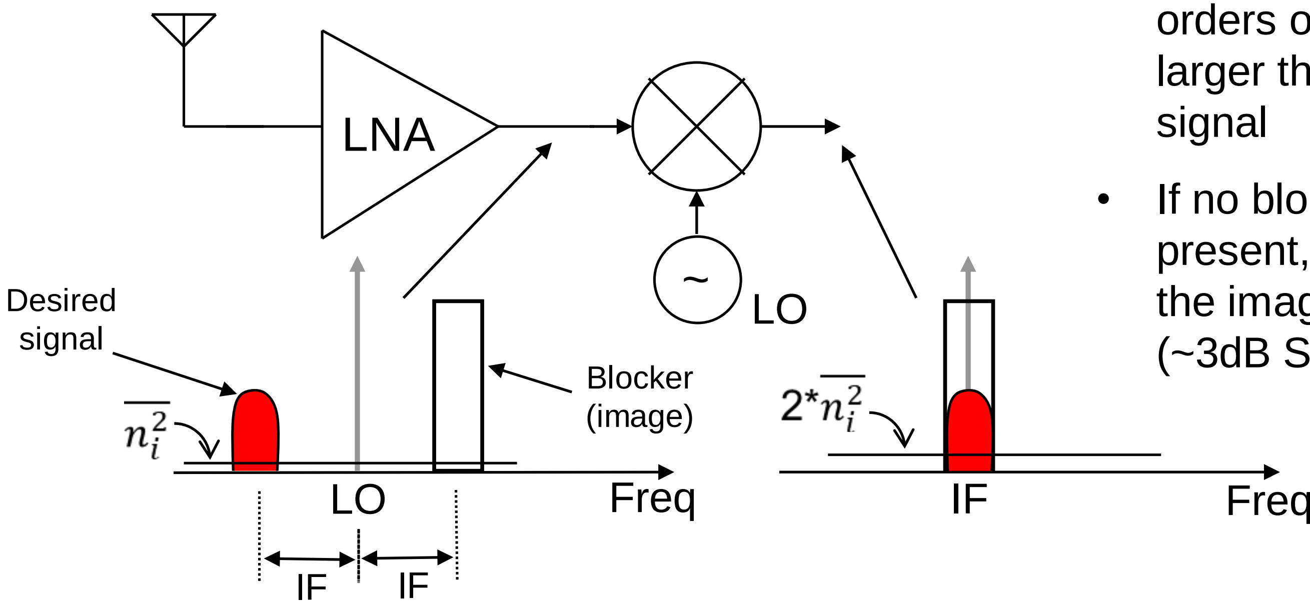
Narrow-band Receiver Radio Architectures

- **Double-conversion single-quad (Superhetrodyne)**
- **Direct-conversion (Single-conversion single-quad, homodyne, Zero-IF)**
- **Double-conversion double-quad**
- **Low-IF**
- **References**

Down-conversion; The image problem:



- Blocker level can be orders of magnitude larger than desired signal
- If no blocker present, you still fold the image noise (~3dB SNR hit)

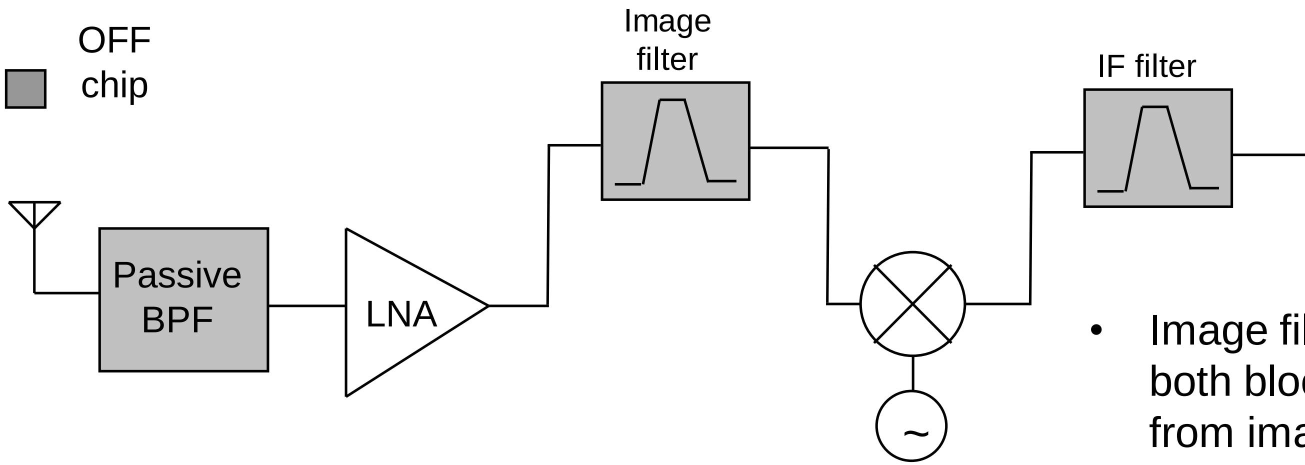
$$m_r(t)\cos(\omega_{LO}+\omega_{IF})t\times\cos(\omega_{LO})t=\frac{1}{2}m_r(t)\big(\cos(2\omega_{LO}+\omega_{IF})t+\cos(\omega_{IF})t\big)$$

$$m_I(t)\cos(\omega_{LO}-\omega_{IF})t\times\cos(\omega_{LO})t=\frac{1}{2}m_I(t)\big(\cos(2\omega_{LO}-\omega_{IF})t+\cos(\omega_{IF})t\big)$$

After the IF lowpass filter following mixer, the output is:

$$IF_{output}=\frac{1}{2}\big(m_r(t)+m_I(t)\big)\cos(\omega_{IF}t)$$

1) The Superhetrodyne Architecture:

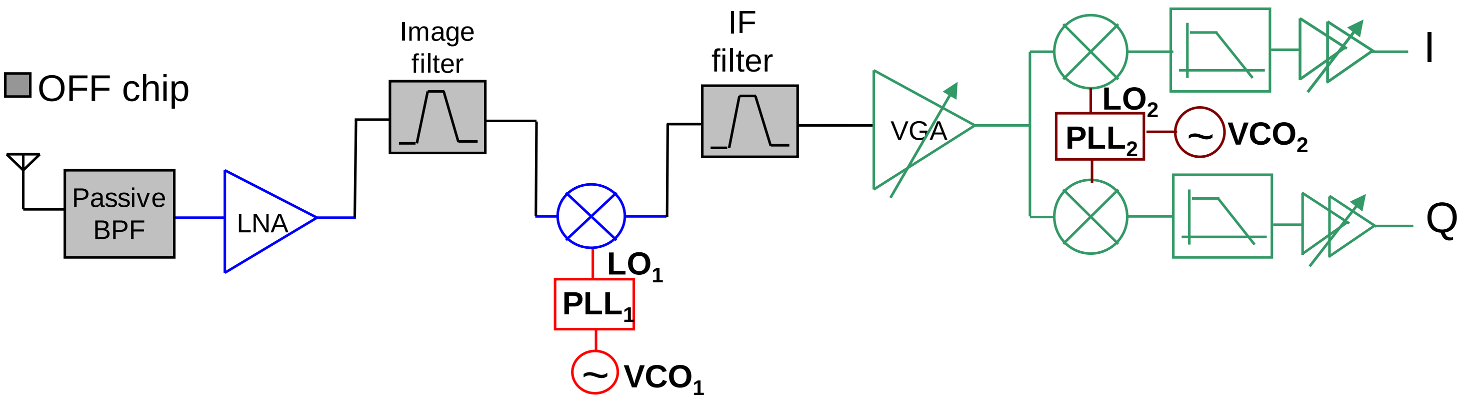


- Image filter removes both blocker and noise from image before down-conversion

The choice of the IF frequency:

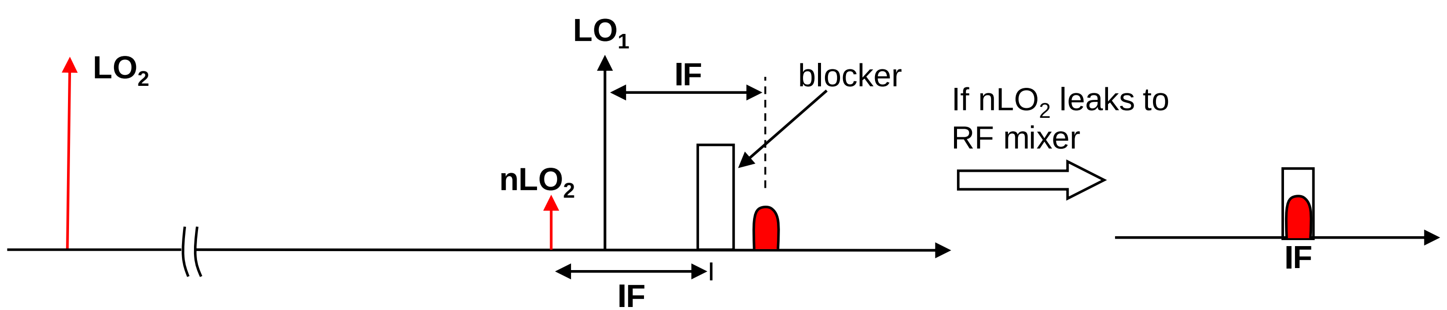
- Relatively low IF requires a very high-Q image filter to provide decent rejection at the image frequency, which translates into higher filter passband loss and so higher Rx NF, and higher cost.
- Relatively high IF results in more current consumption for the subsequent IF stage circuits, especially the IF VGA.
- A typical IF frequency is 100-200MHz.
- One of the most robust and low-current receiver architectures 
- requires several bulky off-chip components 

