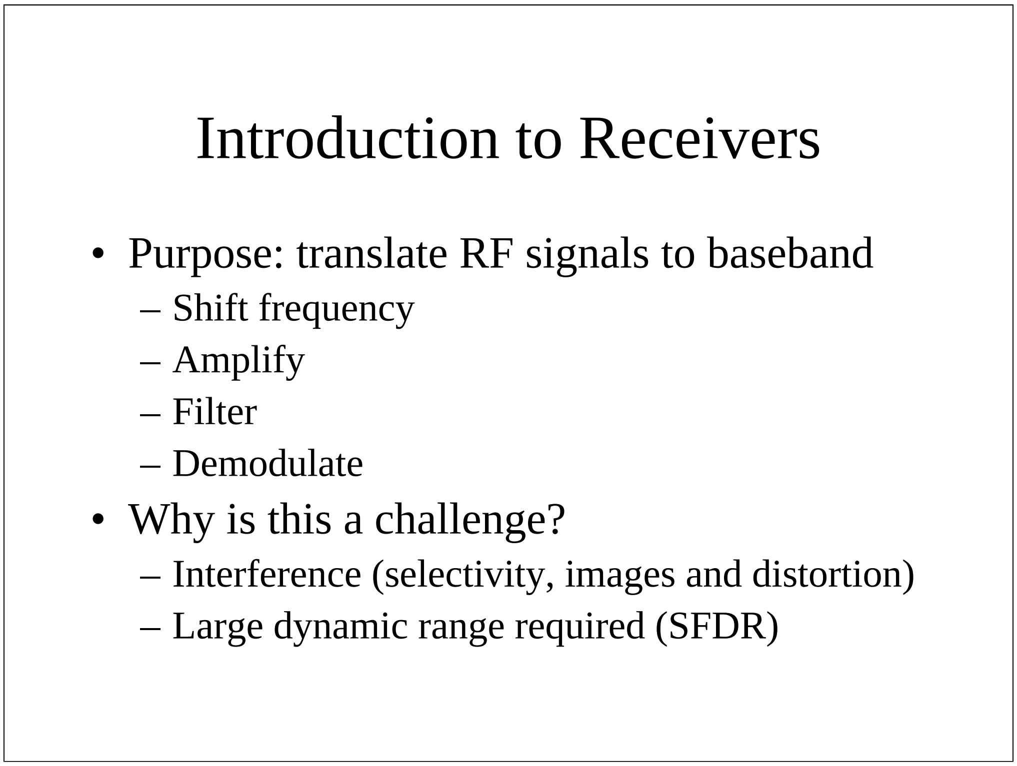


Introduction to Receivers

- 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
	$4x10^{-21}$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

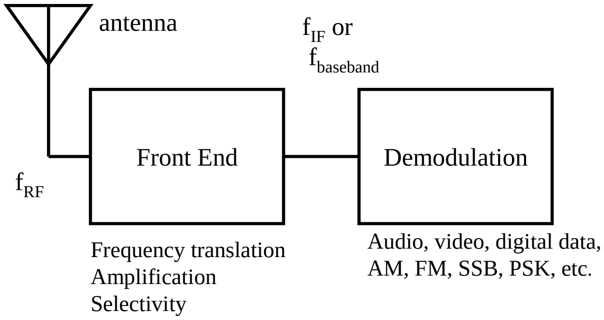
- 2 dominant architectures:
  - Superheterodyne.
    - 1917 E. H. Armstrong
    - Uses intermediate frequency
    - 99% of receivers use this
  - Direct conversion.
    - Becoming more popular for single chip radios
    - Less hardware, but troublesome
- Both use frequency translation
  - Mixer for up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

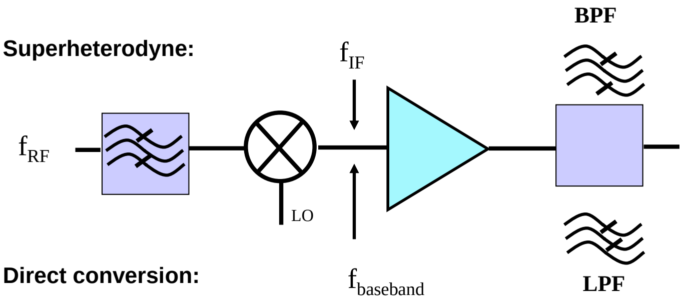
Front End

Demodulation

Frequency translation
Amplification
Selectivity

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

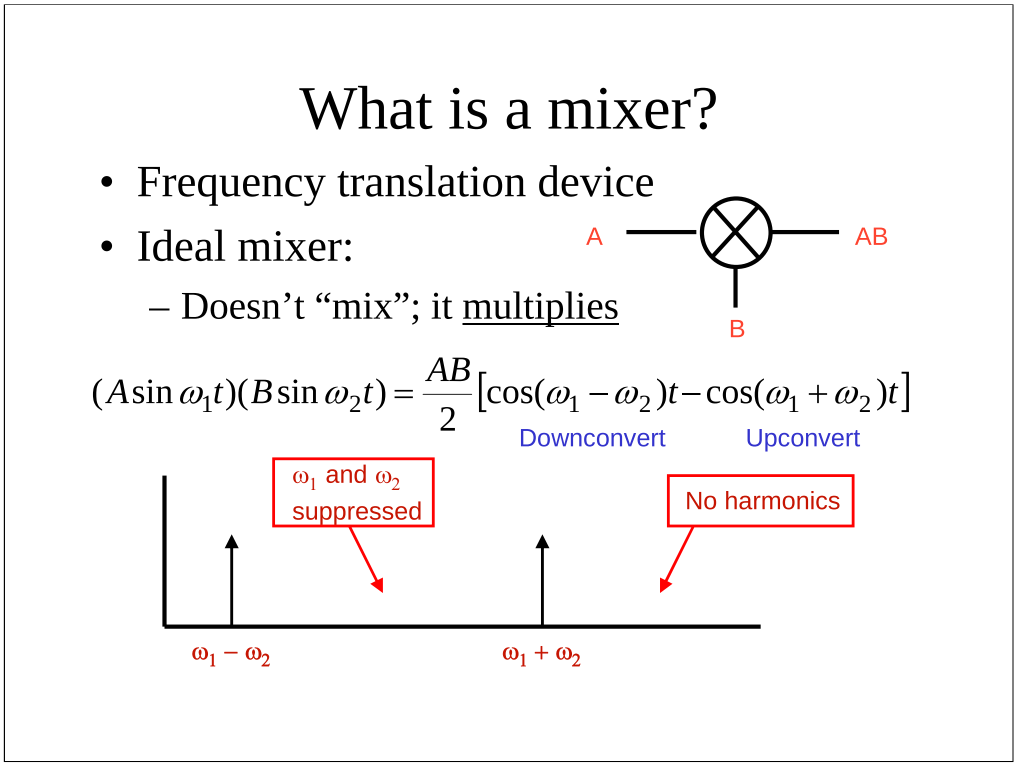
The front end of the receiver performs the frequency translation, channel selection and amplification of the signal.



Channel selection

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 complex image rejecting design because the signal and image fold over onto the same frequency.



What is a mixer?

