Transceiver Architectures (I)

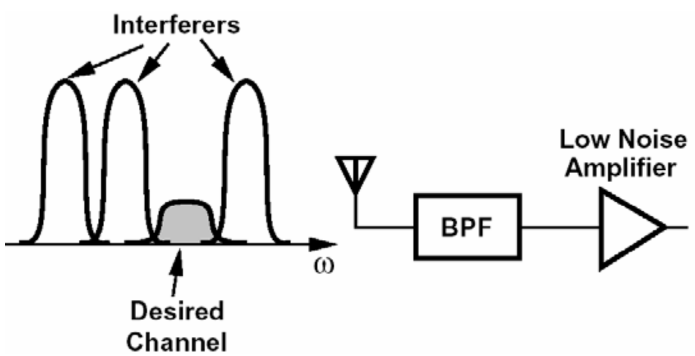
General Considerations

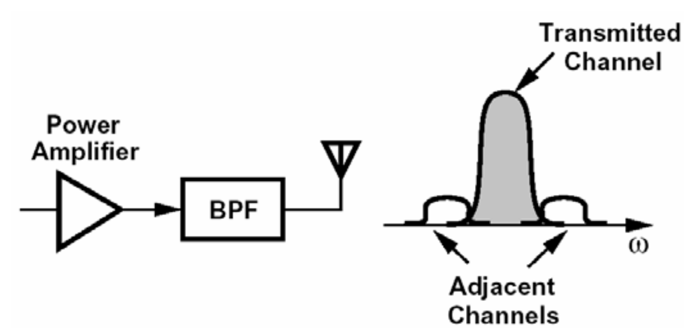
- **RX**

- Sensitivity
- Linearity
- Power Dissipation
- Dynamic Range
- Gain
- Complexity

- **TX**

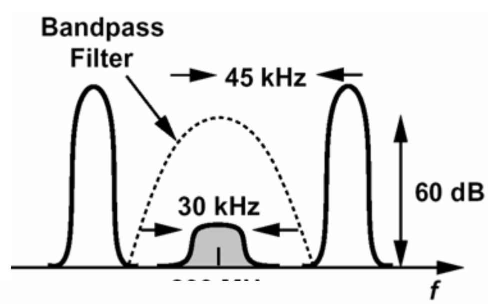
- Output Power
- Spurious Emission
- Power Dissipation
- Linearity
- Efficiency
- Complexity



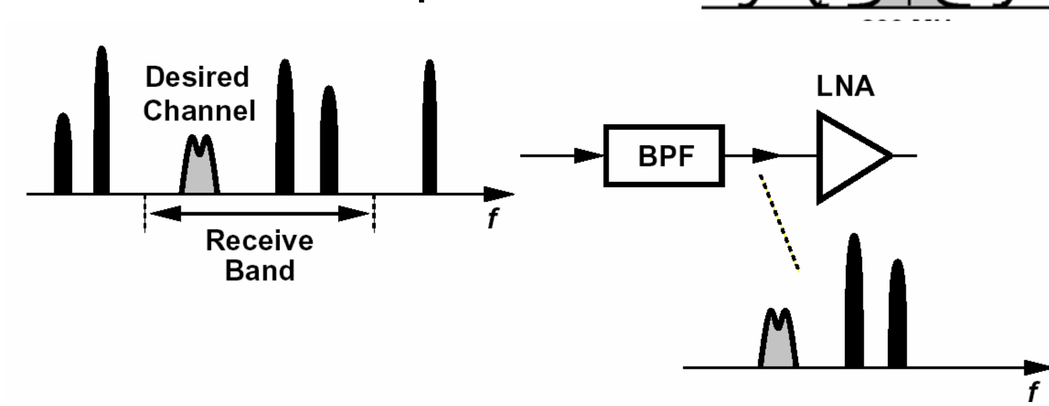


- **Band Selection vs. Channel Selection**

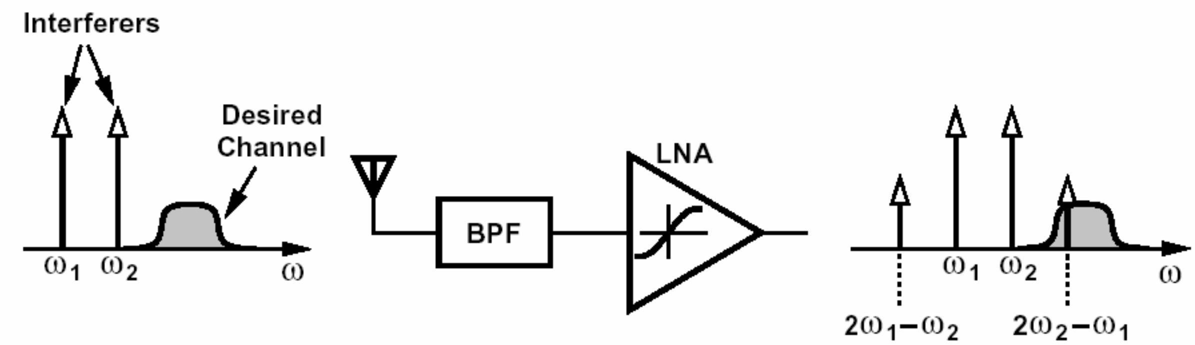
Can we perform "channel selection" at the RX input?



But some "band selection" is possible:

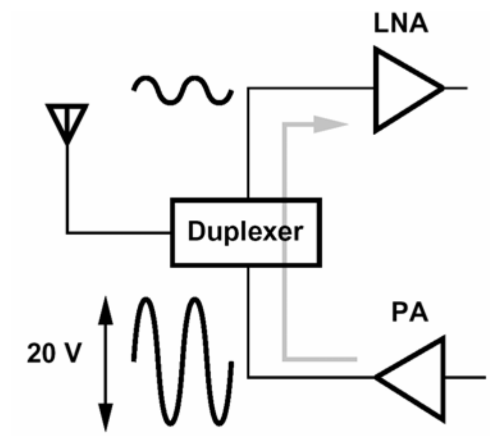


Thus, all stages in the RX chain that precede channel-select filtering must be sufficiently linear:



- **LNA Desensitization by PA**

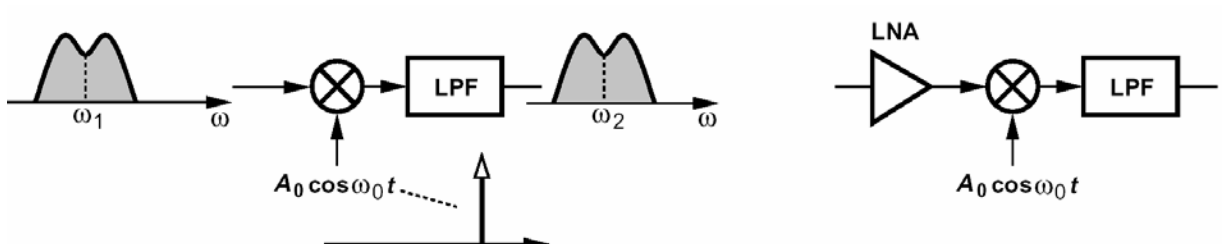
GSM avoids this issue by offsetting The RX and TX time slots.



Receiver Architectures

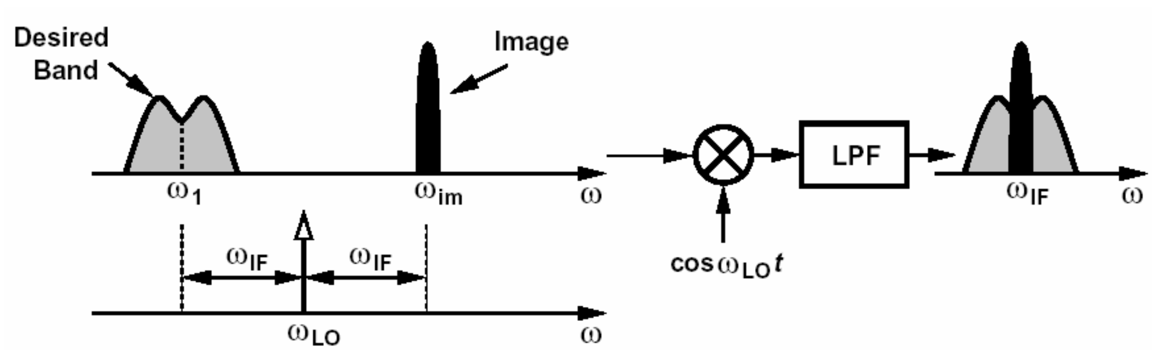
- **Heterodyne Architecture**

Can't filter interferers at RF → "translate" RF channel to lower frequencies:

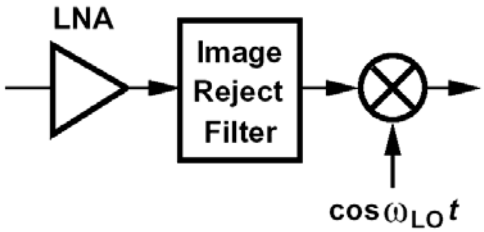


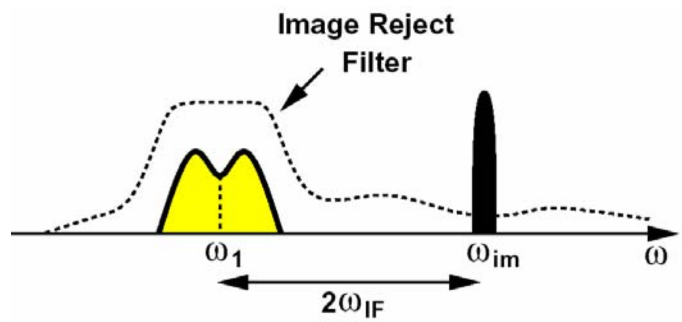
(a) (b)

Problem of Image



More Complete Heterodyne RX:





How does a het. RX cover a band of frequencies?

