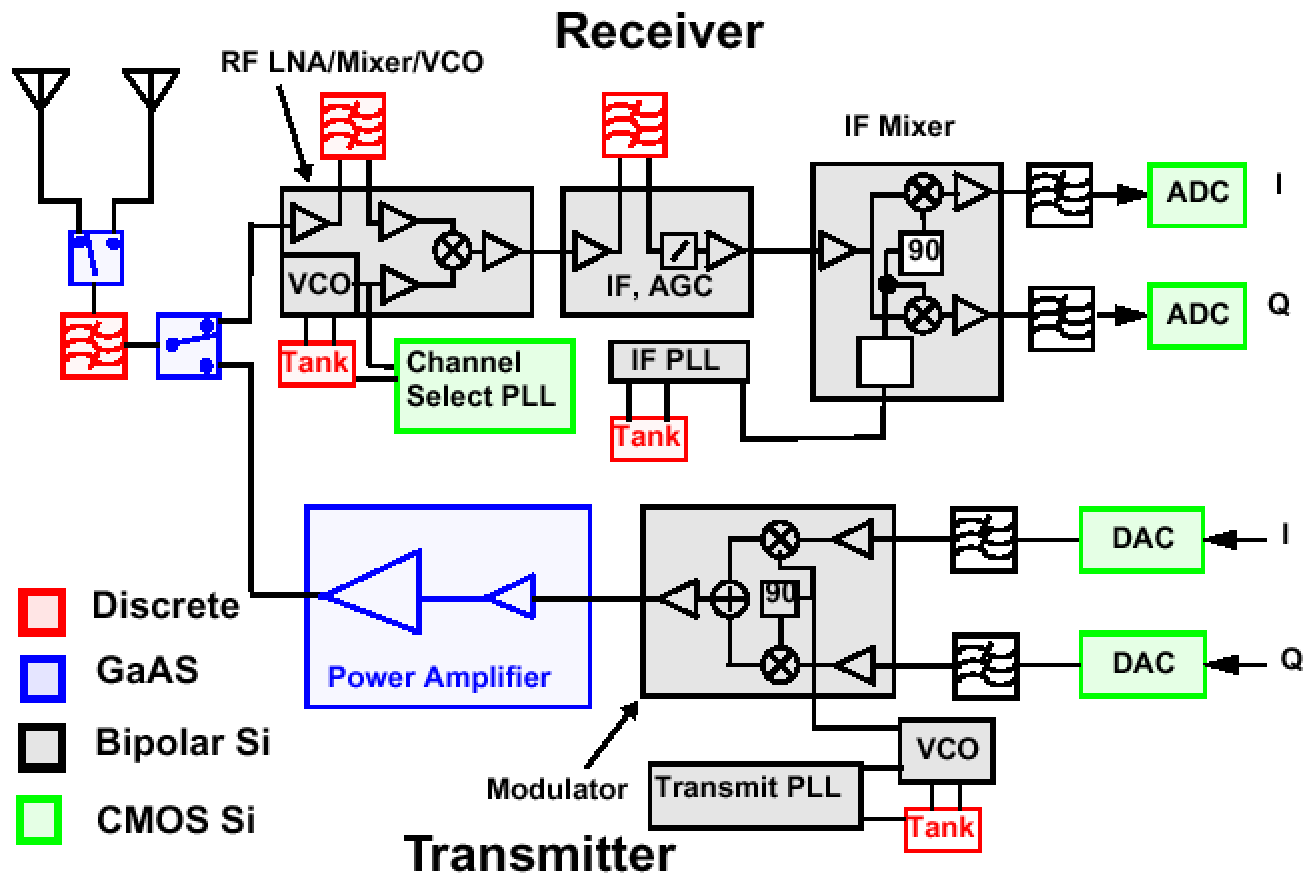
Application Example: Transceiver Design



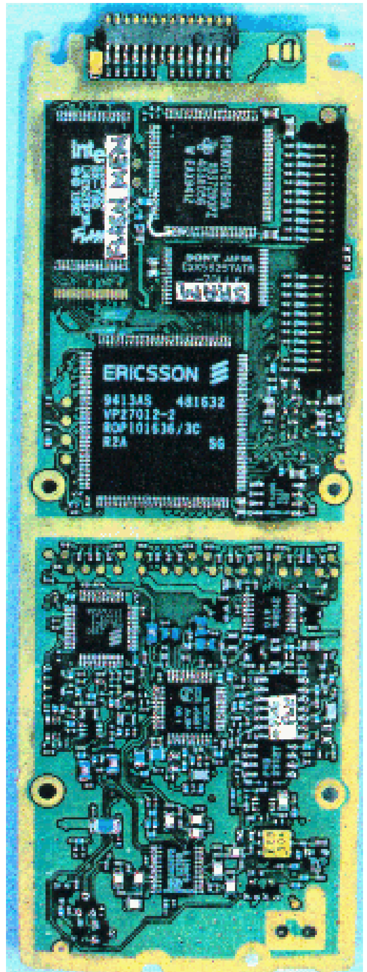


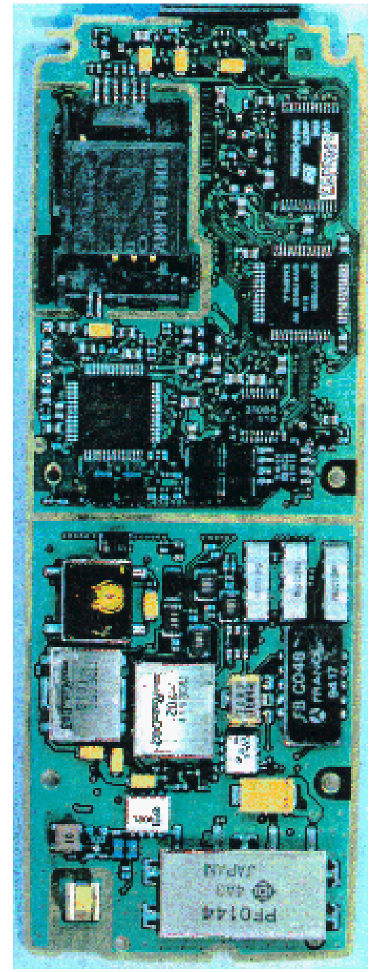
Antenna
Analog Baseband
Audio Interface
TMS320C54x DSP
S/W
RF Interface
Receiver TRF1xxx
Synthesizer TRF2xxx
Modulator TRF3xxx
Power Amplifier TRF7xxx TRF8xxx
RF Section
TSC6000 ASIC Bacplane
ARM7TDMIE (c470) Micro-controller
S/W
User Display
Keyboard
SIM Card
Op Amps
Switches
Regulators
Speaker
Microphone
Digital Baseband Platform
Power Management

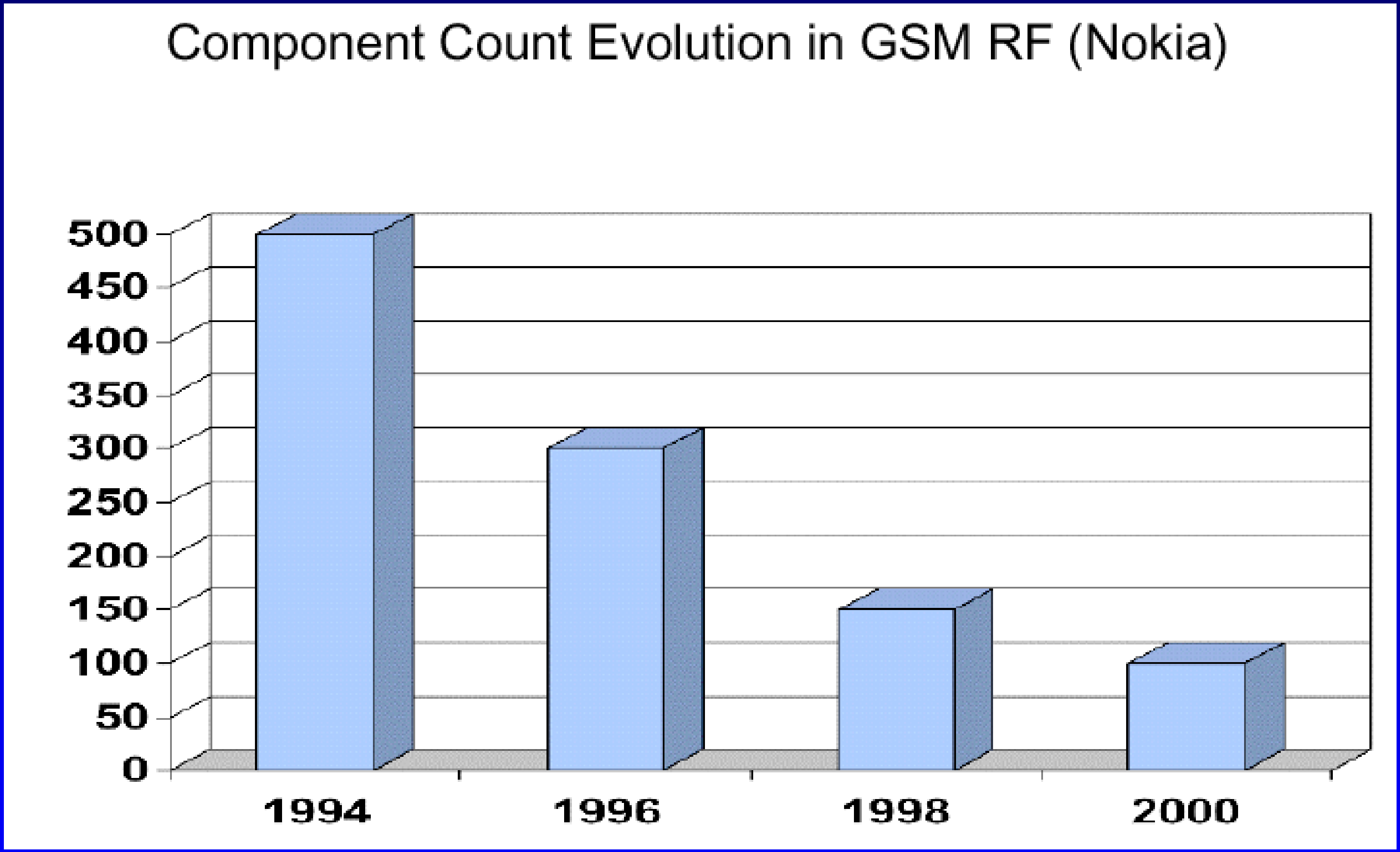
Block Diagram, Typical Multi-Technology RF Transceiver



Existing Solutions are Inefficient

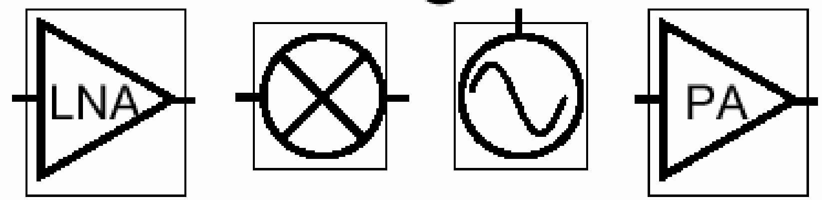




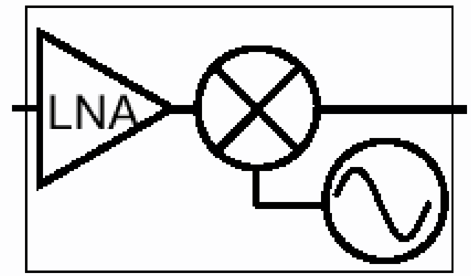

Component Count Evolution in GSM RF (Nokia)
500
450
400
350
300
250
200
150
100
50
0
1994
1996
1998
2000

Evolution of RF Integration

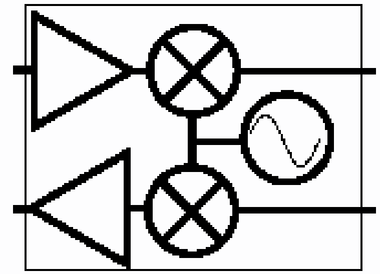
- Discrete functions:



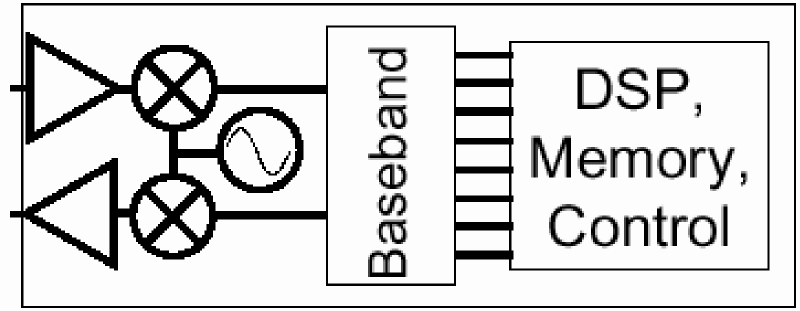
- Partial front-end:



- Integrated front-end:

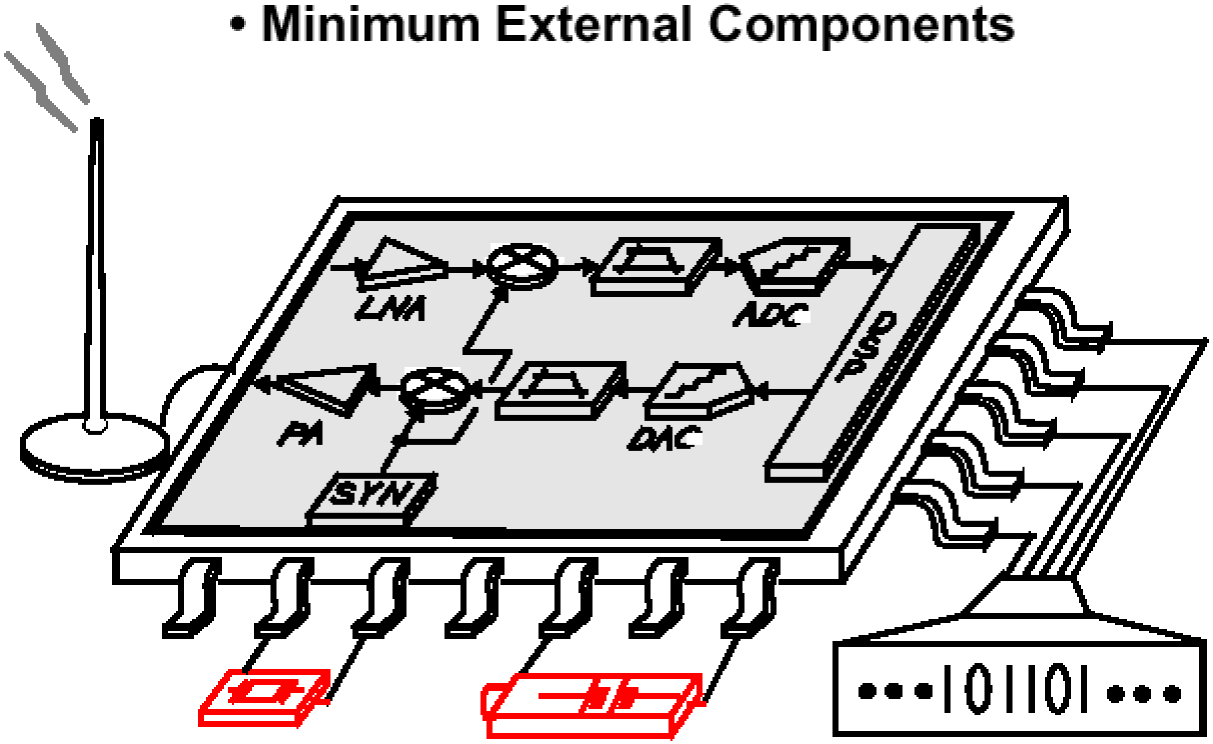


- SoC:

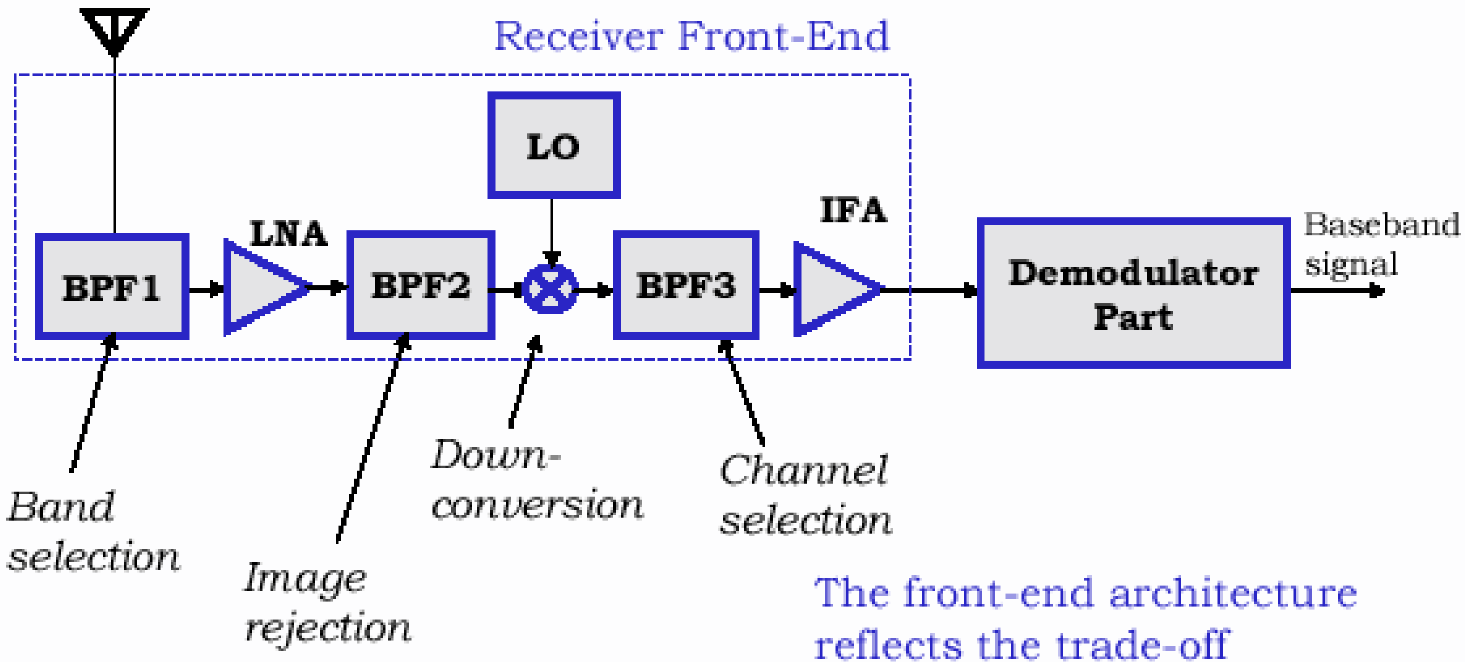


Ultimate Objective:

- Single-Chip, Scaled CMOS or BiCMOS
- Minimum External Components



Heterodyne receiver



The front-end architecture reflects the trade-off between image rejection and band selection.

Receiver Sensitivity

- Input signal level to achieve specified minimum S/N at output
- Expressed in absolute units, dBm or dBuV

- Also used – MDS – minimum detectable signal power dBm

Available Signal Power & Sensitivity

Sensitivity

Minimum Sg such that we have the required SNR at the receiver output for proper signal detection.

Example:

Receiver Sensitivity = -113dBm

Assume

$$R = 50\Omega$$

dBm : $10\log\left(\frac{P}{1\,mW}\right)$

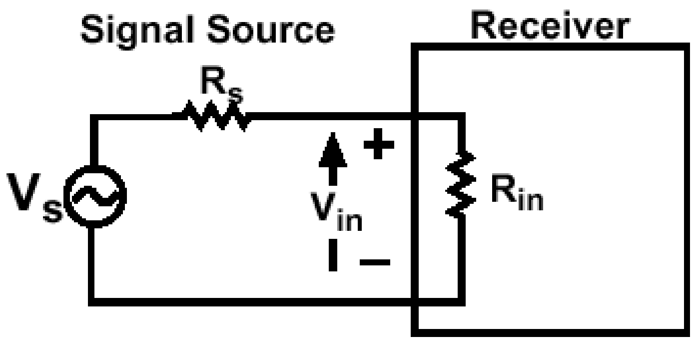
$$P = 10^{(-113/10)} \cdot 1\,mW = 5\times10^{-15}\ \textbf{Watts}$$

$$P = V_{in}^2/R \longleftarrow 50\Omega$$

$$\overline{V_{in_{rms}}} = \sqrt{P \cdot R} = \sqrt{(5\times10^{-15}) \cdot 50\Omega}$$

$$\overline{V_{in_{rms}}} = 0.5\mu V$$

Example Sensitivity for GSM/DECT



Standard	Sensitivity	RMS Input Voltage(V_{in})
DECT	- 83 dBm	15.8 μV
GSM	- 102 dBm	1.8 μV

Dynamic Range

- Noise at lower limit
- Distortion at upper limit
- Difference is Dynamic Range dB
- Number of definitions of Dynamic Range

Bit Error Rate and Noise

- Modern systems are inevitably digital
- BER and noise are inter-related
- As expected, multi-level modulation schemes require higher S/N for same BER.

Gain Compression

- Occurs when system cannot increase its output amplitude in linear proportion to amplitude increase at input
- Gain SATURATION occurs when system output amplitude stops increasing.
- Common measure is ***1 dB compression point***

Selectivity

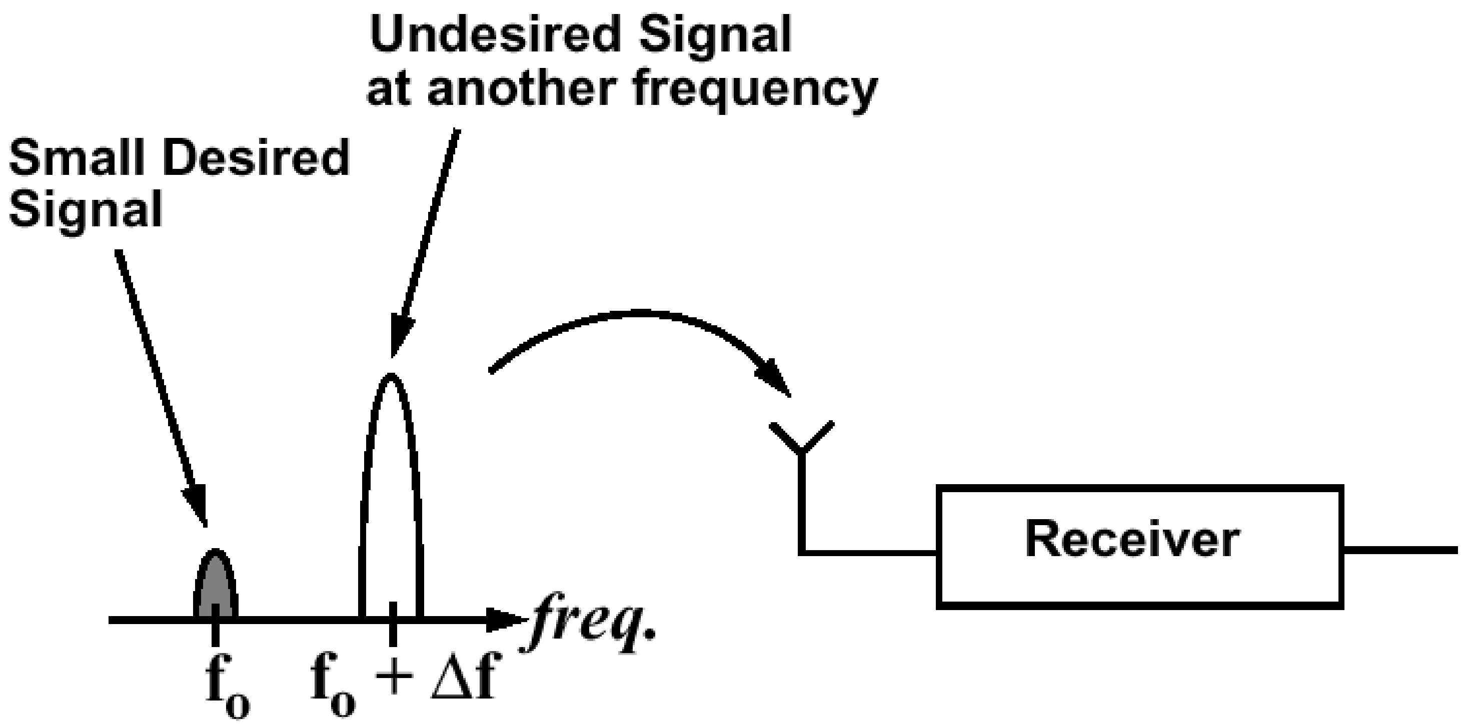
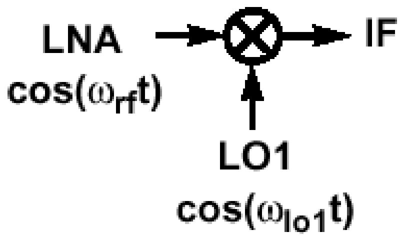
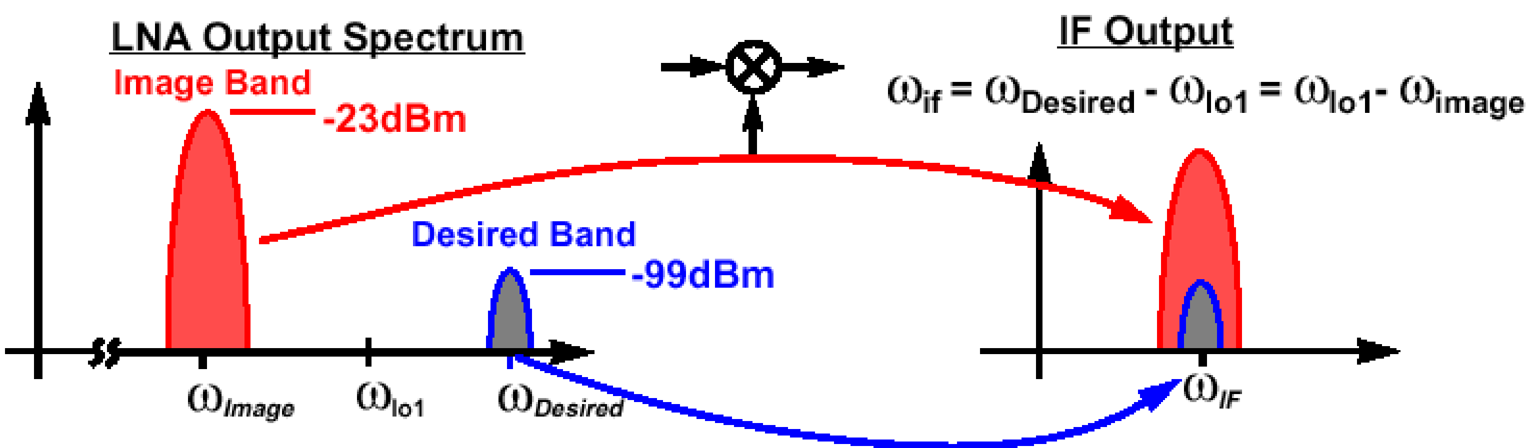


Image Problem



$$\cos(\omega_{rf}t) \bullet \cos(\omega_{lo1}t) =$$

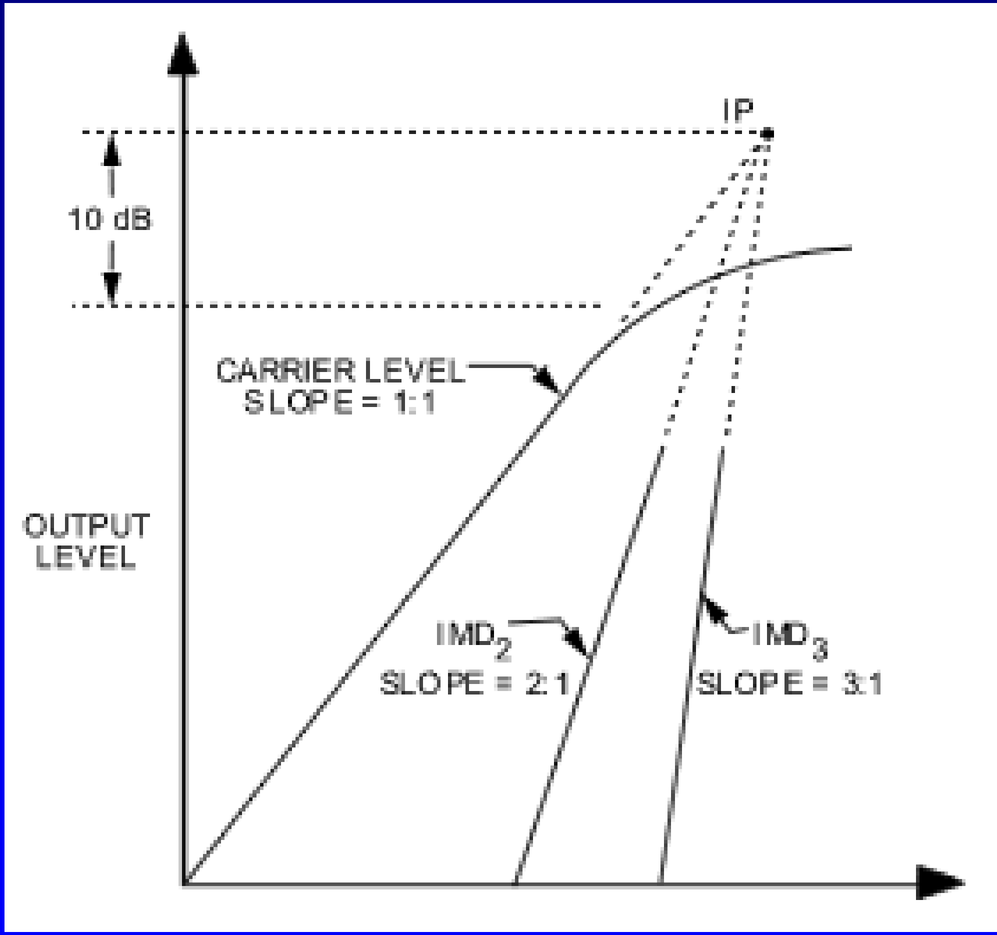
$$1/2\ [\ \cos(\{\omega_{rf} - \omega_{lo1}\}t) + \cos(\{\omega_{rf} + \omega_{lo1}\}t)\ ]$$



