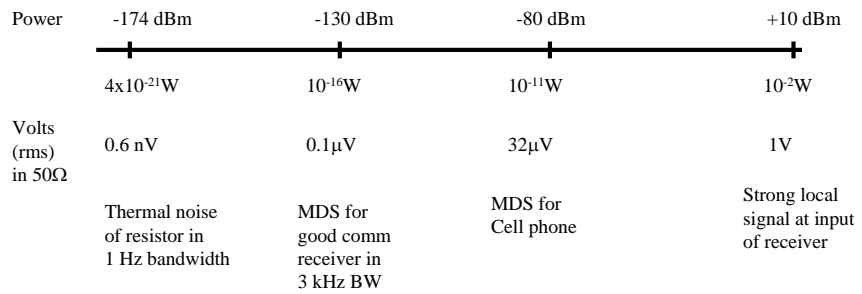# Introduction to Receivers

- Purpose: translate RF signals to baseband
  - Shift frequency
  - Amplify
  - Filter
  - Demodulate
- Why is this a challenge?
  - Interference (selectivity, images and distortion)
  - Large dynamic range required (SFDR)

Many receivers must be capable of handling a very wide range of signal powers at the input while still producing the correct output. This must be done in the presence of noise and interference which occasionally can be much stronger than the desired signal.

Noise sets the threshold for minimum detectable signal power - MDS

Distortion sets the maximum signal power level. The third order input intercept (IIP3) is a figure of merit that is directly related to the intermodulation distortion produced by a particular design.

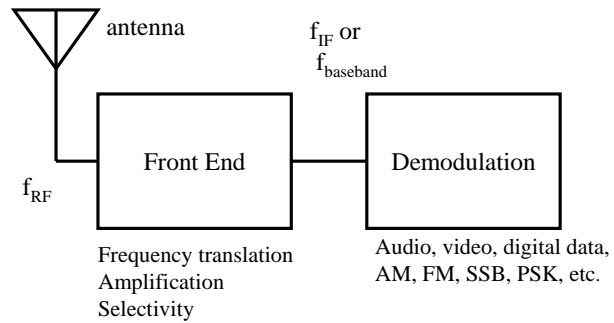| Power	-174 dBm	-130 dBm	-80 dBm	+10 dBm
	4×10^{-21} W	10^{-16} W	10^{-11} W	10^{-2} W
Volts (rms) in 50Ω	0.6 nV	0.1 μV	32 μV	1 V
	Thermal noise of resistor in 1 Hz bandwidth	MDS for good comm receiver in 3 kHz BW	MDS for Cell phone	Strong local signal at input of receiver

RF to baseband

- 2 dominant architectures:
  - Superheterodyne.
    - 1917 E. H. Armstrong
    - Uses intermediate frequency
    - 99% of receivers use this
  - Direct conversion.
    - Becoming more popular for single chip radios
    - Less hardware, but troublesome
- Both use frequency translation
  - Mixer for up or down conversion

Why frequency translation? The original concept in 1917 addressed current technology. The vacuum tubes of that day were not capable of providing any gain above 1 or 2 MHz. By using the nonlinearity of a vacuum tube along with gain at low frequencies (a few hundred kHz typically), receivers could be built that were sensitive in the MHz range. This enabled the power level of radio transmitters to be greatly reduced.

Today, gain is cheap, but the superhet architecture has lived on and has much broader use. It allows the designer to optimize the receiver performance through clever choice of intermediate frequencies and filtering.

Direct conversion is less common but has become recently more popular in single chip radios. It can eliminate off-chip bandpass filters, replacing them with on-chip DSP lowpass filters.
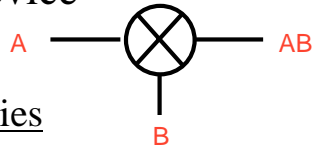
Receiver block diagram

antenna

f_{IF} or
$f_{baseband}$

f_{RF}

Front End

Demodulation

Frequency translation
Amplification
Selectivity

Audio, video, digital data,
AM, FM, SSB, PSK, etc.