- Frequency translation device
- Ideal mixer:
  - Doesn't "mix"; it multiplies

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

Downconvert Upconvert

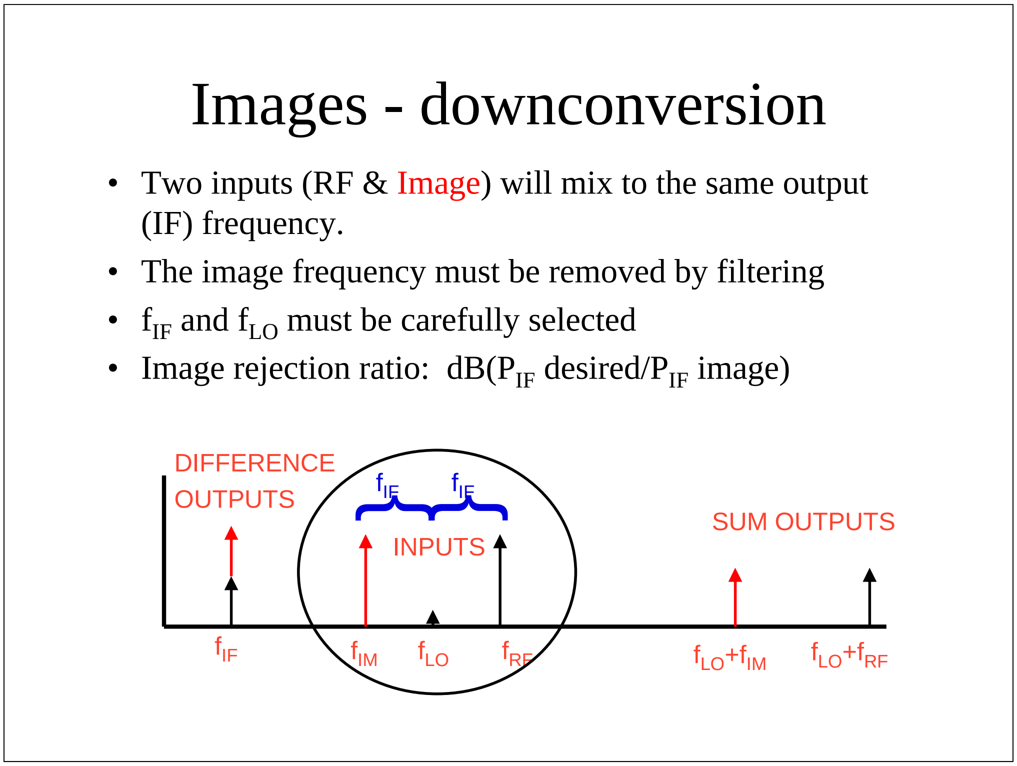
ω_1 and ω_2 suppressed

No harmonics

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 - downconversion

- 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.

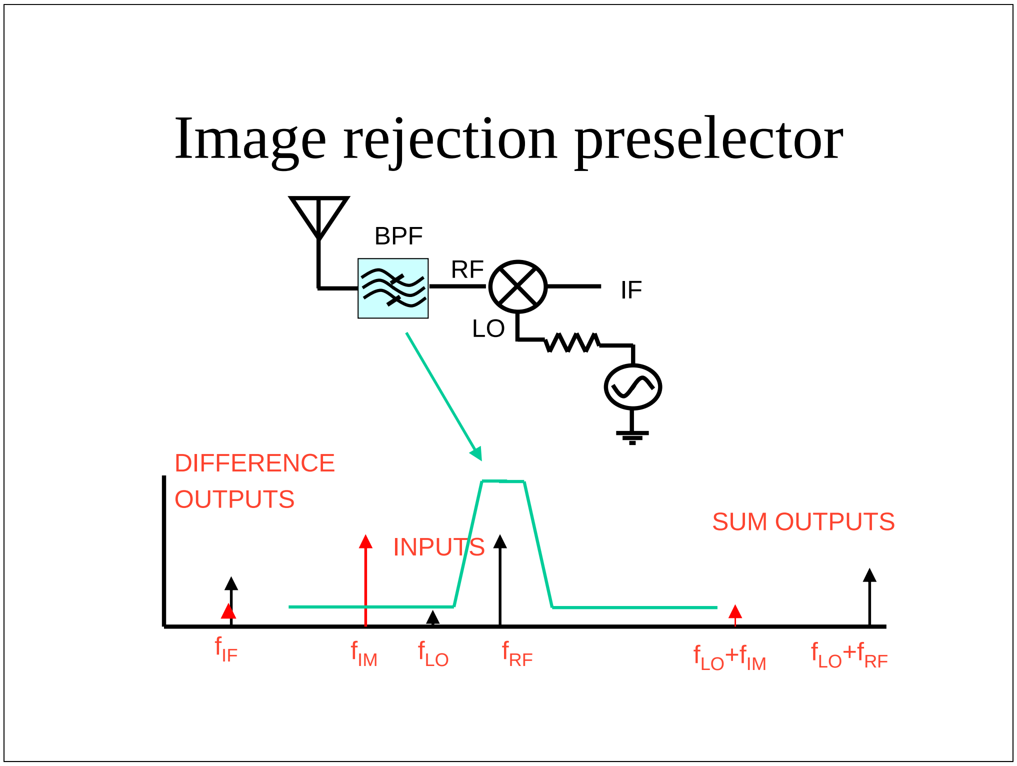


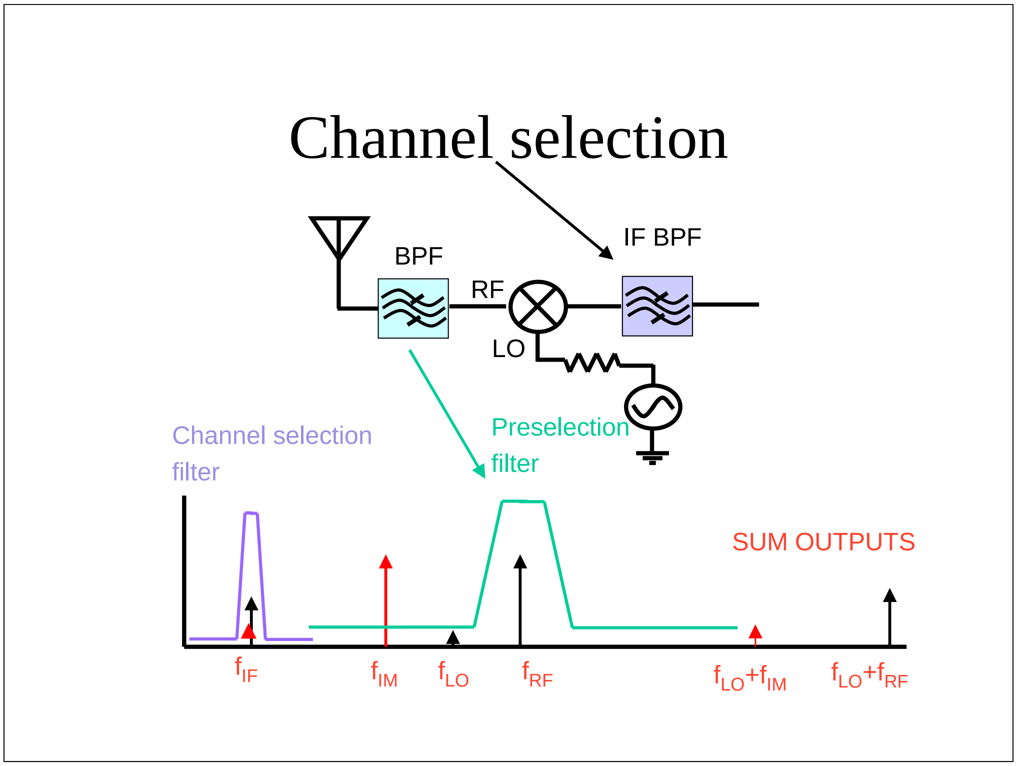
Image rejection preselector

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.