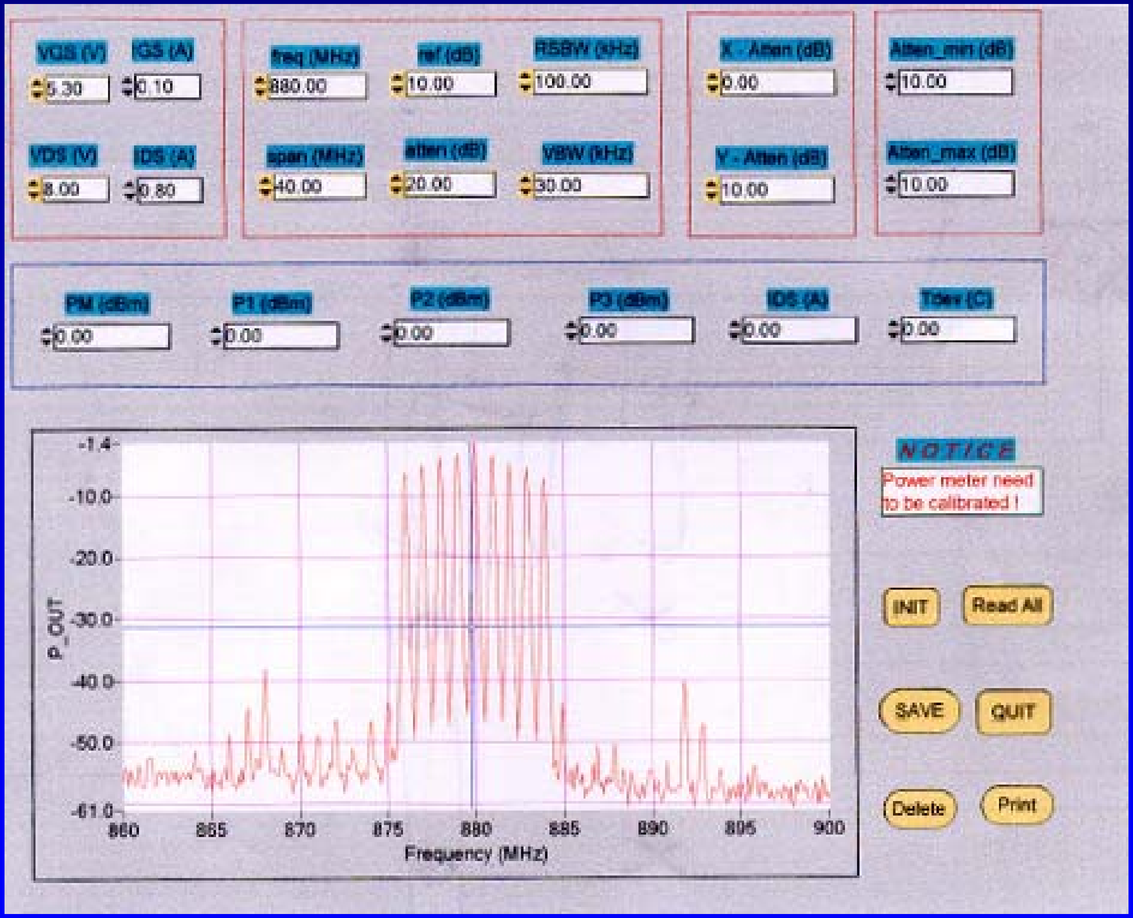
Intermodulation

- Non-linearities in system elements e.g amplifiers, mixers, --- but also filters, (and even cables!).
- Second order $\omega_1 + \omega_2$ $\omega_1 - \omega_2$ IM_2
- Third order $2\ \omega_1 \pm \omega_2$ $2\ \omega_2 \pm \omega_1$ IM_3
  - » +terms outside passband - terms in passband
- Under small signal conditions the power of IM2 varies by 2 dB and IM3 by 3dB per 1dB change in input power level

Intermodulation Intercept Point IP3

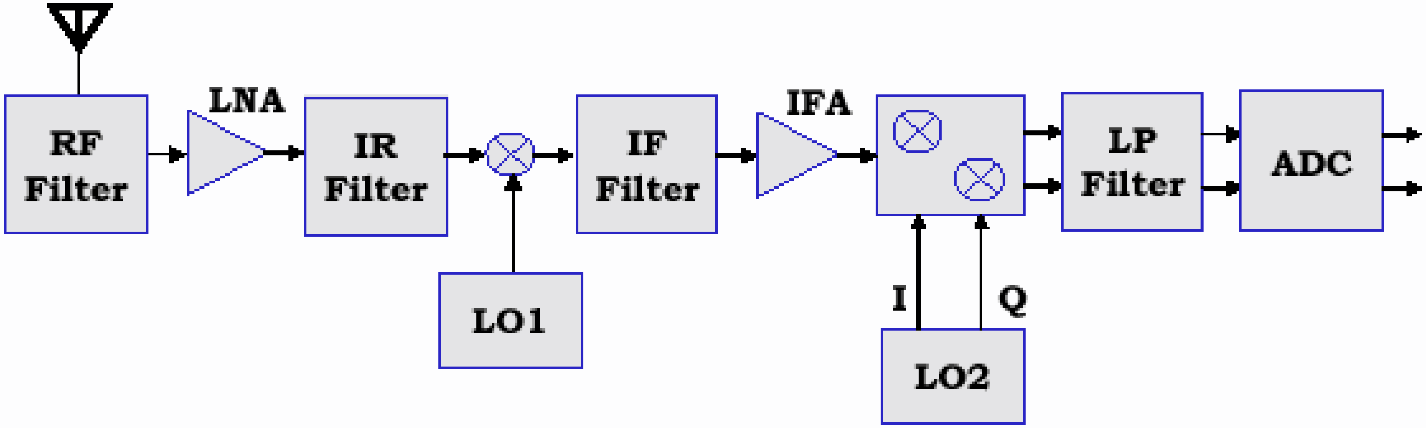


Spectral Regrowth - ACPR



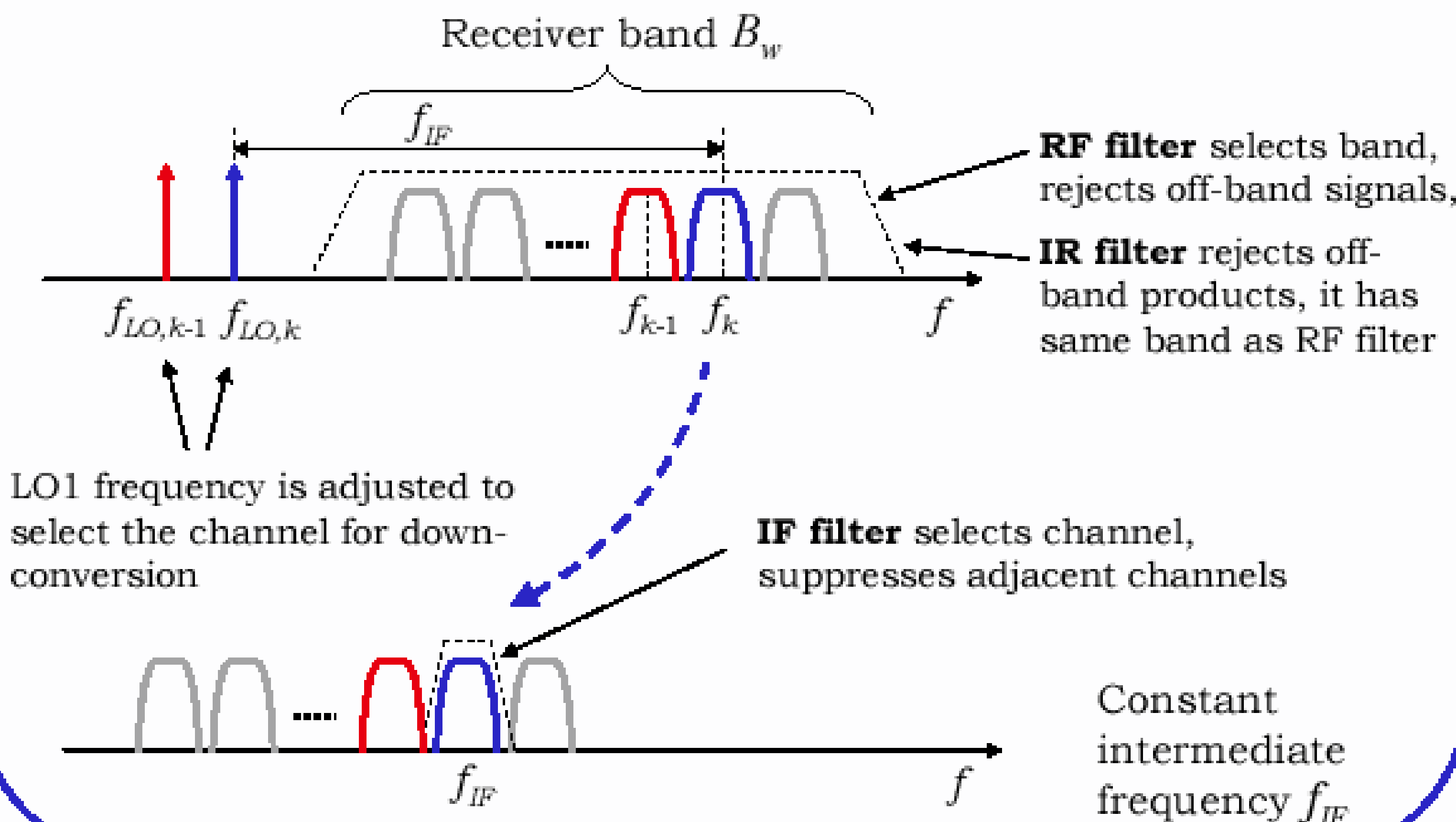
Old & New receiver architectures

- Superheterodyne receiver
  (good sensitivity and selectivity, good image rejection)

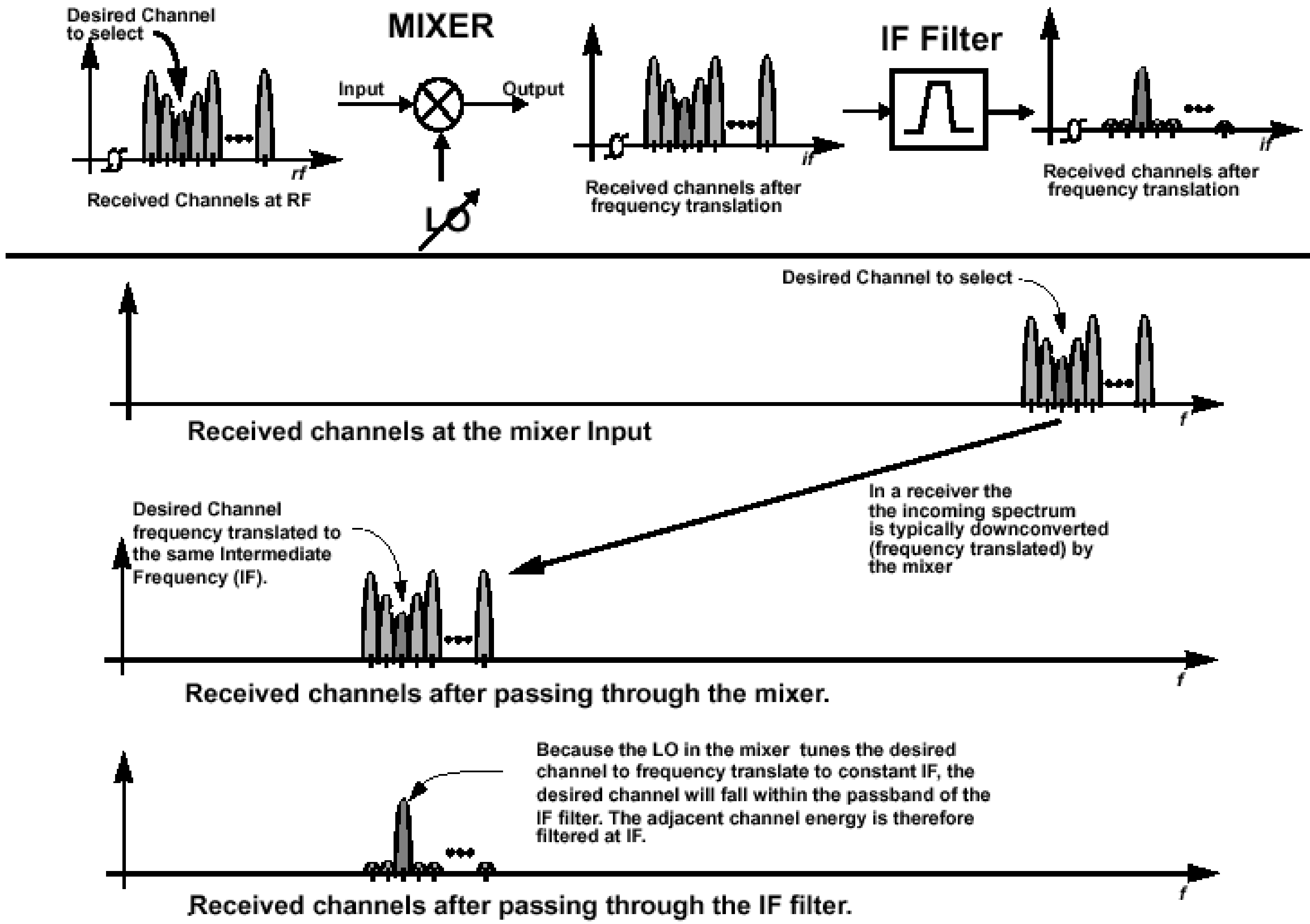


- Discrete IR and IF filters not amenable for integration
- Channel selection done with IF Filter – multi standard programming hardly achieved

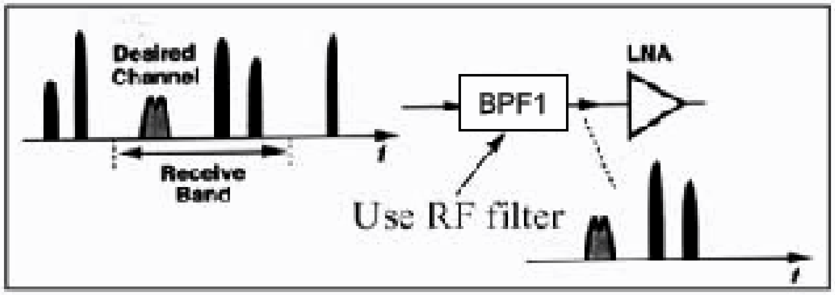
Superheterodyne receiver (cont'd)

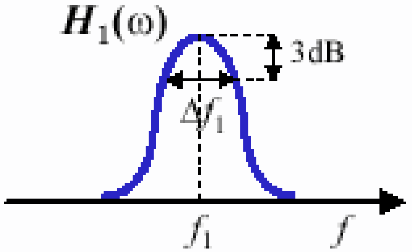


Role of the first mixer & IF filter



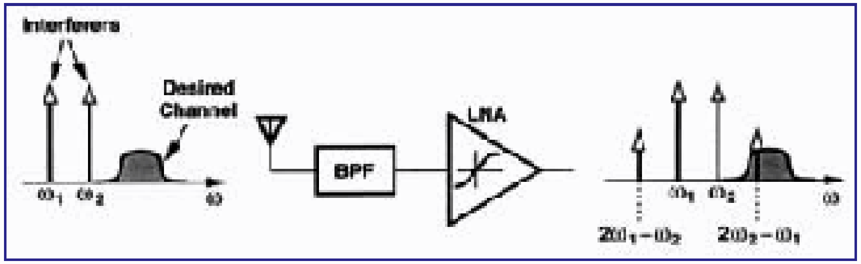
- **Filter design for Front-End**

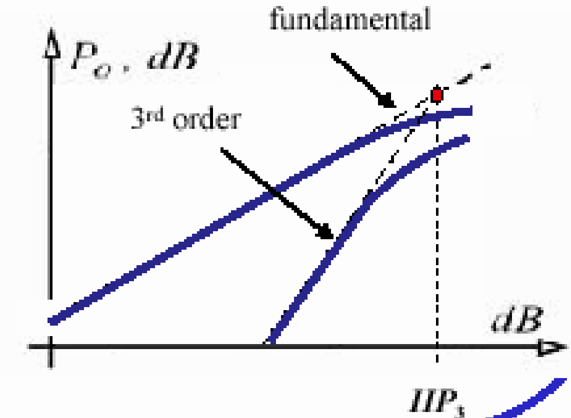




$$Q_1 = \left.\frac{f_1}{\Delta f_1}\right|_{DECT} \approx \frac{1890\text{ MHz}}{20\text{ MHz}} \approx 95$$