The front end of the receiver performs the frequency translation, channel selection and amplification of the signal.
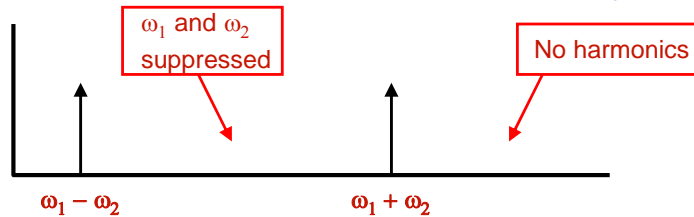
What is a mixer?

- Frequency translation device
- Ideal mixer:
  - Doesn't "mix"; it <u>multiplies</u>

A ———⊗——— AB

B

$$(A\sin\omega_1 t)(B\sin\omega_2 t) = \frac{AB}{2}\left[\cos(\omega_1-\omega_2)t - \cos(\omega_1+\omega_2)t\right]$$

Downconvert   Upconvert

ω_1 and ω_2 suppressed

No harmonics

$\omega_1 - \omega_2$ $\omega_1 + \omega_2$

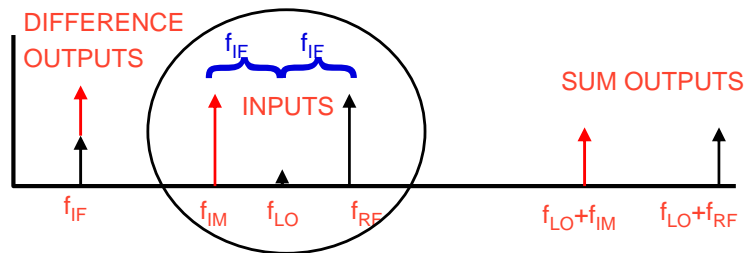
A mixer doesn't really "mix" or sum signals; it multiplies them.

$$(A\sin\omega_1 t)(B\sin\omega_2 t) = \frac{AB}{2}\left[\cos(A\omega_1-\omega_2)t - \cos(\omega_1+\omega_2)t\right]$$

Note that both sum and difference frequencies are obtained by the multiplication of the two input sinusoidal signals. A mixer can be used to either *downconvert* or *upconvert* the RF input signal, A. The designer must provide a way to remove the undesired output, usually by filtering.

Images

- Two inputs (RF & Image) will mix to the same output (IF) frequency.
- The image frequency must be removed by filtering
- f_{IF} and f_{LO} must be carefully selected
- Image rejection ratio: $dB(P_{IF}$ desired$/P_{IF}$ image$)$

DIFFERENCE OUTPUTS

f_{IF} f_{IF}

INPUTS

SUM OUTPUTS

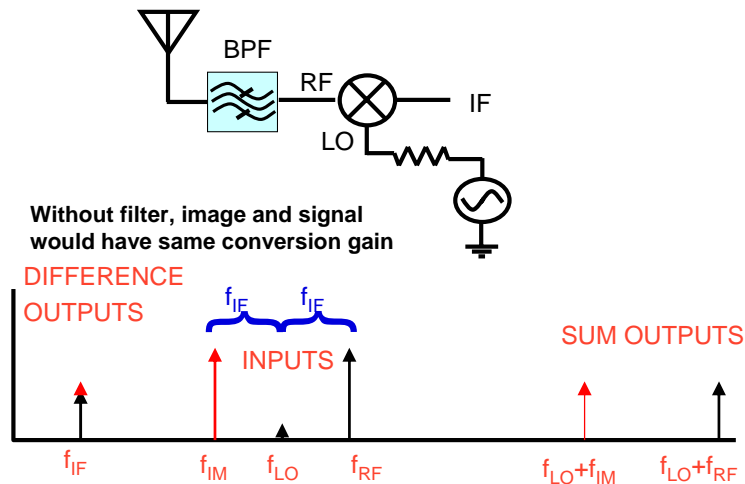f_{IF} f_{IM} f_{LO} f_{RF} $f_{LO}+f_{IM}$ $f_{LO}+f_{RF}$