So far, the spectrum exhibited by the ideal multiplier is free of harmonics and other spurious outputs (*spurs*). The RF and LO inputs do not show up in the output. While accurate analog multiplier circuits can be designed, they do not provide high dynamic range mixers since noise and bandwidth often are sacrificed for accuracy.



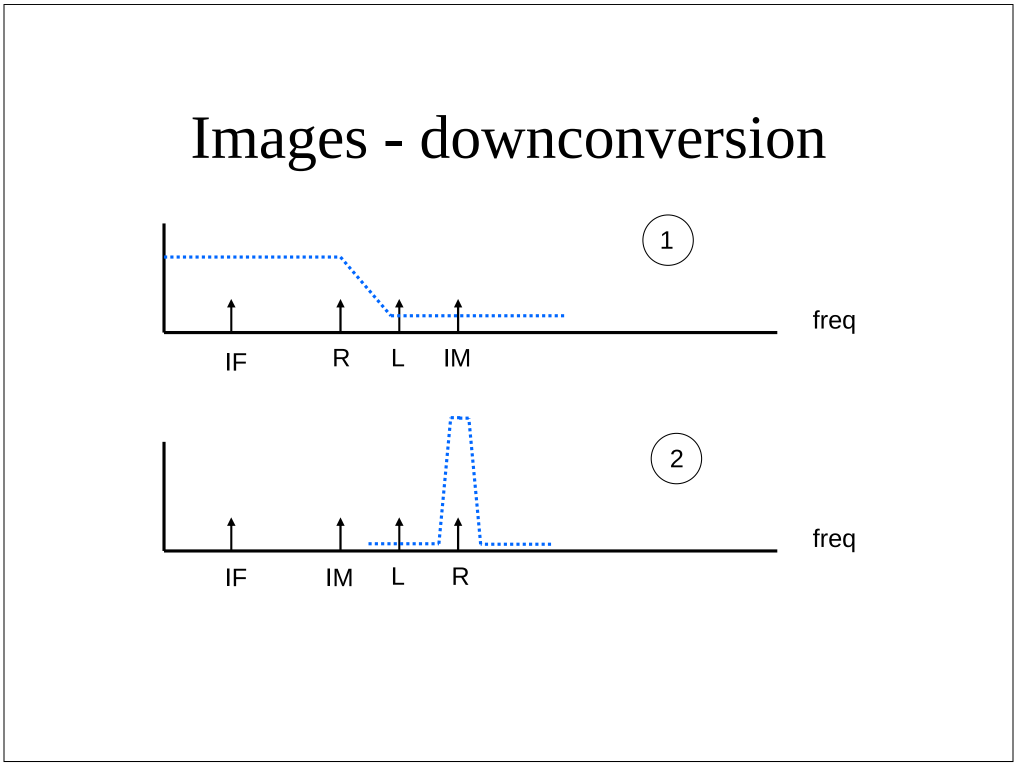
Channel selection

A narrow band, fixed frequency filter (crystal, SAW, ceramic) is often used for channel selection. It is easier to build a high Q narrowband fixed frequency filter at a lower frequency than to build a tunable high Q high frequency filter.

The local oscillator tunes the front end to select the input frequency.

$$f_{IF} = f_{RF} - f_{LO}$$

The example shown above downconverts to a lower intermediate frequency. This is the *superhetrodyne* approach invented by Armstrong. Another choice, the *direct conversion* architecture, downconverts directly to baseband (zero IF). Then, a simple lowpass filter is used for anti-aliasing, an A/D converter and DSP is used for demodulation.



Images - downconversion

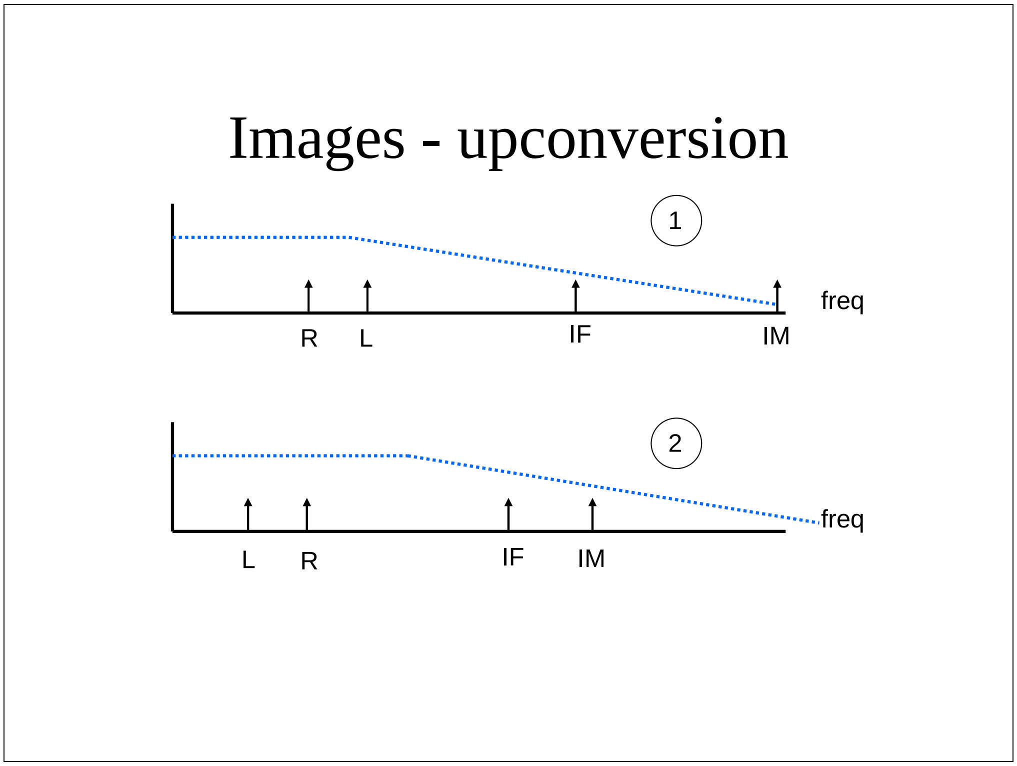
There are two cases that apply with downconversion – IF freq. lower than RF.

Case 1. LO frequency is higher than RF frequency. This places the image frequency 2 x fIF above the RF frequency. A sharp cutoff lowpass filter (LPF) or bandpass filter (BPF) could be used to attenuate the image.

$$f_{IF} = f_{RF} - f_{LO}$$

Case 2. RF frequency is higher than LO frequency. This places the image frequency 2 x fIF below the RF frequency – now inband for a LPF. A sharp cutoff bandpass filter (BPF) must be used to attenuate the image.

$$f_{IF} = f_{LO} - f_{RF}$$



Images - upconversion

The upconversion cases often can use a LPF for image rejection. In fact, the whole reason for upconverting in a receiver is to make image rejection more effective. But, we see that for the same f_{RF}, the two cases give much different results.