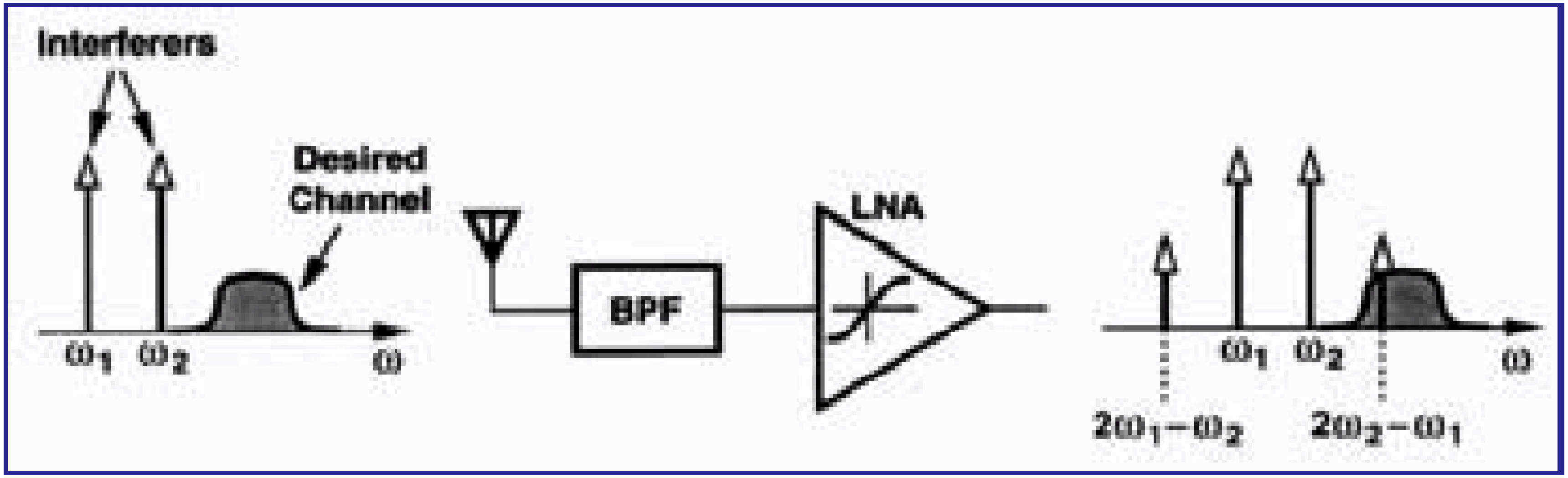
Band selection filtering, BPF of high Q is needed





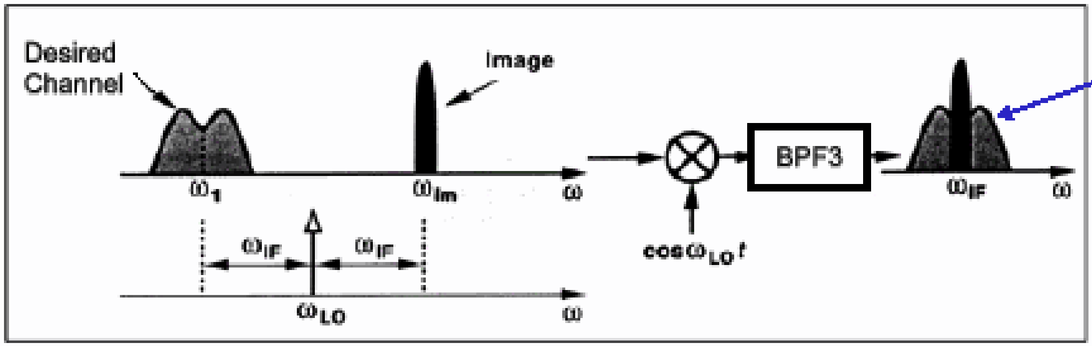
In-band interferers, LNA of high IP3 value is needed for low 3rd order component

cf Razavi pp 120,121


Interferers
Desired
Channel
ω_1
ω_2
ω
BPF
LNA
ω_1
ω_2
ω
$2\omega_1 - \omega_2$
$2\omega_2 - \omega_1$

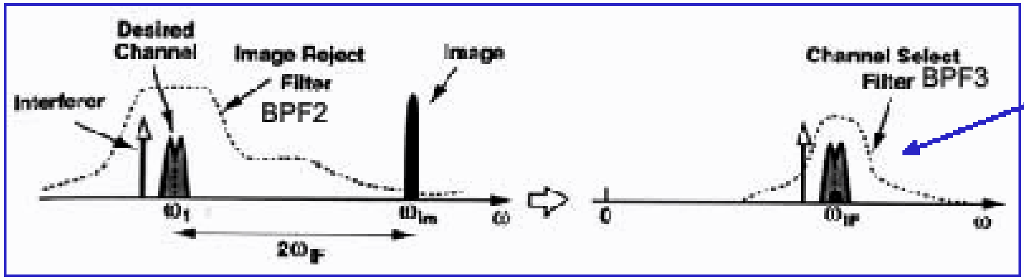
• **Filter design for Front-End** (cont'd)

Choice of LO frequency - problem of images



Corrupted channel signal

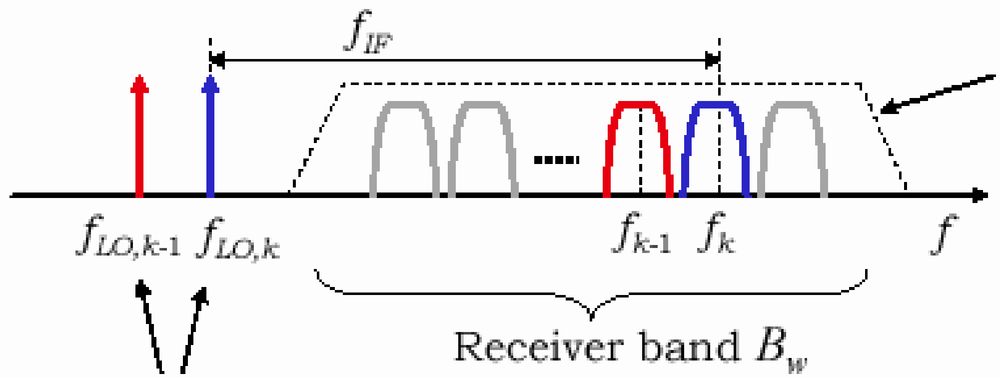
Image tends to overlap the desired channel at the mixer output



In-band interferer suppression

Out-of-band image can be suppressed before mixing, ω_{IF} should be large enough to relax the requirements for Q_2 factor

Choice of LO frequency - (cont'd)

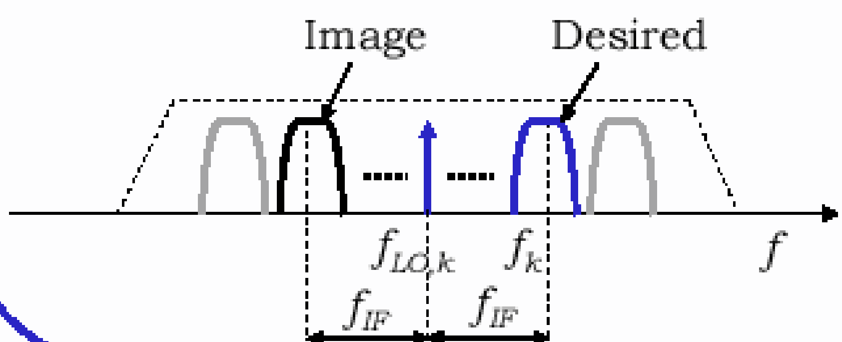


BPF2 rejects off-band products

LO frequency is adjusted to select the channel for down-conversion

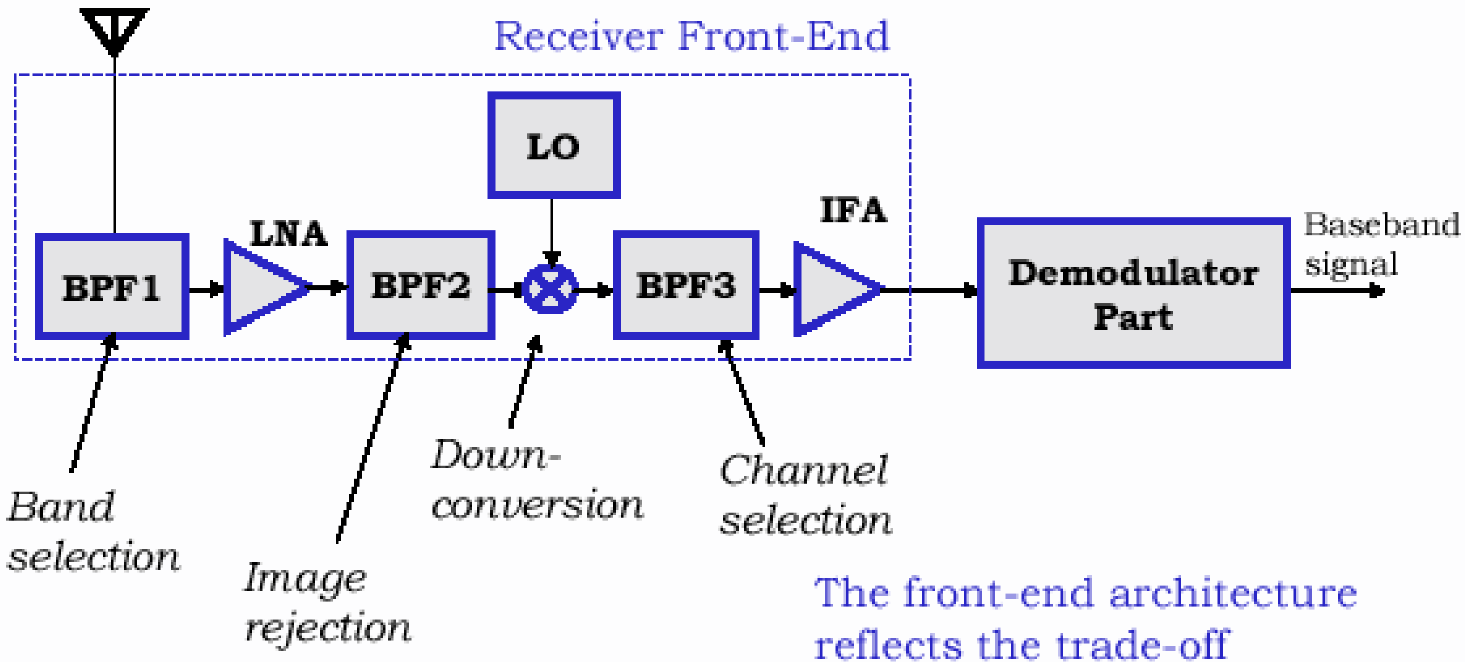
Constant intermediate frequency

$\boxed{f_k - f_{LO,k} = f_{IF}}$ $\boxed{f_{IF} > B_w/2}$



For too small f_{IF} in-band channel becomes an image, – then adjustable BPF2 or quadrature conversion needed – more difficult !

Heterodyne receiver

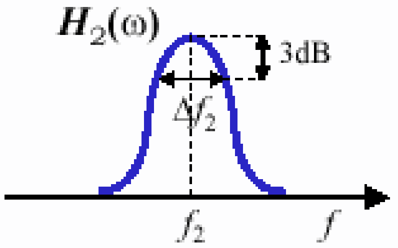


The front-end architecture reflects the trade-off between image rejection and band selection.

- **Filter design for Front-End** (cont'd)

Trade-off between BPF2 and BPF3

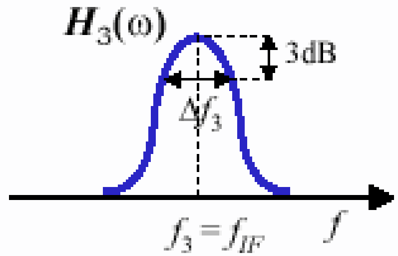
Image Reject Filter



$$Q_2 = \left.\frac{f_2}{\Delta f_2}\right|_{DECT} \approx \frac{1890\text{ MHz}}{B_w}$$

$$B_w = m \cdot 20\text{MHz}$$

Channel Filter



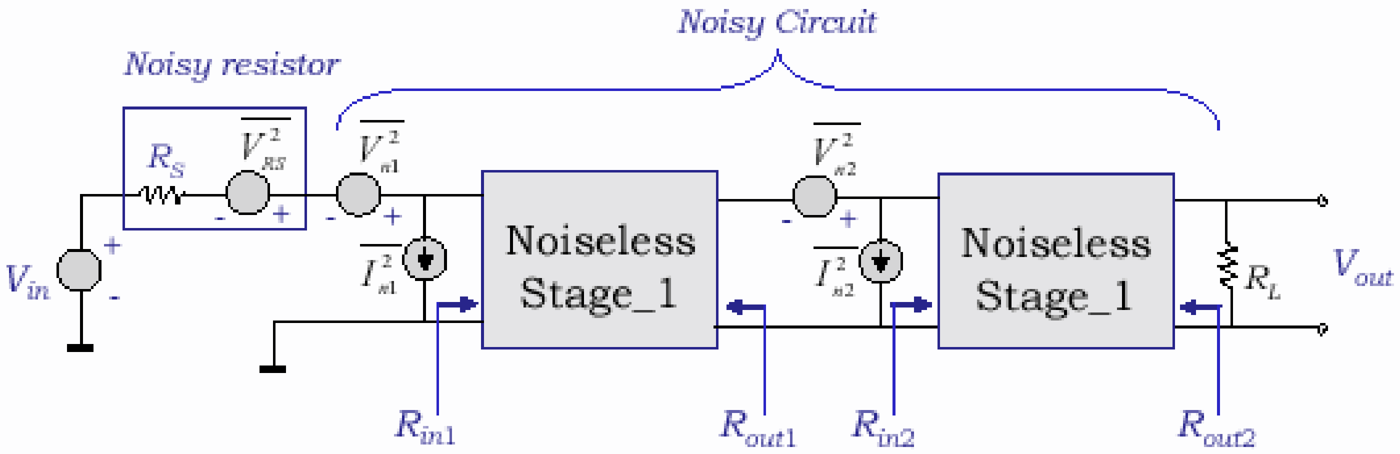
$\Delta f_3 = \Delta f_{ch}$

$$Q_3 = \left.\frac{f_{IF}}{\Delta f_{ch}}\right|_{DECT} \approx \frac{k \cdot B_w}{1.728\text{ MHz}}$$

By increasing B_w the Q_2 becomes smaller, but Q_3 becomes larger

• **Front-End analysis for NF** (cont'd)

Contribution of Component Stages



For $R_S = R_{in1} = R_{out1} = R_{in2} = \ldots$ *etc.*

$$\boxed{NF = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \ldots}$$

General formula for a chain of components ("Friis equation")

To reduce contribution of 2nd, 3rd, .. stages, G_1, G_2, .. should be large enough

Receiver Input SNR & Sensitivity

Standard	10log(BW)	Noise Floor(dBm)	Input SNR
DECT(1.7MHz)	62.3dB	-111.5dBm	28.5dB
GSM(200kHz)	53.0dB	-120.8dBm	18.8dB

Definitions used to Derive Noise Figure

N : Available Noise Power

Sg: Available Signal Power

S : Available Signal Power @ the output of a Network

F : Noise Factor

G : $\dfrac{\text{(Available Signal Power Output)}}{\text{(Available Signal Power at the Input)}}$

Required Receiver Noise Figure

Information used to find the receiver NF

1) Sensitivity
   - Standards
   - Application

2) Signal BW $\longrightarrow$ Noise Floor

3) Modulation Scheme
   - GMSK ?
   - QAM ?
   - DQPSK ?

