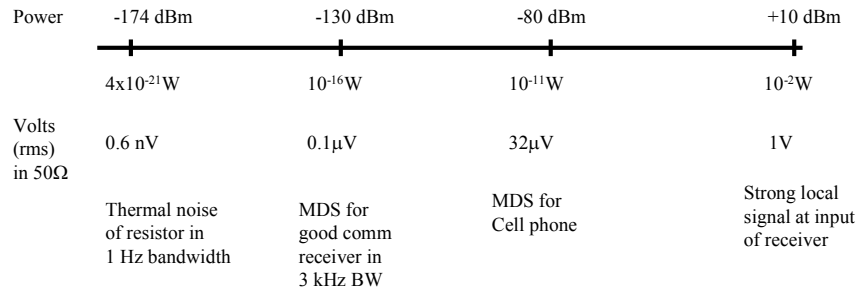# Introduction to Receivers

- Purpose: translate RF signals to baseband
  - Shift frequency
  - Amplify
  - Filter
  - Demodulate
- Why is this a challenge?
  - Interference
  - Large dynamic range required

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.

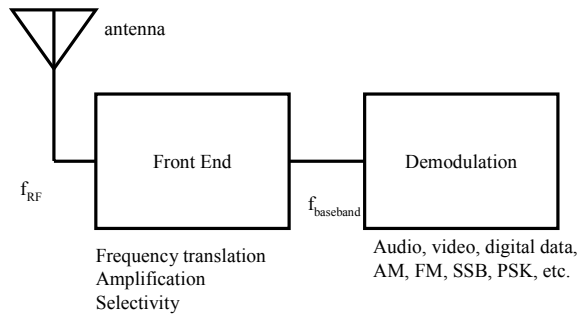| Power	-174 dBm	-130 dBm	-80 dBm	+10 dBm
	4×10^{-21}W	10^{-16}W	10^{-11}W	10^{-2}W
Volts (rms) in 50Ω	0.6 nV	0.1μV	32μV	1V
	Thermal noise of resistor in 1 Hz bandwidth	MDS for good comm receiver in 3 kHz BW	MDS for Cell phone	Strong local signal at input of receiver

RF to baseband

- 2 dominant architectures:
  - Superheterodyne.
    - 1917 E. H. Armstrong
    - Uses intermediate frequency
    - 99% of receivers use this
  - Direct conversion.
    - Niche application
    - 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.
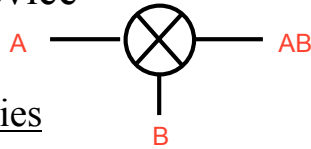
Receiver block diagram

antenna

Front End

Demodulation

f_{RF}

$f_{baseband}$

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.
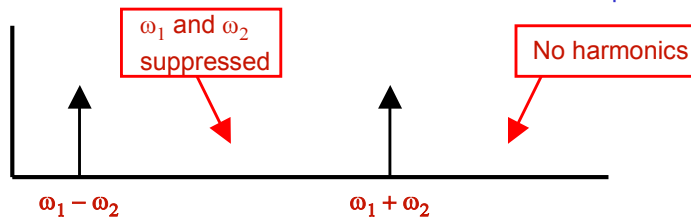
What is a mixer?

- 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.

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

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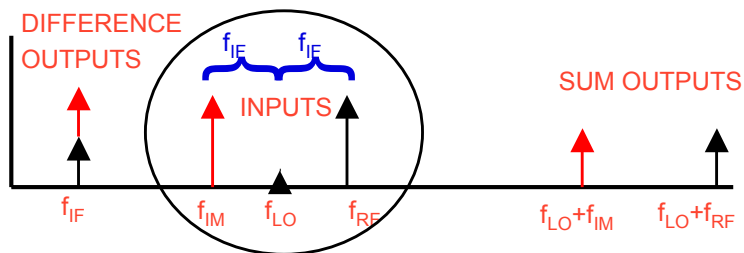
Even in an ideal multiplier, there are two RF input frequencies (F_{RF} and F_{IM}) whose second-order product has the same difference IF frequency.

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

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.