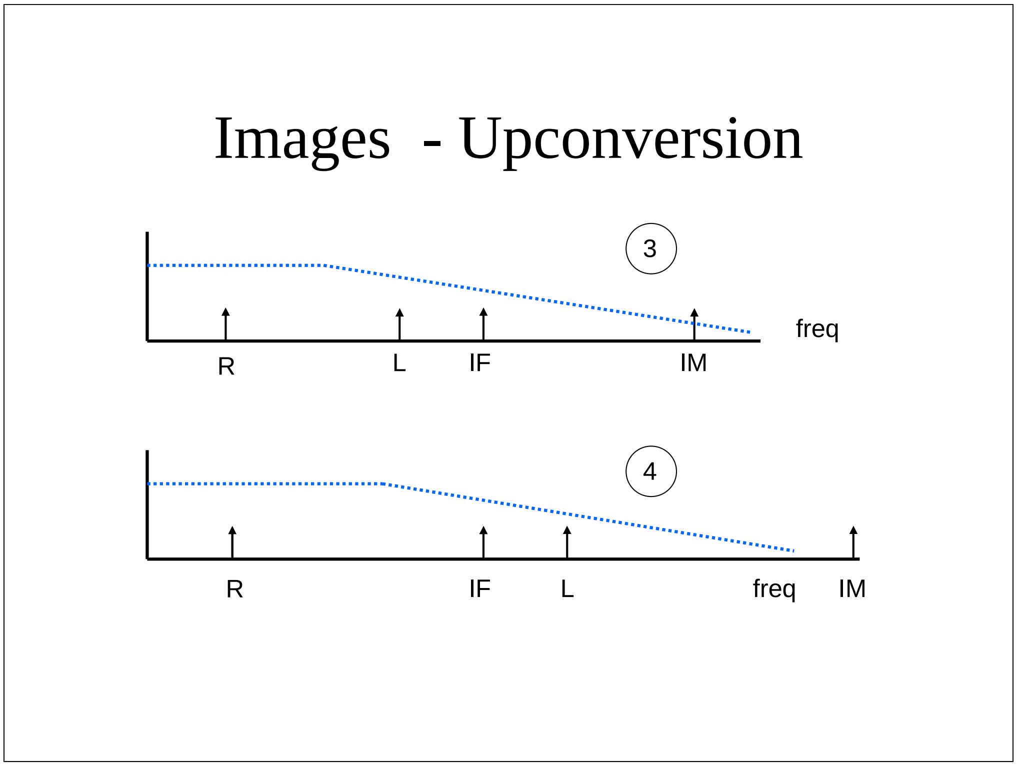
Case 1: Here the LO is higher than RF. Two input frequencies produce the same IF

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

The image frequency is much higher than the RF frequency. This makes it easy to use a simple LPF to get significant image rejection.

Case 2: Same equations, but now the LO is lower than RF. This places the IF and IM frequencies lower, making it more demanding for the LPF to provide significant image rejection.

An IF filter is often used here to block potentially interfering spectral inputs from creating distortion downstream in the receiver where amplification is provided. This function is often called a “roofing filter”.



Images - Upconversion

Or, alternatively, if we chose to keep the same IF frequency, probably a common choice since IF filters are available at only certain frequencies, the picture changes slightly from cases 1 and 2.

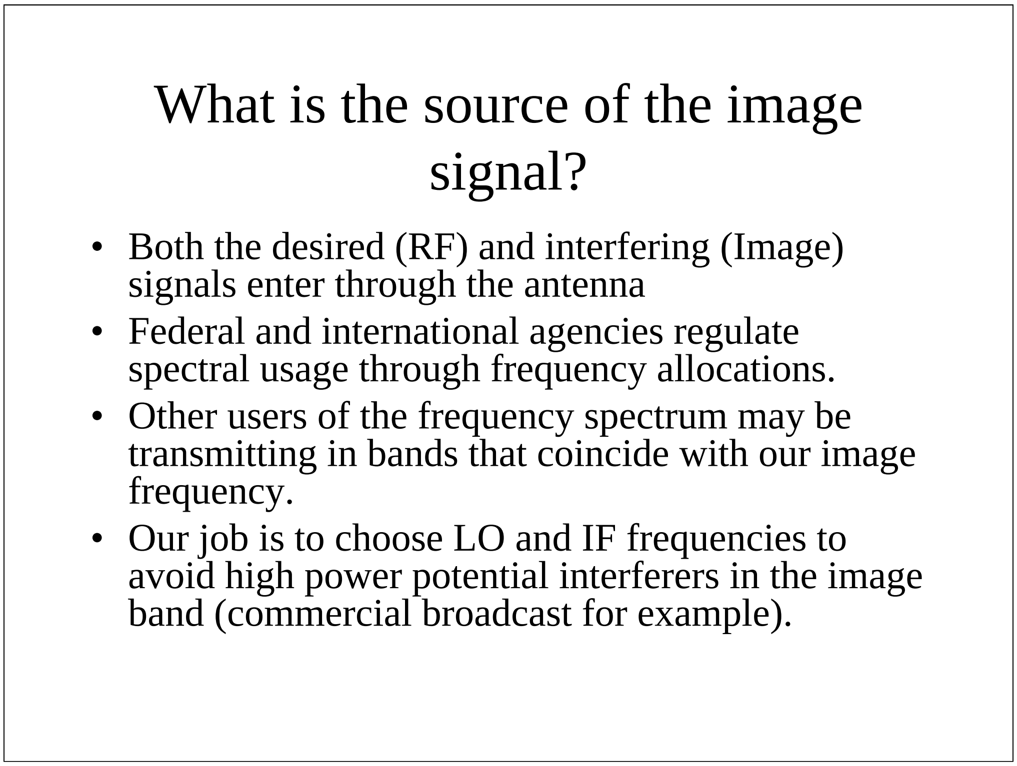
Case 3:

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

Case 4:

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

Once again, the high LO injection leads to a higher image frequency and better image rejection.

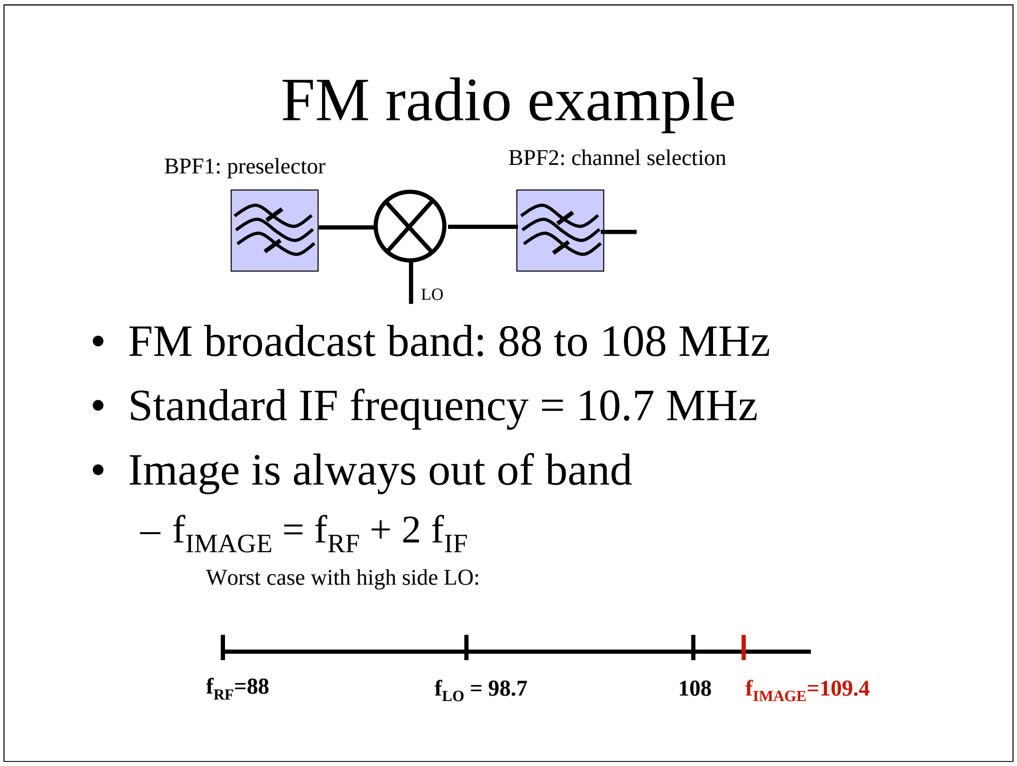


What is the source of the image signal?