   From the BER and modulation method, the Q function may be used to derive the required receiver output SNR.

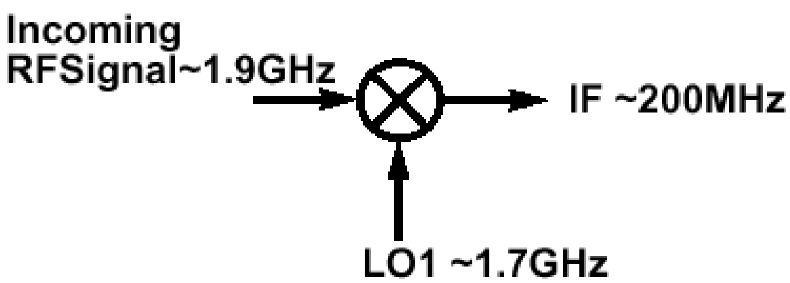
Required Receiver Noise Figure

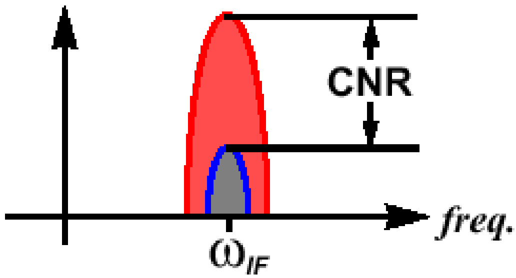
Standard	CNR_{input}	CNR_{output}	BER	Required NF
DECT	28.5dB	~10.5dB	10^{-3}	~18.5 dB
GSM	19.0dB	~9.0dB	10^{-3}	~9.0 dB

$$
\begin{aligned}
NF &= 10\log(F) \\
&= 10\log\left(\frac{CNR_{input}}{CNR_{output}}\right) \\
&= CNR_{input}(dB) - CNR_{output}(dB) \\
&= (Sen's - NFloor)dB - CNR_{output}dB
\end{aligned}
$$

	NF<
DECT :	18.5 dB
GSM :	9.0 dB

Image-Rejection Example: DECT





<u>Example : DECT</u>

- **-Desired Incoming Carrier: (freq. ~1.9GHz, Magn. -73dBm)**
- **-Local Osc. : (freq. ~1.7GHz)**
- **-Imageband :(freq. ~1.5GHz, Magnitude -23dBm)**

$$IR_{required} = -73dBm - (-23dBm) + CNR_{required}$$

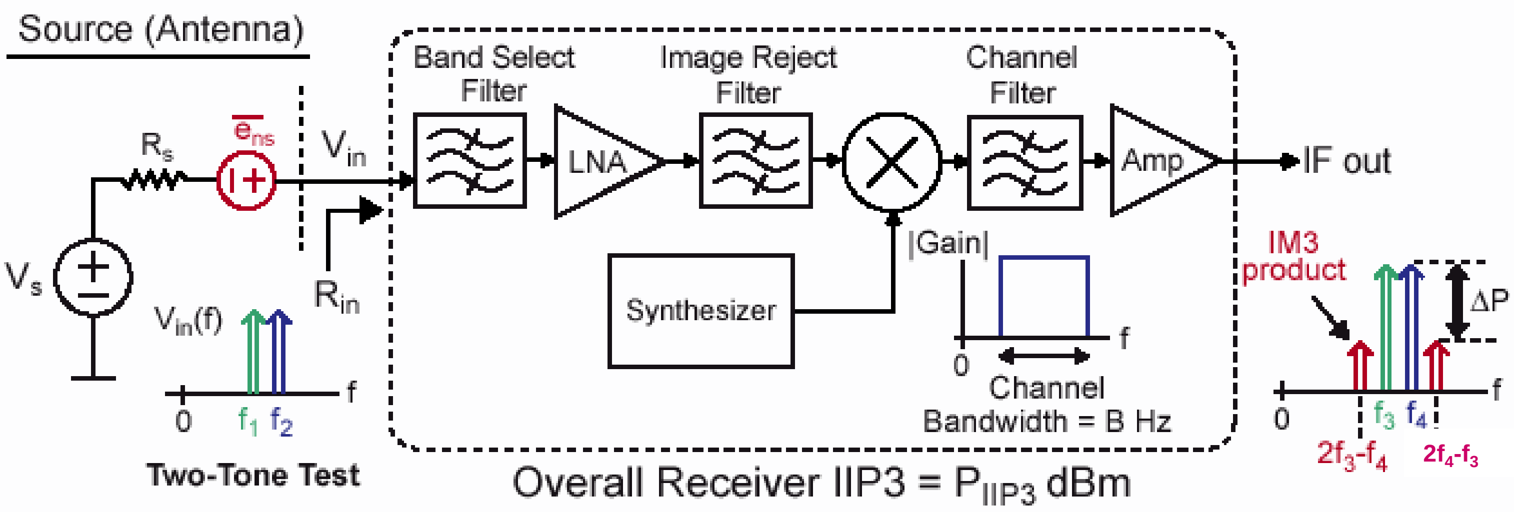
$$IR_{required} = 65dB$$

$$IR_{DECT} \approx 70dB$$

with 200MHz IF

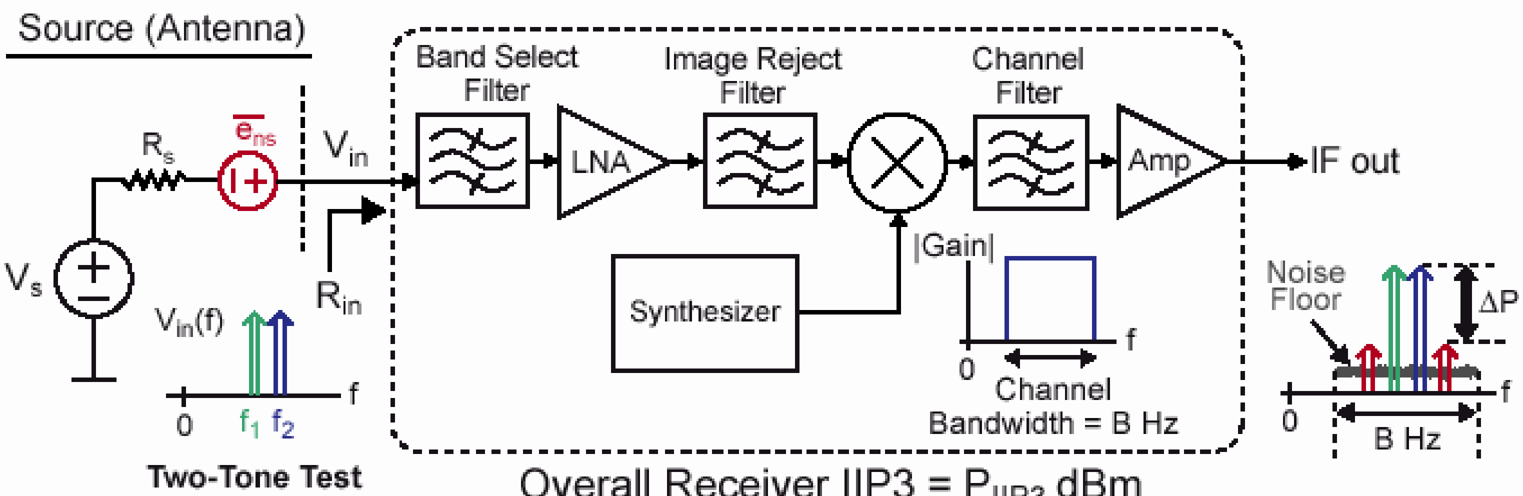
$$IR_{GSM} \approx 80dB$$

The Issue of Receiver Nonlinearity



- Lower limit of input power into receiver is limited by sensitivity (i.e., required SNR, Noise Figure, etc.)
- Upper limit of input power into receiver is determined by nonlinear characteristics of receiver
  - High input power will lead to distortion that reduces SNR (even in the absence of blockers)
  - Nonlinear behavior often characterized by IIP3 performance of receiver

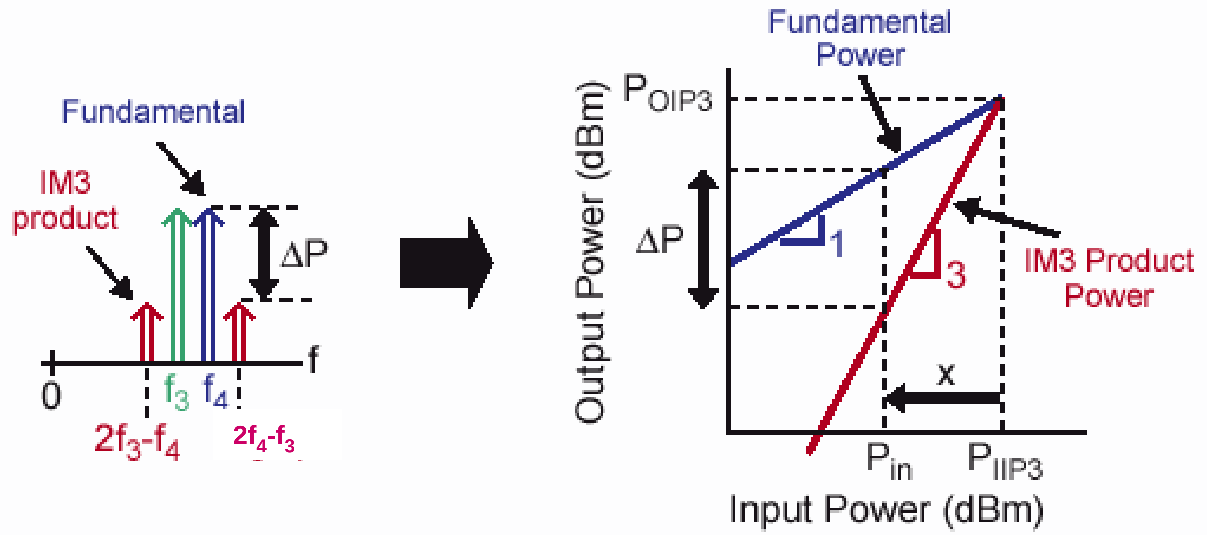
Receiver Dynamic Range



Overall Receiver IIP3 = P_{IIP3} dBm
Overall Receiver Noise Factor = NF

- **Defined as difference (in dB) between max and min input power levels to receiver**
  - **Min input power level set by receiver sensitivity**
  - **Max input power set by nonlinear characteristics of receiver**
    - Often defined as max input power for which third order IM products do not exceed the noise floor in a two tone test

A Key IIP3 Expression



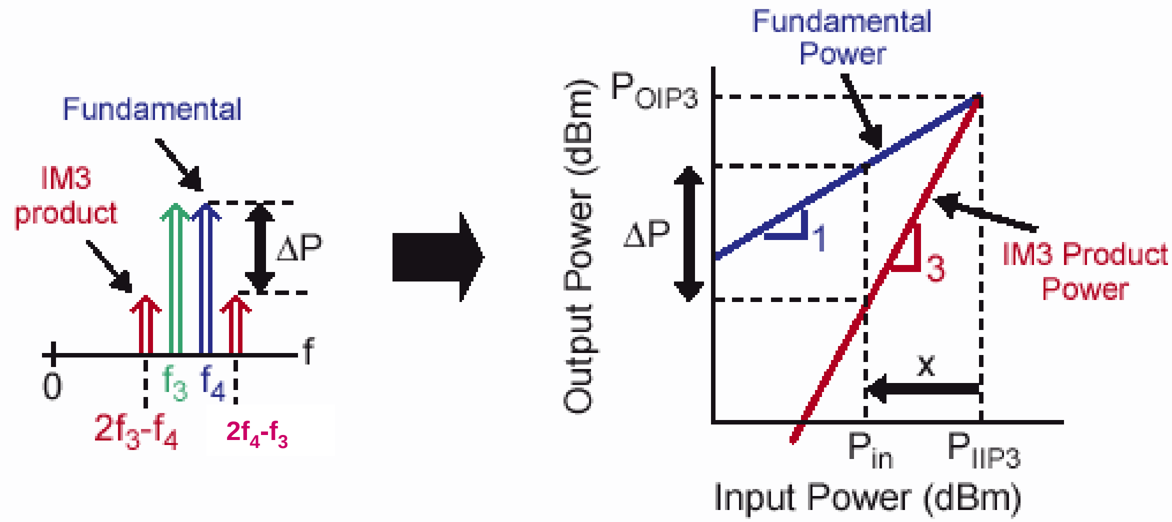
- By inspection of the right figure

$$P_{IIP3} = P_{in} + x \qquad \Delta P = 3x - x = 2x$$

- Combining the above expressions:

$$\Rightarrow \quad P_{IIP3} = P_{in} + \frac{\Delta P}{2} = P_{in} + \frac{P_{out} - P_{IM3,out}}{2}$$

Refer All Signals to Input in Previous IIP3 Expression



- **Difference between fundamental and IM3 products, ΔP, is the same (in dB) when referred to input of amplifier**
  - **Both are scaled by the inverse of the amplifier gain**

$$\Rightarrow \quad P_{IIP3} = P_{in} + \frac{\Delta P}{2} = P_{in} + \frac{P_{in} - P_{IM3,in}}{2}$$

- **Applying algebra:**

$$P_{in} = \frac{2P_{IIP3} + P_{IM3,in}}{3}$$

Calculation of Spurious Free Dynamic Range (SFDR)

- **Key expressions:**
  - **Minimum P_{in} (dBm) set by SNR_{min} and noise floor**

$$\boxed{P_{in,min} = F + SNR_{out,min}}$$

    - Where F is the input referred noise floor of the receiver

$$F = -174 + 10\log(B) + dB(NF)$$

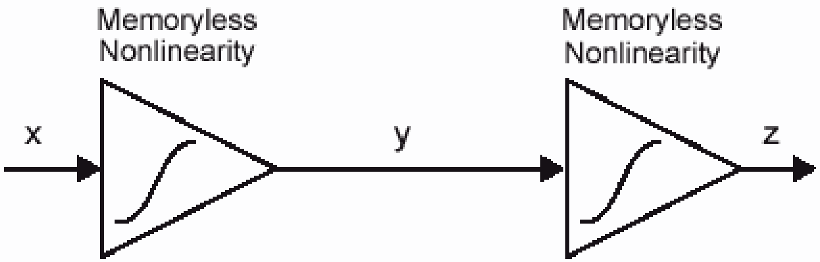
  - **Max P_{in} (dBm) occurs when IM3 products = noise floor**

$$P_{in,max} = \frac{2P_{IIP3} + P_{IM3,in,max}}{3} \Rightarrow \boxed{P_{in,max} = \frac{2P_{IIP3} + F}{3}}$$