Fixed LO **Fixed IF**

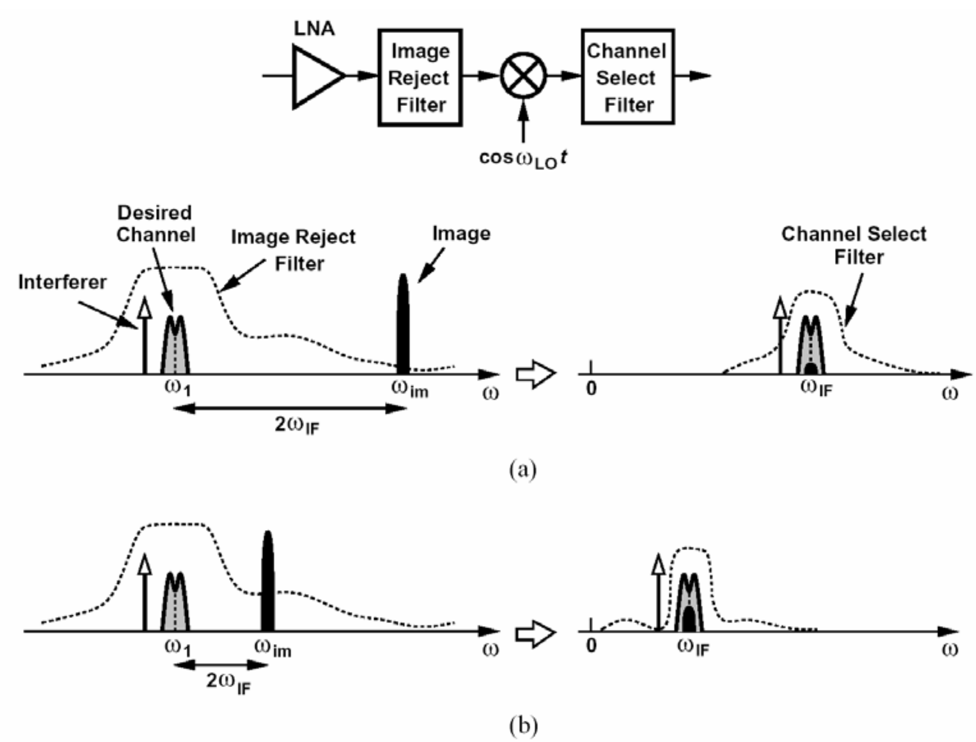
- **Example**

An IEEE802.11g receiver attempts to place the image in the GPS band. Is this possible?

- **Example**

An engineer designing a het. RX for free-space applications reasons that there are no large interferers in space and hence image rejection is unnecessary. Did the engineer take 215C?

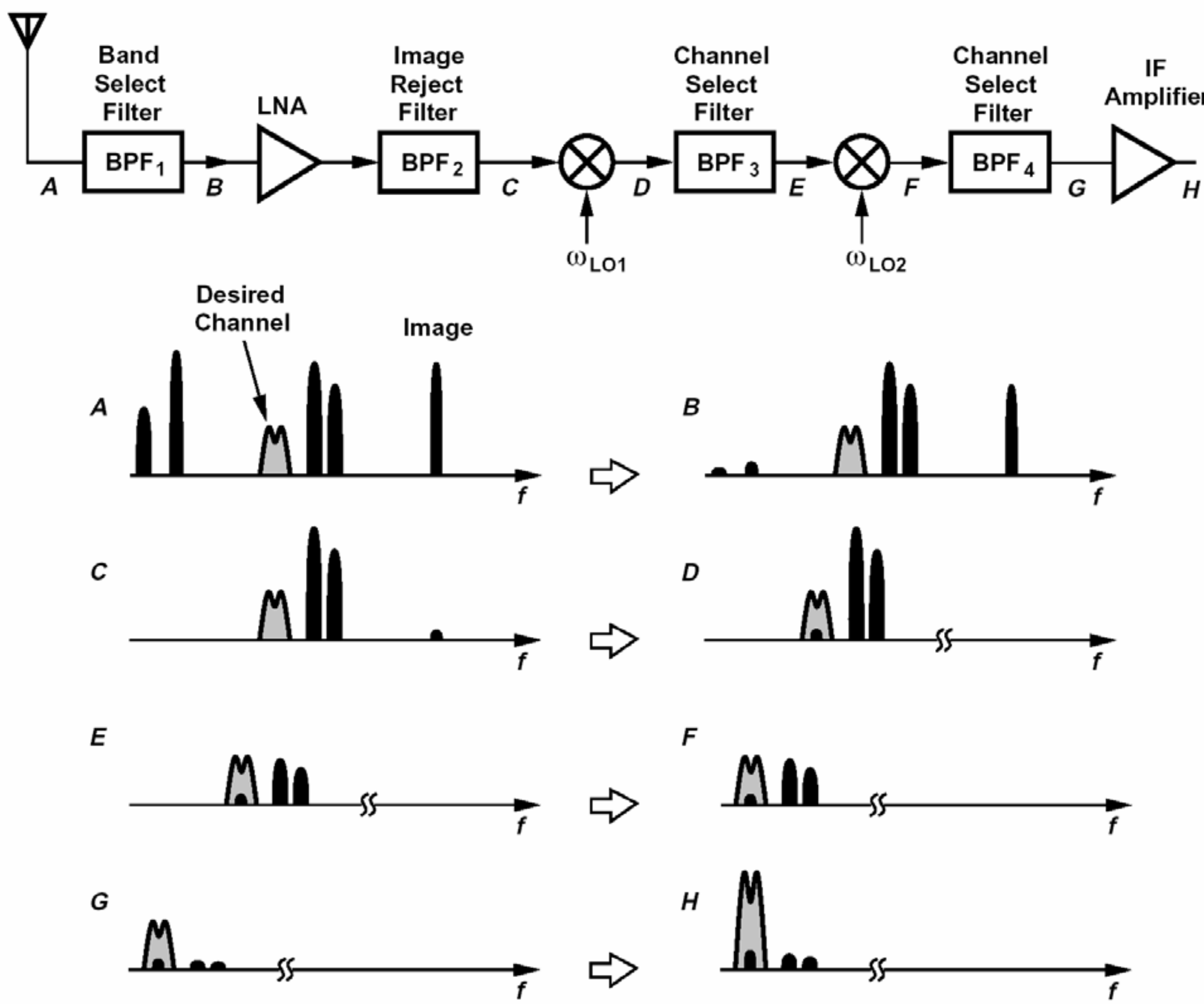
- **Trade-Off Between Image Rejection and Channel Selection**



- **High-Side and Low-Side Injection**

The LO frequency may be chosen higher or lower than the channel of interest:

- **Dual Downconversion**



- How do we choose NF and IP3 of the stages in the chain?

- Every dB of channel-select filtering relaxed the linearity by 1 dB, up to the point where signal compression occurs.

- How about the secondary image?

- **Mixing Spurs**

Each mixing operation convolves the signal and the interferers with many harmonics of the LO:

• **Example**
A 2.4-GHz dual downconversion RX employs a first LO at 1.95 GHz and a second at 400 MHz. Determine some of the mixing spurs.

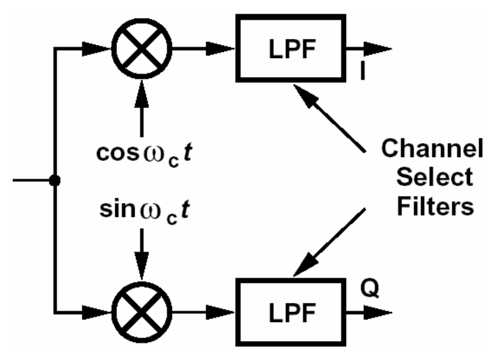
Modern Heterodyne RX Architectures

- **Avoid secondary image.**
- **Use a single LO.**
- **Avoid off-chip filters to the extent possible.**
- **Perform detection in digital domain.**

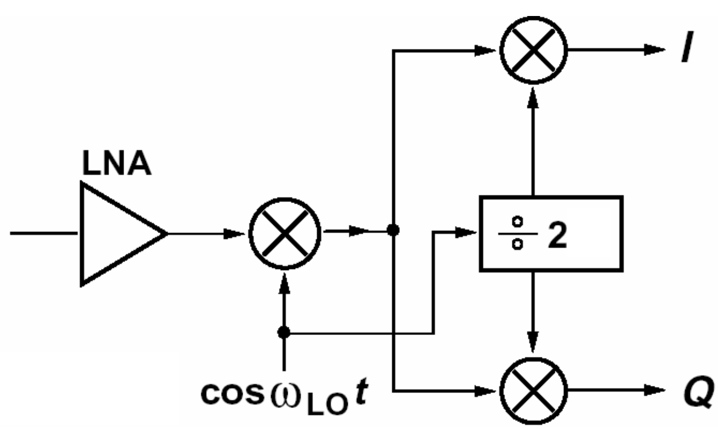
- Downconversion to a Zero IF

Interferers don't fall onto the channel but the channel becomes its own image – an issue if the modulation is "asymmetric."