Even in an ideal multiplier, there are two RF input frequencies (F_{RF} and F_{IM}) whose second-order product has the same difference IF frequency.

$$F_{RF} - F_{LO} = F_{LO} - F_{IM} = F_{IF}$$

The two results are equally valid. One is generally referred to as the "*image*" and is undesired. In the example above, the lower input frequency is designated the image. This would be referred to as low-side LO injection. If the frequencies of image and signal are reversed relative to the LO frequency, we would have high-side LO injection.

Image rejection preselector

BPF

RF

IF

LO

Without filter, image and signal would have same conversion gain

DIFFERENCE OUTPUTS

f_{IF} f_{IF}

INPUTS

SUM OUTPUTS

f_{IF} f_{IM} f_{LO} f_{RF} $f_{LO}+f_{IM}$ $f_{LO}+f_{RF}$

A *bandpass preselection filter* is often used ahead of the mixer to suppress the image signal. The IF and LO frequencies must be carefully selected to avoid image frequencies that are too close to the desired RF frequency to be effectively filtered.

In a receiver front end, out-of-band inputs at the image frequency could cause interference when mixed to the same IF frequency. Also, the noise present at the image would also be translated to the IF band, degrading signal-to-noise ratio.

Alternatively, an *image-rejection mixer* could be designed which suppresses one of the input sidebands by phase and amplitude cancellation. This approach requires two or more I/Q mixers and some phase-shifting networks.

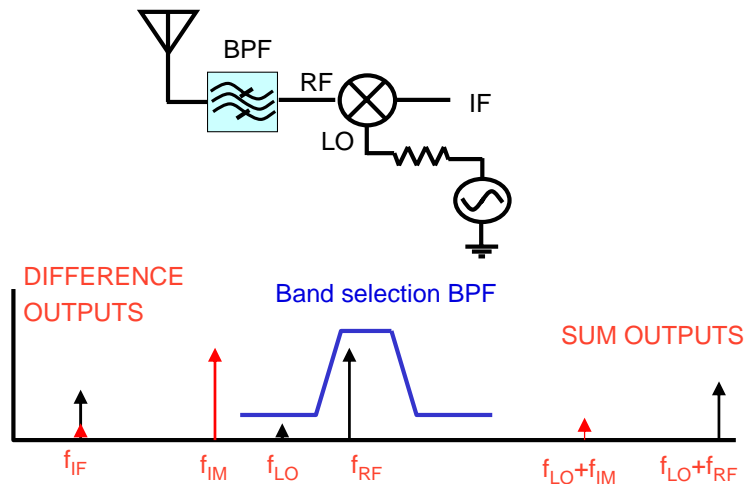Can the preselection filter also be used to select the desired channel?

  the ratio of f_{RF} to the signal bandwidth is too large

  a very high loaded Q would be required: lossy

  very expensive to build a tunable filter with very high Q

It is much easier to design fixed frequency high Q channel selection filters at a lower frequency, the IF frequency.

