Transceiver Architectures

Modulation techniques -> Multiple Access techniques -> Transceiver Architecture

- General Considerations

- Receiver
  - Heterodyne
  - Homodyne
  - Image Reject
  - Digital IF
  - Sub-sampling receiver

- Transmitter

  - Homodyne
  - Heterodyne

LNAs and PAs for 5G

- Carrier Aggregation – LNA and PA should be able to cater to multiple bands simultaneously.
- Flexible Numerology – Channel BW is flexible.
- More channels means higher concentrated RF power in and around the base station, so the problem of isolation between channels without mutual interference is exacerbated.
- LNA must have high dynamic range performance in order to remain robust in the presence of high power signals.
- For Massive MIMO – large no of LNA(Rx) and PA's(Tx) needed in a given volume. Size has to be small.
- Thermal management must be addressed with the increased electronics' and transmitters' power.

General Considerations

The primary criteria for selecting transceiver architectures have been:

- Performance
- Complexity
- Cost
- Power dissipation
- Number of external components (cost and need to drive 50 ohm impedance)

However as IC technologies evolve (e.g., RF CMOS and SiGe BiCMOS) the relative importance of each of these criteria changes and new previously impractical approaches (e.g., Digital IF, Direct conversion) will become possible.

Wireless in urban areas is often called an hostile communication environment.

Impact of narrow bandwidth (e.g., 30 kHz in IS-54 and 200 kHz in GSM) in a receiver:

- need for coding, compression, bandwidth efficient modulation
- avoid leakage to adjacent channels (Fig. 5.1a)
- reject strong neighbor interferers (Fig. 5.1b)

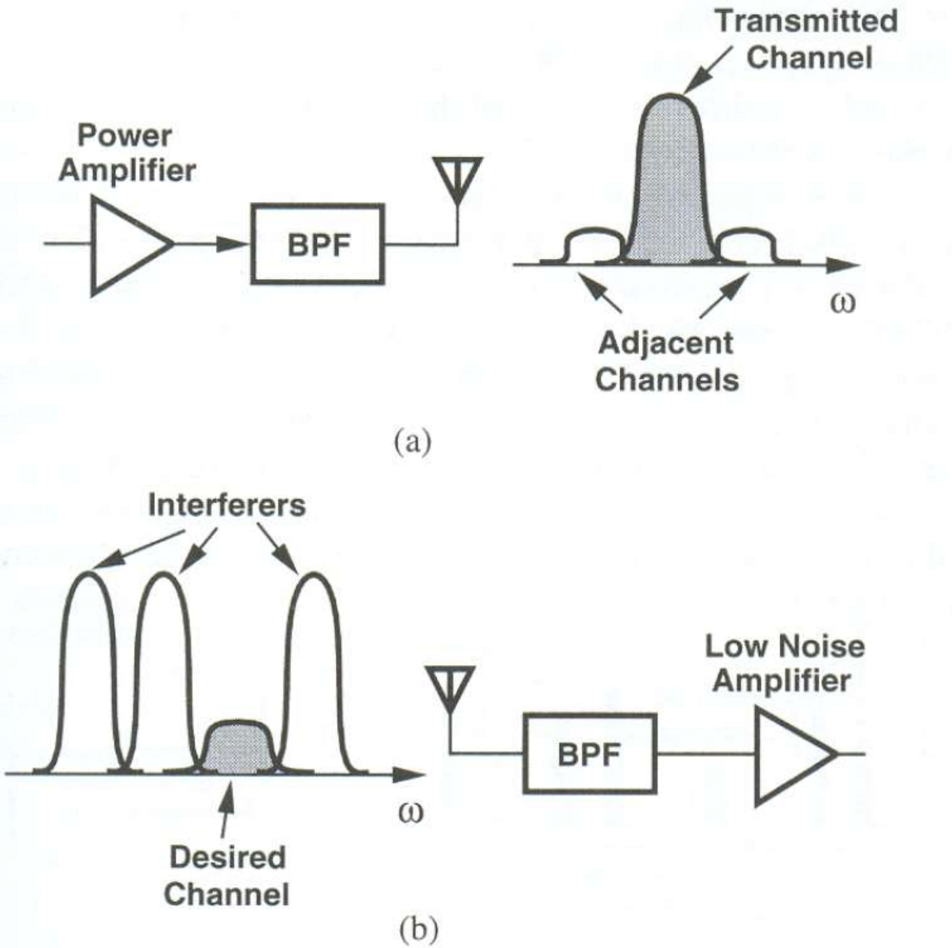


Figure 5.1 (a) Transmitter and (b) receiver front ends of a wireless transceiver.

Example (Fig 5.2):

Consider a 30 kHz channel at 900 MHz. A second order LC Band Pass filter providing 63 dB of attenuation at 45 KHz needs to have a $Q = f_c / 2\Delta f$ of 10^7, where $2\Delta f = 90\ Hz$ is the 3 dB frequency.

- Difficult to implement even with surface acoustic wave filter
- Typically calls for a tradeoff between in-band loss (noise figure) and Q
- Equivalent to a tradeoff between out-band rejection and in-band loss.
- In band loss is translated as increased NF.

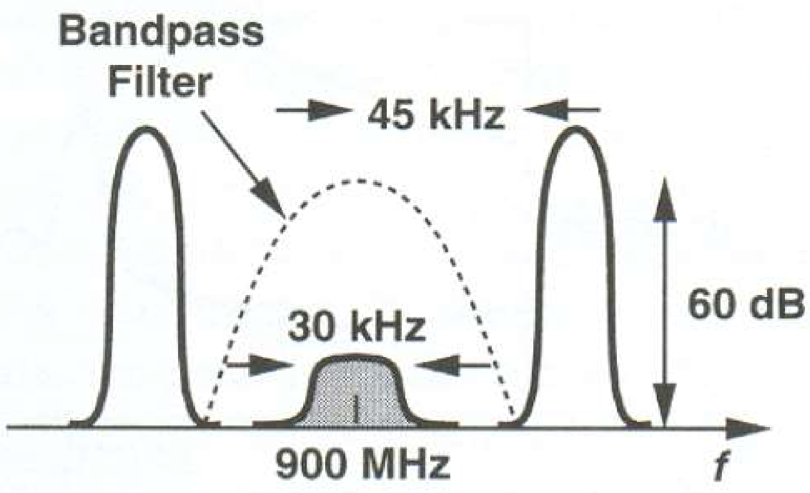


Figure 5.2 Rejection required of a hypothetical front-end bandpass filter.

Example (Fig 5.2):

Now Consider a $\Delta f = 30$ kHz channel at 10 MHz. A second order LC Band Pass filter providing 63 dB of attenuation at 45 KHz needs to have a $Q = f_c / 2\Delta f$ of 1.1×10^5.

- Much easier to implement.
- Both in band loss is lesser and out of band rejection can be higher.