→ Need to separate the signal to two phases → "quadrature downconversion"



- How to reduce the number of LOs to 1?
"Sliding IF RX"



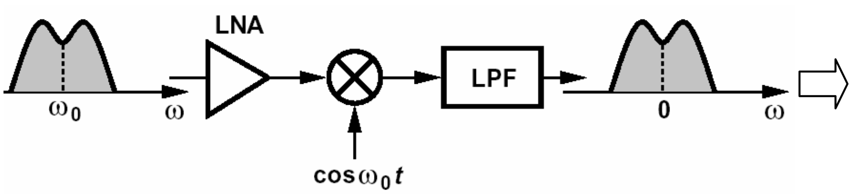
1. What is the LO frequency range?

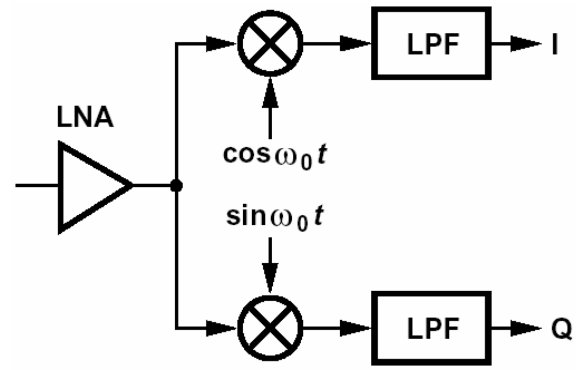
2. What is the IF range?

3. What is the image frequency range?

4. Repeat the above if the divider divides by 4.

Direct-Conversion (aka Homodyne or Zero-IF) Receivers



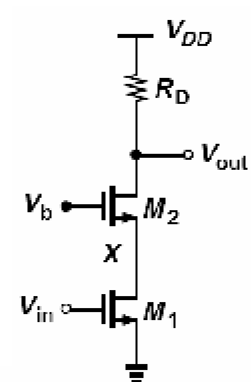


- **No image-rejection necessary → LNA need not drive 50 ohms.**
- **Channel-selection performed by low-pass filters.**
- **Number of mixing spurs is reduced considerably.**

Issues:

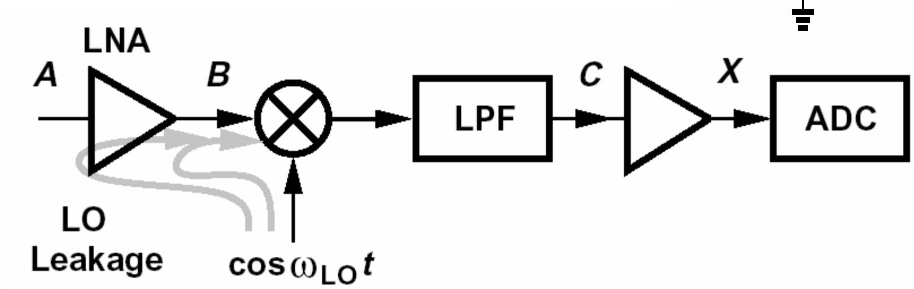
1. LO Leakage:

Example: Study the LO leakage in a cascode LNA.



(Is this serious in het. RX?)

2. DC Offsets



(Is this serious in het. RX?)

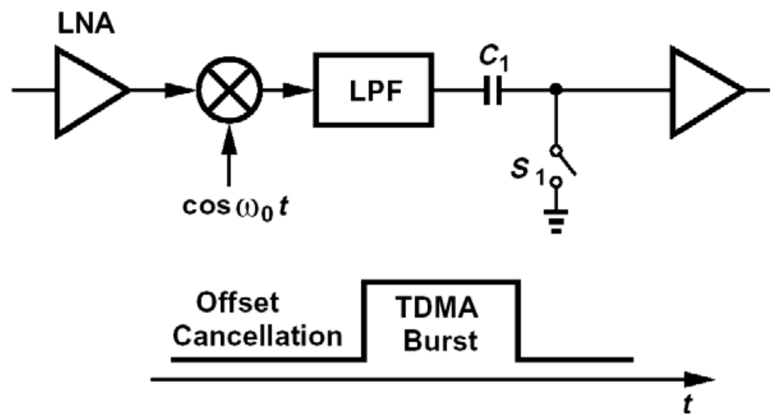
• Example

Explain why the dc offsets observed at the I and Q outputs are often unequal?

• DC Offset Removal Techniques

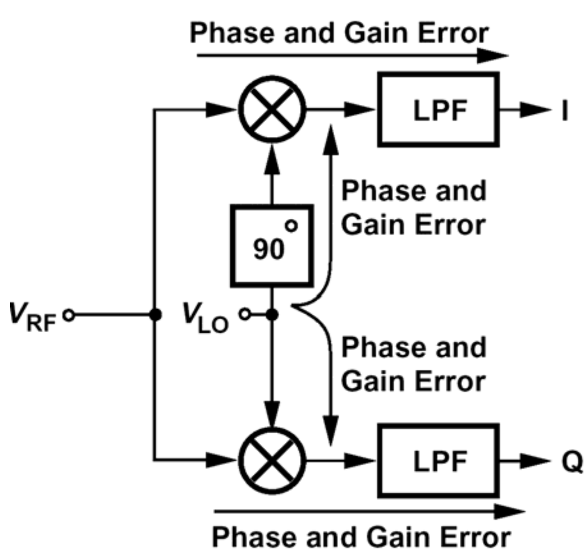
- High-Pass filtering

- Analog Offset Storage

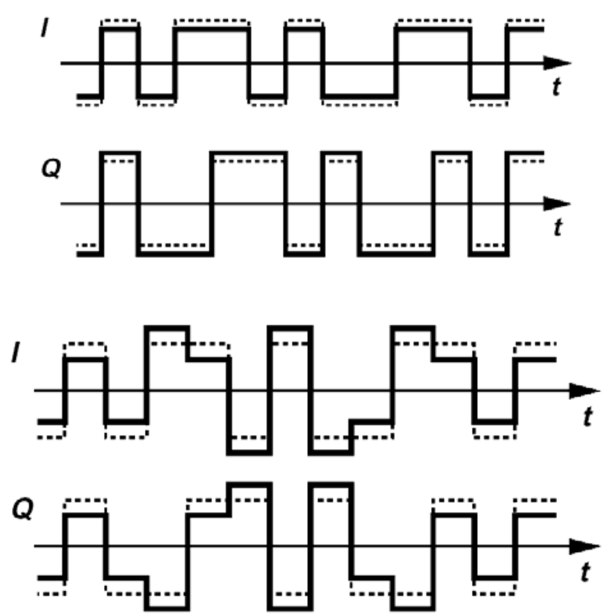


- Digital Offset Storage

3. I/Q Mismatch



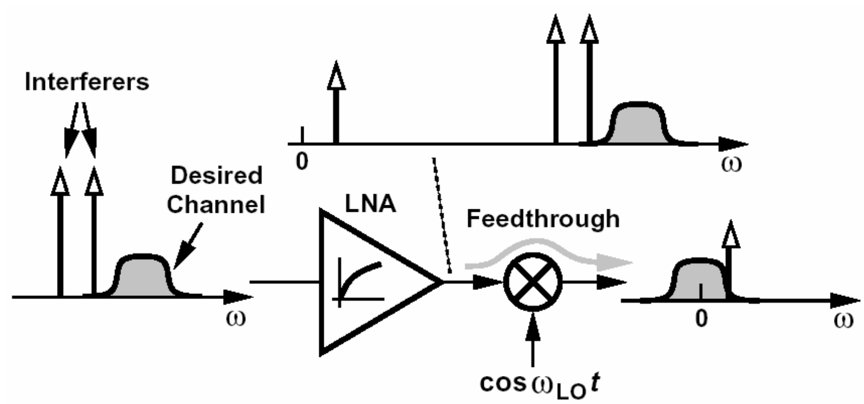
(Is I/Q



mismatch serious in het. RX?)

4. Even-Order Distortion

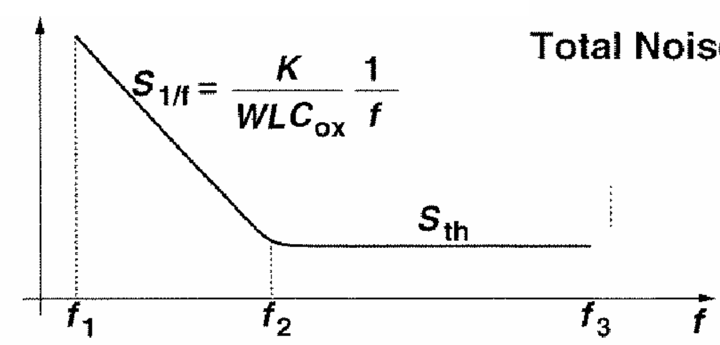
What happens if a mixer has asymmetry?



This effect is quantified by the "IP2."

- Even-order distortion also demodulates AM components, particularly those on <u>variable-envelope interferers</u>.