Image rejection preselector

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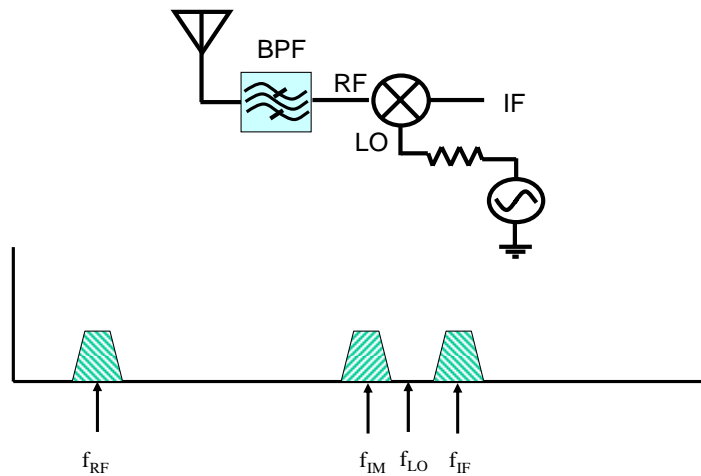> the ratio of f_{RF} to the signal bandwidth is too large
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> very expensive to build a tunable filter with very high Q

It is much easier to design fixed frequency high Q channel selection filters at a lower frequency, the IF frequency.

Upconversion images

In this case, even if there is only one signal at the input, fRF, there will be outputs from the mixer at:
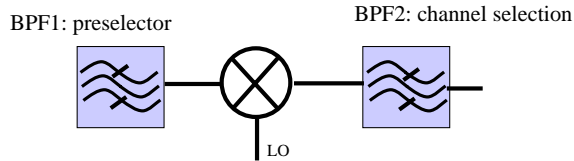
$$F_{IF} = F_{RF} + F_{LO}$$

$$F_{IM} = F_{LO} - F_{RF}$$

The image is also frequency-reversed from the IF output.

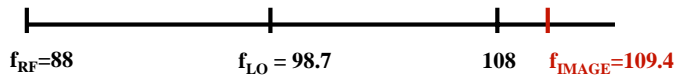Additional filtering or an image-rejecting mixer is needed to reduce this image frequency.

FM radio example

BPF1: preselector   BPF2: channel selection

LO

- FM broadcast band: 88 to 108 MHz
- Standard IF frequency = 10.7 MHz
- Image is always out of band
  - $f_{IMAGE} = f_{RF} + 2\,f_{IF}$

Worst case with high side LO:

$f_{RF}=88$ $f_{LO} = 98.7$ 108 $f_{IMAGE}=109.4$

Both the RF and IMAGE frequency will be translated to the same IF frequency. With a 10.7 MHz IF frequency, the image is always outside of the FM broadcast band. Therefore, strong in-band FM signals are never to be found at the image frequency.

A preselection filter can be used to reject this image that is 21.4 MHz away from the desired RF signal. In the usual implementation, this filter is a bandpass filter with narrow bandwidth, and is tuned, tracking the LO frequency.

Why does it use LO injection on the high side? (above the RF in frequency)

AM Radio Example

BPF1: preselector   BPF2: channel selection

LO
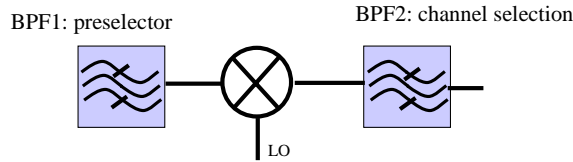
- AM broadcast band: 530 to 1700 KHz

- Standard IF frequency = 455 KHz

- Image is often in-band.

- High Q tunable preselector filter is needed

Worst case with high side LO:

f_{RF}=530 f_{LO} = 985 f_{IMAGE}=1400   1700

LO frequency selection: we always have 2 choices.

       image rejection and oscillator implementation affect the choice

1. $F_{LO1} = F_{RF} - F_{IF}$

     530 - 455 = 75 KHz

     1700 - 455 = 1245 KHz

2. $F_{LO1} = F_{RF} + F_{IF}$

     530 + 455 = 985 KHz

     1700 + 455 = 2155 KHz

LO choice #1 requires a 16.6 to 1 tuning range for the LO; #2 only requires 2.2 to 1.
The oscillator will be much easier to implement.

What about image rejection?