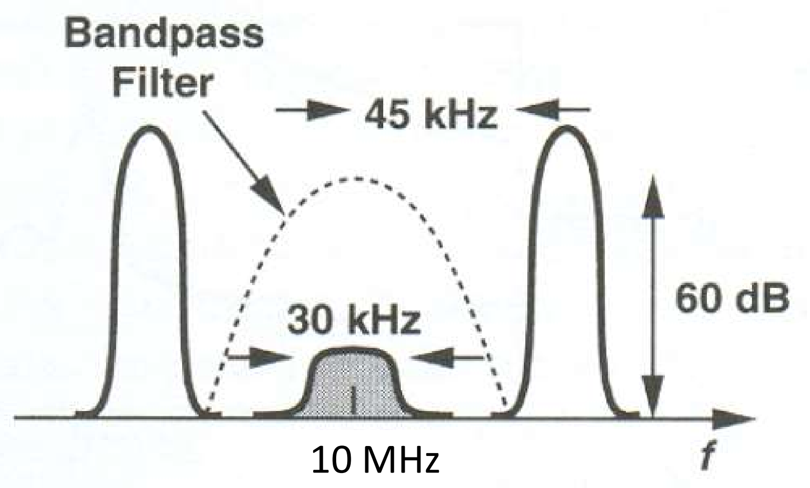


Figure 5.2 Rejection required of a hypothetical front-end bandpass filter.

Band and Channel

It is important to distinguish between the band and the channel. For example in GSM:

- band is 935-960 MHz (25 MHz)
- channel bandwidth is 200 kHz

Band selection and channel selection are usually implemented separately:

- The RF front takes care of the band selection (removes out-band interferers).
- The IF or baseband stage take care of the IF channel selection (removes in-band interferers).

Example: Figure 5.3

Importance of Non-Linearities in Receiver

Large in-band interferers still accompany the received signal after the front-end band-pass filter.

The linearity (IP3) of the LNA and mixer must be high to reduce intermodulation.

See Figure 5.5

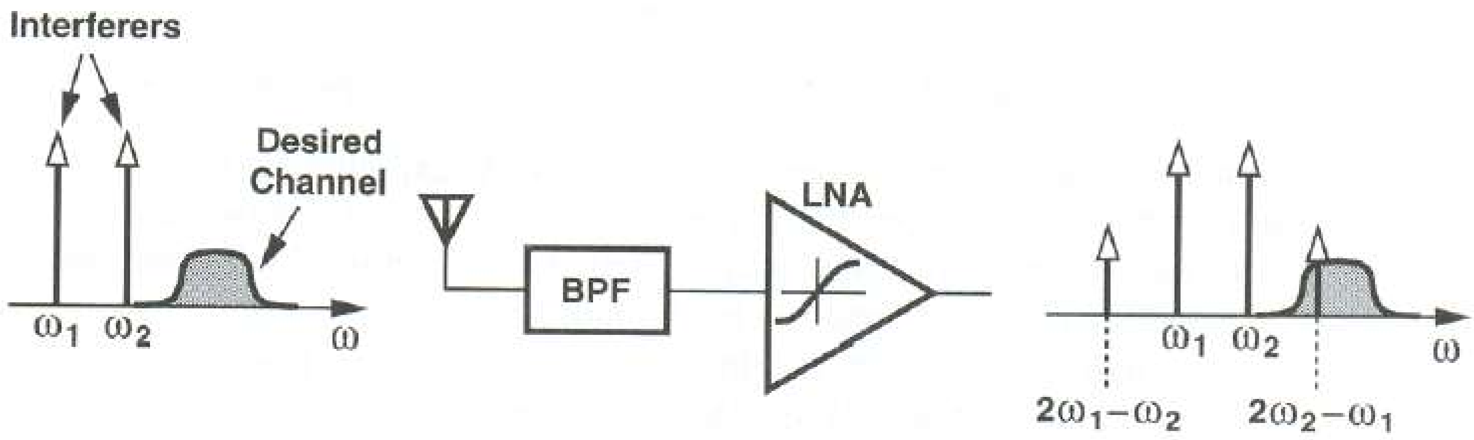


Figure 5.5 Effect of nonlinearity in the front end.

Band select filter

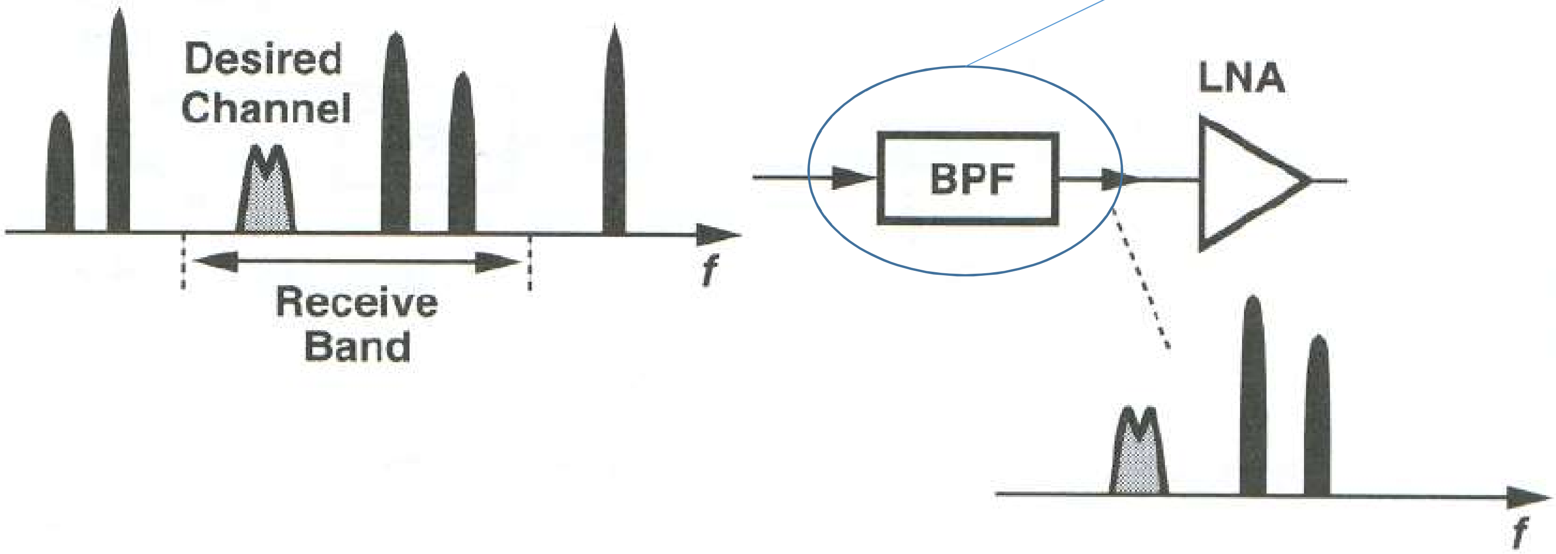


Figure 5.3 Band selection at the front end of a receiver.

Other Receiver Issues

Dynamic Range

- Typically 100 dB

Supply noise and voltage changes as the PA is turned on and off

- Need for noise immunity and supply rejection in all building blocks.
- Frequency synthesizer in transceiver are pushed by supply fluctuation.