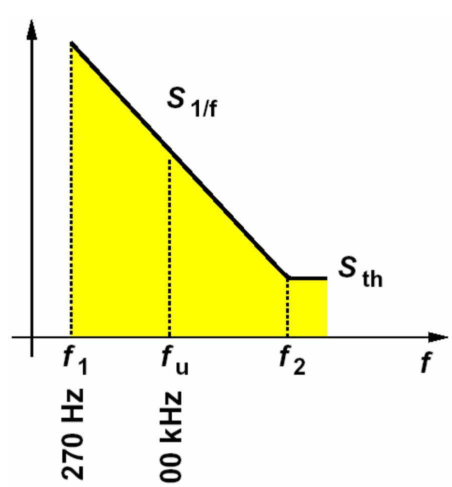
5. Flicker Noise



$$\text{Total Noise Power} = \frac{K}{WLC_{ox}} \ln\frac{f_2}{f_1} + (f_3 - f_2)S_{th}$$

$$= \left(f_2 \ln\frac{f_2}{f_1} + f_3 - f_2\right)S_{th}$$

Example: Calculate the 1/f noise penalty In GSM.



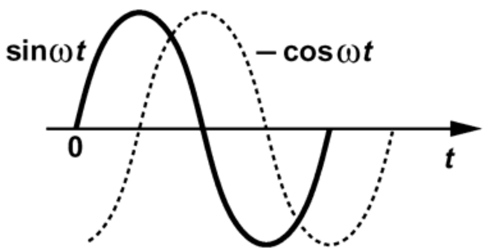
Transceiver Architectures (II)

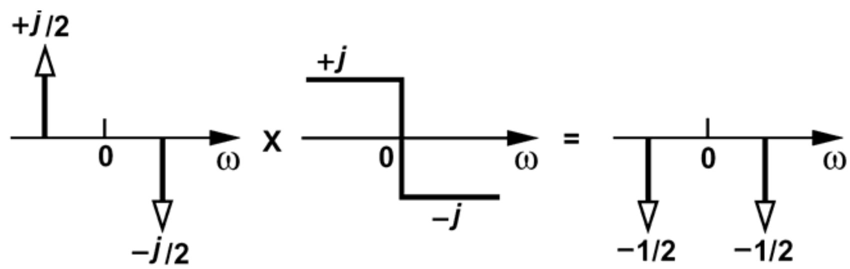
Image-Reject Receivers

Since the image and the signal lie on the two sides of the LO frequency, it is possible to architect the RX so that it can distinguish between the two and reject one (hopefully the image).

- **90^o Phase Shift**

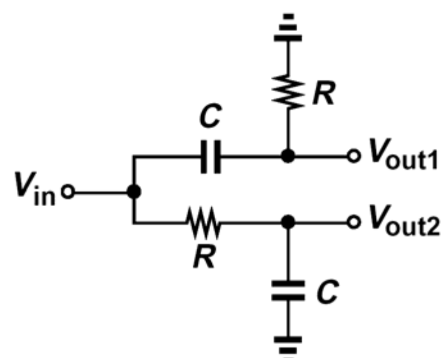
How do we shift a modulated signal by 90 degrees?





In general, for a narrowband signal:

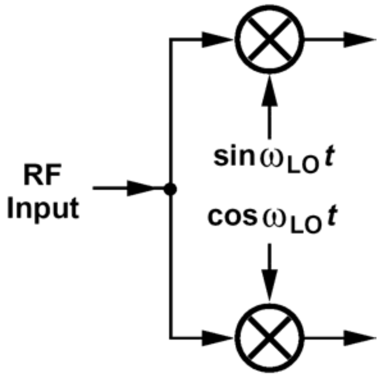
Thus, Hilbert transform distinguishes between positive and negative frequencies. The phase shift can be realized by an RC-CR network:



Example: Plot the spectrum of Acos ωt + jAsin ωt.

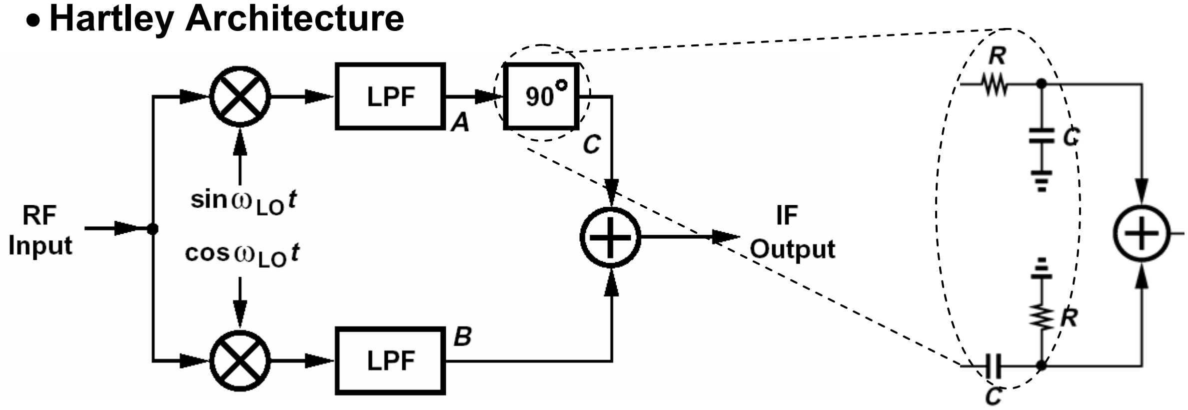
Exercise: A narrowband signal I(t) with a real spectrum is shifted by 90^o to produce Q(t). Plot the spectrum of I(t)+jQ(t).

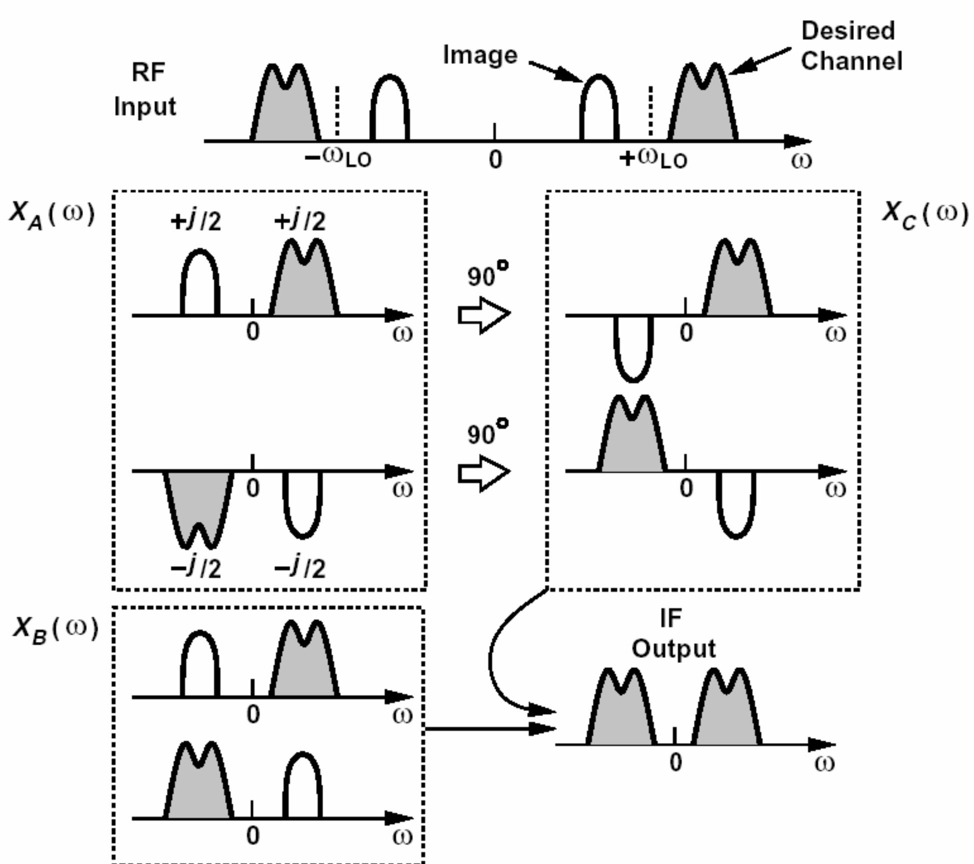
Another 90° shift circuit: "Quadrature downconverter"



Exercise: Repeat the above analysis for low-side injection.

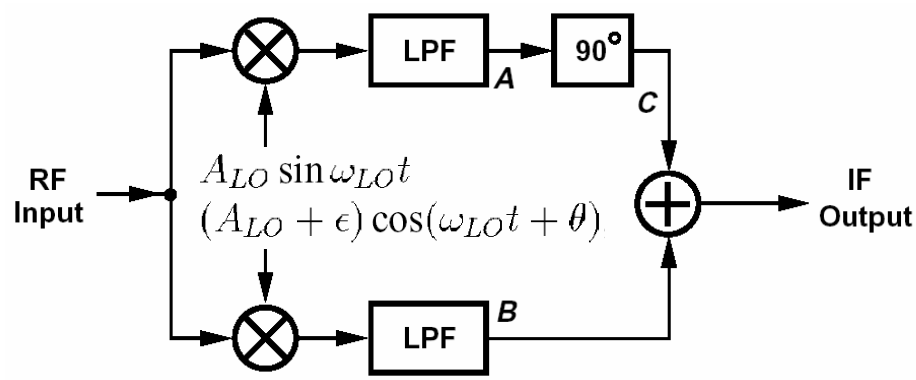
- **Hartley Architecture**





Exercise: An engineer constructs the above topology but uses high-side injection. Explain what happens and why the engineer probably graduated from the other school across town.