LO planning in a Superhet Architecture:

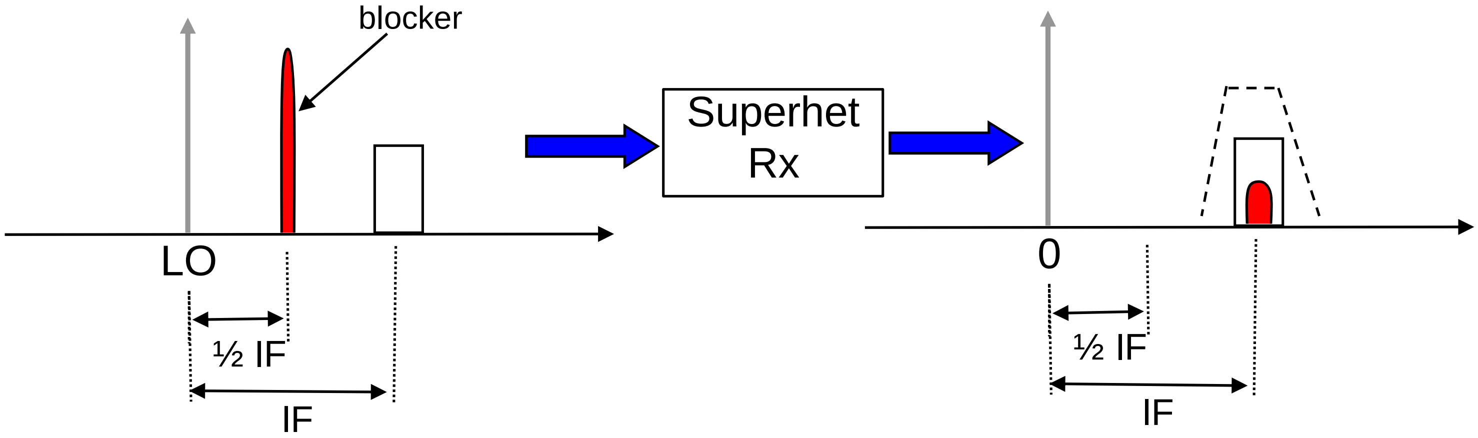


● Two separate VCO's and synthesizers are usually needed. The IF LO2 is usually fixed, while the RF LO1 is variable to down convert the desired signal to fall within the IF SAW filter bandwidth. The solution is a 3-4 chip solution with three external SAW filters.

● LO_1 should never be made close to be an integer multiple of LO_2 for any channel. The N^{th} harmonic of the fixed LO2 could leak into RF mixer causing unwanted intermod.



The ½ IF problem in superhet architecture:



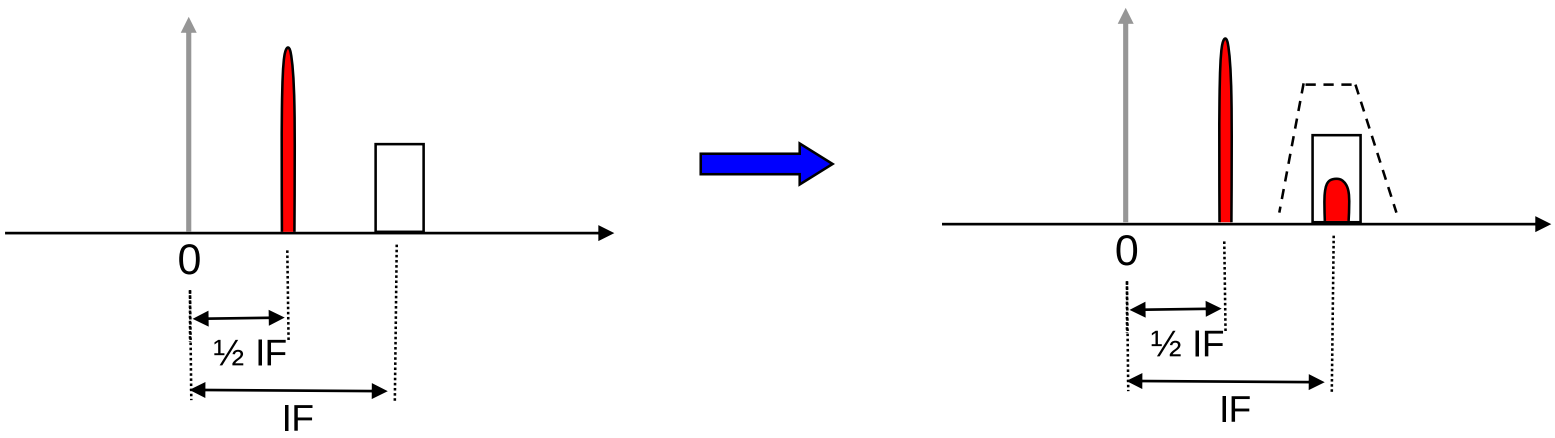
Let us assume there is an undesired blocker half way between the desired signal and the LO, as shown. There are two mechanism this blocker can fold onto the desired band. The first if the RF front-end has strong second order non-linearity.

$$\left[m_{blocker}(t)\cos(\omega_{LO}+0.5\omega_{IF})t\right]^2 = \left(m_{blocker}(t)\right)^2 + \left(m_{blocker}(t)\right)^2\cos(2\omega_{LO}+\omega_{IF})t$$

If the LO has also a large second order component, the result would be a component of the blocker folding onto the IF band, right on top of the desired band

$$\left[\left(m_{blocker}(t)\right)^2\cos(2\omega_{LO}+\omega_{IF})t\right]\cos(2\omega_{LO})t = \left(m_{blocker}(t)\right)^2\cos(\omega_{IF})t + \ldots$$

Note that the blocker folds with twice its signal bandwidth due to the square.



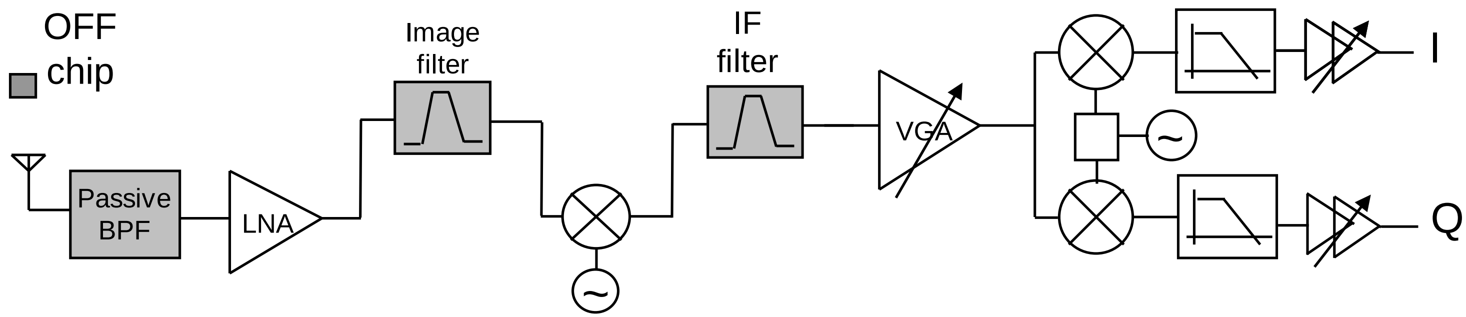
The second means by which the blocker can fold onto the desired band if the IF stage has a strong second order nonlinearity.

$$\left[m_{blocker}(t)\cos(0.5\omega_{IF})t\right]^2 = \left(m_{blocker}(t)\right)^2 + \left(m_{blocker}(t)\right)^2\cos(\omega_{IF})t$$

Note again here that the blocker folds with twice its signal bandwidth due to the square.

It is therefore an extremely important decision to chose the IF frequency so that there is no strong half IF blocker anywhere in the system, or if there is any, the desired second order nonlinearity of the receiver is carefully calculated.

Superhet; Dual conversion single-quad:



Disadvantages:

• requires several bulky off-chip SAW filters.

• generally two different synthesizers are required

• a three-chip solution: RF, IF and synthesizer

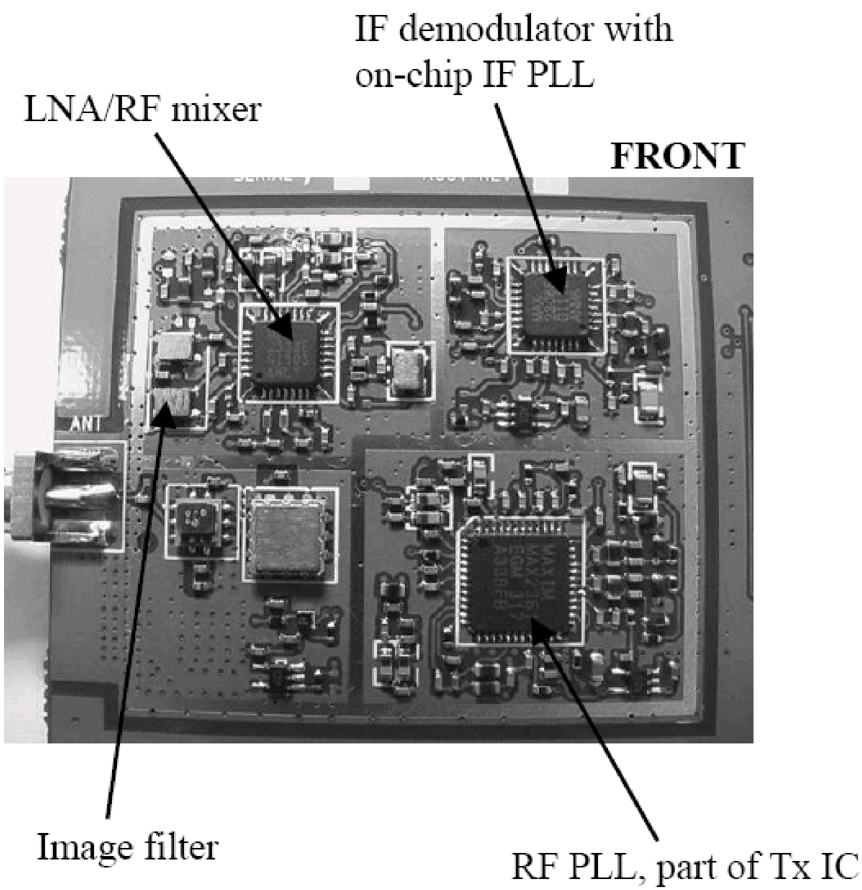
Advantages:

• robust.