Front End Duplexer Transition Bandwidth and Rejection

See example in Figure 5.4:

- Rejection of only 20/56 dB at 20/40 MHz offset between the transmit and receive band.
- Leakage leads to :
  - desensitization: 1W (30 dBm) transmitted signal at the antenna leads to -26 dBm which is close to the -25 dBm, the 1dB compression point of LNA.
  - frequency synthesizer of receiver pulled by transmitter (Fig 5.6) i.e the PLL in Rx can shift frequency based on Tx leakage.
  - TDD better for preventing leakage (preferred in 5G).

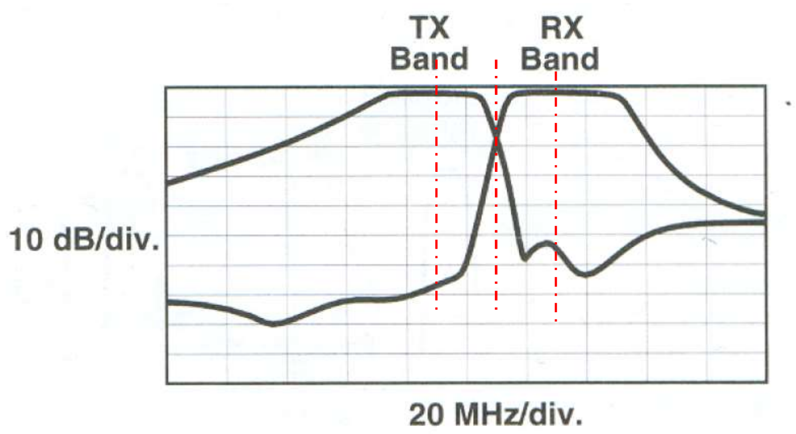


Figure 5.4 Typical duplexer characteristic.

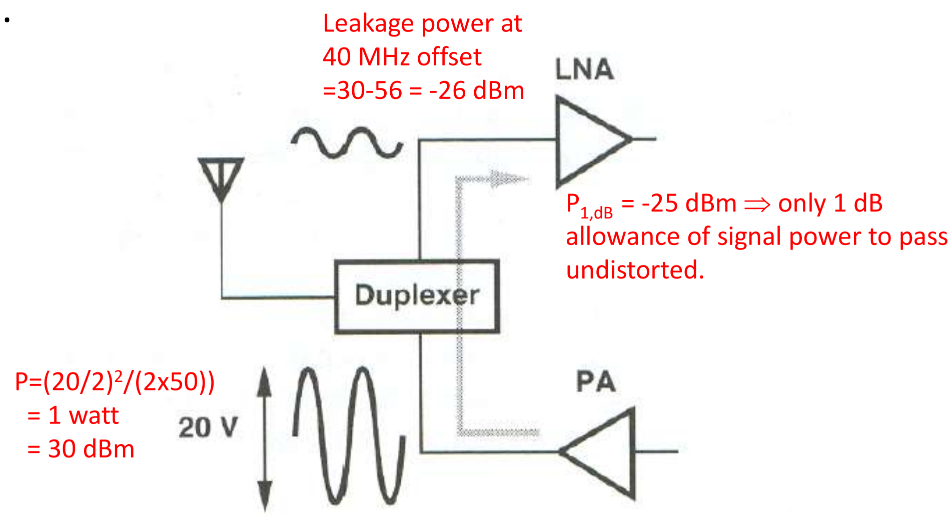


Figure 5.6 Desensitization of LNA by PA output leakage.

Transmit Path Issues

Impact of Loss on Transmit Path

- Consider a 1 W amplifier. A 2 dB loss in the front-end bandpass filter leads to a 370 mW loss of power. Typically more than the entire receive path.

Spectral Regrowth

- The front end bandpass filter cannot suppress the out-of-channel spectral regrowth since BP filter is for all channels.
- PA needs to be linear by design or a proper modulation should be used (recall GMSK vs QPSK).

Heterodyne Receiver

The **Heterodyne Receiver** is based on down conversion:

- Translates the signal to a lower frequency f_{IF} : the intermediate frequency IF using a mixer and a local oscillator f_{LO}. (See Figure 5.7a)

$$\omega_{IF} = |\omega_{LO} - \omega_{RF}|$$

- This relaxes the Q requirement of the channel selection: $Q = f_{IF} \,/\, \Delta f$

Requirements of Down-Conversion

- Need to use an LNA before mixer as real mixers are noisy (Noise Figure on the order of the conversion loss: $F = L_c$) (See Figure 5.7b)
- Down-conversion is not demodulation (except for zero-IF down conversion)
- The local oscillator does not need to be synchronized to the transmitter RF carriers even for subsequent coherent demodulation (except for zero-IF)
- The local oscillator needs to be very stable and low noise (-120 dBc/Hz at 60 kHz offset set) so as to not scramble the channels and corrupt the phase (zero-crossing).

$$\cos \underbrace{\omega_1}_{\omega_{RF}} t \times \cos \underbrace{\omega_0}_{\omega_{LO}} t$$

$$= \underbrace{\frac{1}{2}\cos(\omega_1+\omega_0)t}_{\text{filtered out}} + \underbrace{\frac{1}{2}\cos(\omega_1-\omega_0)t}_{\text{downconverted product}}$$