- With 455 KHz IF, image can be in-band.
  - Potential interference problem
  - First BPF must be very selective and tunable

- Can we redesign the receiver to use fixed low-pass preselector?
  - Use higher $F_{IF} \gg F_{RF}$.
  - Preselector admits entire AM band
  - No tuning allowed

LPF1: preselector;
Band selection

BPF2: channel selection

LO

Insertion loss

dB

- X dB/decade slope

Image rejection

1700 KHz

f_{IMAGE}

log f
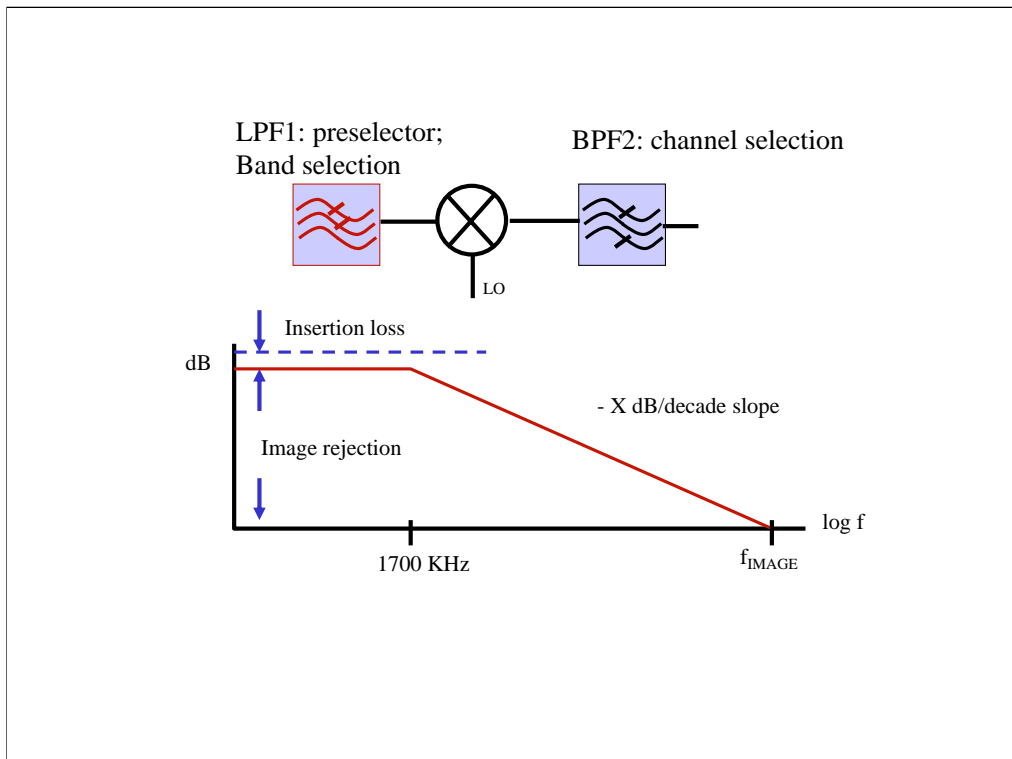
Let's make the preselection filter simple and cheap: 2 poles give - 40 dB/decade.

We will design according to two requirements:

minimum of 40 dB image rejection ratio

inexpensive IF filter: try 10.7 MHz IF frequency

Let: $f_{RF, min}$ = 530 KHz. $f_{IMAGE} = f_{RF,min} + 2 f_{IF}$ = 21.93 MHz

LPF filter cutoff frequency must be at 1700 KHz to cover entire AM band, so check image rejection to see if meet spec. With -40 dB/decade, we will beat the spec. The filter will be 40 dB down at 17 MHz.