- Both the desired (RF) and interfering (Image) signals enter through the antenna
- Federal and international agencies regulate spectral usage through frequency allocations.
- Other users of the frequency spectrum may be transmitting in bands that coincide with our image frequency.
- Our job is to choose LO and IF frequencies to avoid high power potential interferers in the image band (commercial broadcast for example).

Having said the above, we also have a cost consideration. IF filters are available only at certain frequencies if we want inexpensive mass-produced filters. Here are some common ones: 455 kHz, 10.7 MHz, 21.4 MHz, 45 MHz, 70 MHz.

There are also filters available in the VHF/UHF range.



FM radio example

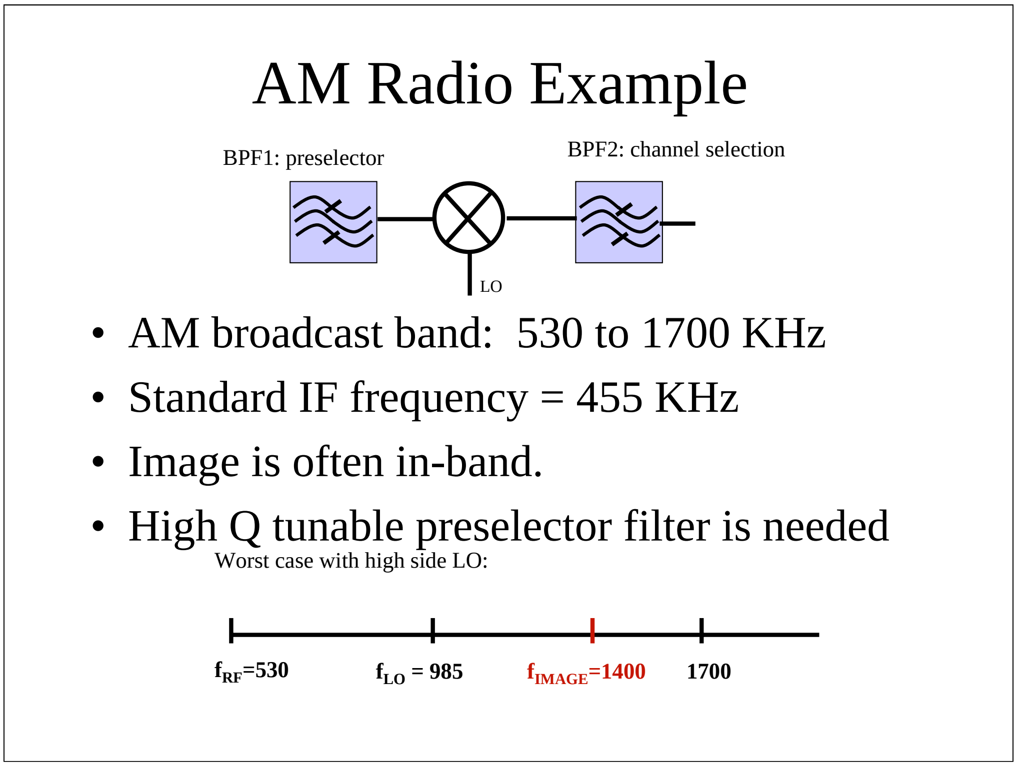
- FM broadcast band: 88 to 108 MHz
- Standard IF frequency = 10.7 MHz
- Image is always out of band
  - $f_{IMAGE} = f_{RF} + 2\ f_{IF}$

Worst case with high side LO:

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

- 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:

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

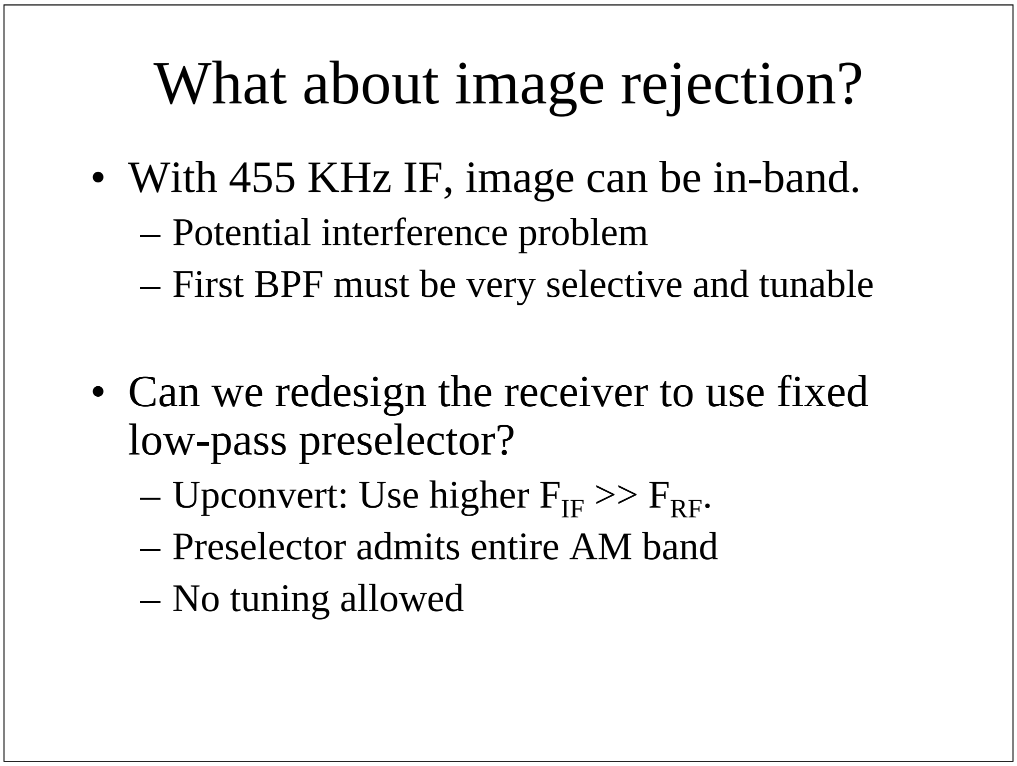
1700 - 455 = 1245 KHz

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

530 + 455 = 985 KHz

1700 + 455 = 2155 KHz

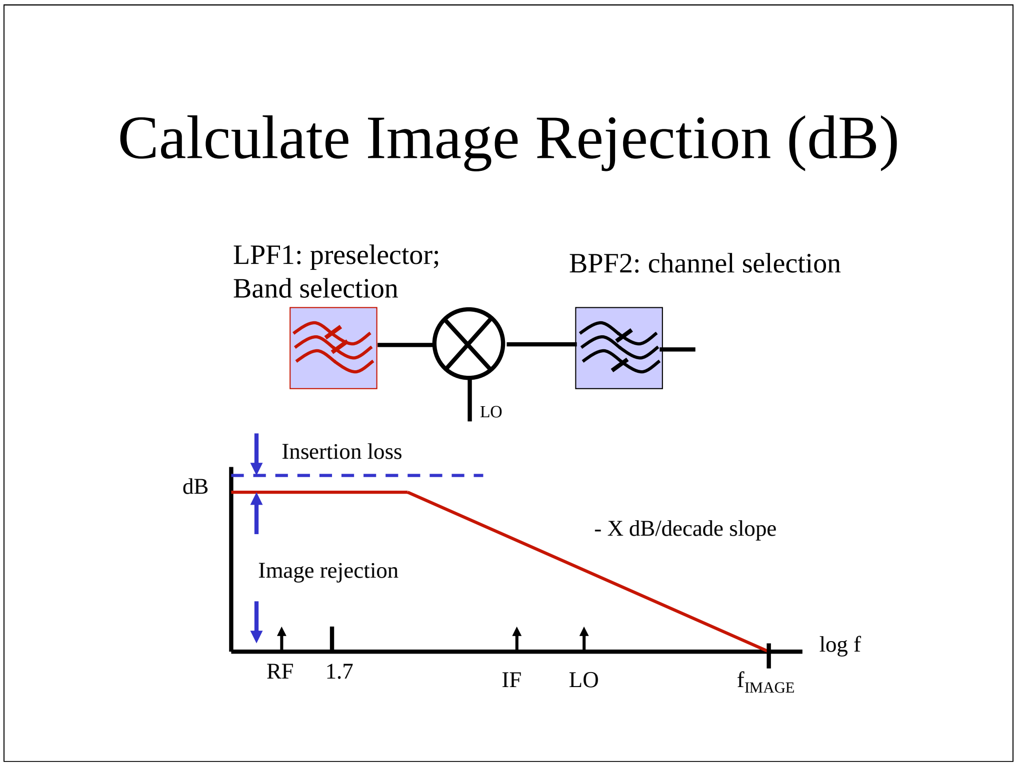
LO choice #1 requires a 16.6 to 1 tuning range for the LO; #2 only requires 2.2 to 1. The oscillator will be much easier to implement.



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?
  - – Upconvert: Use higher $F_{IF} >> F_{RF}$.
  - – Preselector admits entire AM band
  - – No tuning allowed

What is the source of the image signal? Both desired (RF) and image (IM) signals enter the receiver from the antenna. The image signal, if present, would be generated by another spectrum user



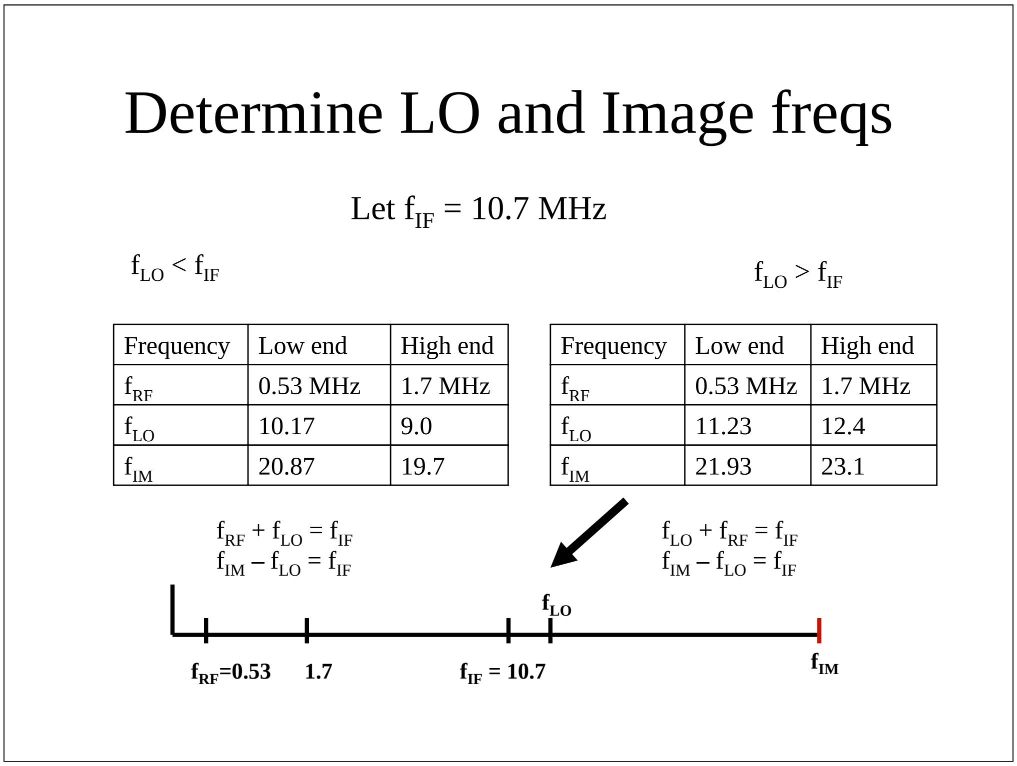
Calculate Image Rejection (dB)

We will use an upconversion approach to achieve a high image frequency. 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



Determine LO and Image freqs

Let $f_{IF} = 10.7$ MHz

$f_{LO} < f_{IF}$

Frequency	Low end	High end
f_{RF}	0.53 MHz	1.7 MHz
f_{LO}	10.17	9.0
f_{IM}	20.87	19.7

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

$f_{LO} > f_{IF}$

Frequency	Low end	High end
f_{RF}	0.53 MHz	1.7 MHz
f_{LO}	11.23	12.4
f_{IM}	21.93	23.1

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

Again, 2 choices of LO frequency. $f_{IM} – f_{LO} = f_{IF}$

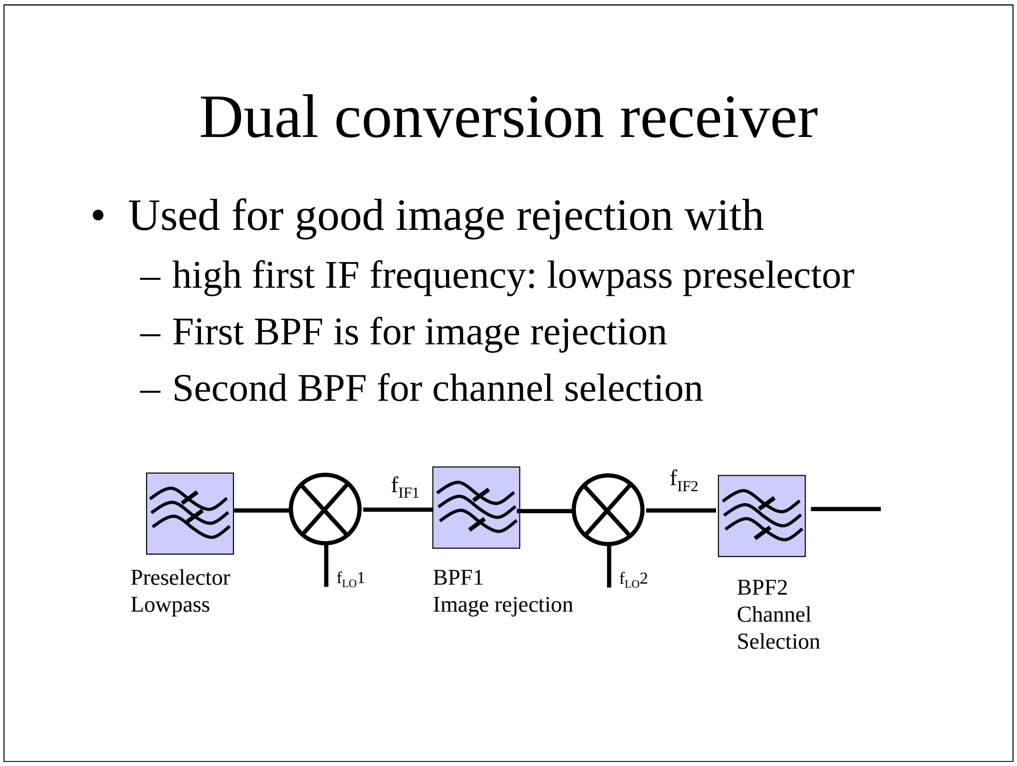
The worst case image frequency with low LO injection would be for $f_{RF} = 1.7$ MHz. In this case, $f_{IM} = 19.7$ MHz