- Effect of Mismatches:



$$x_{sig}(t) = \frac{(A_{LO} + \epsilon)A_{RF}}{2} \cos[(\omega_{LO} - \omega_{RF})t + \theta] + \frac{A_{LO}A_{RF}}{2} \cos(\omega_{LO} - \omega_{RF})t$$
$$x_{im}(t) = \frac{(A_{LO} + \epsilon)A_{im}}{2} \cos[(\omega_{LO} - \omega_{im})t + \theta] - \frac{A_{LO}A_{im}}{2} \cos(\omega_{LO} - \omega_{im})t.$$

Compute the image-to-signal ratio at the ouput and divide it by the image-to-signal ratio at the input:

$$IRR = \frac{A^2 - 2AB\cos\theta + B^2}{A^2 + 2AB\cos\theta + B^2}.$$

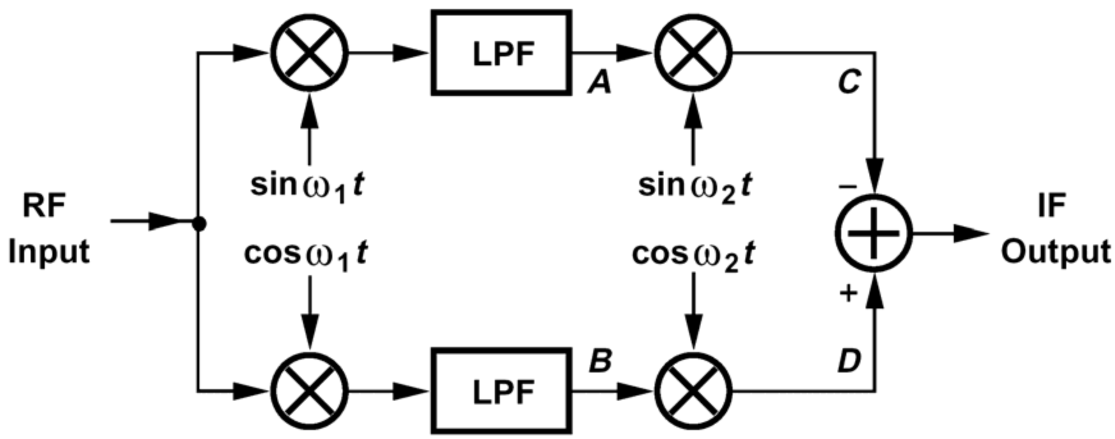
Exercise: Prove that for $\epsilon \ll A_{LO}$ and $\theta \ll 1$ rad

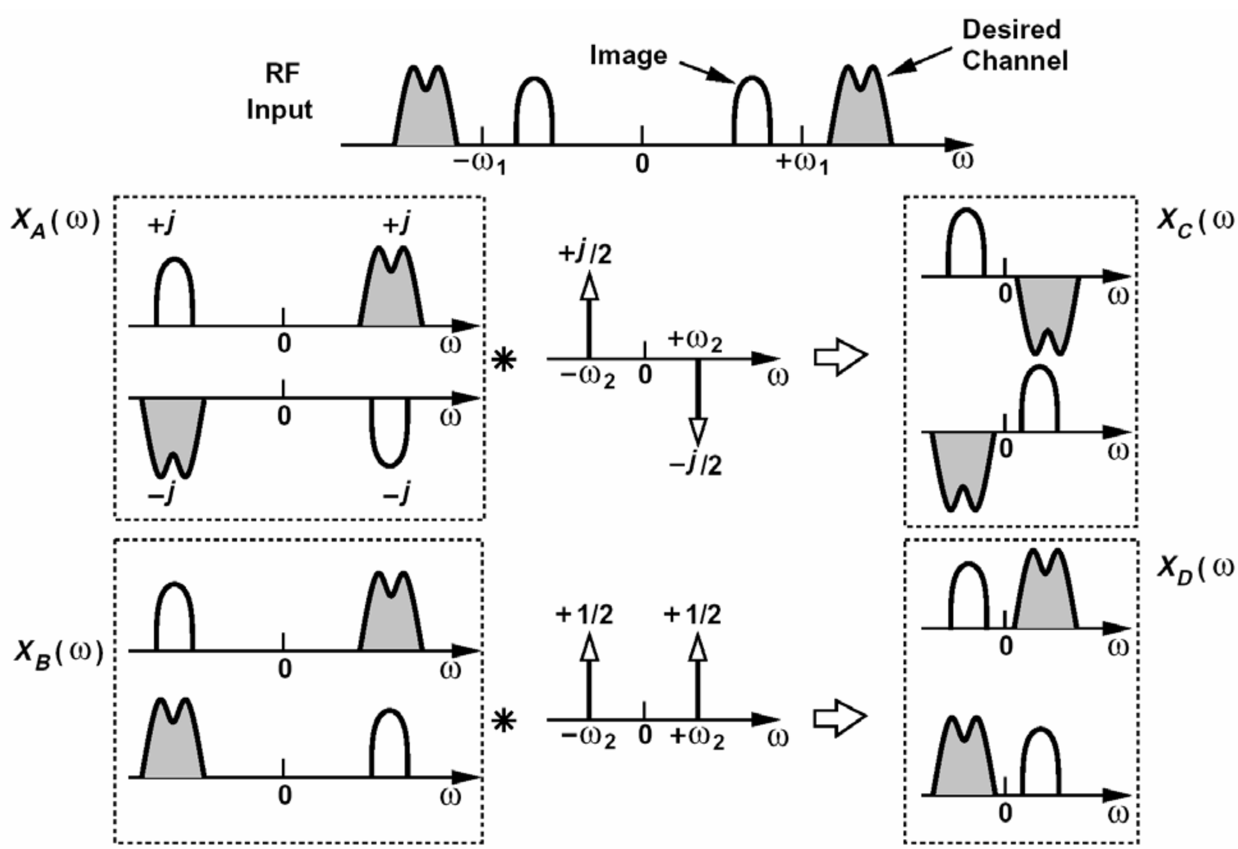
For example, an IRR of 60 dB requires a phase mismatch of 0.1 degree. Typical IRR is around 30-35 dB.

- Other issues in Hartley architecture: (1) voltage addition at the output; (2) amplitude imbalance in the RC-CR section at frequencies away from 1/(RC); (3) variation of RC with process and temperature.

Exercise: Try 90-degree phase shift in RF path. What happens if sine and cosine are swapped?

- **Weaver Architecture**



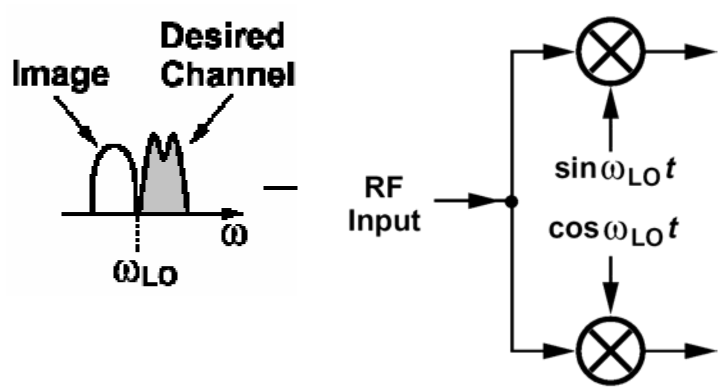


- **No dependence on RC**
- **Output summation in current domain**
- **But must avoid secondary image.**

Low-IF Receivers

Direct conversion presents two issues in GSM applications: (1) high flicker noise in baseband, and (2) difficulty in offset removal. "Low-IF" receivers overcome these issues by exploiting the relaxed adjacent channels spec of GSM.

In GSM, the adjacent channel can be only 9 dB higher than the desired channel.



What do the spectra at I and Q look like?

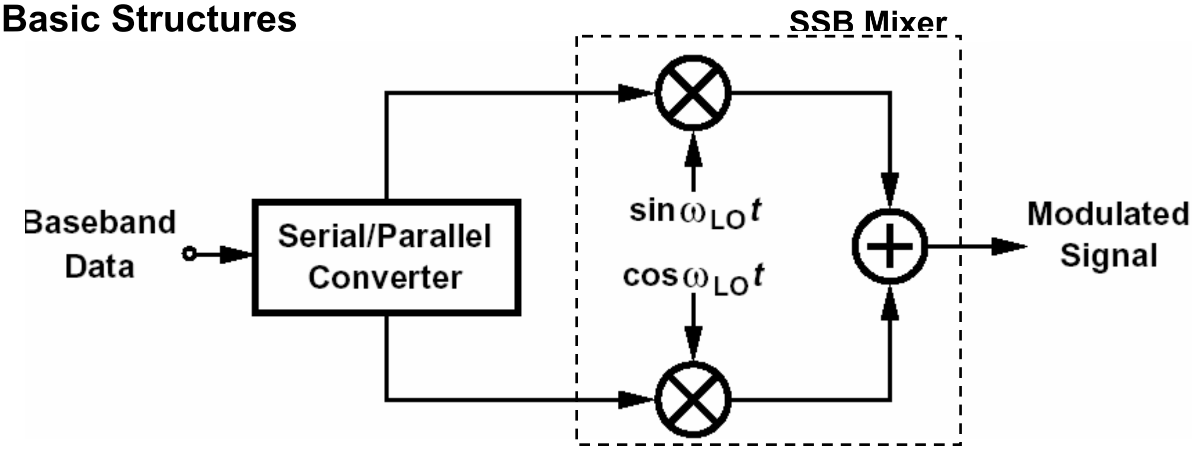
Other low-IF receivers choose a higher IF so that an analog filter can perform both image rejection and channel selection. Such a filter is called a "polyphase filter." But then,

(1) The image is no longer in the adjacent channel and hence quite large;
(2) Baseband ADCs must digitize a broad band, consuming high power;
(3) Polyphase filters are generally quite power hungry.