So, at 21.93 MHz: $\log(21.93/17) = 0.11$ attenuation = $40 + 0.11 * 40 = 44.4$ dB

Determine LO frequency

- $f_{RF} + f_{LO} = f_{IF}$ (low LO)
  - $f_{LO,530} = 10.17$ MHz
  - $f_{LO,1700} = 9.0$ MHz
- $f_{LO} - f_{RF} = f_{IF}$ (high LO)
  - $f_{LO,530} = 11.23$ MHz
  - $f_{LO,1700} = 12.4$ MHz

$f_{RF}=0.53$ 1.7 $f_{IF} = 10.7$ $f_{IMAGE}=21.93$
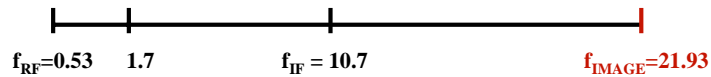
Again, 2 choices of LO frequency. Either one would work well for either image rejection or oscillator implementation.

Dual conversion receiver

- Used for good image rejection with
    - high first IF frequency: lowpass preselector
    - First BPF is for image rejection
   - Second BPF for channel selection

Preselector Lowpass $\quad f_{LO}1 \quad$ BPF1 Image rejection $\quad f_{LO}2 \quad$ BPF2 Channel Selection

f_{IF1} $\qquad$ f_{IF2}
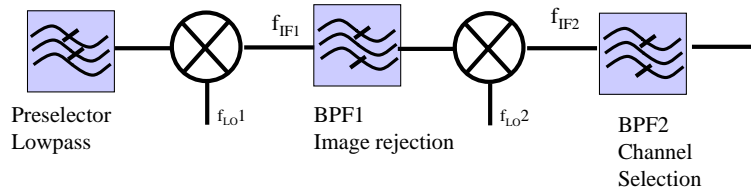
A high first IF frequency, as shown in the previous example, places the image frequency well away from the desired signal. Then, a simple lowpass filter can be used for preselection in some cases.

But, this high first IF may present problems for channel selection. If a narrow modulation bandwidth is used, the filter bandwidth of BPF1 will be small. Then, a high loaded Q is required, with the associated high losses. In order to gain added flexibility in managing images and spurs, as well as providing for a lower Q channel selection filter, a second mixer is often used to downconvert to a much lower second IF frequency. With this architecture, we avoid having to trade off selectivity for sensitivity.

Automatic Gain Control

- Need to maintain a linear signal path to avoid distortion and to keep a constant signal level at the output
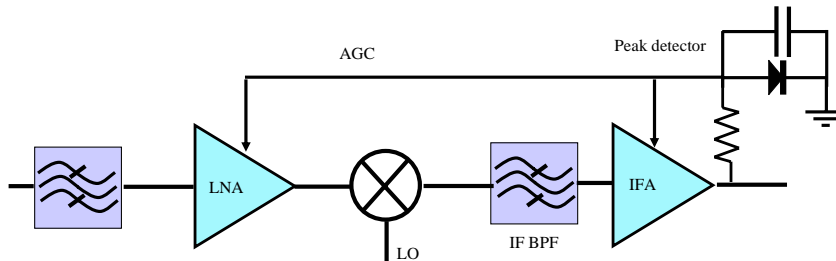
Automatic gain control (AGC or RSSI) is used as a low frequency feedback loop within a receiver. The signal amplitude is measured with a peak detector and rectified. This control voltage can then be used to control the gain of amplifier stages so that the signal path can remain linear.

In some cases, the LNA can be switched out of the system or attenuation switched into the loop to handle strong signals.

The AGC path must accommodate the delay found in the filters. This can make the loop unstable unless the AGC voltage to the LNA and other early stages (pre-filtering) are suitably delayed.