• high-dynamic range SAW filters relaxes that of the active circuits, drastically reducing their required dynamic range .. Easier to design

• low current consumption (<20mA for WCDMA)

Example of a CDMA tranceiver reference design:



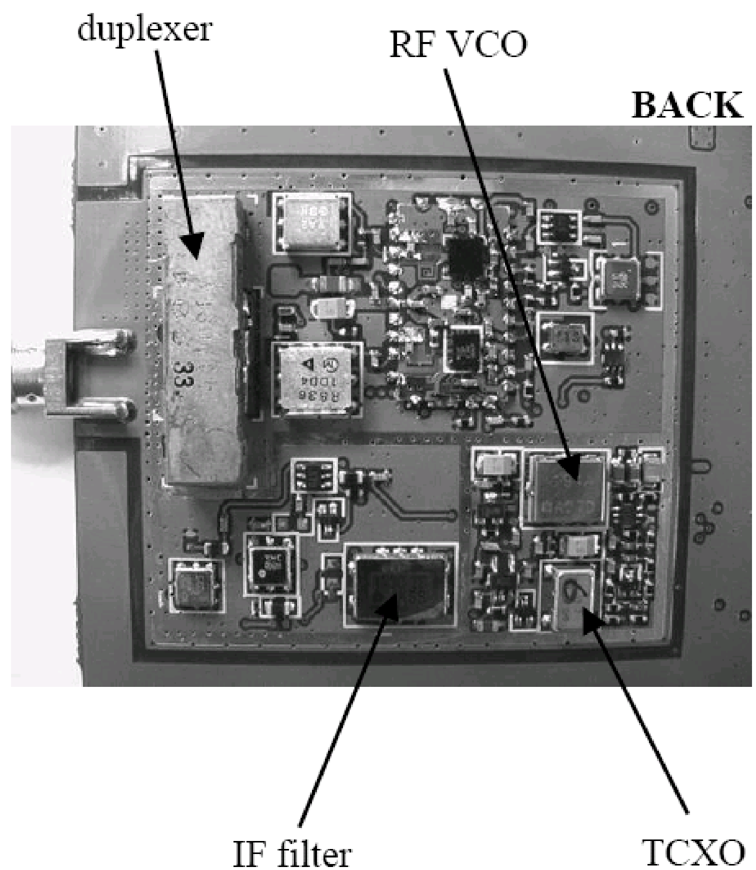
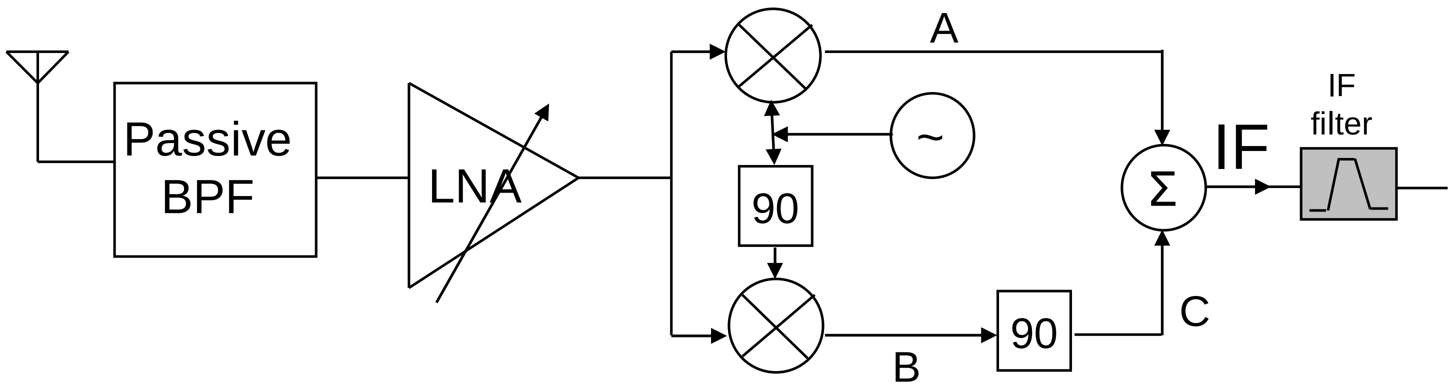


Image suppression by proper phasing (Hilbert Architecture):



$$RF = m_r(t)\cos(\omega_{LO}+\omega_{IF})t + m_I(t)\cos(\omega_{LO}-\omega_{IF})t$$

$$A = RF \times \cos(\omega_{LO}t) = \frac{1}{2}\begin{Bmatrix} m_r(t)\left(\cos(2\omega_{LO}+\omega_{IF})t + \cos(\omega_{IF})t\right) \\ + m_I(t)\left(\cos(2\omega_{LO}-\omega_{IF})t + \cos(\omega_{IF})t\right) \end{Bmatrix}$$

$$B = RF \times \sin(\omega_{LO}t) = \frac{1}{2}\begin{Bmatrix} m_r(t)\left(\sin(2\omega_{LO}+\omega_{IF})t - \sin(\omega_{IF})t\right) \\ + m_I(t)\left(\sin(2\omega_{LO}-\omega_{IF})t + \sin(\omega_{IF})t\right) \end{Bmatrix}$$

$$C = \frac{1}{2}\begin{Bmatrix} m_r(t)\left(-\cos(2\omega_{LO}+\omega_{IF})t + \cos(\omega_{IF})t\right) \\ + m_I(t)\left(-\cos(2\omega_{LO}-\omega_{IF})t - \cos(\omega_{IF})t\right) \end{Bmatrix}$$

$$IF = A + C = m_r(t)\cos(\omega_{IF})t$$

$$IF' = A - C = m_I(t)\cos(\omega_{IF})t$$

(Hilbert Architecture): Disadvantages:

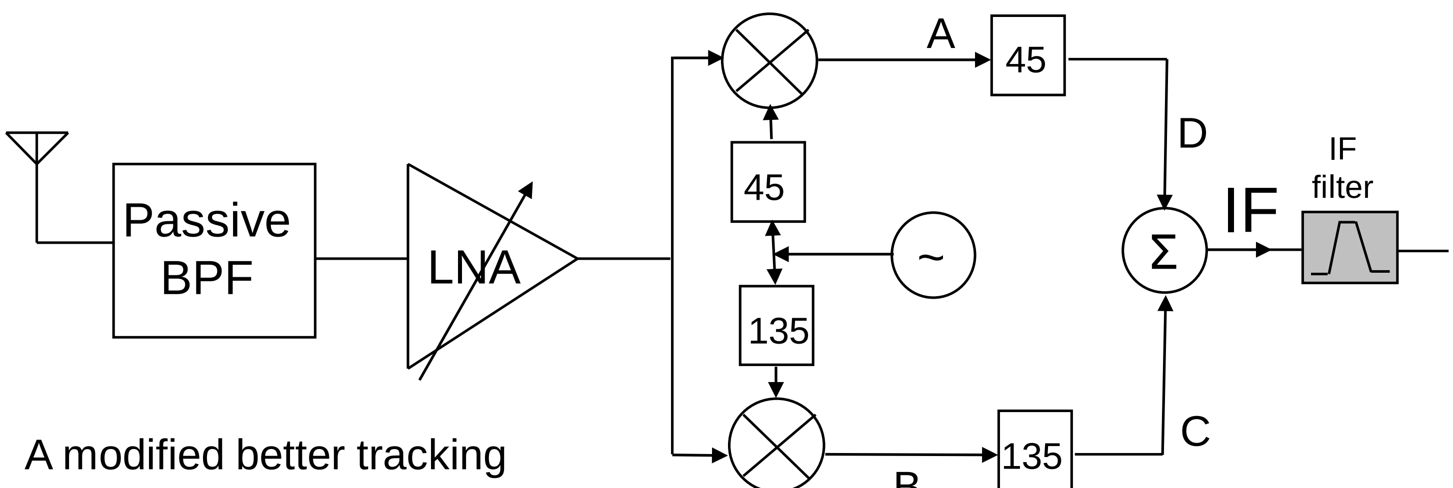
• requires extremely good phase and gain matching. Only ~35dB of image rejection is possible without trimming or tuning. This is not enough in some applications where the image is 60dB higher than the desired signal.

• consumes more current .. A bit power hungry

Advantages:

• eliminates the external image SAW filter.