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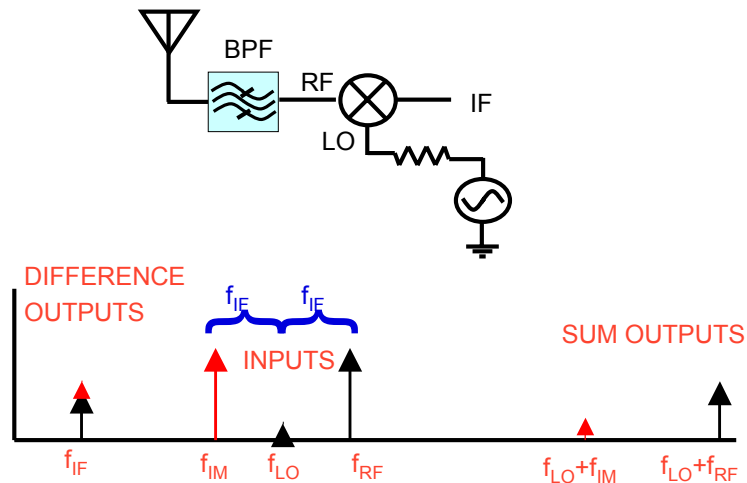
A *bandpass preselection filter* is often used ahead of the mixer to suppress the image signal. The IF and LO frequencies must be carefully selected to avoid image frequencies that are too close to the desired RF frequency to be effectively filtered.

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 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

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.

Superheterodyne: f_{IF}

f_{RF}

LO

Direct conversion: $f_{baseband}$
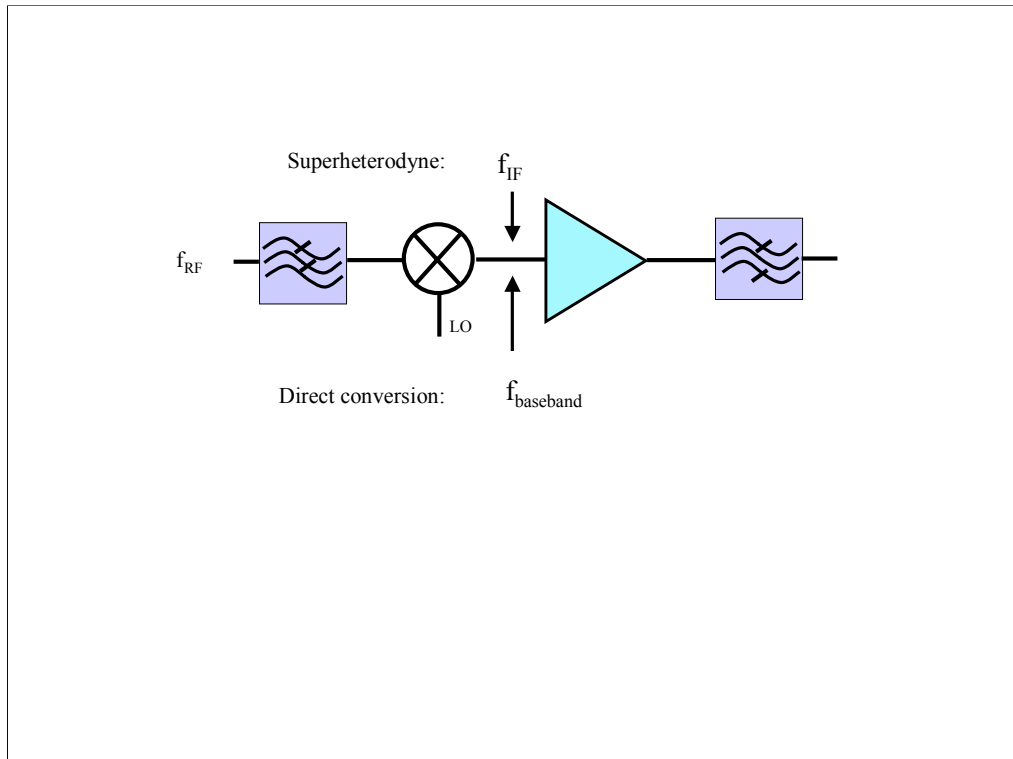
The superheterodyne or superhet architecture uses an intermediate (IF) frequency following the mixer. This is selected such that amplifiers and channel selection filters are available with suitable performance. Image rejection also plays a role as will be seen later.

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

- ## <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

Compare Superhet with Direct Conversion

- **<u>Direct Conversion:</u>**
  - 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.
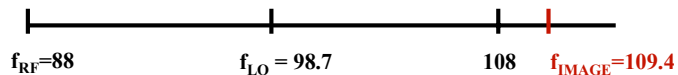
FM radio example

BPF1: preselector   BPF2: channel selection

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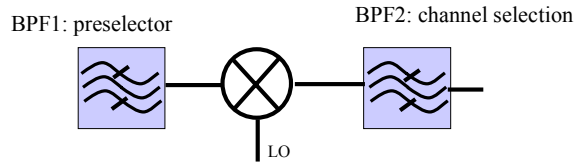
- FM broadcast band: 88 to 108 MHz
- Standard IF frequency = 10.7 MHz
- Image is always out of band
  - $f_{IMAGE} = f_{RF} + 2\ f_{IF}$

    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. 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.