Compare Superhet with Direct Conversion

- ## <u>Superhet:</u>
  - Benefits:
    1. Low cost, high quality fixed frequency IF bandpass filters are available
    2. $1/f$ noise at IF is negligible
    3. Good dynamic range with AGC
  - Challenges:
    1. Image and spurious signal control
    2. Off-chip filters consume power, area
    3. Power dissipation
    4. Simple image control solutions (LPF for example) may create a strong signal overload problem
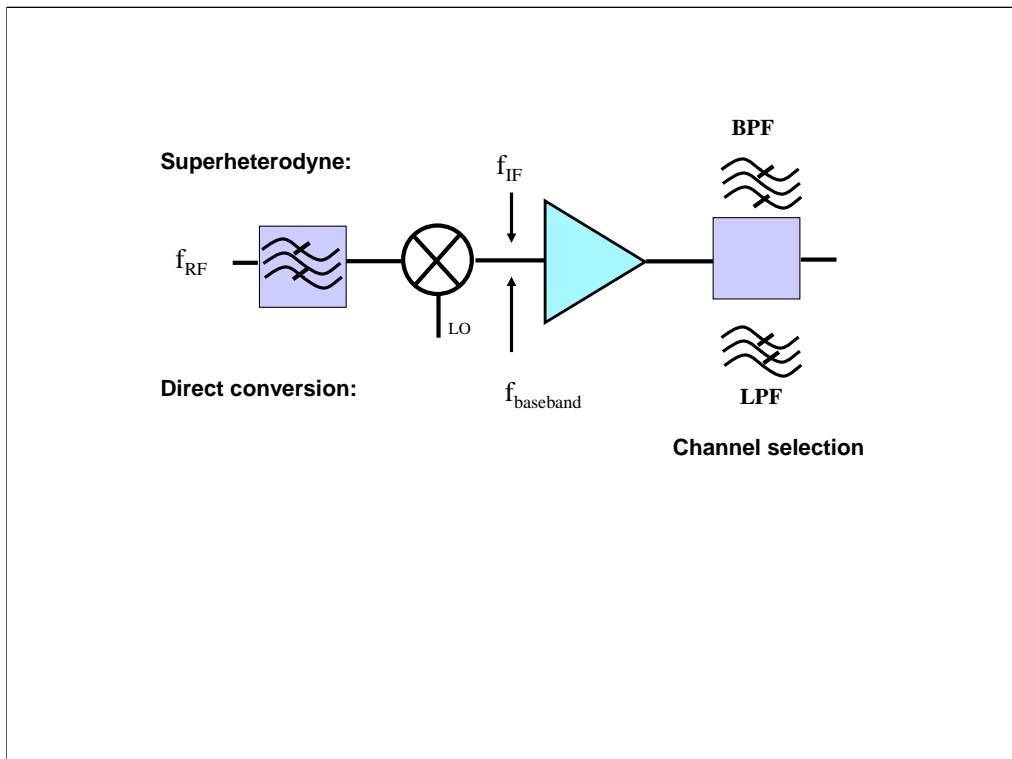
The superheterodyne or superhet architecture uses an intermediate (IF) frequency following the mixer. This is selected such that amplifiers and channel selection filters are available with suitable performance. Image rejection also plays a role as will be seen later.

The direct conversion mixes down to DC. The advantage is that filters can be integrated on chip using active or digital filter design approaches. But, LO leakage causes a DC offset. Also, the mixer in most cases must be a more complex image rejecting design because the signal and image fold over onto the same frequency.

Compare Superhet with Direct Conversion

- ## Direct Conversion:
    - Benefits:
        1. simplest receiver architecture
        2. baseband filtering can be done digitally or with active filters
    - Challenges:
        1. 1/f noise
        2. DC offset can be caused by LO to RF leakage at mixer input
        3. Requires image rejecting mixer – precision
        4. Second order distortion. If there is a strong input signal, the second order nonlinearity creates a signal at 2f. This mixes with the LO at frequency f producing another source of DC offset.

The susceptibility to DC offset from LO feedthrough and second-order distortion can be reduced by careful design. The local oscillator is often set to twice the frequency and divided by 2 to avoid LO leakage. Balanced circuits in the mixer and amplifier will help to suppress second-order distortion. Finally, many have opted for a low frequency IF rather than a DC IF to avoid offset problems. This has its own hazards with regard to image rejection.