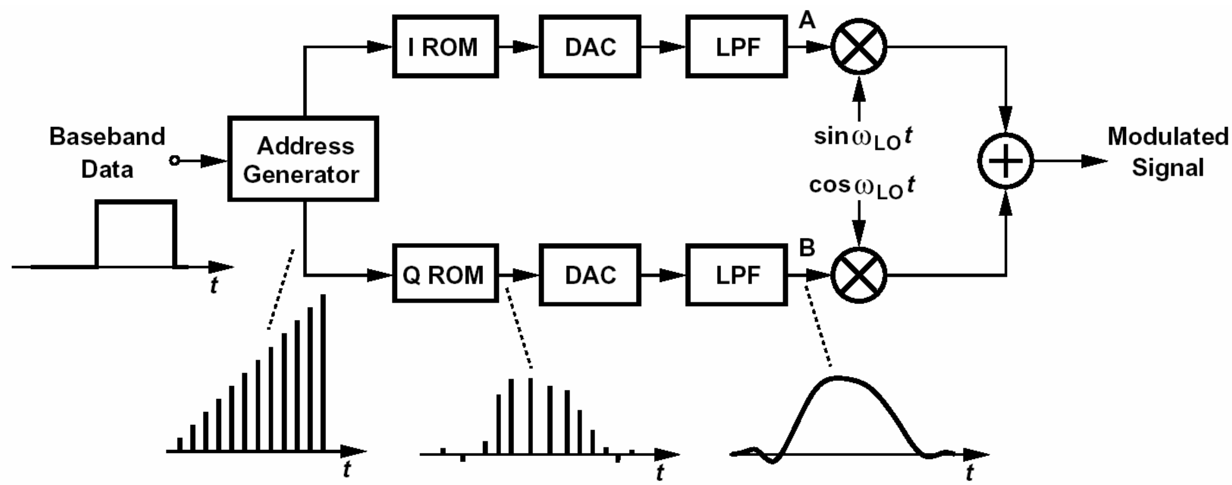
Exercise: which one of direct-conversion issues are serious in low-IF receivers as well?

Transmitter Architectures

• Basic Structures



- Baseband Pulse Shaping



- Effect of I/Q Mismatch

Apply two quadrature tones to baseband inputs and find the undesired sideband magnitude:

$$\begin{aligned} v_{out}(t) &= V_0 \sin\omega_{in}t \sin\omega_{LO}t + V_0(1+\epsilon)\cos\omega_{in}t\cos(\omega_{LO}t+\theta) \\ &\approx \frac{V_0}{2}[1+(1+\epsilon)\cos\theta]\cos(\omega_{in}-\omega_{LO})t - \frac{V_0}{2}(1+\epsilon)\sin\theta\sin(\omega_{LO}-\omega_{in})t + \\ &\quad \frac{V_0}{2}[-1+(1+\epsilon)\cos\theta]\cos(\omega_{in}+\omega_{LO})t - \frac{V_0}{2}(1+\epsilon)\sin\theta\sin(\omega_{LO}+\omega_{in})t \end{aligned}$$

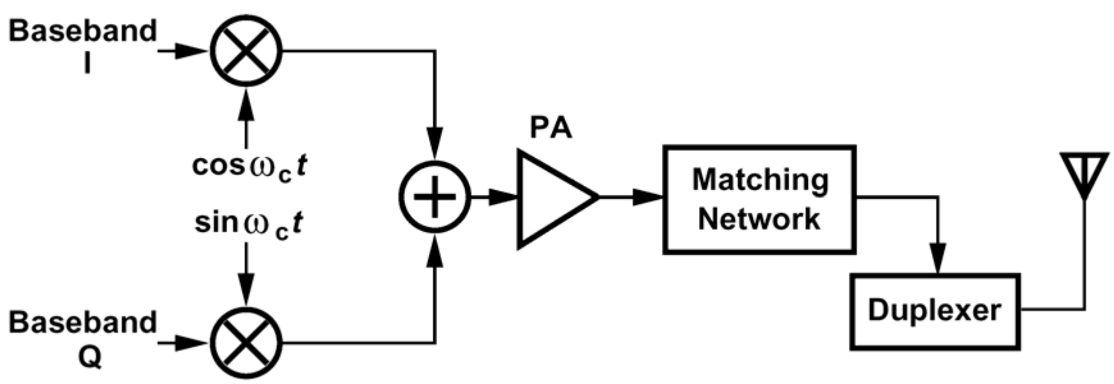
The ratio of desired sideband to undesired sideband is a measure of I/Q matching:

$$\frac{P_+}{P_-} = \frac{1 - (1+\epsilon)\cos\theta + \epsilon}{1 + (1+\epsilon)\cos\theta + \epsilon}$$

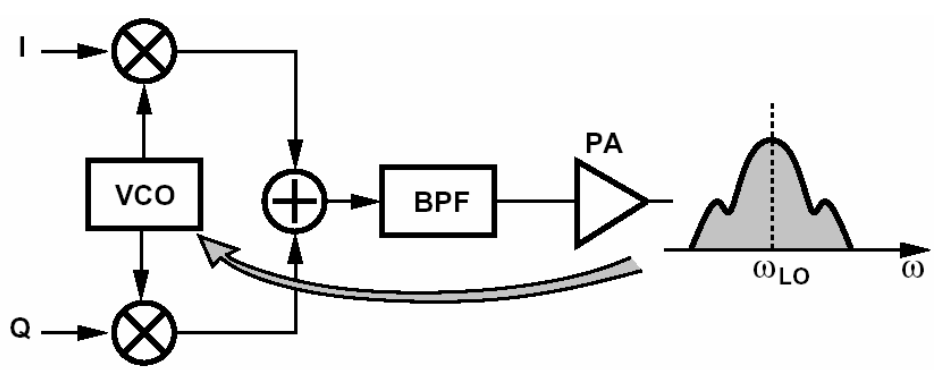
Exercise: Prove that this equation is the same as that obtained for IRR of receivers.

In practice, the tolerable mismatches for a given modulation scheme are determined by detailed simulations.

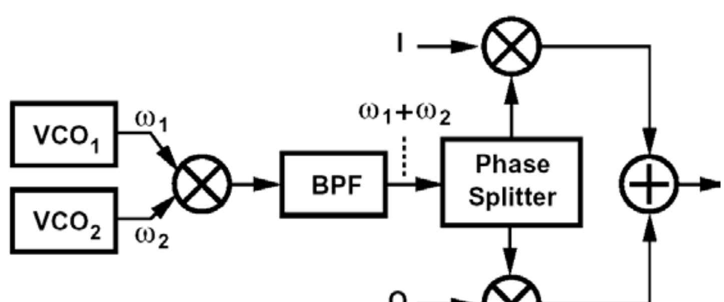
• Direct-Conversion Transmitters
Inverse of receiver counterpart:



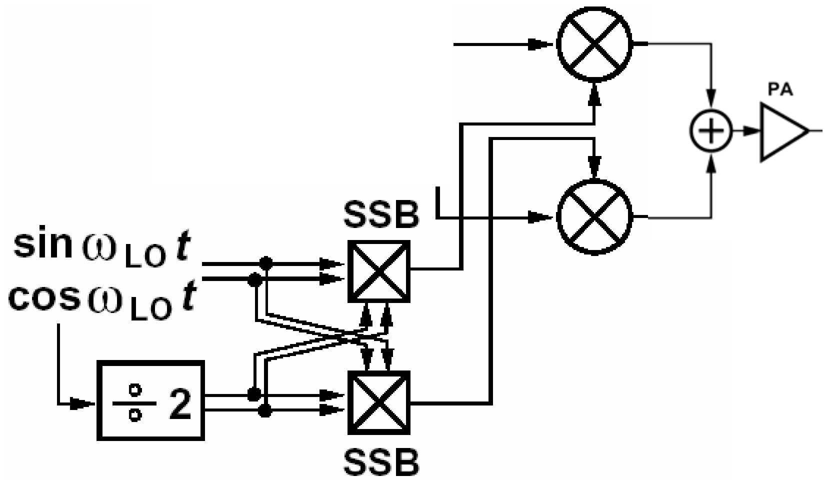
- Problem of "Pulling"



Solution: "Offset LO:"