- **Dynamic range: subtract min from max P_{in} (in dB)**

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

Calculation of Overall IIP3 for Cascaded Stages



- **Assume nonlinearity of each stage characterized as**

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

$$z(t) = \beta_1 y(t) + \beta_2 y^2(t) + \beta_3 y^3(t)$$

- **Multiply nonlinearity expressions and focus on first and third order terms**

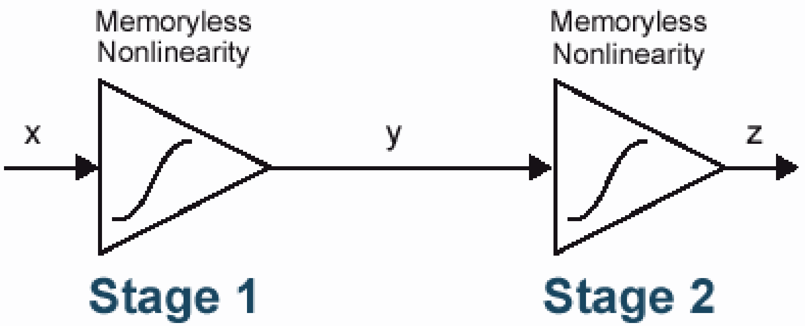
$$z(t) = \alpha_1\beta_1 x(t) + (\alpha_3\beta_1 + 2\alpha_1\alpha_2\beta_2 + \alpha_1^3\beta_3)x^3(t) + \cdots$$

- **Resulting IIP3 expression**

$$A_{IP3} = \sqrt{\frac{4}{3}\left|\frac{\alpha_1\beta_1}{\alpha_3\beta_1 + 2\alpha_1\alpha_2\beta_2 + \alpha_1^3\beta_3}\right|}$$

Perrott MIT

Alternate Expression for Overall IIP3



- Worst case IIP3 estimate – take absolute values of terms

$$A_{IP3} \approx \sqrt{\frac{4}{3}\frac{|\alpha_1\beta_1|}{|\alpha_3\beta_1| + |2\alpha_1\alpha_2\beta_2| + |\alpha_1^3\beta_3|}}$$

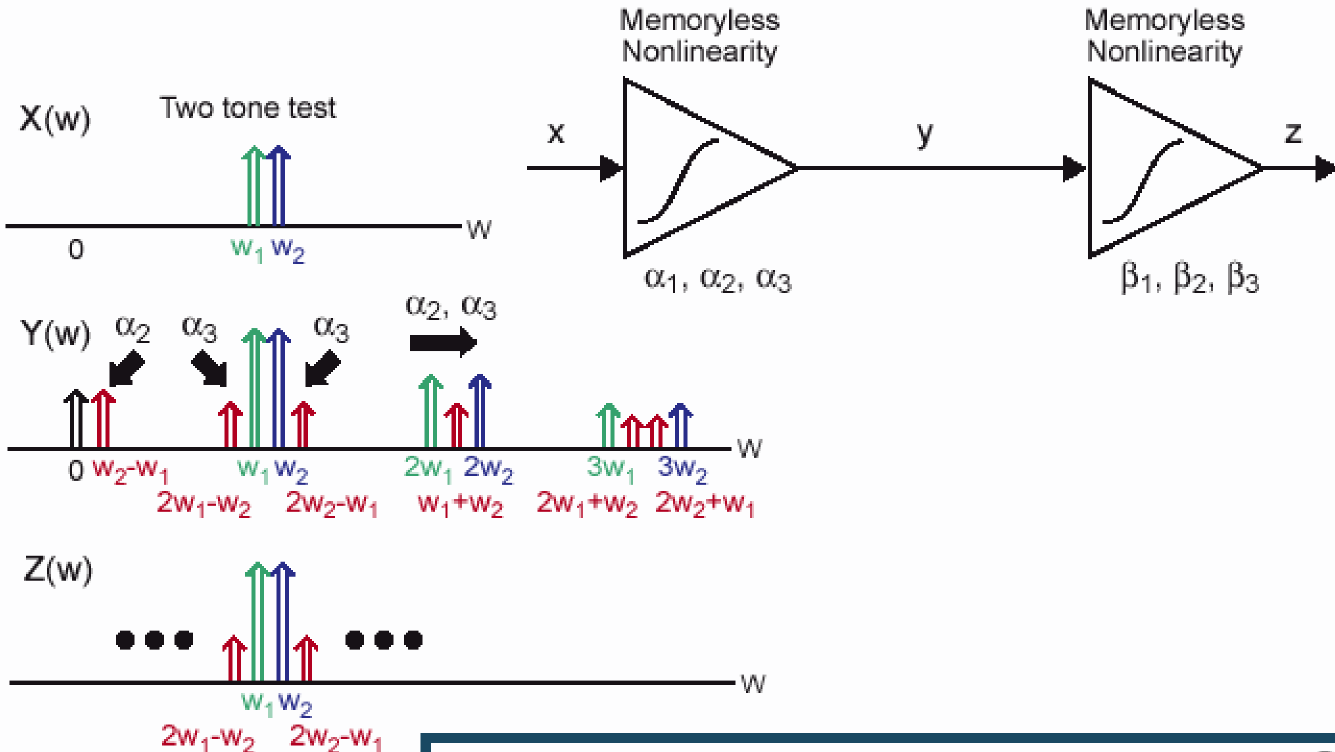
- Square and invert the above expression

$$\frac{1}{A_{IP3}^2} \approx \frac{3}{4}\frac{|\alpha_3\beta_1| + |2\alpha_1\alpha_2\beta_2| + |\alpha_1^3\beta_3|}{|\alpha_1\beta_1|}$$

- Express formulation in terms of IIP3 of stage 1 and stage 2

$$\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{3|\alpha_2\beta_2|}{2|\beta_1|} + \frac{\alpha_1^2}{A_{IP3,2}^2}$$

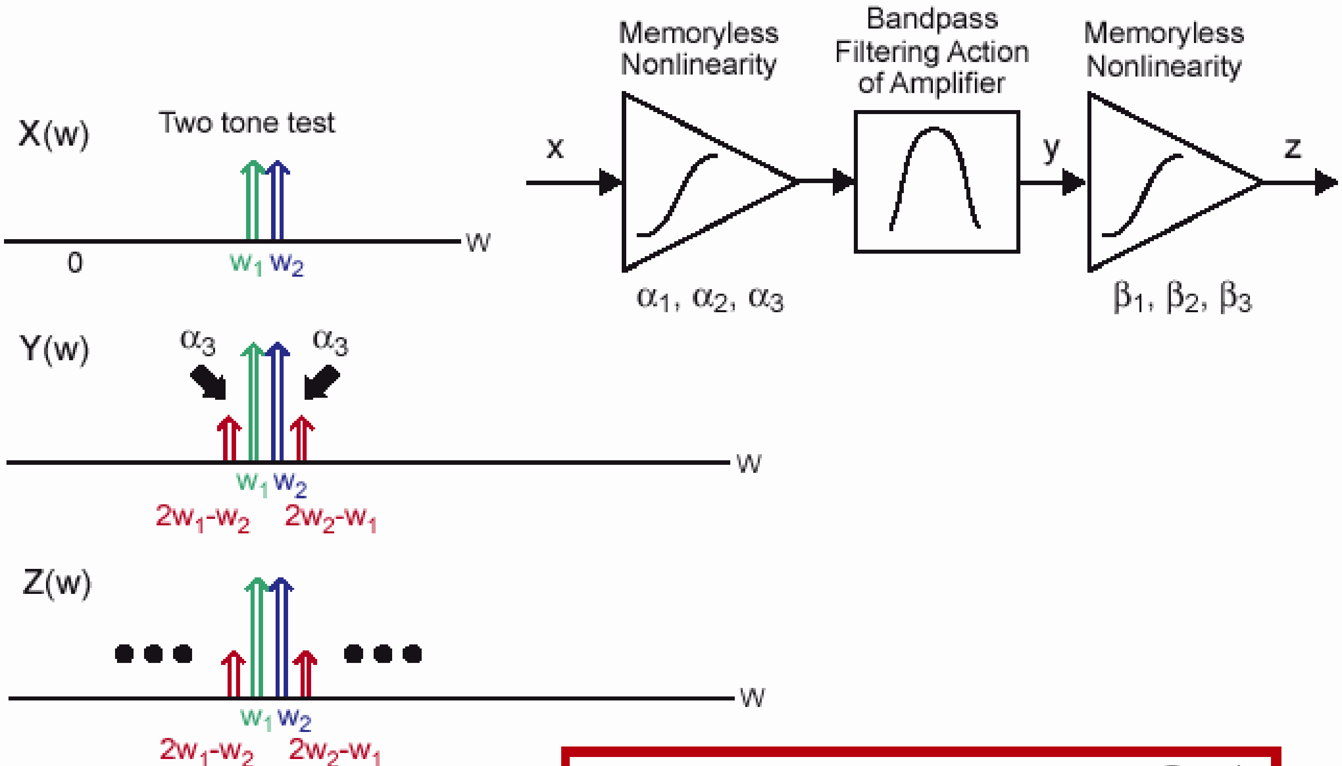
A Closer Look at Impact of Second Order Nonlinearity



$$\boxed{\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{3|\alpha_2\beta_2|}{2|\beta_1|} + \frac{\alpha_1^2}{A_{IP3,2}^2}}$$

- Influence of α_2 of Stage 1 produces tones that are at frequencies far away from two tone input

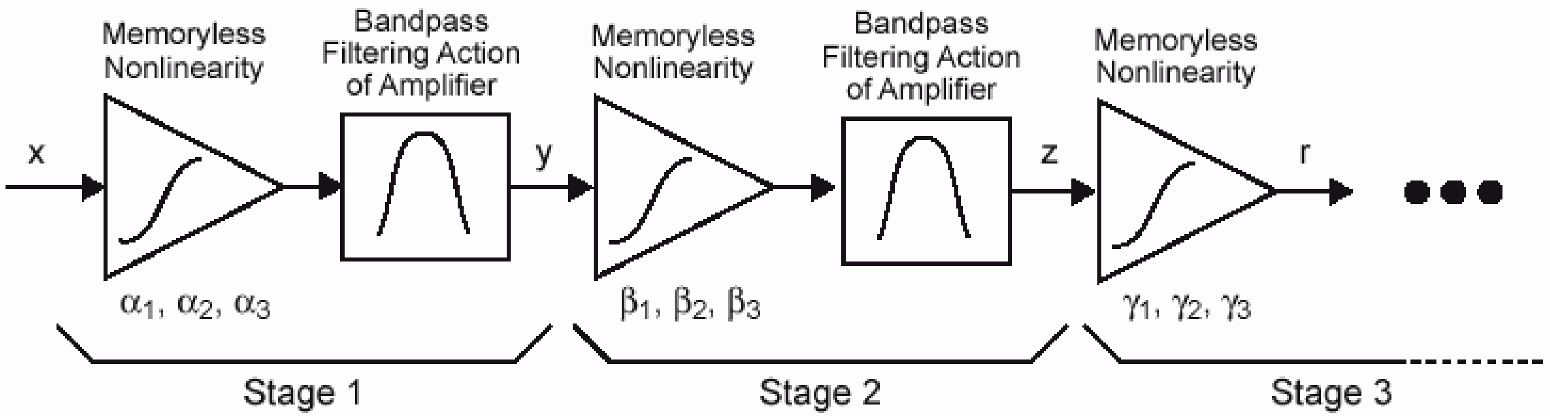
Impact of Having Narrowband Amplification



$$\boxed{\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{\alpha_1^2}{A_{IP3,2}^2}}$$

- **Removal of outside frequencies dramatically simplifies overall IIP3 calculation**

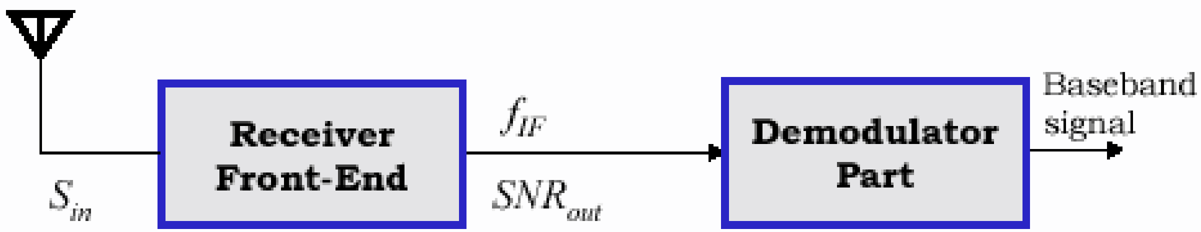
Cascaded IIP3 Calculation with Narrowband Stages



$$\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{\alpha_1^2}{A_{IP3,2}^2} + \frac{\alpha_1^2\beta_1^2}{A_{IP3,3}^2} + \cdots$$

- **Note that α_1 and β_1 correspond to the loaded voltage gain values for Stage 1 and 2, respectively**

- **Front-End analysis for IP3**

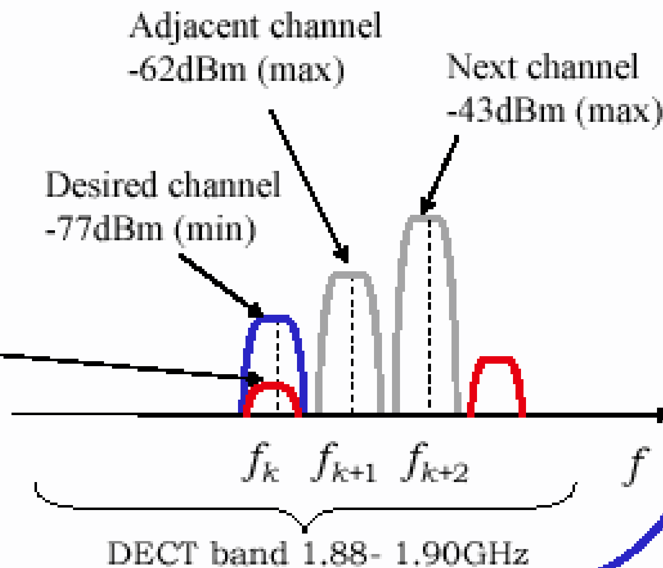


From DECT specs:

$S_{in,min}$ = -77dBm, $SNR_{out,min}$ = 25dB

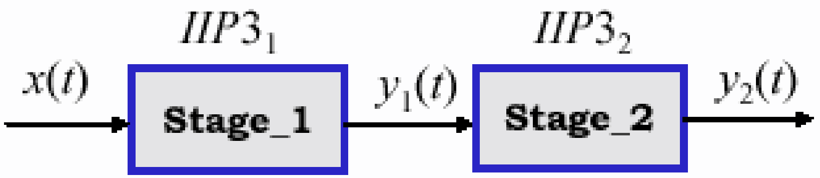
Desensitization requirements for DECT: -77, -62, -43 dBm

Adjacent channels result in IM3 product located at desired frequency (intermodulation)



- **Front-End analysis for IP3** (cont'd)

Contribution of Component Stages



$$\left.\begin{aligned} y_1 &= \alpha_1 x + \alpha_2 x^2 + \alpha_3 x^3 \\ y_2 &= \beta_1 y_1 + \beta_2 y_1^2 + \beta_3 y_1^3 \end{aligned}\right\} \quad y_2 = \underbrace{(\alpha_1\beta_1)}_{\alpha_{1,eq}} x + \underbrace{(\alpha_3\beta_1 + 2\alpha_1\alpha_2\beta_2 + \alpha_1^3\beta_3)}_{\alpha_{3,eq}} x^3 + \ldots$$

$$A^2_{IIP3,1} = \frac{4|\alpha_1|}{3|\alpha_3|} \quad \Rightarrow \quad A^2_{IIP3} = \frac{4|\alpha_{1,eq}|}{3|\alpha_{3,eq}|} = \frac{4|\alpha_1\beta_1|}{3|\alpha_3\beta_1 + 2\alpha_1\alpha_2\beta_2 + \alpha_1^3\beta_3|}$$

- Contribution of Component … (cont'd)

$$\frac{1}{A_{IIP3}^2} = \frac{3\left|\alpha_3\beta_1 + 2\alpha_1\alpha_2\beta_2 + \alpha_1^3\beta_3\right|}{4\left|\alpha_1\beta_1\right|}$$

$$= \left|\frac{1}{A_{IIP3,1}^2} + \frac{3\alpha_2\beta_2}{2\beta_1} + \frac{\alpha_1^2}{A_{IIP3,2}^2}\right|$$

$$\approx \frac{1}{A_{IIP3,1}^2} + \frac{\alpha_1^2}{A_{IIP3,2}^2}$$

$$\boxed{\begin{aligned} &IIP3 = A_{IIP3}^2 / 50\Omega \\ &\alpha_1^2 = G_1 \qquad \text{(power gain)} \end{aligned}}$$

$$\boxed{\frac{1}{IIP3} \approx \frac{1}{IIP3_1} + \frac{G_1}{IIP3_2} + \frac{G_1G_2}{IIP3_3} + \dots}$$

General formula for a chain of components

Note ! Here IIP3's are non-logarithmic quantities

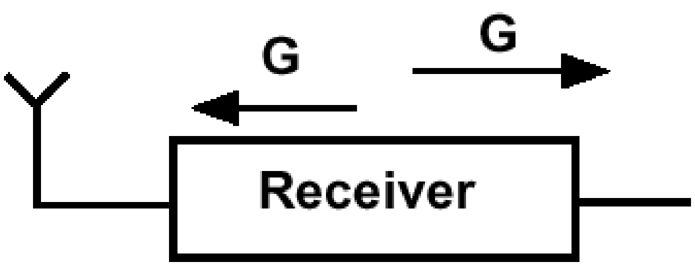
Linear components have $(1/IIP3) = 0$

The main contributors to total IIP3 of the front-end are usually LNA and mixer.