Direct Conversion

a) Multiplication of the input signal with a cosine function
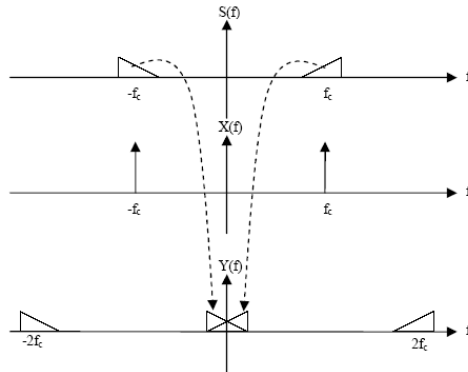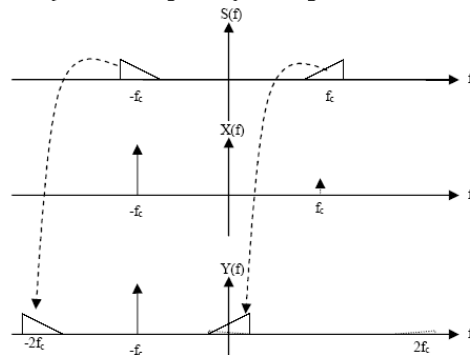

$y(t) = s(t) \cdot x(t)$
$x(t) = \cos(\omega_c \cdot t)$

$\Rightarrow Y(f) = S(f) * X(f)$
$\Rightarrow$ image frequency signal superimposes the baseband signal **and cannot be separated any more! (comes from second frequency component of X(f)**

Figure from R. Vogt, ETH Zurich

b) Multiplication with a <u>complex</u> time function, containing <u>only one</u> frequency component at $-f_c$

x(t) has an <u>asymmetric</u> spectral density of the amplitude
$\Rightarrow$ x(t) is a <u>complex</u> function:

$$X(f) = \delta(f+f_c) \ \Rightarrow$$

$$\underline{x}(t) = e^{-j\omega_c t} \qquad \omega_c = 2\pi f_c$$
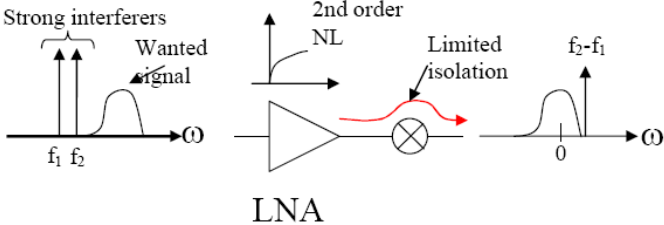
Figure from R. Vogt, ETH Zurich

Figure from R. Vogt, ETH Zurich

⇒ The low-IF receiver
The RF signal is not downconverted to DC, but to a „very low"
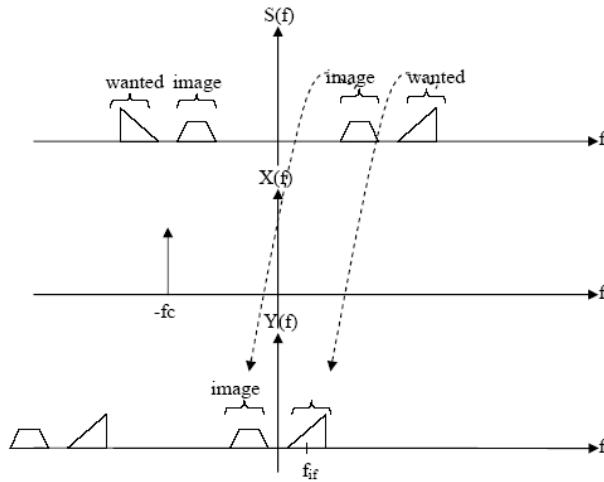center frequency

Figure from R. Vogt, ETH Zurich

Additional reading

- See Razavi, RF Microelectronics, Chap. 5, Prentice-Hall, 1998. (on eres web)