AM Radio Example

BPF1: preselector

BPF2: channel selection

LO
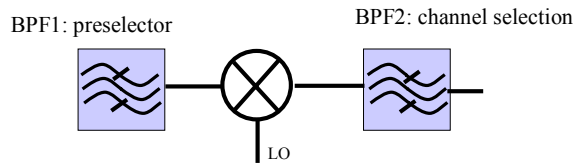
- AM broadcast band: 530 to 1700 KHz
- Standard IF frequency = 455 KHz
- Image is often in-band.
- High Q tunable preselector filter is needed

Worst case with high side LO:

f_{RF}=530 f_{LO} = 985 f_{IMAGE}=1400   1700
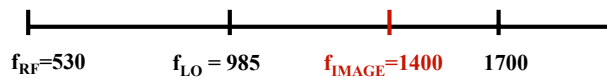
LO frequency selection: we always have 2 choices.

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
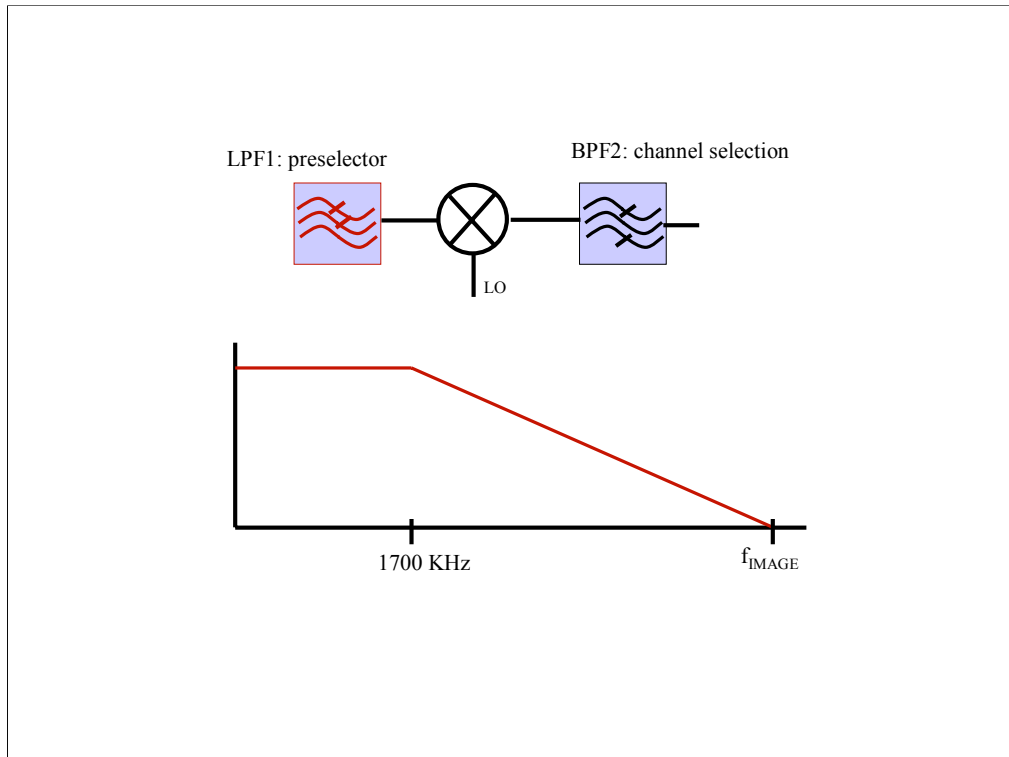
Let's make the preselection filter simple and cheap: 2 poles gives - 40 dB/decade.
We will design according to two requirements:

        minimum of 40 dB image rejection ratio

        inexpensive IF filter: try 10.7 MHz IF frequency

Worst case: fRF, min = 530 KHz. fIMAGE = fRF,min + 2 fIF = 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
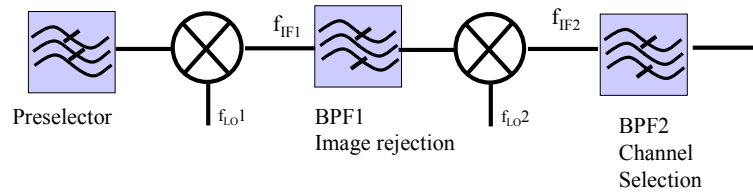
- $f_{RF} + f_{LO} = f_{IF}$ (low LO)
  - $f_{LO,530} = 10.17$ MHz
  - $f_{LO,1700} = 9.0$ MHz
- $f_{LO} - f_{RF} = f_{IF}$ (high LO)
  - $f_{LO,530} = 11.23$ MHz
  - $f_{LO,1700} = 12.4$ MHz