• offers better integration, but still a second IF chip is needed for final down conversion



A modified better tracking architecture

Impact of gain and phase imbalance on image rejection

Let us assume that signals at I and Q experience non-identical gain. Furthermore, the phase is not exactly quadrature and has some phase error. To find the impact of both gain and phase imbalance on image rejection, let us re-write the equations as follows:

$$RF = m_r(t)cos(\omega_{LO} + \omega_{IF})\mathrm{t} + m_I(t)cos(\omega_{LO} - \omega_{IF})\mathrm{t}$$

$$A = RF \times \left(1+\frac{\alpha}{2}\right)cos\left(\omega_{LO}t + \frac{\emptyset}{2}\right) = \frac{1}{2}\left\{\begin{array}{l} m_r(t)\left(1+\frac{\alpha}{2}\right)\left(cos\left(2\omega_{LO}t + \omega_{IF}t + \frac{\emptyset}{2}\right) + cos\left(\omega_{IF}t - \frac{\emptyset}{2}\right)\right) \\ +m_I(t)\left(1+\frac{\alpha}{2}\right)\left(cos\left(2\omega_{LO}t - \omega_{IF}t + \frac{\emptyset}{2}\right) + cos\left(\omega_{IF}t + \frac{\emptyset}{2}\right)\right) \end{array}\right\}$$

$$B = RF \times \left(1-\frac{\alpha}{2}\right)sin\left(\omega_{LO}t - \frac{\emptyset}{2}\right) = \frac{1}{2}\left\{\begin{array}{l} m_r(t)\left(1-\frac{\alpha}{2}\right)\left(sin\left(2\omega_{LO}t + \omega_{IF}t - \frac{\emptyset}{2}\right) - sin\left(\omega_{IF}t + \frac{\emptyset}{2}\right)\right) \\ +m_I(t)\left(1-\frac{\alpha}{2}\right)\left(sin\left(2\omega_{LO}t - \omega_{IF}t - \frac{\emptyset}{2}\right) + sin\left(\omega_{IF}t - \frac{\emptyset}{2}\right)\right) \end{array}\right\}$$

$$C = \frac{1}{2}\left\{\begin{array}{l} m_r(t)\left(1-\frac{\alpha}{2}\right)\left(-cos\left(2\omega_{LO}t + \omega_{IF}t - \frac{\emptyset}{2}\right) + cos\left(\omega_{IF}t + \frac{\emptyset}{2}\right)\right) \\ +m_I(t)\left(1-\frac{\alpha}{2}\right)\left(-cos\left(2\omega_{LO}t - \omega_{IF}t - \frac{\emptyset}{2}\right) - cos\left(\omega_{IF}t - \frac{\emptyset}{2}\right)\right) \end{array}\right\}$$

$$IF = A + C = \frac{1}{2}m_r(t)\left\{\left(1+\frac{\alpha}{2}\right)\cos\left(\omega_{IF}t - \frac{\emptyset}{2}\right) + \left(1-\frac{\alpha}{2}\right)\cos\left(\omega_{IF}t + \frac{\emptyset}{2}\right)\right\} + \frac{1}{2}m_I(t)\left\{\left(1+\frac{\alpha}{2}\right)\cos\left(\omega_{IF}t + \frac{\emptyset}{2}\right) - \left(1-\frac{\alpha}{2}\right)\cos\left(\omega_{IF}t - \frac{\emptyset}{2}\right)\right\}$$

$$= m_r(t)\left\{cos\frac{\emptyset}{2}\cos(\omega_{IF}t) - \frac{\alpha}{2}sin\frac{\emptyset}{2}\sin(\omega_{IF}t)\right\} + m_I(t)\left\{\frac{\alpha}{2}cos\frac{\emptyset}{2}\cos(\omega_{IF}t) + sin\frac{\emptyset}{2}\sin(\omega_{IF}t)\right\}$$

Image rejection equation

The image rejection in dB can then be written as:

$$IRR(dB) = 10log\,\frac{image\_power}{signal\_power} = \frac{\left(\frac{\alpha}{2}cos\,\frac{\emptyset}{2}\right)^2 + \left(sin\,\frac{\emptyset}{2}\right)^2}{\left(cos\,\frac{\emptyset}{2}\right)^2 + \left(\frac{\alpha}{2}\,sin\,\frac{\emptyset}{2}\right)^2}$$

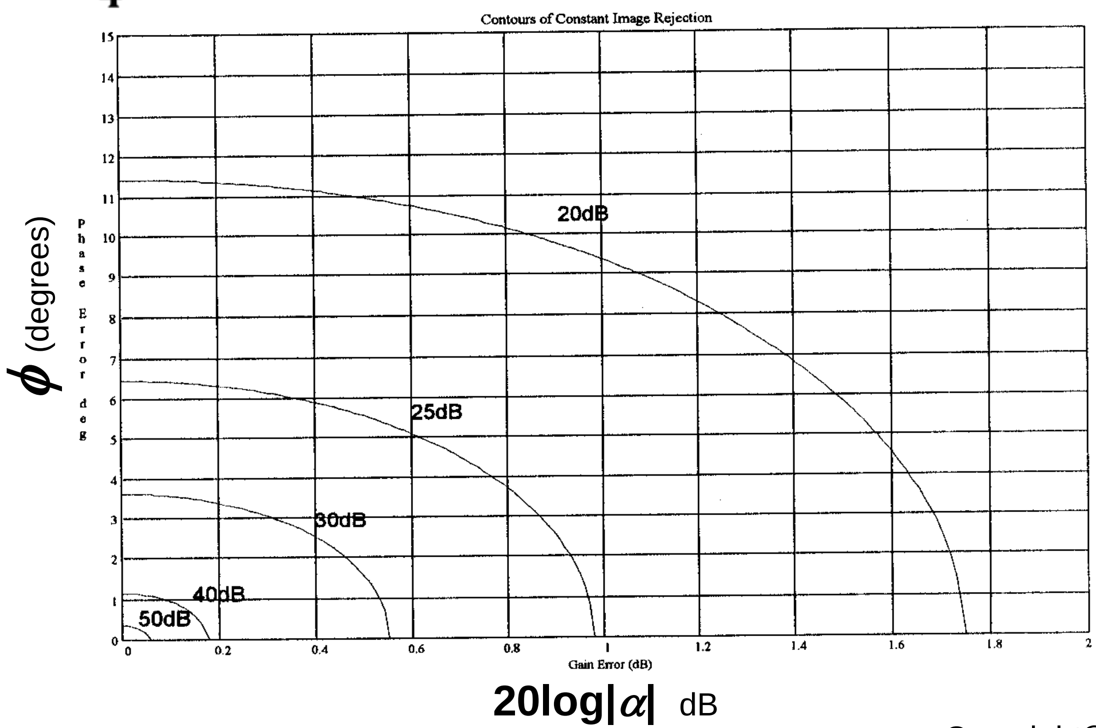
ϕ is in rad

For small ϕ:

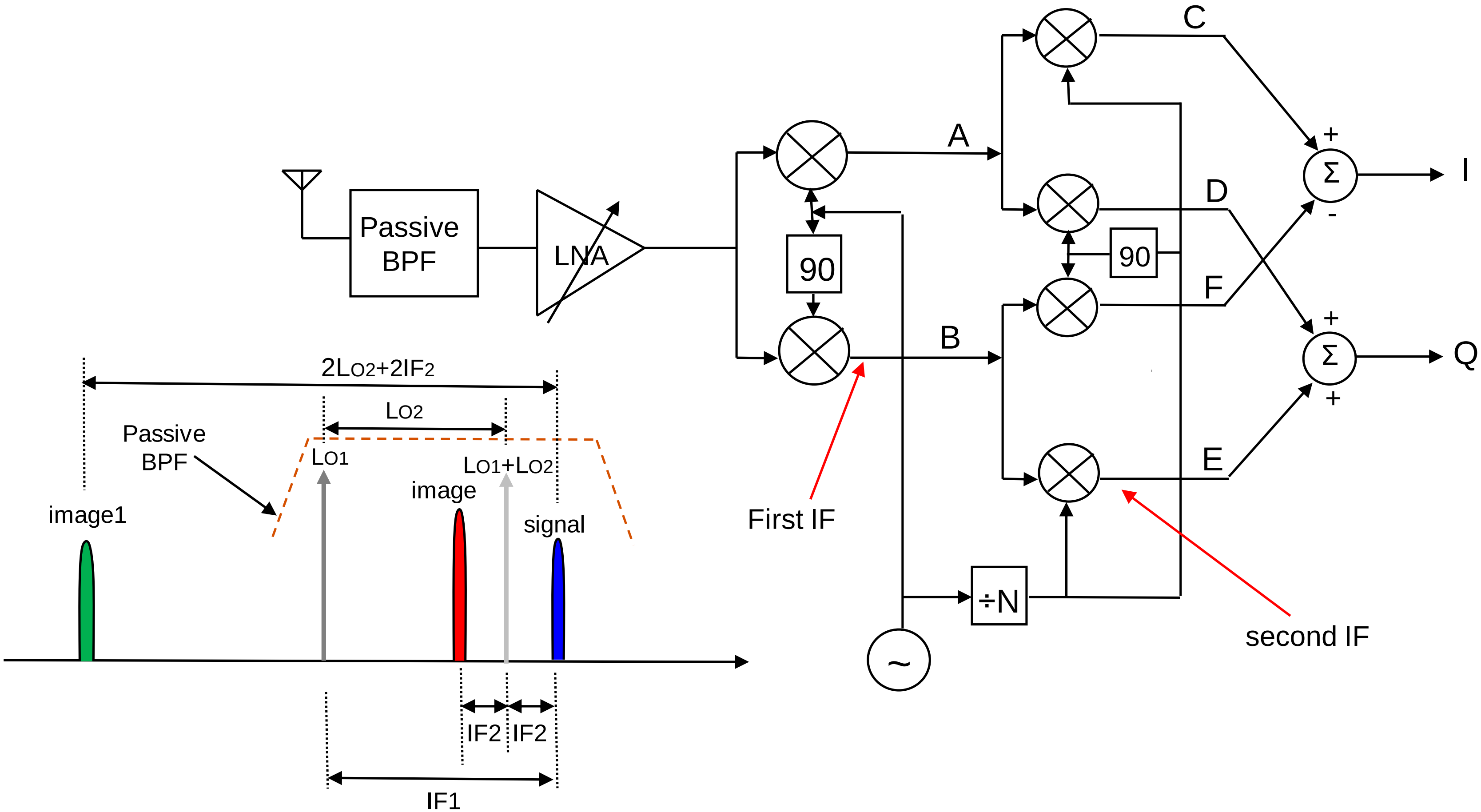
$$\cos\emptyset \approx 1 - \frac{\emptyset^2}{2}$$
$$\sin\emptyset \approx \emptyset$$