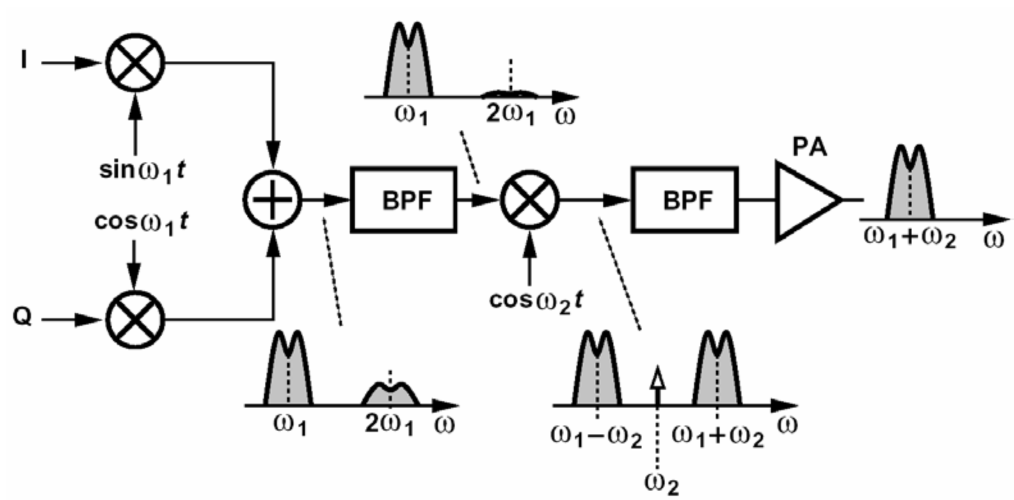


Use SSB mixers to avoid filters:

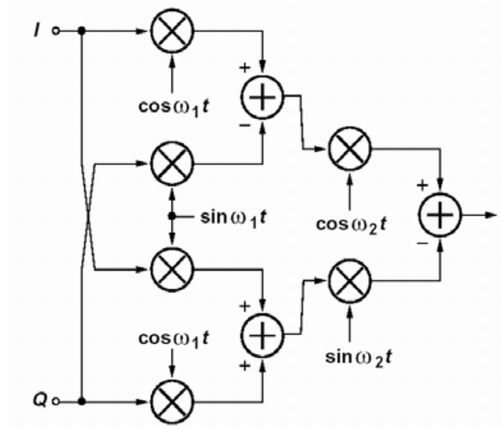


- Problem of Carrier Feedthrough
DC offsets in baseband lead to carrier feedthrough in RF.

• Two-Step Transmitters



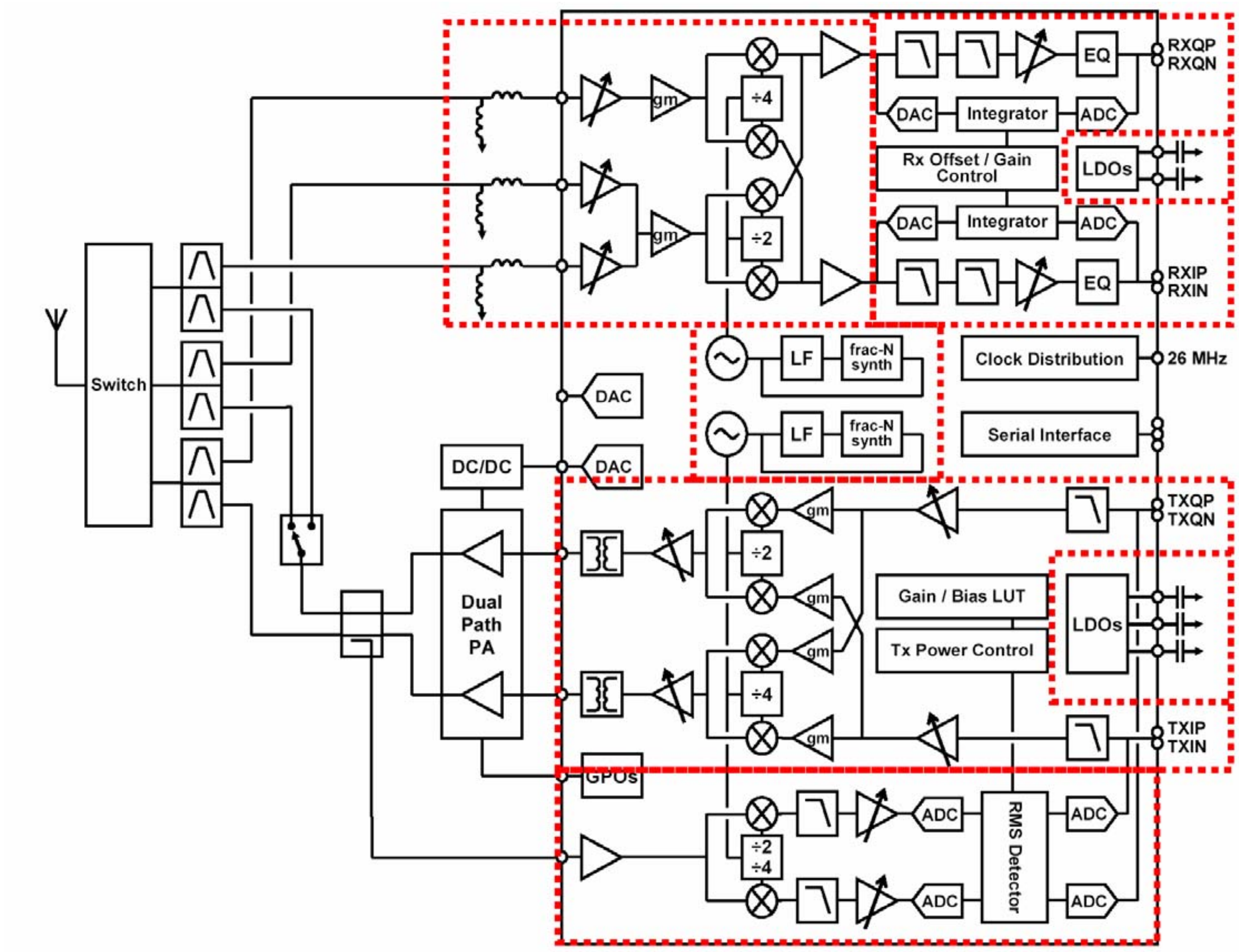
Use SSB mixers to relax filtering:



Exercise: How do we avoid two LOs in two-step transmitters?