Worst case:

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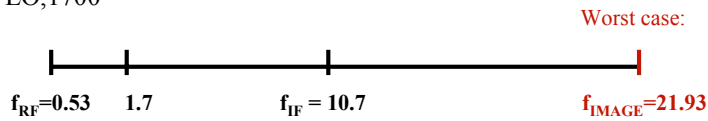
Again, 2 choices of LO frequency. Either one would work well for either image rejection or oscillator implementation.

Dual conversion receiver

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

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

f_{IF1} $\quad$ f_{IF2}

Dual conversion receiver

1st IF
88 or 94 MHz

2nd IF
455 kHz

869-894 MHz (AMPS)
890-915 MHz (GSM)
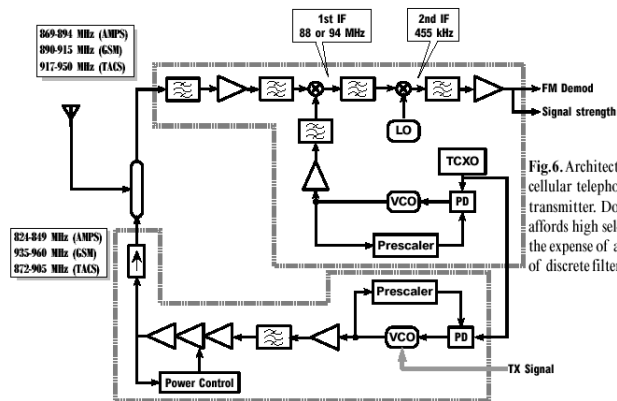917-950 MHz (TACS)

FM Demod

Signal strength

LO

TCXO

Fig.6. Architecture of a cellular telephone receiver and transmitter. Double conversion affords high selectivity, but at the expense of a large number of discrete filters.

VCO   PD

Prescaler

824-849 MHz (AMPS)
935-960 MHz (GSM)
872-905 MHz (TACS)
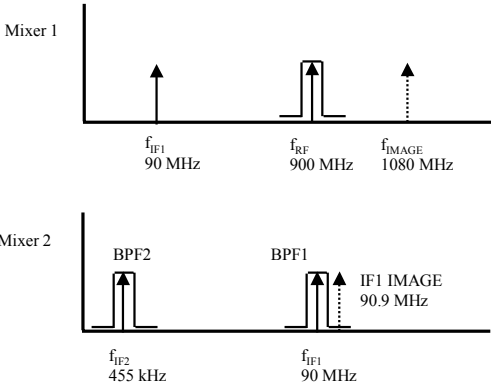
Prescaler

VCO   PD

TX Signal

Power Control

Ref. A. Abidi, "Low-power radio frequency IC's for portable communications,"
Proc. IEEE, 83, #4, pp. 544-569, April 1995.

The single conversion high fIF receiver approach (fIF >> fRF) only works if high IF filters are available with the required center frequency and bandwidth.

Low fIF works when the images can be controlled by a suitable tunable preselection filter.
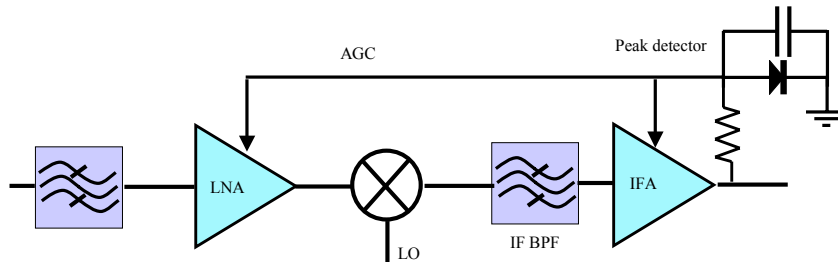
In many cases these might not exist, so a frequently used alternative architecture is the dual conversion receiver. Two mixers are used. The first LO is tunable; the second LO is fixed.

Frequency plan

Mixer 1

f_{IF1}
90 MHz

f_{RF}
900 MHz

f_{IMAGE}
1080 MHz

Mixer 2

BPF2

BPF1

IF1 IMAGE
90.9 MHz

f_{IF2}
455 kHz

f_{IF1}
90 MHz

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.