For small ϕ and α, the IRR can be approximated to:

$$\boldsymbol{IRR(dB) \approx 10log\,\frac{\alpha^2 + \emptyset^2}{4}}$$



Double conversion double quad architecture:



- The dual conversion double quad architecture has the advantage of de-sensitizing the receiver to gain and phase imbalance of I and Q paths.
- Make sure LO2 and IF2 values are chosen so image1 from first down-conversion falls out of band (rejected by external SAW passive BP filter).

$$RF = m_r(t)\cos(\omega_{LO1}+\omega_{LO2}+\omega_{IF})t + m_I(t)\cos(\omega_{LO1}+\omega_{LO2}-\omega_{IF})t$$

$$A = \text{Lowpass}\{RF\times\cos(\omega_{LO1}t)\} = \frac{1}{2}\begin{Bmatrix} m_r(t)\cos(\omega_{LO2}+\omega_{IF})t \\ +m_I(t)\cos(\omega_{LO2}-\omega_{IF})t \end{Bmatrix}$$

$$B = \text{Lowpass}\{RF\times\sin(\omega_{LO1}t)\} = \frac{1}{2}\begin{Bmatrix} -m_r(t)\sin(\omega_{LO2}+\omega_{IF})t \\ -m_I(t)\sin(\omega_{LO2}-\omega_{IF})t \end{Bmatrix}$$

$$C = \text{Lowpass}\{A\times\cos(\omega_{LO2}t)\} = \frac{1}{2}\begin{Bmatrix} m_r(t)\cos(\omega_{IF})t \\ +m_I(t)\cos(\omega_{IF})t \end{Bmatrix}$$

$$D = \text{Lowpass}\{A\times\sin(\omega_{LO2}t)\} = \frac{1}{2}\begin{Bmatrix} m_r(t)\sin(\omega_{IF})t \\ -m_I(t)\sin(\omega_{IF})t \end{Bmatrix}$$

$$E = \text{Lowpass}\{B\times\cos(\omega_{LO2}t)\} = \frac{1}{2}\begin{Bmatrix} m_r(t)\sin(\omega_{IF})t \\ -m_I(t)\sin(\omega_{IF})t \end{Bmatrix}$$

$$F = \text{Lowpass}\{B\times\sin(\omega_{LO2}t)\} = \frac{1}{2}\begin{Bmatrix} -m_r(t)\cos(\omega_{IF})t \\ -m_I(t)\cos(\omega_{IF})t \end{Bmatrix}$$

$$I = C - F = \left(m_r(t)+m_I(t)\right)\cos(\omega_{IF})t$$

$$Q = D + E = \left(m_r(t)-m_I(t)\right)\sin(\omega_{IF})t$$

The above analysis assumes ideal quadrature LO generation. But what if there are some phase errors?

gain error analysis:

$$RF = m_r(t)\cos(\omega_{LO1}+\omega_{LO2}+\omega_{IF})t + m_I(t)\cos(\omega_{LO1}+\omega_{LO2}-\omega_{IF})t$$

$$A = \text{Lowpass}\left\{RF\times\left(1+\frac{\Delta a_1}{2}\right)\cos(\omega_{LO1}t)\right\} = \frac{1}{2}\left(1+\frac{\Delta a_1}{2}\right)\begin{Bmatrix} m_r(t)\left(\cos(\omega_{LO2}+\omega_{IF})t\right) \\ +m_I(t)\left(\cos(\omega_{LO2}-\omega_{IF})t\right)\end{Bmatrix}$$

$$B = \text{Lowpass}\left\{RF\times\left(1-\frac{\Delta a_1}{2}\right)\sin(\omega_{LO1}t)\right\} = \frac{1}{2}\left(1-\frac{\Delta a_1}{2}\right)\begin{Bmatrix} -m_r(t)\left(\sin(\omega_{LO2}+\omega_{IF})t\right) \\ -m_I(t)\left(\sin(\omega_{LO2}-\omega_{IF})t\right)\end{Bmatrix}$$

$$C = \text{Lowpass}\left\{A\times\left(1+\frac{\Delta a_2}{2}\right)\cos(\omega_{LO2}t)\right\} = \frac{1}{2}\left(1+\frac{\Delta a_2}{2}\right)\left(1+\frac{\Delta a_1}{2}\right)\begin{Bmatrix} m_r(t)\left(\cos(\omega_{IF})t\right) \\ +m_I(t)\left(\cos(\omega_{IF})t\right)\end{Bmatrix}$$

$$D = \text{Lowpass}\left\{A\times\left(1-\frac{\Delta a_2}{2}\right)\sin(\omega_{LO2}t)\right\} = \frac{1}{2}\left(1-\frac{\Delta a_2}{2}\right)\left(1+\frac{\Delta a_1}{2}\right)\begin{Bmatrix} m_r(t)\left(\sin(\omega_{IF})t\right) \\ -m_I(t)\left(\sin(\omega_{IF})t\right)\end{Bmatrix}$$

$$E = \text{Lowpass}\left\{B\times\left(1+\frac{\Delta a_2}{2}\right)\cos(\omega_{LO2}t)\right\} = \frac{1}{2}\left(1+\frac{\Delta a_2}{2}\right)\left(1-\frac{\Delta a_1}{2}\right)\begin{Bmatrix} m_r(t)\left(\sin(\omega_{IF})t\right) \\ -m_I(t)\left(\sin(\omega_{IF})t\right)\end{Bmatrix}$$

$$F = \text{Lowpass}\left\{B\times\left(1-\frac{\Delta a_2}{2}\right)\sin(\omega_{LO2}t)\right\} = \frac{1}{2}\left(1-\frac{\Delta a_2}{2}\right)\left(1-\frac{\Delta a_1}{2}\right)\begin{Bmatrix} -m_r(t)\left(\cos(\omega_{IF})t\right) \\ -m_I(t)\left(\cos(\omega_{IF})t\right)\end{Bmatrix}$$

$$I = C - F = \left(1+\Delta a_2\Delta a_1\right)\left(m_r(t)+m_I(t)\right)\cos(\omega_{IF})t$$

$$Q = D + E = \left(1-\Delta a_2\Delta a_1\right)\left(m_r(t)-m_I(t)\right)\sin(\omega_{IF})t$$

As seen the gain mismatch error gets reduced due to the product of two small values. A typical gain error of such architecture can be as good as 0.1dB 1-sigma at 2.5GHz.

Phase error analysis:

$$RF = m_r(t)\cos(\omega_{LO1}+\omega_{LO2}+\omega_{IF})t + m_I(t)\cos(\omega_{LO1}+\omega_{LO2}-\omega_{IF})t$$

$$A = \text{Lowpass}\left\{RF \times \left(\cos\left((\omega_{LO1}t)+\frac{\phi_1}{2}\right)\right)\right\} = \frac{1}{2}\left\{\begin{matrix} m_r(t)\left(\cos\left((\omega_{LO2}+\omega_{IF})t-\frac{\phi_1}{2}\right)\right) \\ +m_I(t)\left(\cos\left((\omega_{LO2}-\omega_{IF})t-\frac{\phi_1}{2}\right)\right)\end{matrix}\right\}$$

$$B = \text{Lowpass}\left\{RF \times \left(\sin\left((\omega_{LO1}t)-\frac{\phi_1}{2}\right)\right)\right\} = \frac{1}{2}\left\{\begin{matrix} -m_r(t)\left(\sin\left((\omega_{LO2}+\omega_{IF})t+\frac{\phi_1}{2}\right)\right) \\ -m_I(t)\left(\sin\left((\omega_{LO2}-\omega_{IF})t+\frac{\phi_1}{2}\right)\right)\end{matrix}\right\}$$

$$C = \text{Lowpass}\left\{A \times \left(\cos\left((\omega_{LO2}t)+\frac{\phi_2}{2}\right)\right)\right\} = \frac{1}{2}\left\{\begin{matrix} m_r(t)\left(\cos\left((\omega_{IF})t-\frac{\phi_1}{2}-\frac{\phi_2}{2}\right)\right) \\ +m_I(t)\left(\cos\left((\omega_{IF})t+\frac{\phi_1}{2}+\frac{\phi_2}{2}\right)\right)\end{matrix}\right\}$$

$$D = \text{Lowpass}\left\{A \times \left(\sin\left((\omega_{LO2}t)-\frac{\phi_2}{2}\right)\right)\right\} = \frac{1}{2}\left\{\begin{matrix} m_r(t)\left(\sin\left((\omega_{IF})t+\frac{\phi_1}{2}+\frac{\phi_2}{2}\right)\right) \\ -m_I(t)\left(\sin\left((\omega_{IF})t-\frac{\phi_1}{2}-\frac{\phi_2}{2}\right)\right)\end{matrix}\right\}$$