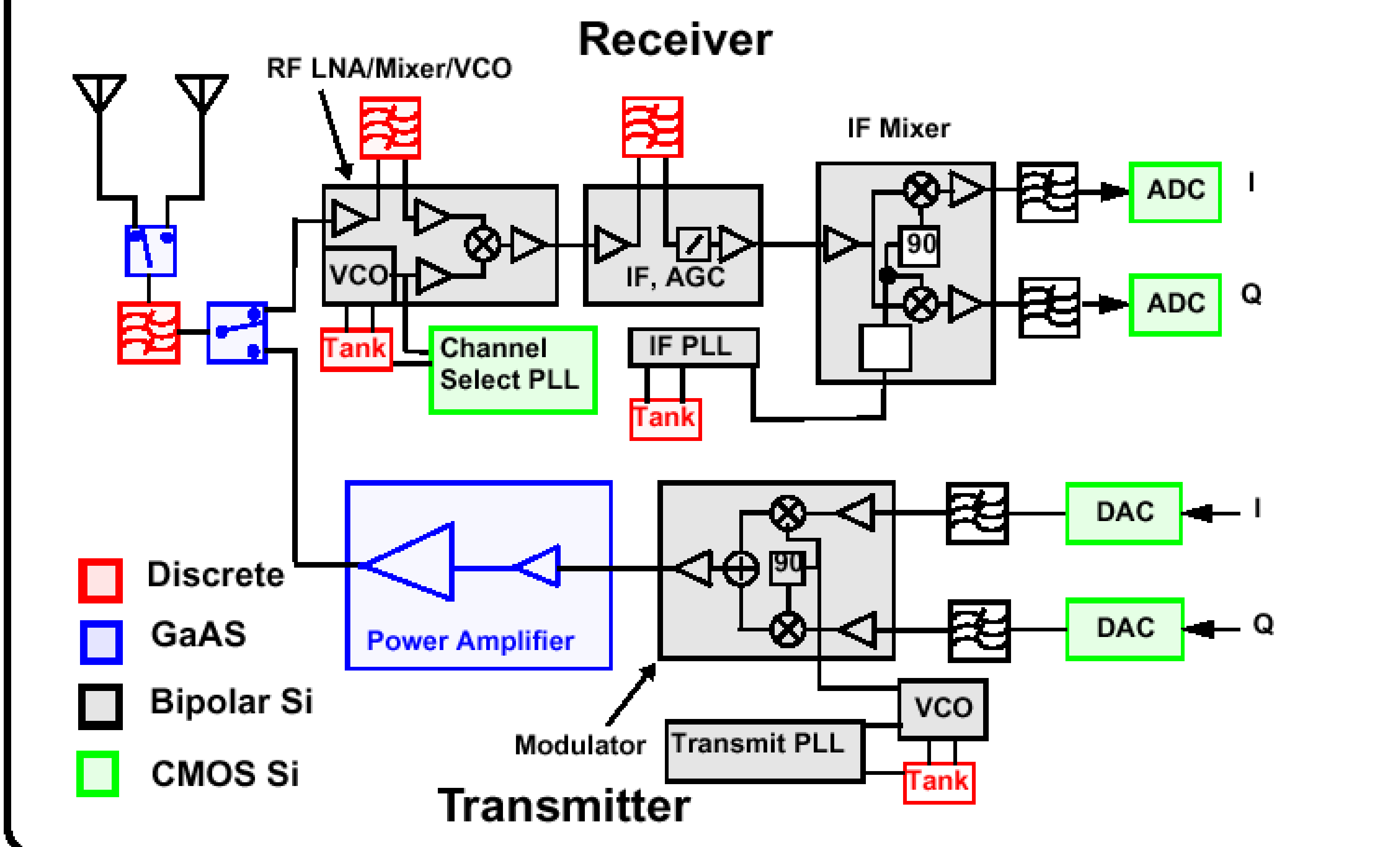
Trade-off between NF & Intermodulation

NF ⟷ **IP3**

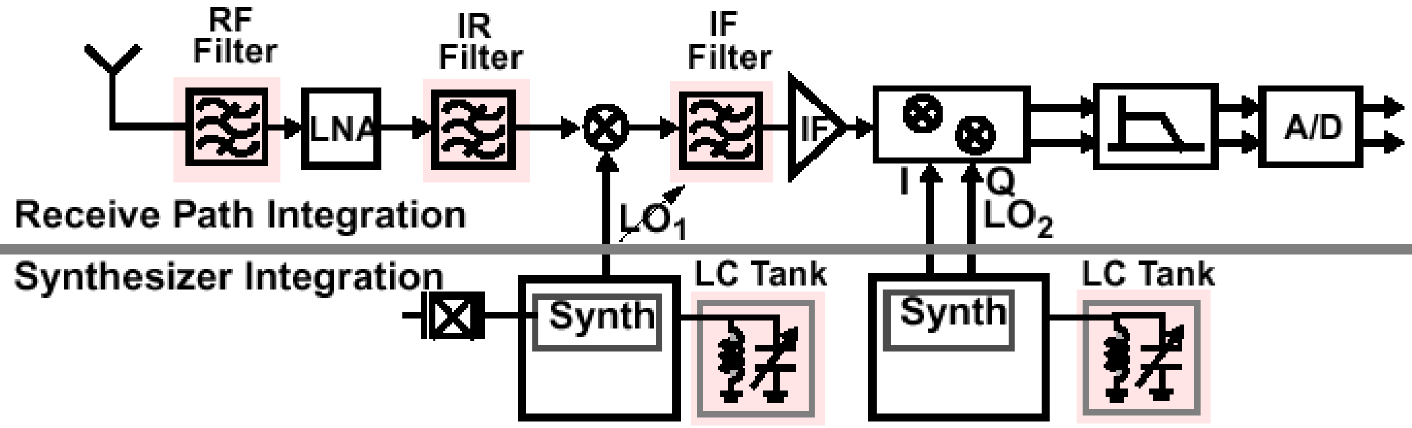
High Gain @ Front-end | Low Gain @ Front-end



Block Diagram, Typical Multi-Technology RF Transceiver



Challenges of Receiver Integration



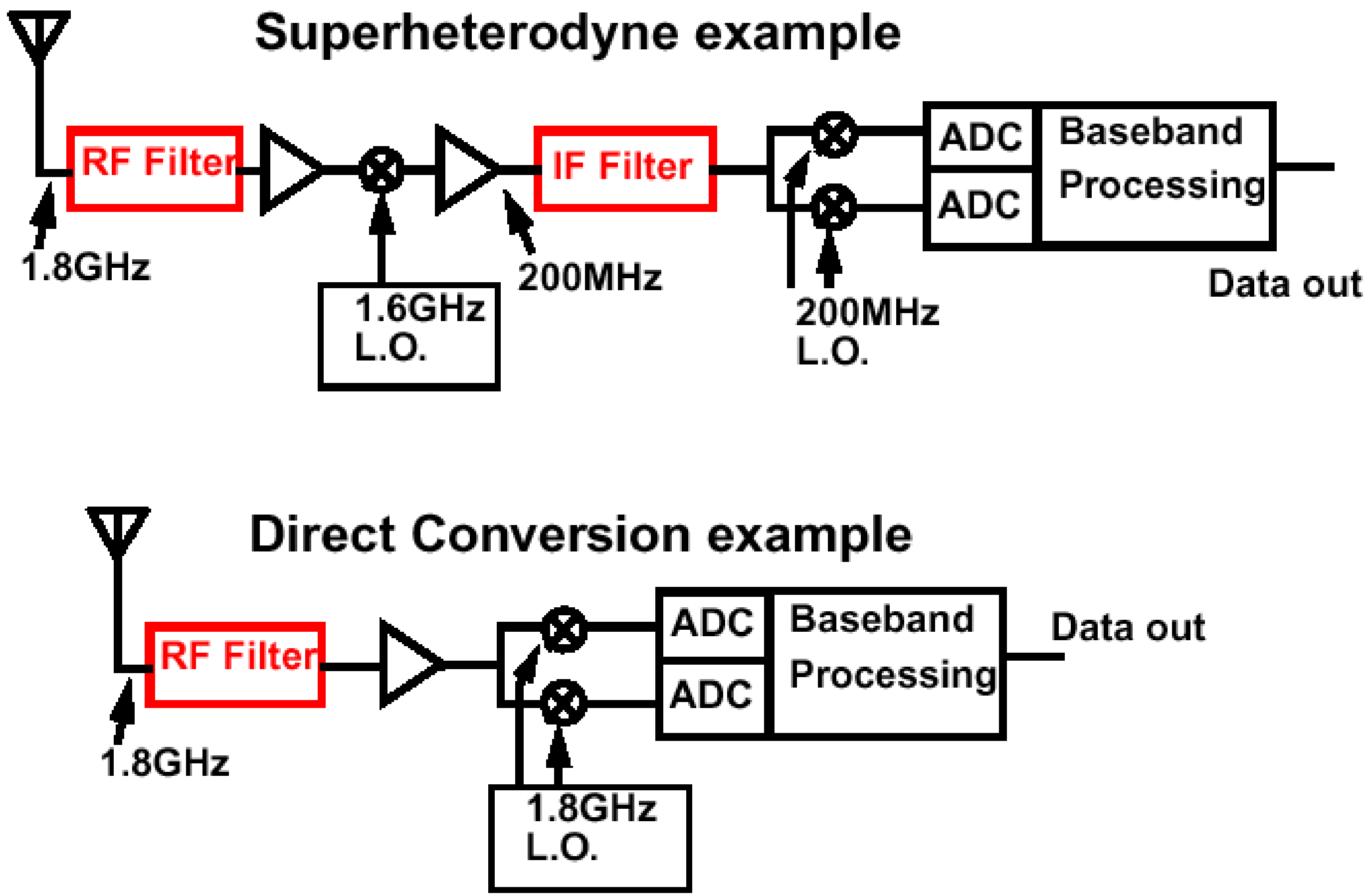
Problems with synthesizer integration:

- Poor phase noise performance of on-chip VCOs
- Channel-select synthesizer required at RF

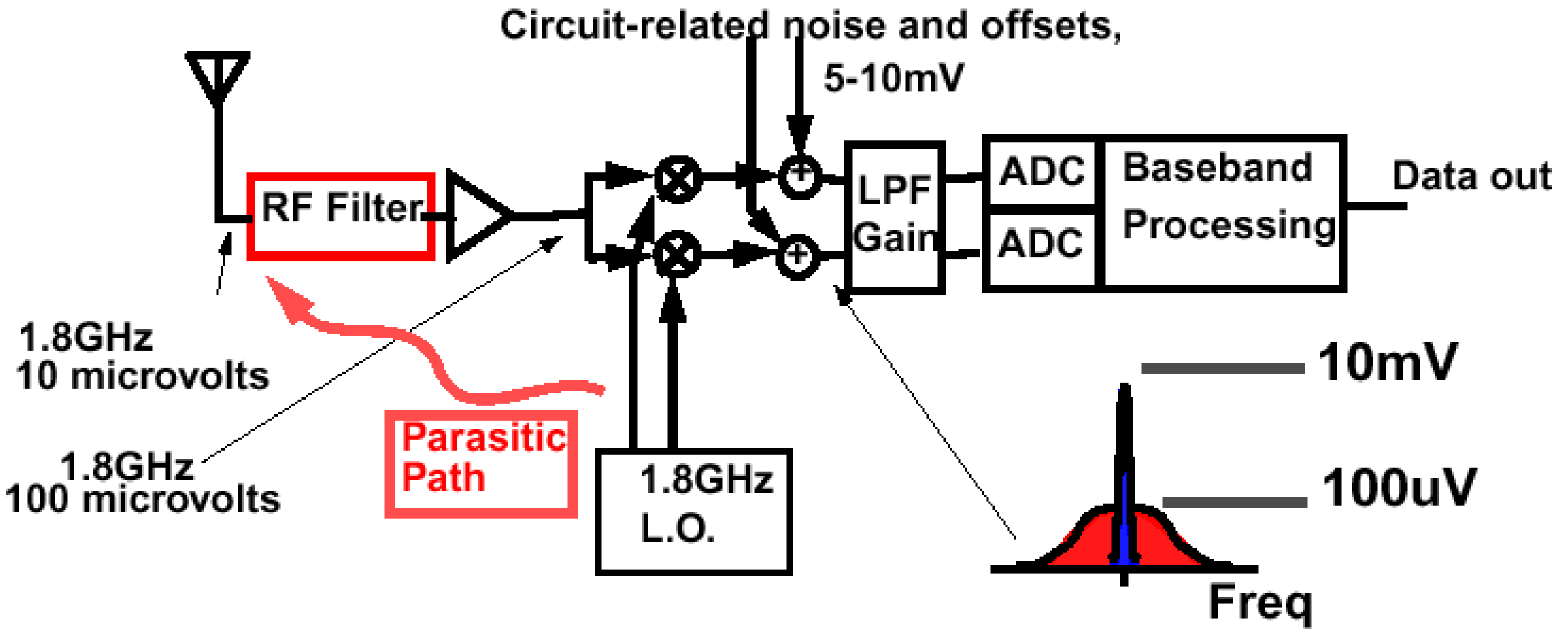
Challenges in receive path integration:

- Image & noise filtering required
- Discrete high-Q IF channel select filter required