$$\omega_2 = |\omega_1-\omega_0| = \omega_{IF}$$

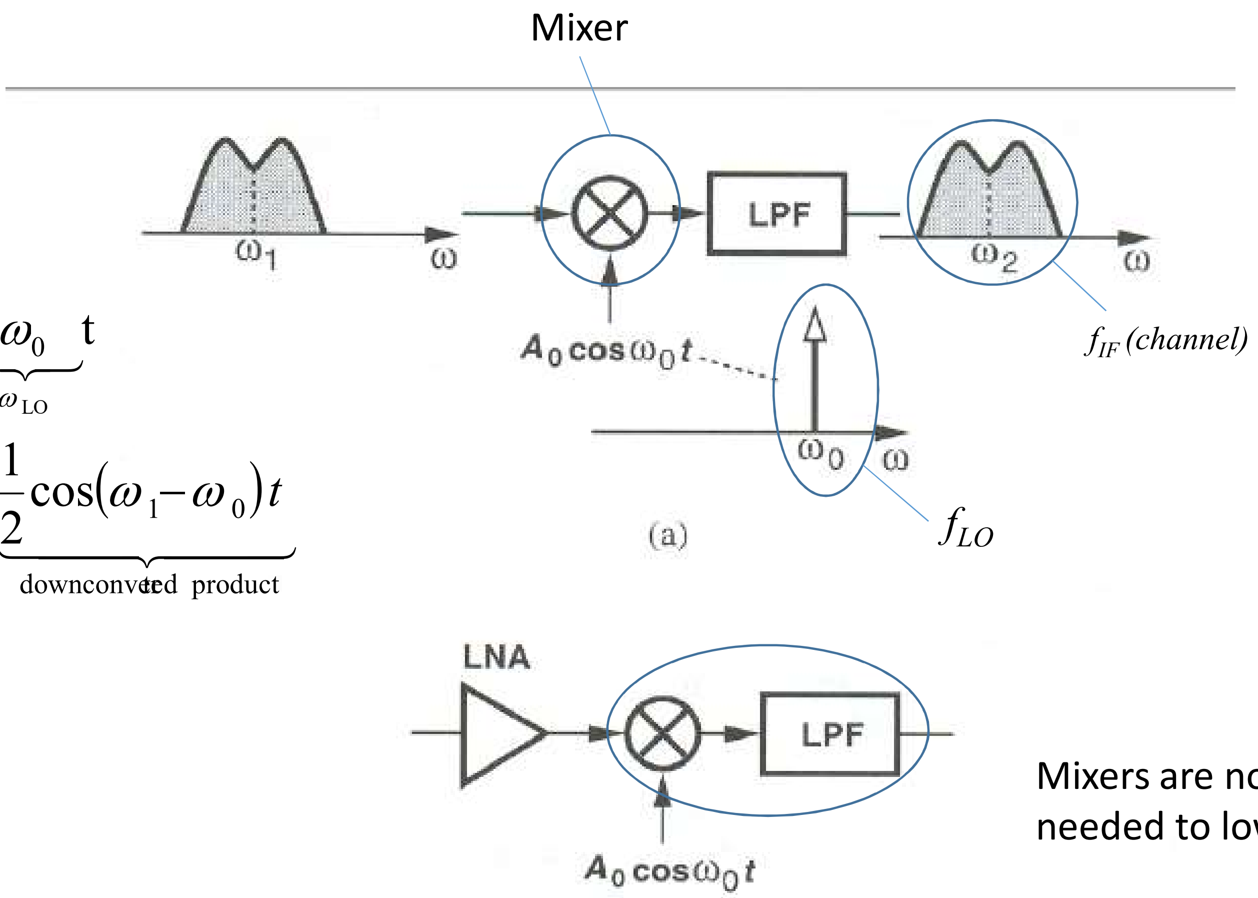


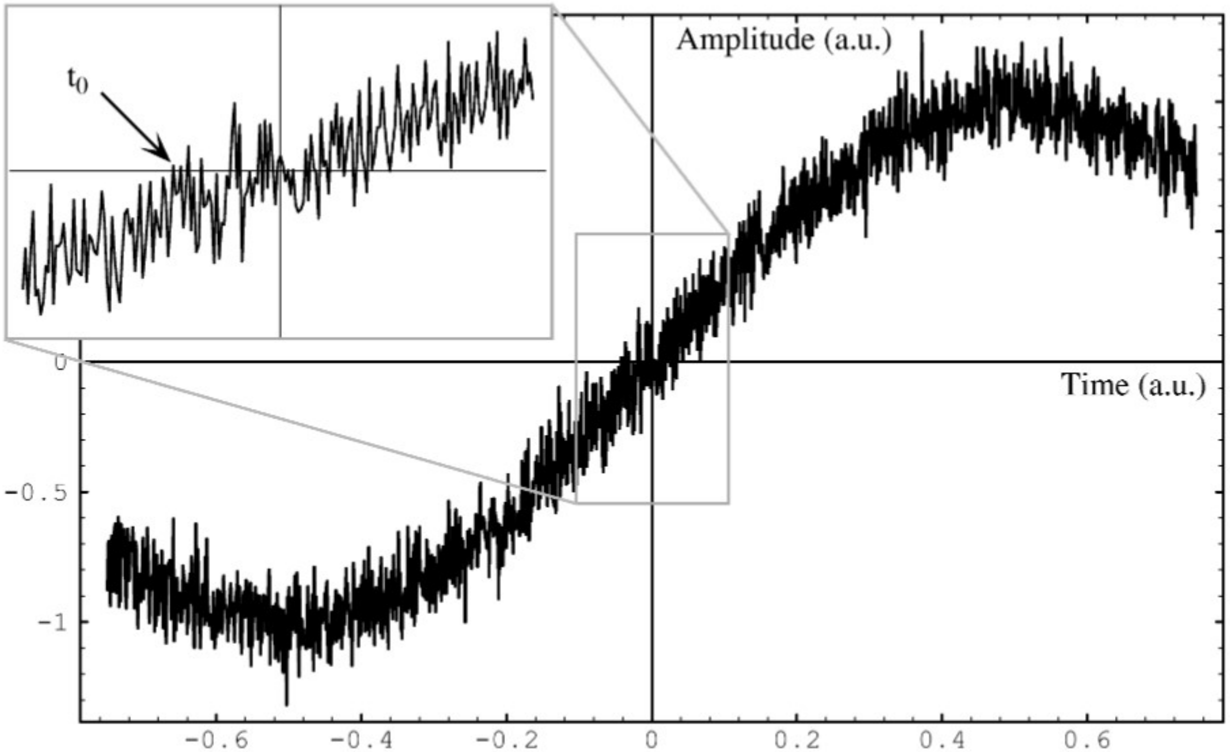
Figure 5.7 (a) Simple heterodyne downconversion, (b) inclusion of an LNA to lower the noise figure.

Down conversion mixing

or

Down conversion

Mixers are noisy so a LNA is needed to lower noise figure



$$\underbrace{p(\Delta\varphi(t))}_{\substack{\text{PSD of phase}\\ \text{variation}}} \approx \frac{\overbrace{\left\langle \overline{n(t)^2} \right\rangle}^{\text{mean squared noise power}}}{\underset{\substack{\uparrow\\ \text{Amplitude of signal}}}{4A^4}} \underbrace{p(\Delta A(t))}_{\substack{\text{PSD of amplitude}\\ \text{variation}}}$$

"Amplitude to phase noise conversion in electronic circuits" Edoardo Milotti, PHYSICAL REVIEW E, Jan 1998

How to Select the LO and IF?

Problem of Image (See Figure 5.9)

- If $\omega_{RF,desired} = \omega_{LO} - \omega_{IF}$ then the image $\omega_{RF,image} = \omega_{LO} + \omega_{IF}$ is also downconverted.
- The image power being usually out-of band can be much higher than the desired signal
- Mitigation of the image problem can be done using
  - an image reject mixer (Hartley and Weaver discussed later on for homodyne architecture)
  - an image reject filter between LNA and mixer with large ω_{IF} .

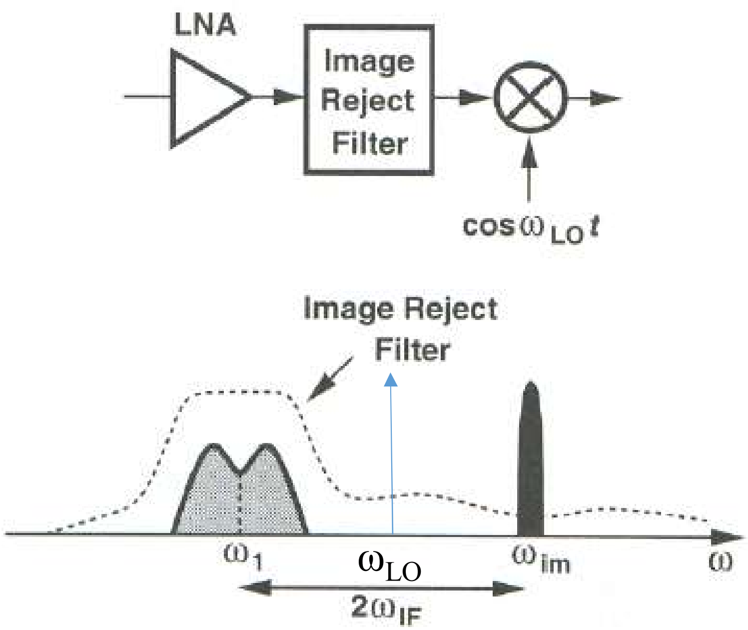


Figure 5.9 Image rejection by means of a filter.