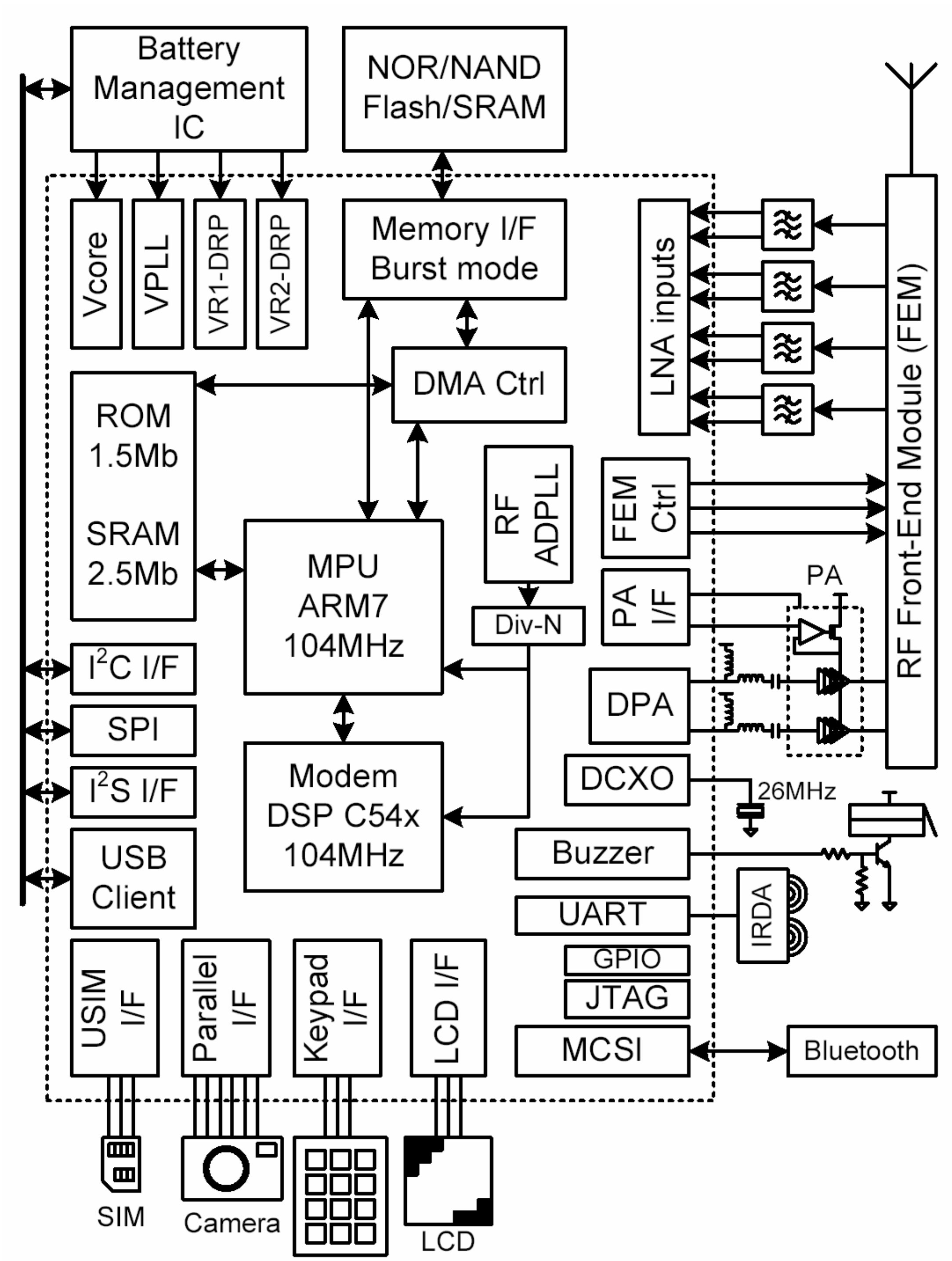
Case Studies

1. Tri-Band WDMA Transceiver: 900 MHz, 2 GHz, 2.5 GHz



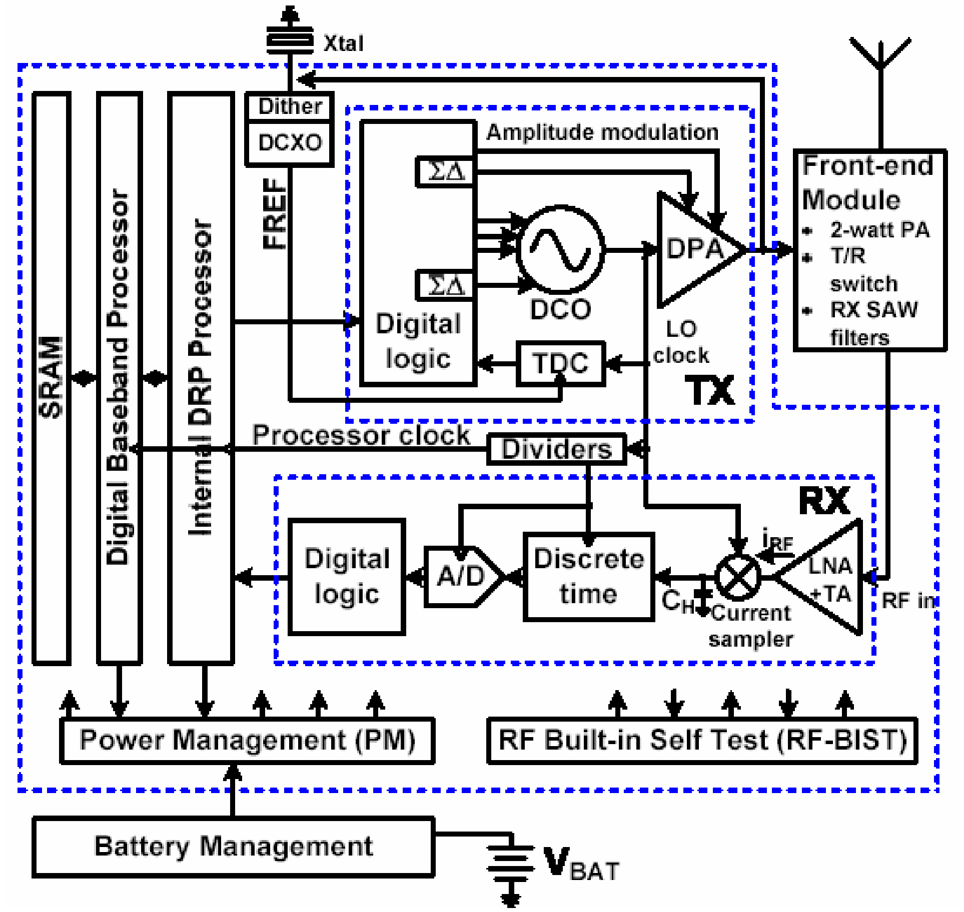
[Tenbroek, ISSCC08]

2. Quad-Band GSM Transceiver



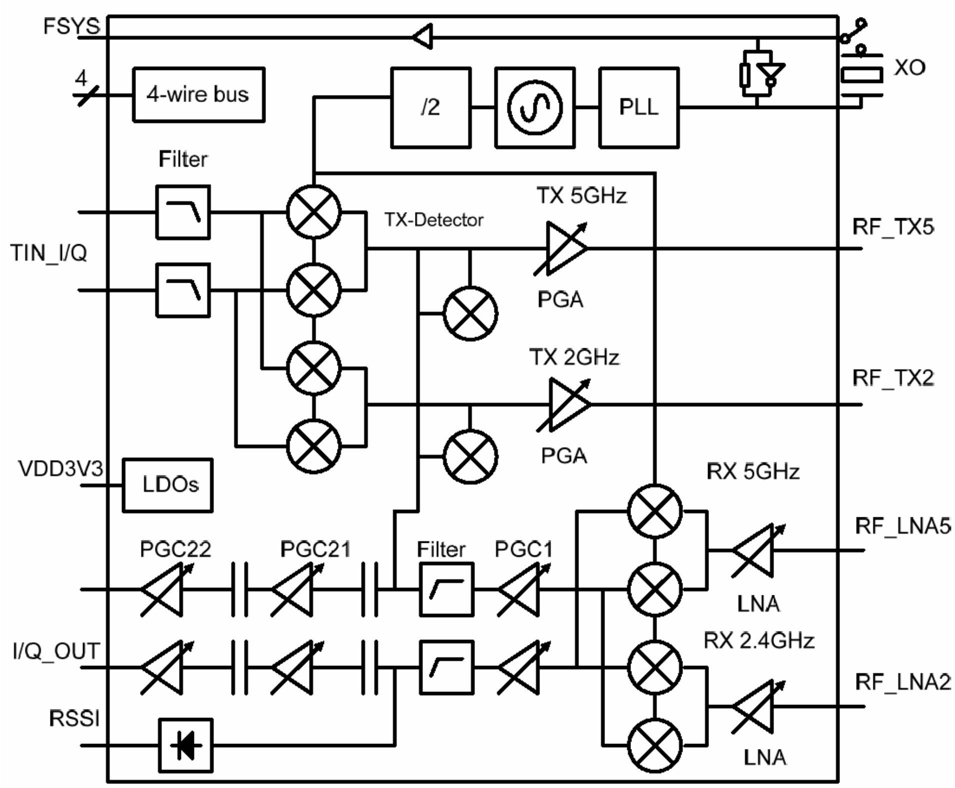
[Staszewiski, ISSCC08]

Detailed architecture for one band:

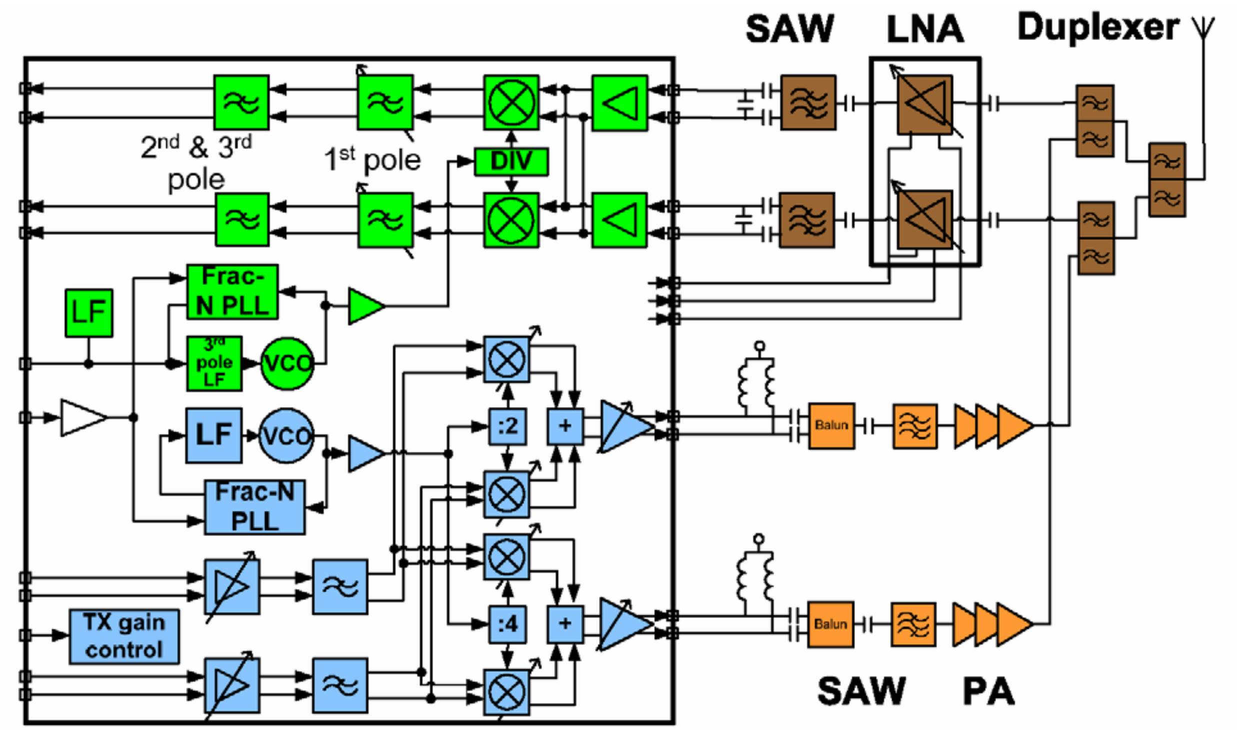


3. 11a/b/g Transceiver

[Simon, ISSCC07]



4. CDMA2000 Transceiver



[Zipper, ISSCC07]