Direct Conversion RF Transceivers

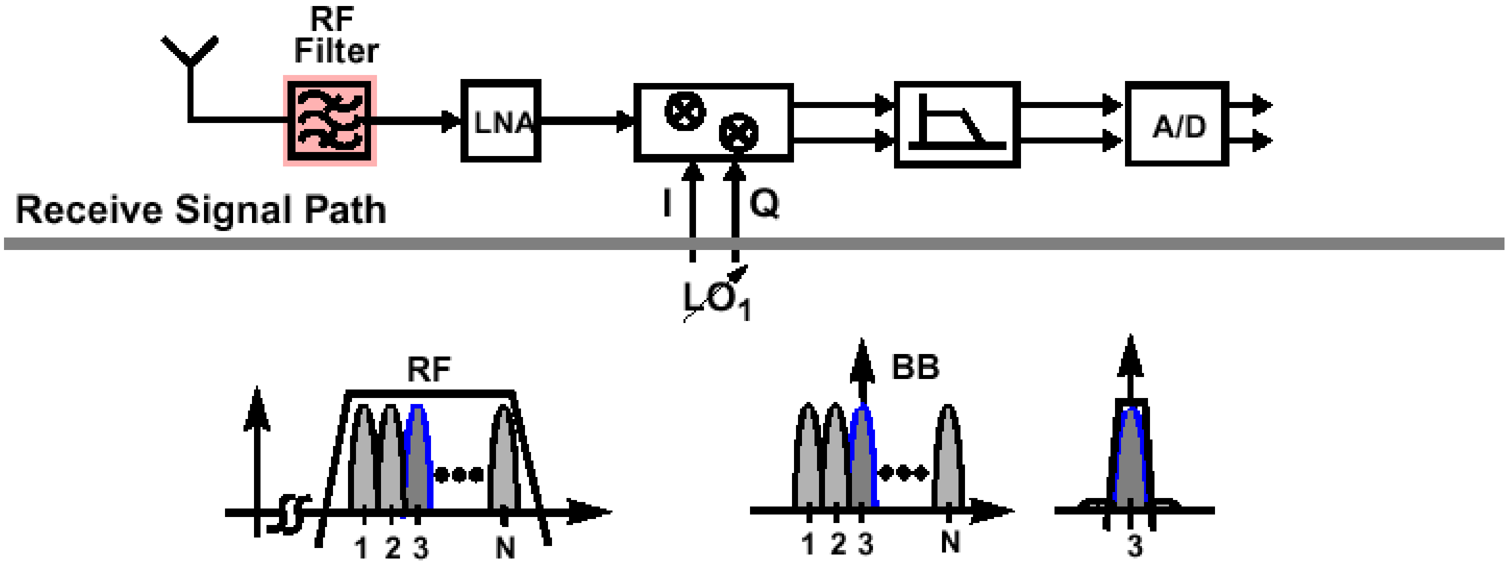


Low-Frequency Errors in Direct Conversion Receivers



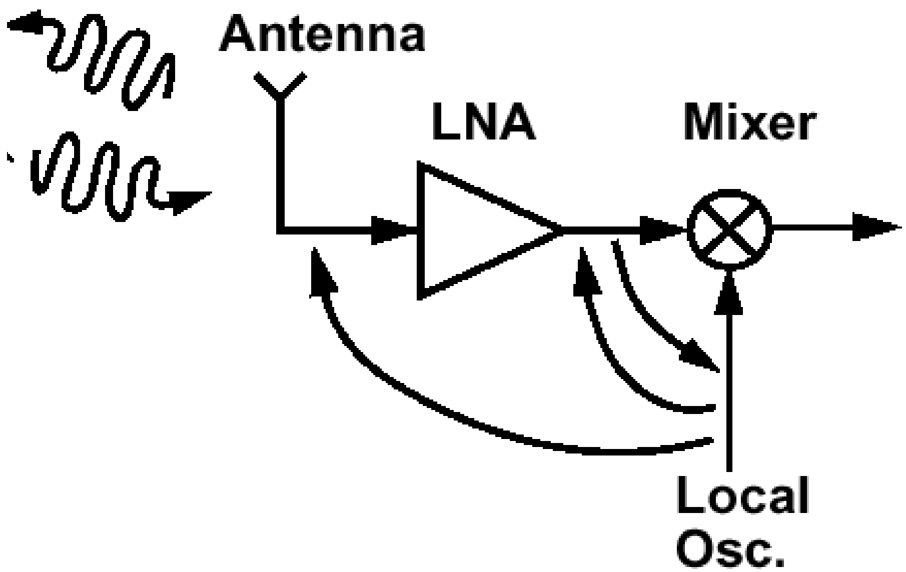
- Desired signal often has L. F. information
- Time-varying offsets 100X bigger than signal

Direct Conversion



- The need for discrete component filters eliminated
- LO leak creates DC offset
- RF channel-select synthesizer still required

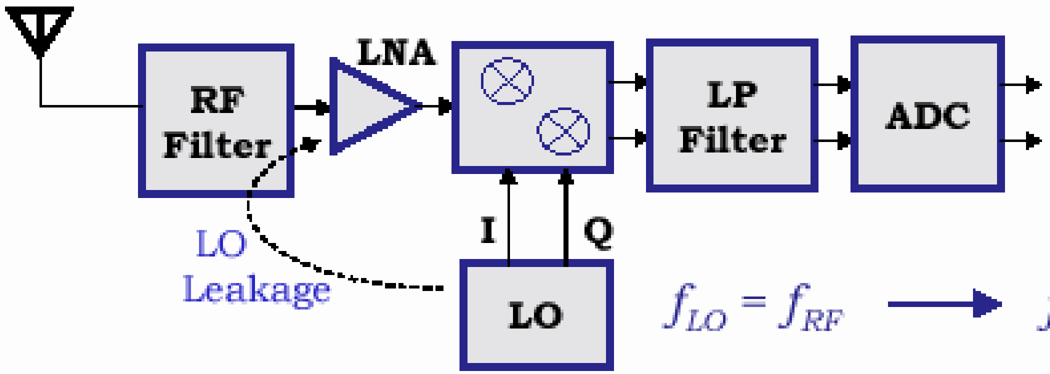
DC Offset in Direct Conversion



Mechanism for LO Leakage

1) LO leaks to the mixer input.
2) LO couples to the LNA input or antenna.
3) Large blockers radiate from the mixer RF port to the mixer LO input.

Direct conversion receiver



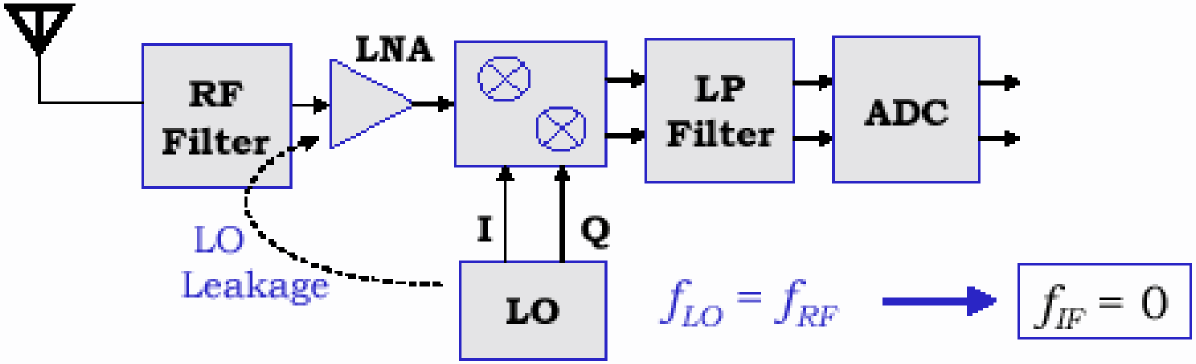
$f_{LO} = f_{RF} \longrightarrow f_{IF} = 0$

- Fewer components than heterodyne
- Image filtering avoided – no IR and IF filters
- Easy to integrate LP filters
- AD conversion in baseband – lowest requirements for ADC

Old & New receiver architectures (cont'd)

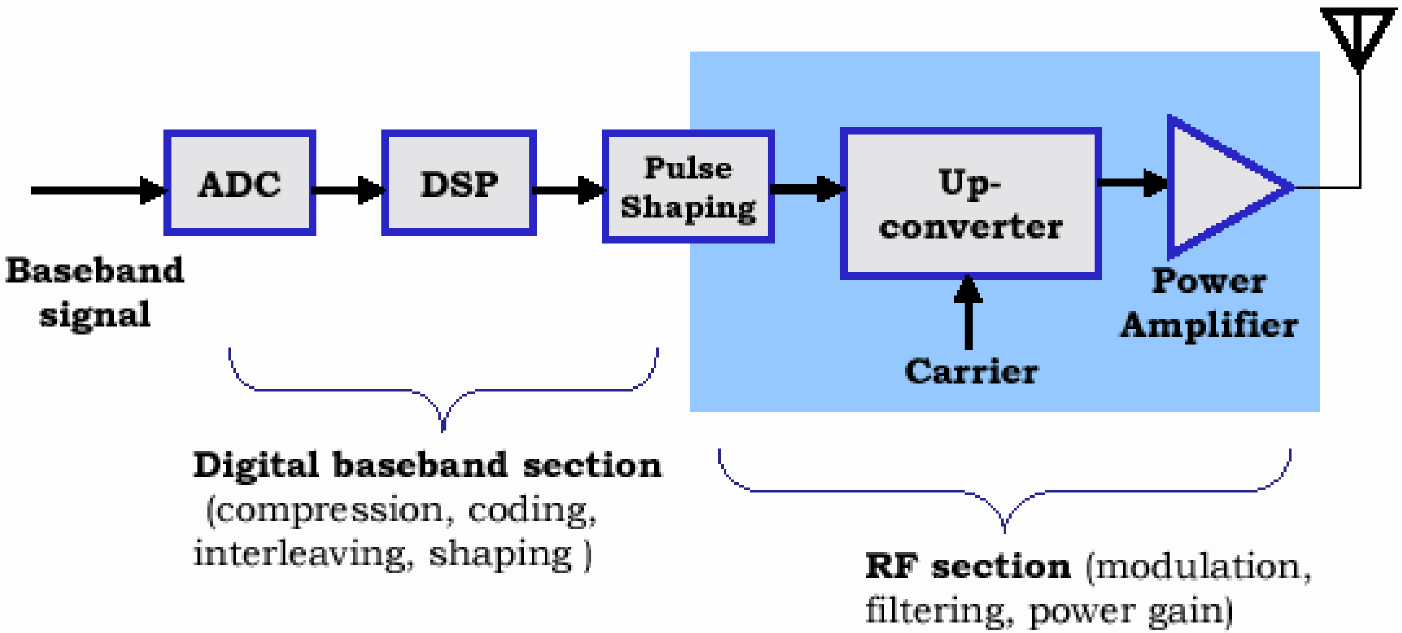
- Direct receiver (homodyne) –

  (fewer components, image filtering avoided – no IR and IF filters)



- Large DC offset can corrupt weak signal or saturate LNA (LO mixes itself), Adaptive DC offset cancellation – eg. By DSP baseband control
- Flicker noise (1/f) can be difficult to distinguish from signal
- Channel selection with LPF, (noise-linearity-power tradeoff are critical)

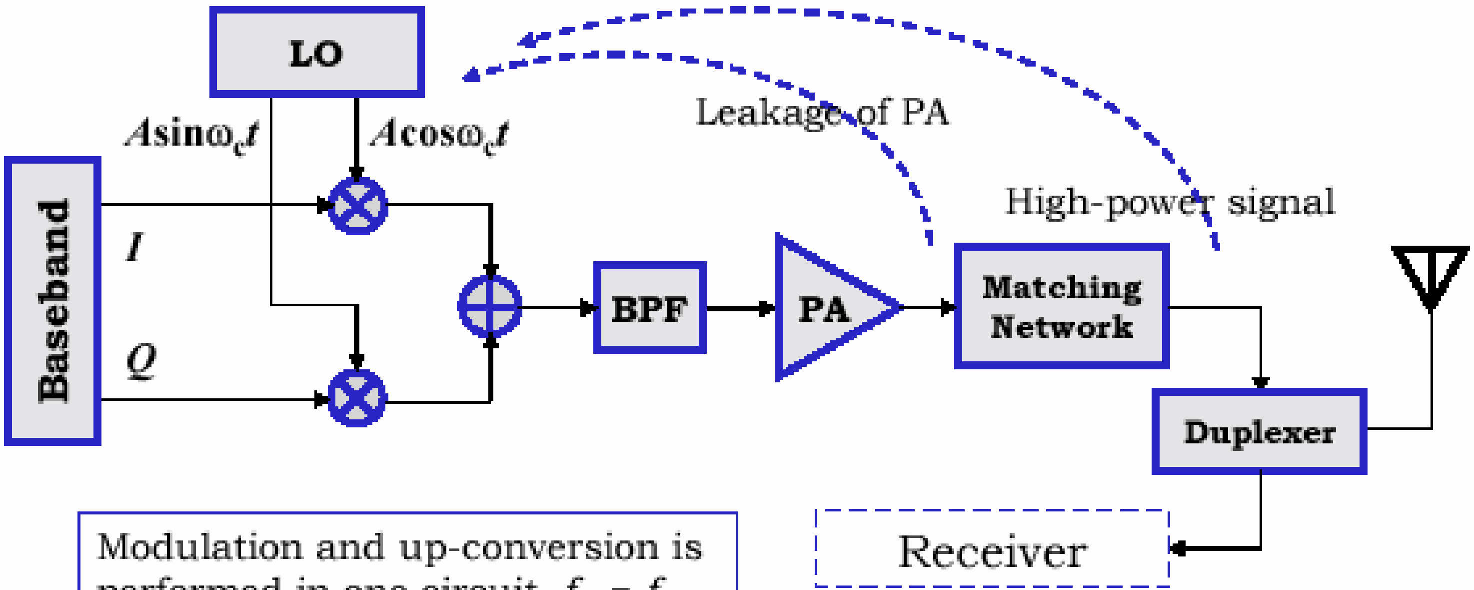
Transmitters



Pulse shaping to minimize ISI and limit signal BW

Noise is not critical in a transmitter

- Direct conversion transmitter



Modulation and up-conversion is performed in one circuit, $f_{LO} = f_c$

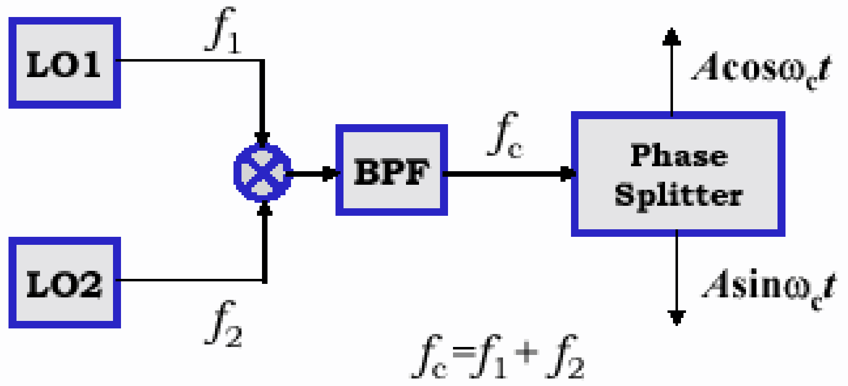
BPF suppresses harmonics

LO must be shielded to reduce corruption

I and Q modulators must be symmetrical, otherwise crosstalk

- Direct conversion transmitter (cont'd)

LO with offset frequency



Here LO1 and LO2 work at far different frequency from PA, LO's corruption is alleviated