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

$$\omega_{im} = 2\omega_{LO} - \omega_1 = \omega_{LO} + \omega_{IF}$$

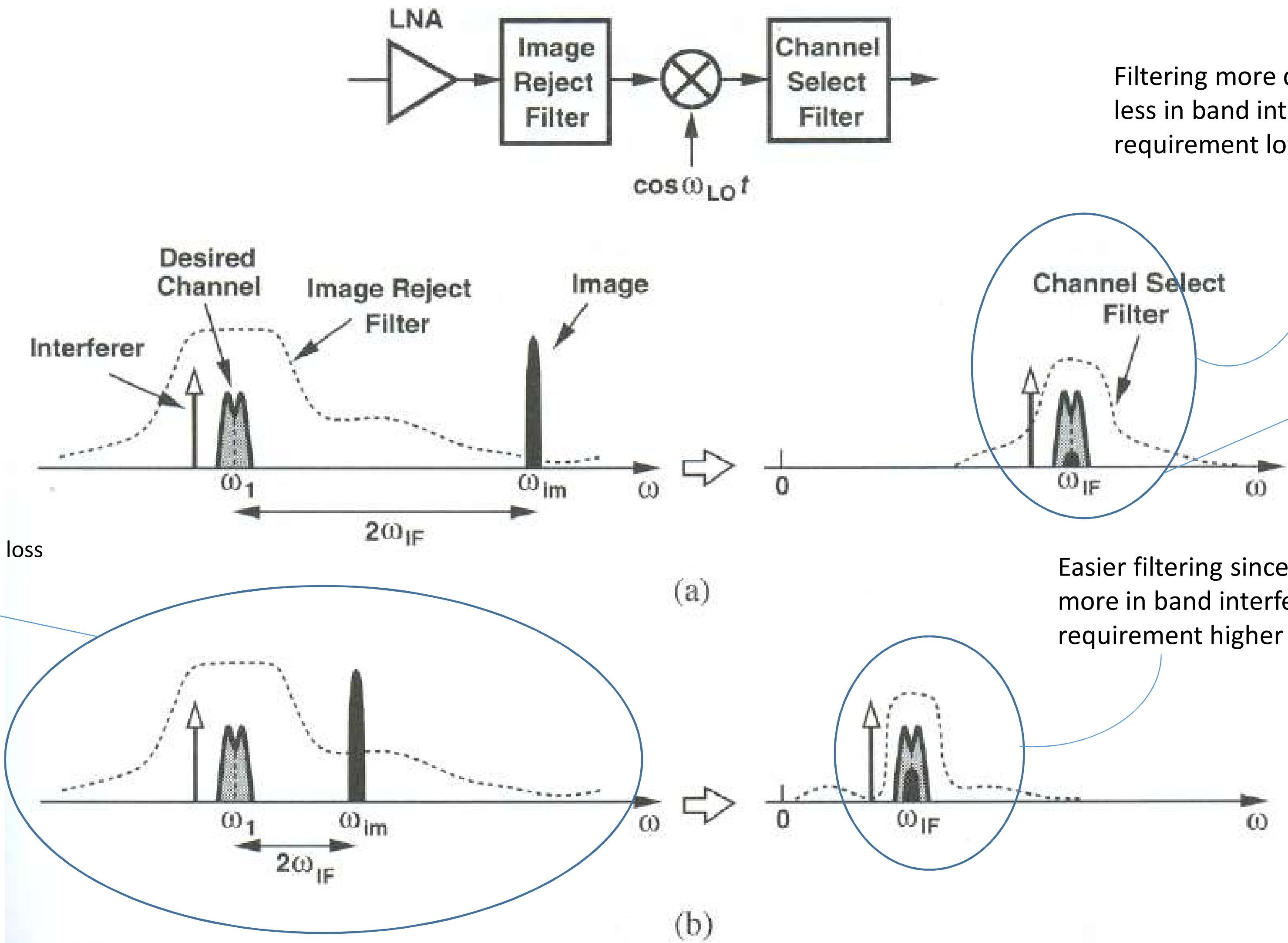
How large can $2\omega_{IF}$ be?

See Figure 5.10

- A large ω_{IF} is required to get good image rejection since $\omega_{RF,image} = \omega_{RF,desired} + 2\,\omega_{IF}$.
- For large ω_{IF} , image will also be reduced by preliminary BPF, but if ω_{IF} is small, then it is a problem
- But with a large ω_{IF} the Q of the IF filter becomes an issue.
- Large IF leads to a poor channel selection as the Q of the IF filter degrades.
- Calls for a trade off between image-rejection and channel selection.
- Referred as a trade off between sensitivity and selectivity.
- High-side (supradyne) versus
- low-side injection (infradyne)
  - Infradyne: $\omega_{LO} < \omega_{RF}$ leads to easier design of LO and mixers (since LO freq is lesser than RF freq)
  - Supradyne: $\omega_{LO} > \omega_{RF}$ if required to avoid noisy lower band
- In FDD the duplexer may also serve to reject the image if the IF is high.

Filtering more difficult since IF higher, but less in band interferers, so $P_{i,mds}$ requirement lower (higher sensitivity)

Or tolerate more in band loss



or tolerate more in band loss
-> undesirable

Easier filtering since IF lower, but more in band interferers, so $P_{i,mds}$ requirement higher (lesser sensitivity).

Figure 5.10 Rejection of image versus suppression of interferers for (a) high IF and (b) low IF.

Other factors influencing ω_{IF}

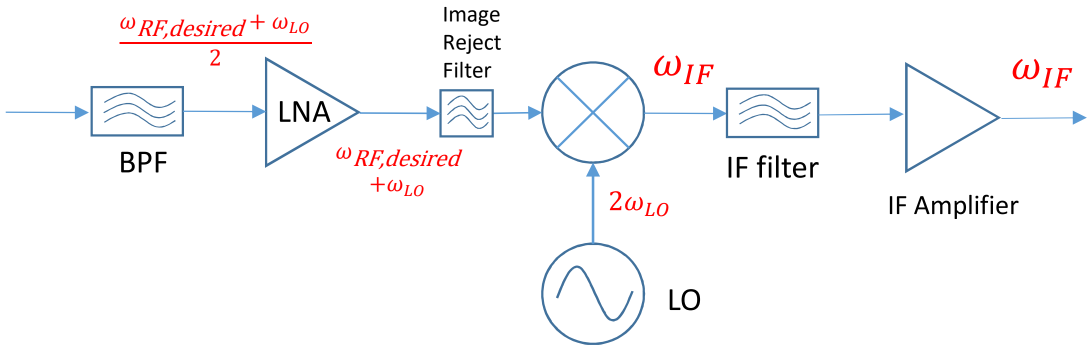
868 - 895 MHz SAW filter

- Availability and size of filters => Higher Q implies higher size => Need external components.