The worst case image frequency with high LO injection would be for $f_{RF} = 0.53$ MHz. In this case, $f_{IM} = 21.93$ MHz.

As we have seen previously, the higher LO frequency will give us better image rejection:

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

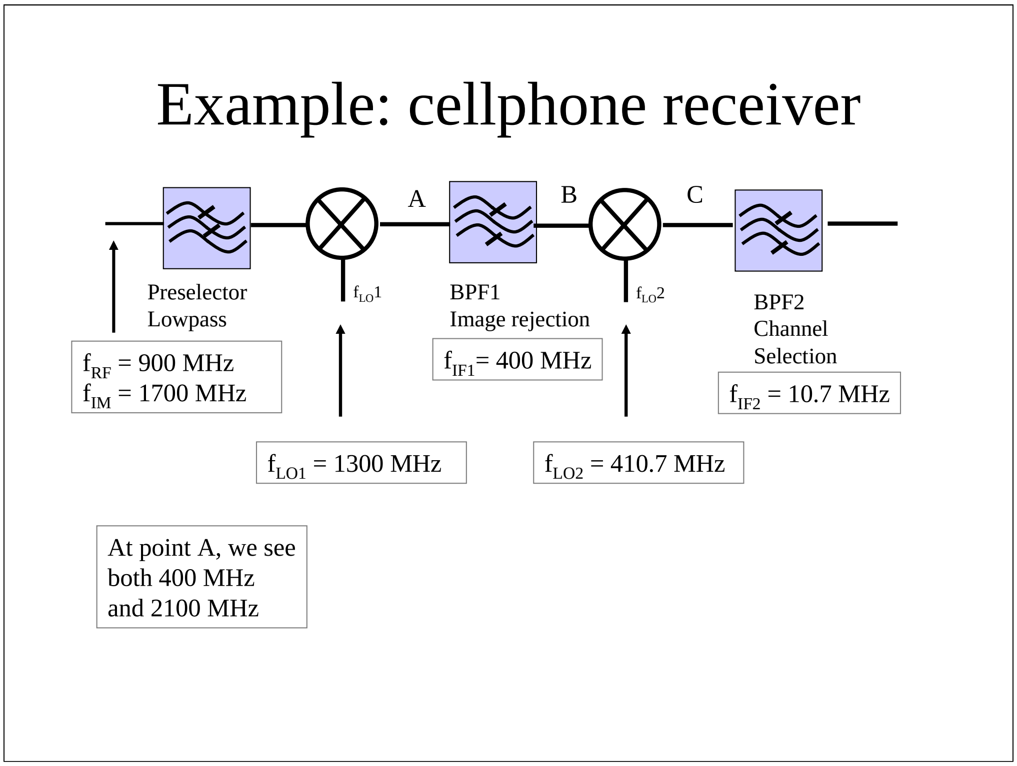


Dual conversion receiver

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

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.



Example: cellphone receiver

f_{RF} = 900 MHz
f_{IM} = 1700 MHz

f_{IF1}= 400 MHz

f_{IF2} = 10.7 MHz

f_{LO1} = 1300 MHz

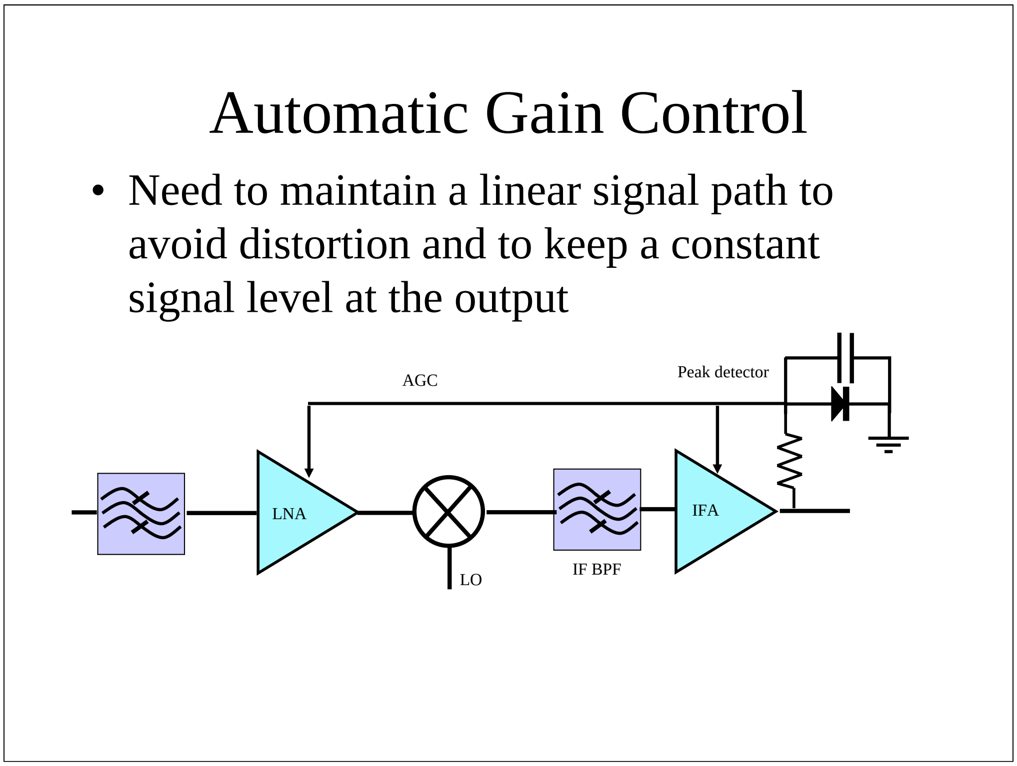
f_{LO2} = 410.7 MHz

At point A, we see both 400 MHz and 2100 MHz

The output of the first mixer contains both the down and upconversion terms: 400 MHz and 2100 MHz. The higher frequency is easily removed by BPF1.

BPF1 must also prevent an image from passing though the second mixer. At point B, the IF frequency is 410.7, but the image frequency would be 421.4 MHz. So, the bandwidth of BPF1 must be small enough to reject signals at 421.4 MHz.