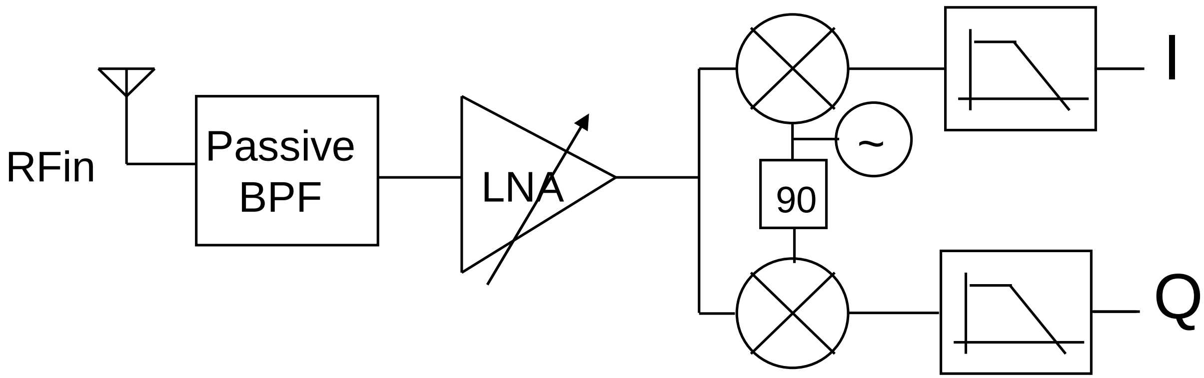
$$E = \text{Lowpass}\left\{B \times \left(\cos\left((\omega_{LO2}t)+\frac{\phi_2}{2}\right)\right)\right\} = \frac{1}{2}\left\{\begin{matrix} m_r(t)\left(\sin\left((\omega_{IF})t+\frac{\phi_1}{2}-\frac{\phi_2}{2}\right)\right) \\ -m_I(t)\left(\sin\left((\omega_{IF})t-\frac{\phi_1}{2}+\frac{\phi_2}{2}\right)\right)\end{matrix}\right\}$$

$$F = \text{Lowpass}\left\{B \times \left(\sin\left((\omega_{LO2}t)-\frac{\phi_2}{2}\right)\right)\right\} = \frac{1}{2}\left\{\begin{matrix} -m_r(t)\left(\cos\left((\omega_{IF})t+\frac{\phi_1}{2}+\frac{\phi_2}{2}\right)\right) \\ -m_I(t)\left(\cos\left((\omega_{IF})t-\frac{\phi_1}{2}-\frac{\phi_2}{2}\right)\right)\end{matrix}\right\}$$

Can you derive the final result? → Homework 1 !!!

The direct conversion (Zero-IF) Architecture:

Why not eliminate the IF completely and mix the RF signal with an LO at the exact same frequency as the desired RF signal?



$$RF_{in} = m_r(t)\cos(\omega_{RF} t + \varphi(t))$$
$$I = LPF\left[RF_{in} \times \cos(\omega_{LO} t)\right] = 0.5 m_r(t)\left(\cos(\varphi t)\right)$$
$$\text{for } \omega_{RF} = \omega_{LO} = \omega_0$$
$$Q = LPF\left[RF_{in} \times \sin(\omega_{LO} t)\right] = -0.5 m_r(t)\left(\sin(\varphi t)\right)$$

⇒ No image anymore with perfect I/Q matching!

What if there is I/Q mismatch in direct-conversion? Can there still be an image?

Impact of I/Q mismatch in direct-conversion Architecture:

I/Q cross talk

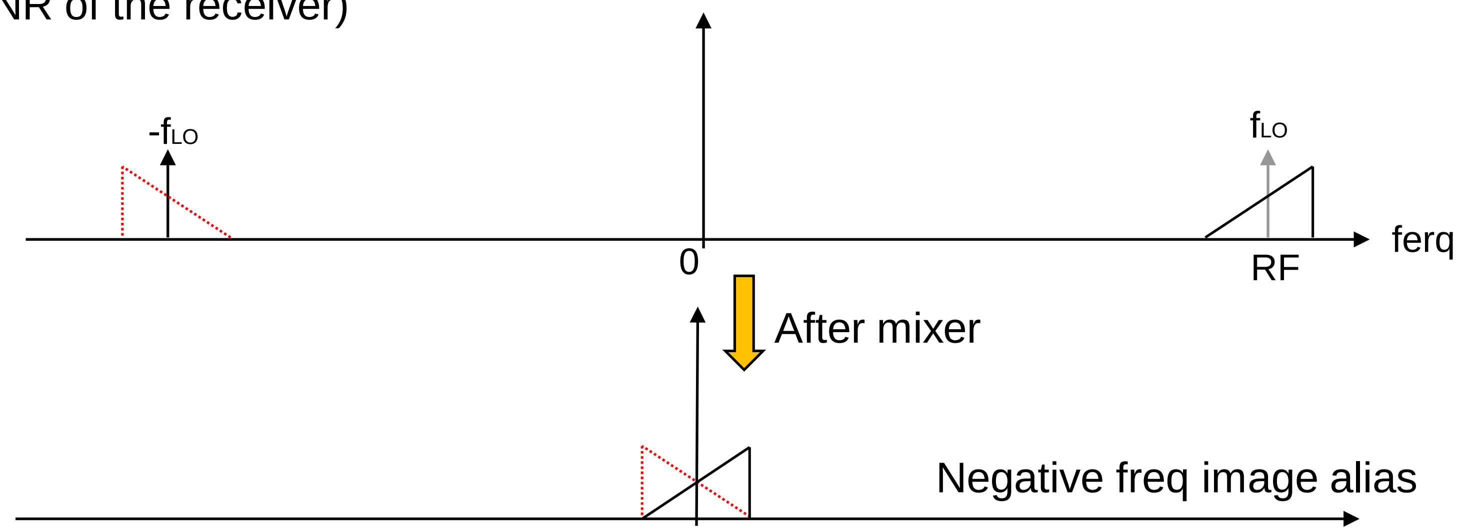
$$RF_{in} = m_r(t)\cos(\omega_{RF}t + \varphi(t))$$

$$I = LPF\left[RF_{in} \times \left(1+\frac{\delta}{2}\right)\cos(\omega_{LO}t+\theta)\right] = 0.5\left(1+\frac{\delta}{2}\right)m_r(t)\left(\cos(\varphi t)\cos\theta - \sin(\varphi t)\sin\theta\right)$$

for $\omega_{RF} = \omega_{LO}$, and finite I/Q gain and phase mismatch of δ and 2θ, respectively

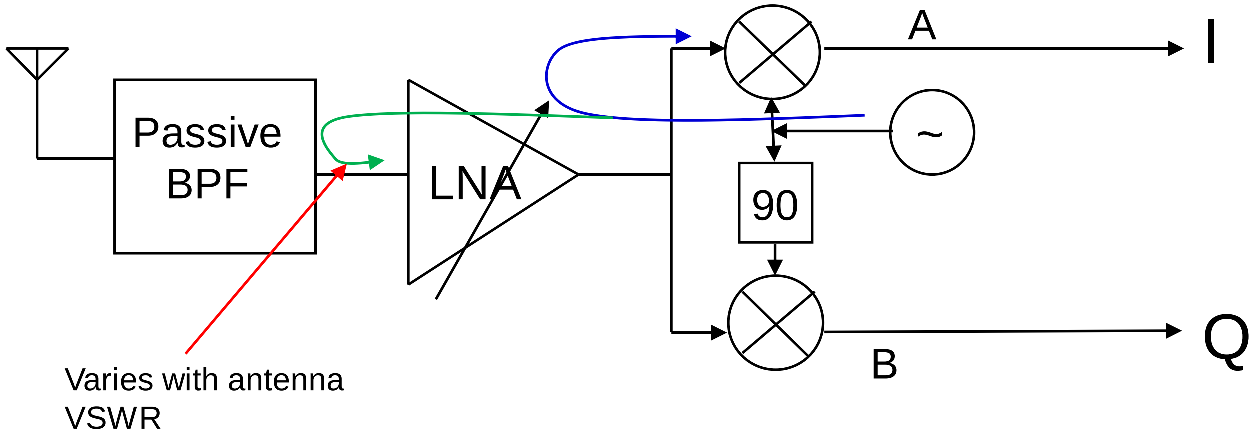
$$Q = LPF\left[RF_{in} \times \left(1-\frac{\delta}{2}\right)\sin(\omega_{LO}t-\theta)\right] = -0.5\left(1-\frac{\delta}{2}\right)m_r(t)\left(\sin(\varphi t)\cos\theta - \cos(\varphi t)\sin\theta\right)$$

Image from same desired signal composed of Q signal leaking into I and I signal leaking into Q (I/Q cross talk). This results in degradation of SNR. Since the image comes from the signal itself, the image rejection requirement is alleviated (set by target SNR of the receiver)



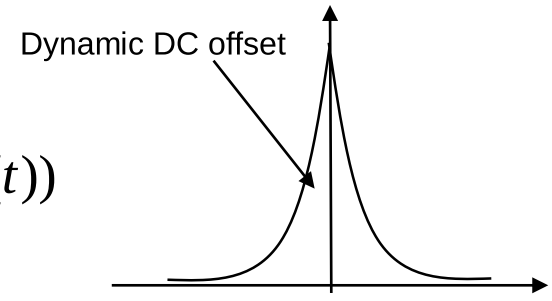
Problems with Zero-IF conversion:

1. LO self mixing:



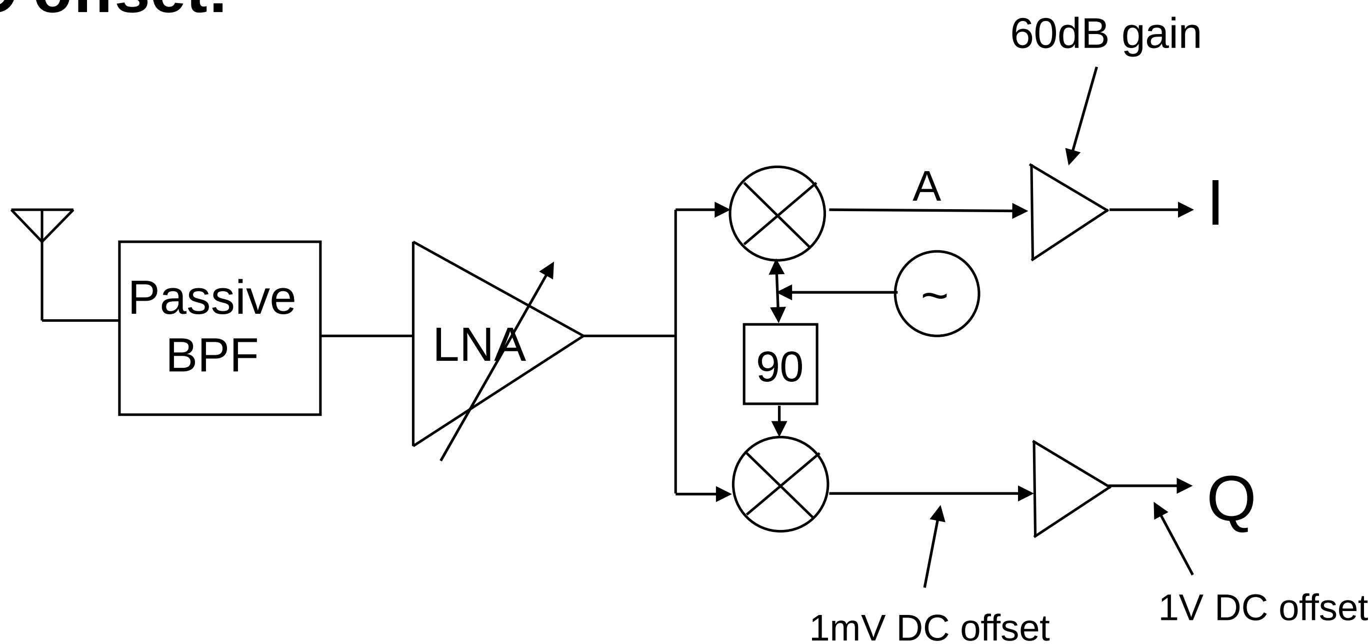
$$LO = p(t)\cos(\omega_{LO}t + \varphi(t))$$

$$LO \times LO = p(t)^2 + p(t)^2\cos(2\omega_{LO}t + 2\varphi(t))$$



LO self mixing degrades DC-offset in direct-conversion receiver. Static one can be calibrated out but dynamic one (time varying) can be a problem

2. DC offset:



- Since the signal is converted down to DC, the signal path post mixer is DC coupled. This makes a slight DC offset to appear as volts and most likely to saturate the subsequent baseband circuitry. AC coupling is expensive since large AC coupling caps should be used to achieve low highpass corner (<1kHz). Also any offset transients due to RF gain switching will result in a large DC transient that will take long time (few ms for a 1kHz corner) to settle.
- Two common techniques for DC offset removal: A) analog servo loops B) digital DC-offset calibrations

3. Sensitivity to second order distortion (IP2):

Let us assume two jammers separated by Δf

$$s1 = m_1(t)\cos(\omega_1 t)$$

$$s2 = m_2(t)\cos(\omega_1 + \Delta\omega)t$$

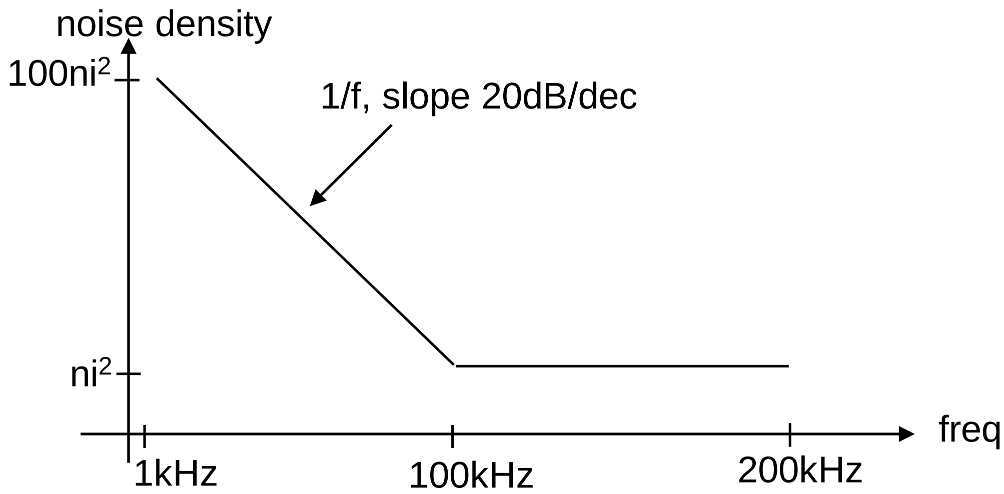
$$(s1 + s2)^2 = \left[m_1(t)\cos(\omega_1 t)\right]^2 + \left[m_2(t)\cos(\omega_1 + \Delta\omega)t\right]^2 + 2m_1(t)m_2(t)\cos(\omega_1 t)\cos(\omega_1 + \Delta\omega)t$$

$$= m_1(t)^2 + m_2(t)^2 + m_1(t)m_2(t)\cos(\Delta\omega t)$$

It can be seen than the second order distortion in the receiver results in two low frequency distortion that folds into the desired signal after being downconverted around DC:

1. The baseband modulation around the jammer carrier gets folded into baseband with twice bandwidth
2. The two jammers beat against each other and produce a component only Δf away from DC. If Δf is close enough, the IM2 distortion will fall into the desired signal band. Even if Δf does not fall within the desired signal band, it can be close enough to clip the entire receiver if it does not get filtered out properly before it reaches the VGA. Note that *s2* can be a simple CW jammer in some systems

4. Sensitivity to 1/f flicker noise



Since the down converted signal is centered around DC (low frequency), the device 1/f noise becomes important. For example, if the 1/f noise corner of a GSM receiver is at half the desired signal bandwidth as shown above, the degradation this could cause to the effective noise is (assuming noise integration starting at 1kHz):

$$\overline{n_{ave}^2} = \frac{1}{200k}\left[\int_{1kHz}^{100kHz} \frac{a}{f} df + \int_{100kHz}^{200kHz} b\, df\right] \quad ; \quad \text{where } a = 1k\left(100\overline{n_i^2}\right) ; b = \overline{n_i^2}$$

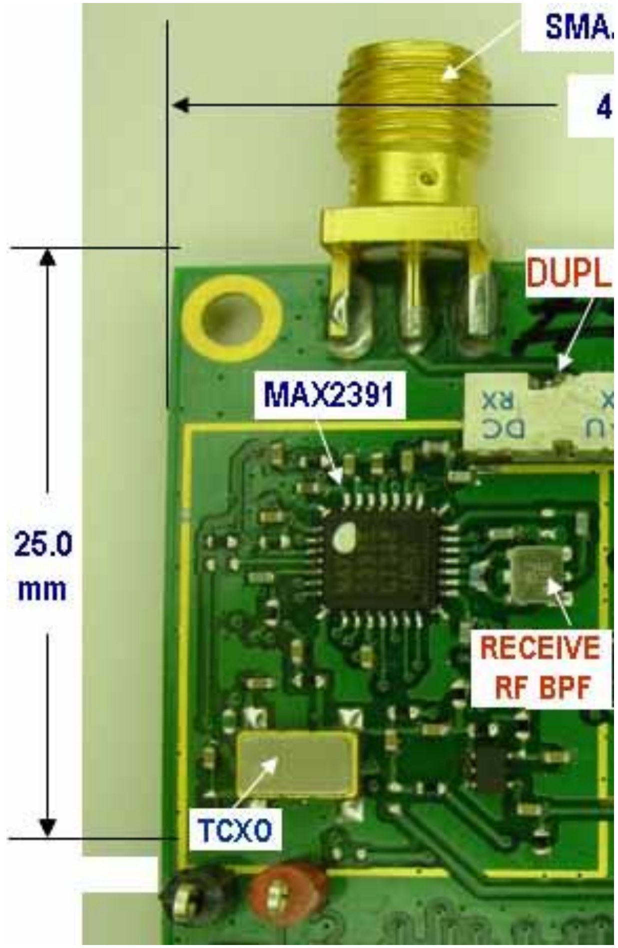
$$\Rightarrow \overline{n_{ave}^2} = \frac{1}{200k}\left[a \ln \frac{100k}{1k} + b\left(200k - 100k\right)\right] = \frac{1}{200k}\left[11.5a + 100kb\right] = 6.25\overline{n_i^2}$$

This is a very challenging task in CMOS design given the relatively large 1/f noise corner compared to bipolar. Therefore, device sizing is necessary to bring the device 1/f noise corner to an acceptable level (<0.5dB noise impact).