- Form Factor (especially for MIMO)
  - Smaller filters => lower Q => lower IFs more suitable.

- Loss of image reject filter, image power

Problem of Half IF



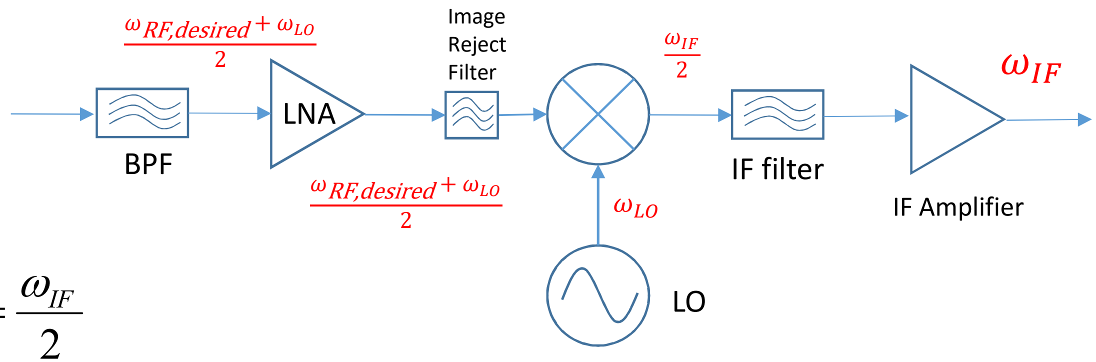
Assume we have (Scenario 1):

· an interferer at $\frac{\omega_{\text{RF,desired}}+\omega_{LO}}{2}$

· the interferer undergoes second-order distortion in the LNA doubling its frequency.

· the LO contains significant amount of 2nd order harmonic $2\omega_{\text{LO}}$ the mixer output includes then an interferer component:

$$\left|\left(\omega_{\text{RF,desired}}+\omega_{\text{LO}}\right)-2\omega_{LO}\right|=\omega_{IF}$$



Alternately (Scenario 2):

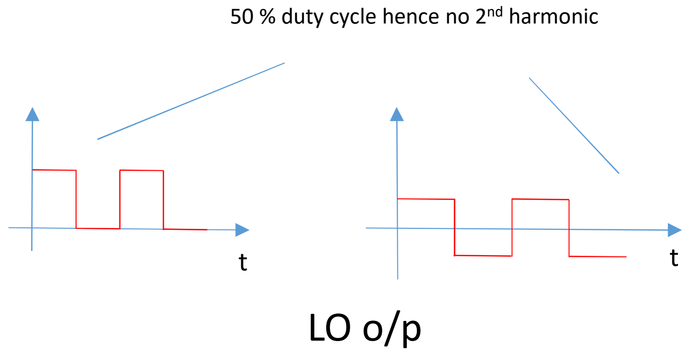
· an interferer at $\frac{\omega_{\text{RF,desired}}+\omega_{LO}}{2}$

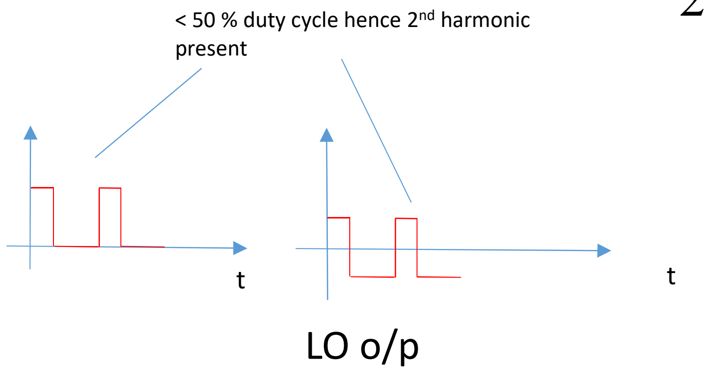
· down converted to $\frac{\omega_{\text{RF,desired}}+\omega_{LO}}{2}-\omega_{LO}=\frac{\omega_{\text{RF,desired}}-\omega_{LO}}{2}=\frac{\omega_{IF}}{2}$

· the interferer undergoes *second - order distortion* in the IF amplier doubling its frequency to ω_{IF}.

Remediation Techniques for Half IF Problem

- Reduce second order distortion in RF and IF paths. (common in MOSFETS)
- Reduce 2nd order harmonics in LO by maintaining a 50% LO duty cycle (no second harmonics).
- Image reject filter providing sufficient attenuation at $\dfrac{\omega_{\mathrm{RF,desired}} + \omega_{LO}}{2}$





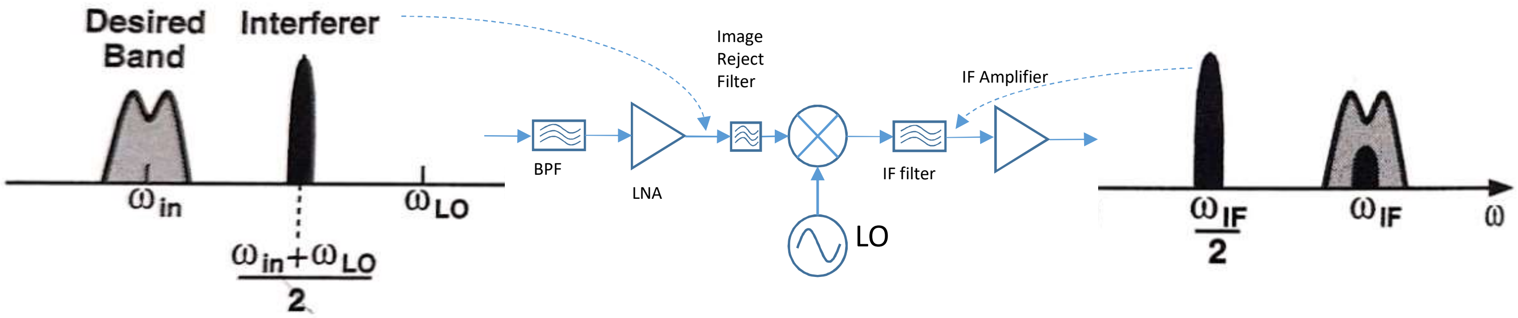
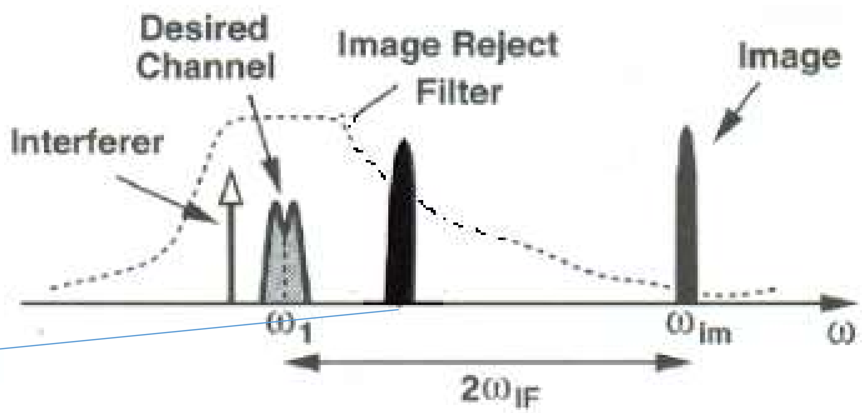


Figure 5.11 Problem of half IF in heterodyne reception.



$$\frac{\omega_{in} + \omega_{LO}}{2}$$

Using image reject filter to remove interferer

Dual IF Topology

The trade-off between sensitivity and selectivity in a single IF heterodyne is usually too severe. The solution is to introduce a 2nd IF (see Figure 5.12)

- A large 1st IF can then be selected to achieve a high image rejection
- A low 2nd IF can then be selected to achieve a high channel selectivity

Need For Progressive Filtering:

- Assume 40 dB gain from A to G (Figure 5.12). If the two IF filters provide no channel selection, the IP3 of the IF amplifier would typically need to be more than 40 dB above that of the LNA IP3(+ 30 dBm).
- Instead each IF filter gradually reduces the adjacent channel interferers relaxing the linearity requirement.
- Loosely stated as: “Every dB of gain requires one dB of pre filtering."