Direct-conversion receiver reference design

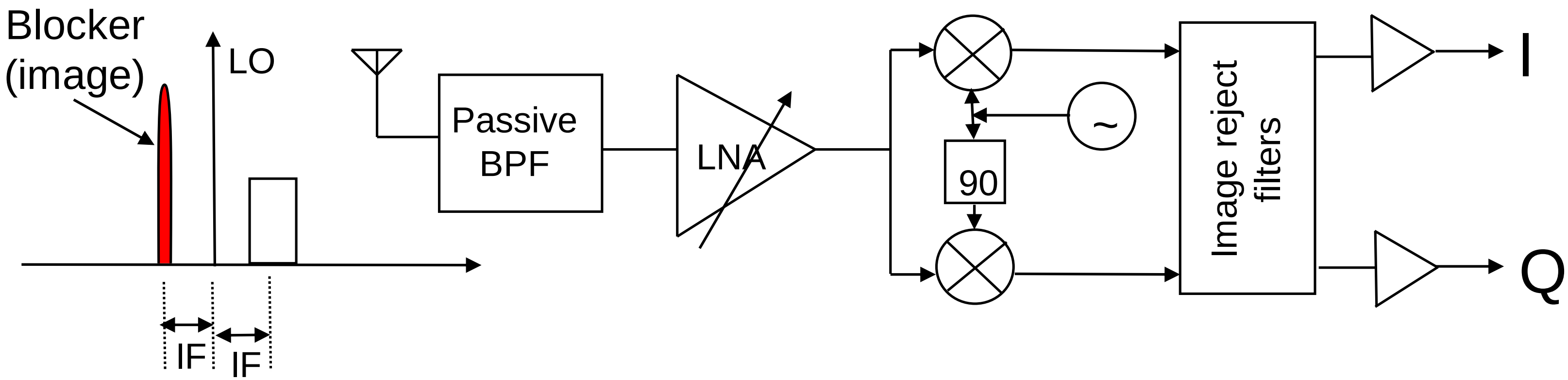
Advantages:

- high integration
- great platform for multi- band receiver
- low power (not as good as superhet)!



- Very popular architecture for modern systems such as WiFi, 3G WCDMA/UMTS, 4G LTE and 5G

Low-IF Architecture:



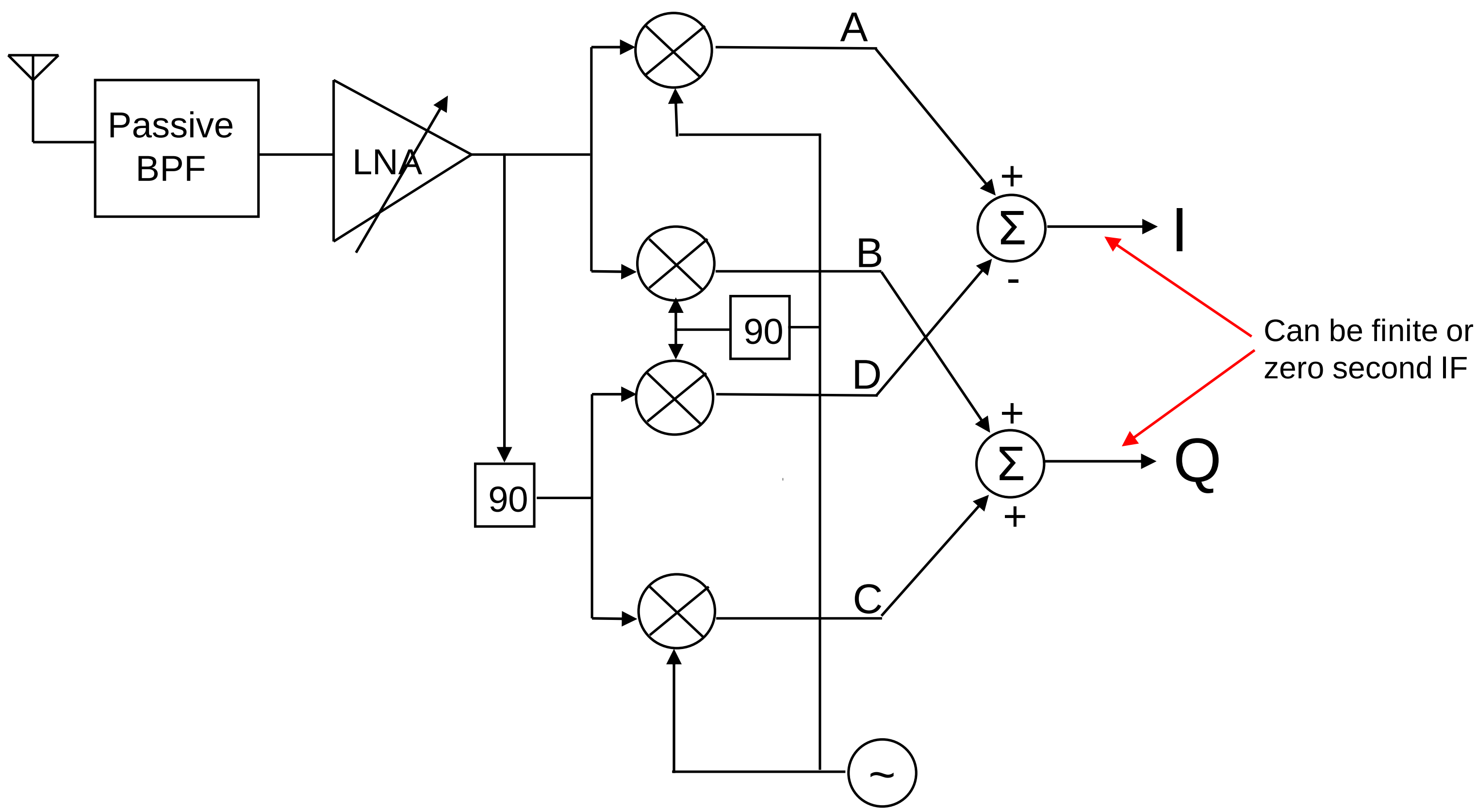
● Why not avoid signal around DC by choosing an IF frequency that is low enough so IF filters and circuitry can be integrated on chip, yet high enough to avoid the problems around DC. A typical low IF frequency is one or twice the signal bandwidth.

● the single quad architecture above still suffers sensitivity of image rejection to phase and gain mismatch. A typical 35dB image rejection is not enough for most systems to be able to handle a large image signal with finite dynamic range integrated IF circuitry. Need IRR calibrations

● the image reject filters perform both channel selection and image rejection at the same time. The design of such filters will be discussed in subsequent lectures.

→ Popular architecture for systems with narrow-band signals that has large energy content close to DC (such as Bluetooth, GPS, and GSM)

The double quad low-IF Architecture:



Improved image rejection due to desensitization to quadrature gain and phase error.

Signal path analysis:

$$RF_I = m_r(t)\cos(\omega_{LO}+\omega_{IF})t + m_I(t)\cos(\omega_{LO}-\omega_{IF})t$$

$$RF_q = -m_r(t)\sin(\omega_{LO}+\omega_{IF})t - m_I(t)\sin(\omega_{LO}-\omega_{IF})t$$

$$A = RF_I \times \cos(\omega_{LO}t) = \frac{1}{2}\begin{Bmatrix} m_r(t)\left(\cos(2\omega_{LO}+\omega_{IF})t + \cos(\omega_{IF})t\right) \\ + m_I(t)\left(\cos(2\omega_{LO}-\omega_{IF})t + \cos(\omega_{IF})t\right) \end{Bmatrix}$$

$$B = RF_I \times \sin(\omega_{LO}t) = \frac{1}{2}\begin{Bmatrix} m_r(t)\left(\sin(2\omega_{LO}+\omega_{IF})t - \sin(\omega_{IF})t\right) \\ + m_I(t)\left(\sin(2\omega_{LO}-\omega_{IF})t + \sin(\omega_{IF})t\right) \end{Bmatrix}$$

$$C = RF_q \times \cos(\omega_{LO}t) = \frac{1}{2}\begin{Bmatrix} m_r(t)\left(-\sin(2\omega_{LO}+\omega_{IF})t - \sin(\omega_{IF})t\right) \\ + m_I(t)\left(-\sin(2\omega_{LO}-\omega_{IF})t + \sin(\omega_{IF})t\right) \end{Bmatrix}$$

$$D = RF_q \times \sin(\omega_{LO}t) = \frac{1}{2}\begin{Bmatrix} m_r(t)\left(\cos(2\omega_{LO}+\omega_{IF})t - \cos(\omega_{IF})t\right) \\ + m_I(t)\left(\cos(2\omega_{LO}-\omega_{IF})t - \cos(\omega_{IF})t\right) \end{Bmatrix}$$

$$IF_I = \left(m_r(t)+m_I(t)\right)\cos(\omega_{IF})t$$

$$IF_Q = \left(m_I(t)-m_r(t)\right)\sin(\omega_{IF})t$$

Same analysis as before!

References:

[1] A. A. Abidi, “Radio Frequency Integrated Circuits for Portable Communications,” Proc. CICC, San Diego, pp 151-158, May 1994.

[2] A. A. Abidi, “Direct Conversion Radio Transceivers for Digital Communications,” Proc. ISSCC, pp 186-187, Feb 1995.

[3] J. Carlos, M. Steyaert “A Single-Chip 900MHz CMOS Receiver Front-end with High Performance Low-IF Topology ,” IEEE JSSC, Vol. 30, no. 12, pp 1483-1492, Dec. 1995.

[4] B. Razavi, *RF Microelectronics* , Prentice Hall Ptr. 1998.

[5] J. Carlos, M. Steyaert, *CMOS Wireless Transceiver Design* , Kluwer Academic Publishers. 1997.

[6] *Practical RF System Design,* William F. Egan, ISBN: 0-471-20023-9, Hardcover 416 pages, April 2003, Wiley-IEEE Press.