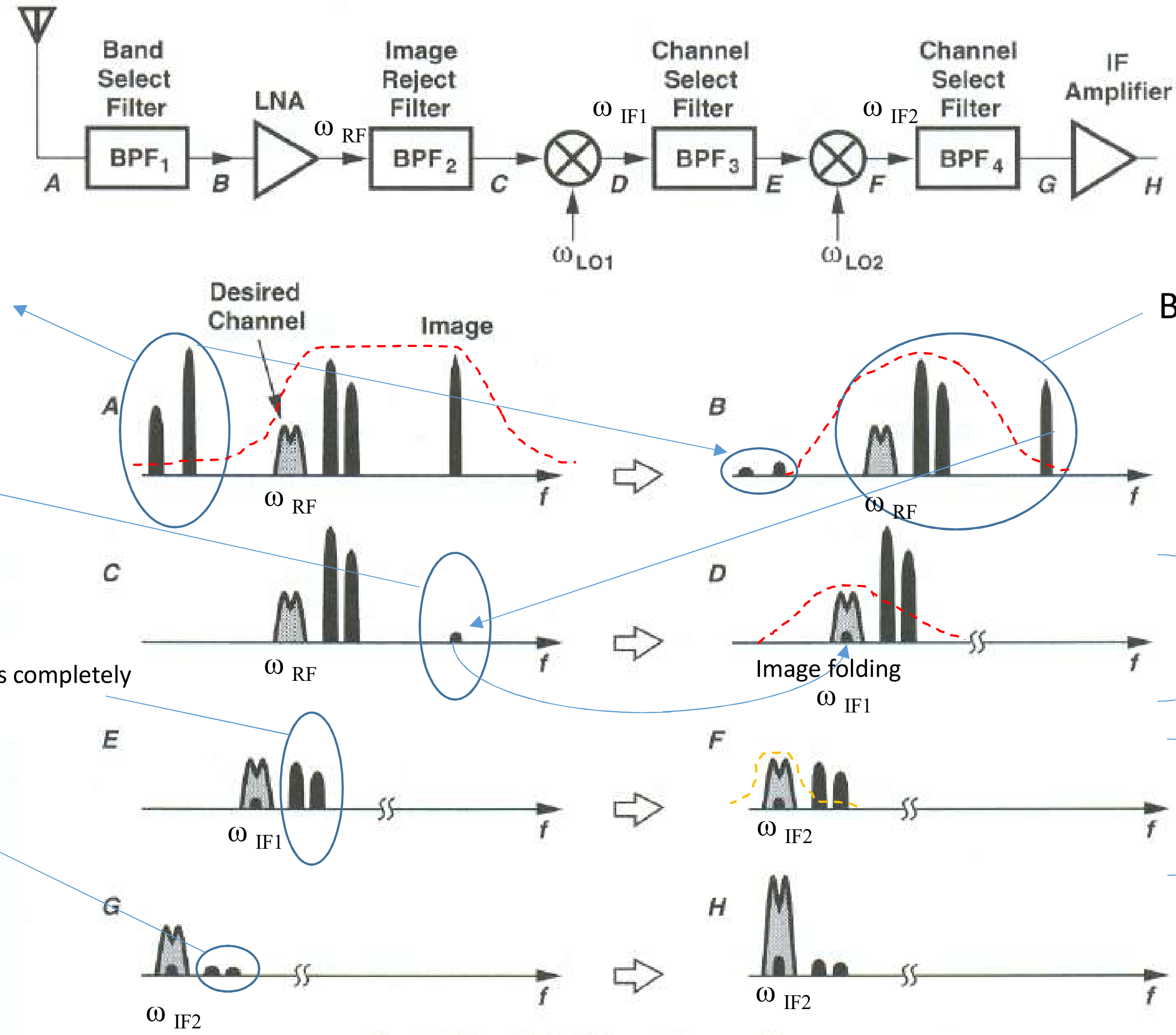


Image suppressed
But interferers remain
but Q requirement is lower

Could not eliminate interferers completely
But relaxes Q requirement.

second IF complete
suppression of interferers
With lower Q filter

first down conversion

second
down conversion

Figure 5.12 Dual-IF heterodyne receiver.

Disadvantages

- More power consumption
- Noise also is folded and added.
- Multiple filtering needed (increase in NF) to avoid high IP3 requirement.
- Mixer spur – multiple mixing can generate additional frequency components.
- In modern receivers LO1 and LO2 are related. Say LO2= (1/2) LO1

$$\omega_{IF1} = \omega_{RF} - \omega_{LO1}$$

$$\omega_{IF2} = 0 = \omega_{IF1} - \omega_{LO2} = \omega_{RF} - \omega_{LO1} - \omega_{LO2} = \omega_{RF} - \omega_{LO1} - \frac{\omega_{LO1}}{2}$$

$$\Rightarrow \omega_{RF} = \frac{3}{2}\omega_{LO1} \Rightarrow \omega_{LO1} = \frac{2}{3}\omega_{RF}$$

What Happens after the 2nd Down Conversion?

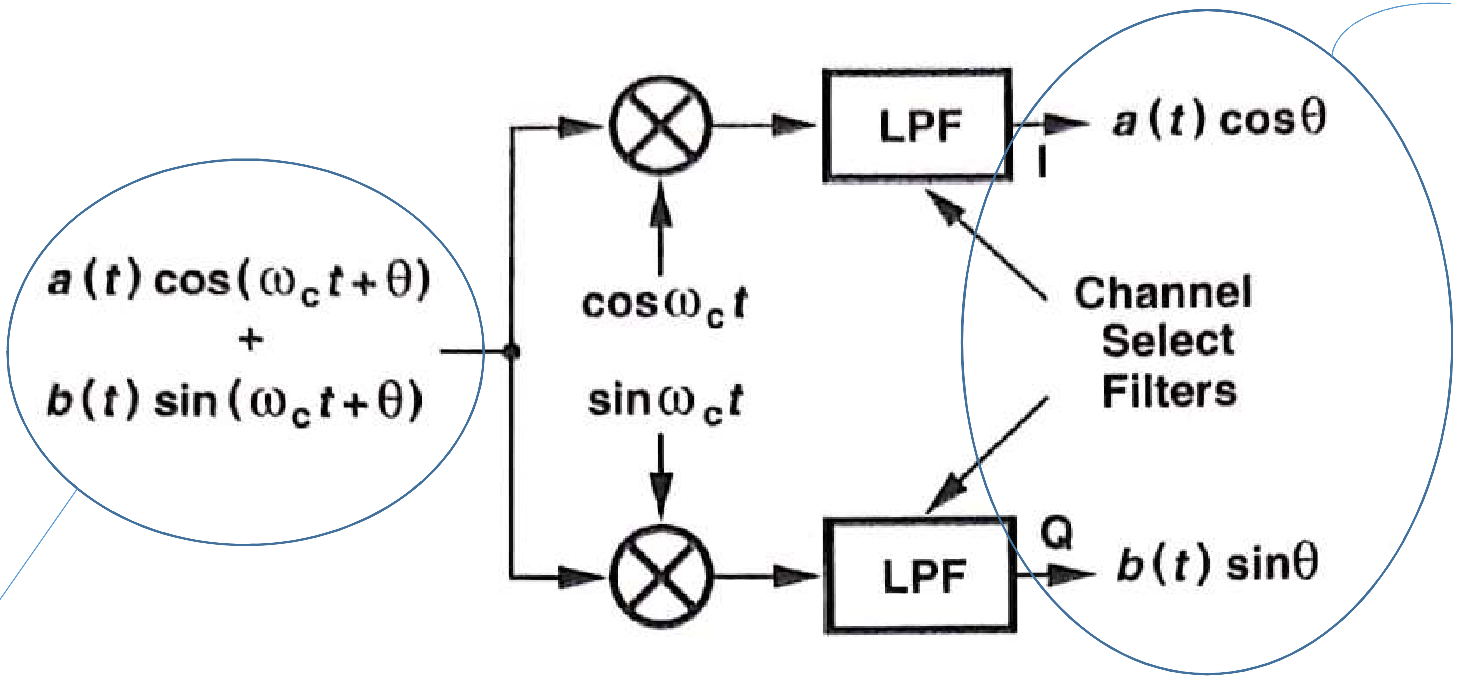
In **FM systems** the demodulation is performed at the 2nd IF frequency $\omega_{IF,2}$ generating the baseband signal.

In **digital systems** the second down-conversion generates the in-phase (I) and quadrature (Q) components of the signal while translating the spectrum to zero frequency(See Figure 5.13).

The A/D converters sample then the I and Q channels. Their resolution (4-10 bits) depends on the filtering required and the signal range provided by the front-end AGC circuit.

Digital non-zero IF or sampling IF i.e. when signals are directly sampled from the IF instead of baseband are possible but have prohibitively high speed and high linearity requirements and are used so far in base stations where many channels need to be processed simultaneously.

AGC to reduce
or increase signal



second IF

Figure 5.13 Quadrature downconversion.

Drawbacks and Advantage of Heterodyne

Drawbacks:

- Complexity: need for careful frequency planning (spurious frequency components)
- Needs for external components if using image-reject filter
- Trade-off between gain, noise-figure, stability and power dissipation.

Advantages:

- Excellent selectivity and sensitivity
- Still considered the most reliable reception techniques

Example

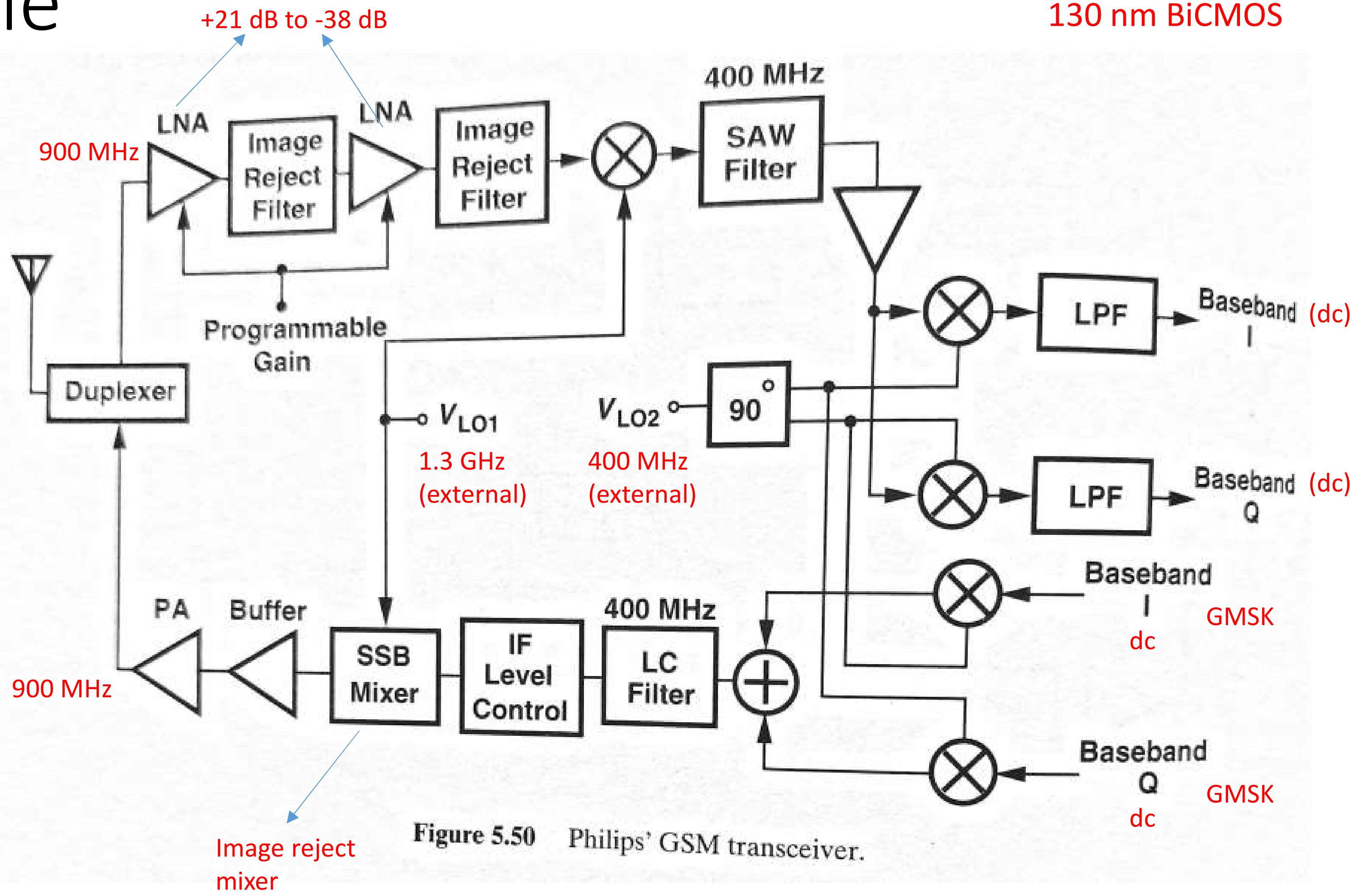


Figure 5.50 Philips' GSM transceiver.