At C, we have both 10.7 MHz and 810.7 MHz. $f_{IF2} = f_{LO2} - f_{IF1}$. But we also get the sum term. The higher frequency is easily removed by BPF2. This can be a narrow bandwidth filter for channel selection.



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.

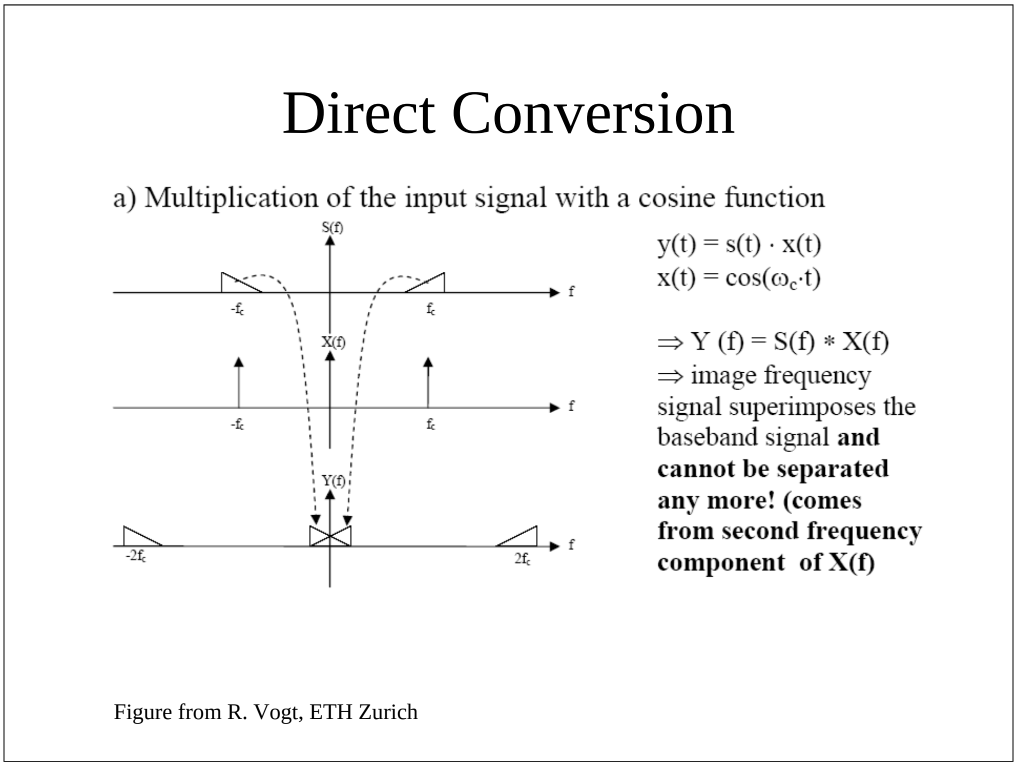
Compare Superhet with Direct Conversion

- **Superhet:**
  - 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

- **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

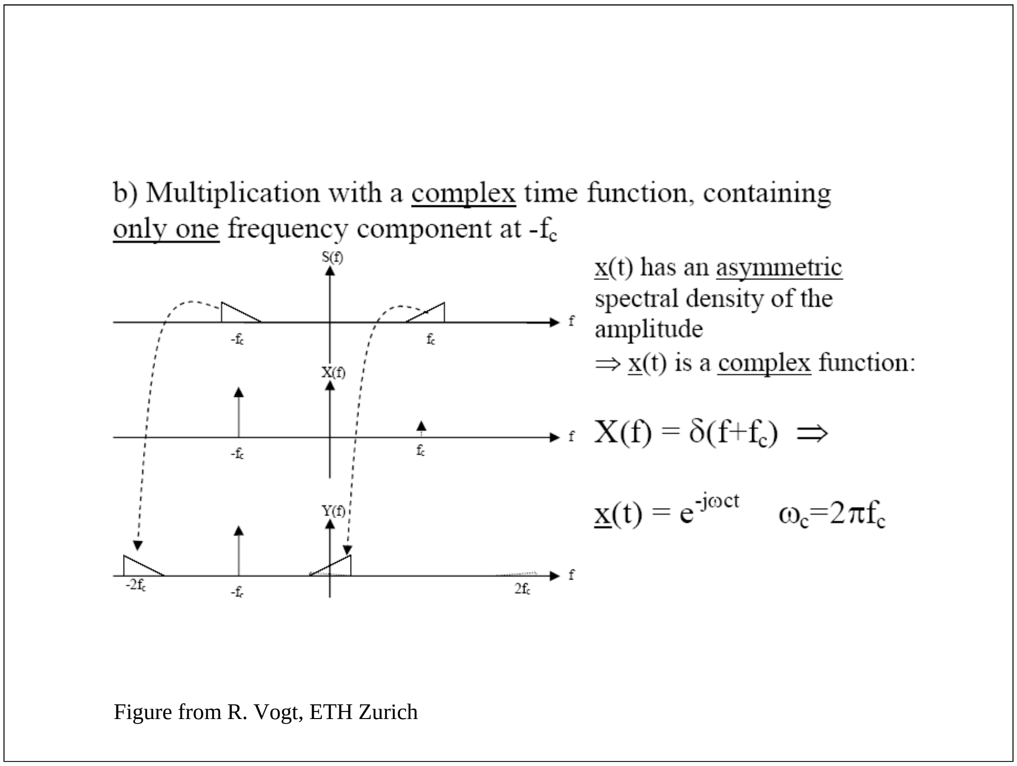
a) Multiplication of the input signal with a cosine function

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

$\Rightarrow Y(f) = S(f) * X(f)$
$\Rightarrow$ 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

Both positive and negative frequency components are mixed to zero frequency. Their images overlap and cannot be separated.



b) Multiplication with a complex time function, containing only one frequency component at -f$_c$

$\underline{x}(t)$ has an asymmetric spectral density of the amplitude

⇒ $\underline{x}(t)$ is a complex function:

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

$$\underline{x}(t) = e^{-j\omega ct} \quad \omega_c=2\pi f_c$$

Figure from R. Vogt, ETH Zurich

With a complex LO frequency, only the positive frequency signal is mixed to baseband. However, the signal and its image, symmetric about 0 frequency, must still be separated with a complex bandpass filter. These will be discussed later in the context of image reject mixer design.

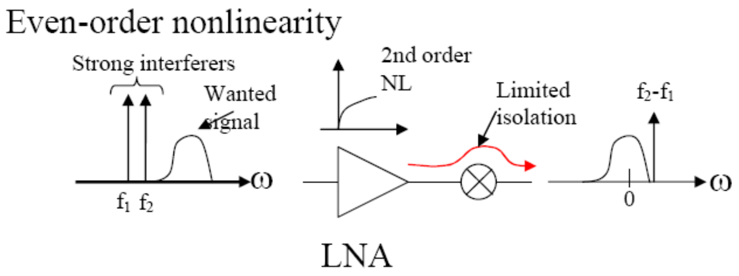


Figure from R. Vogt, ETH Zurich

Suppose $V_{out,LNA} = a_1V_1 + a_2V_2^2$. We will then get a difference term

$$a_2\cos(\omega_1-\omega_2)t$$

which will be at a low frequency. The RF – IF feedthrough from the mixer allows this signal to pass through to the output.

If the input signal has an amplitude modulation, where w_m is the modulation frequency and w_c the carrier frequency,

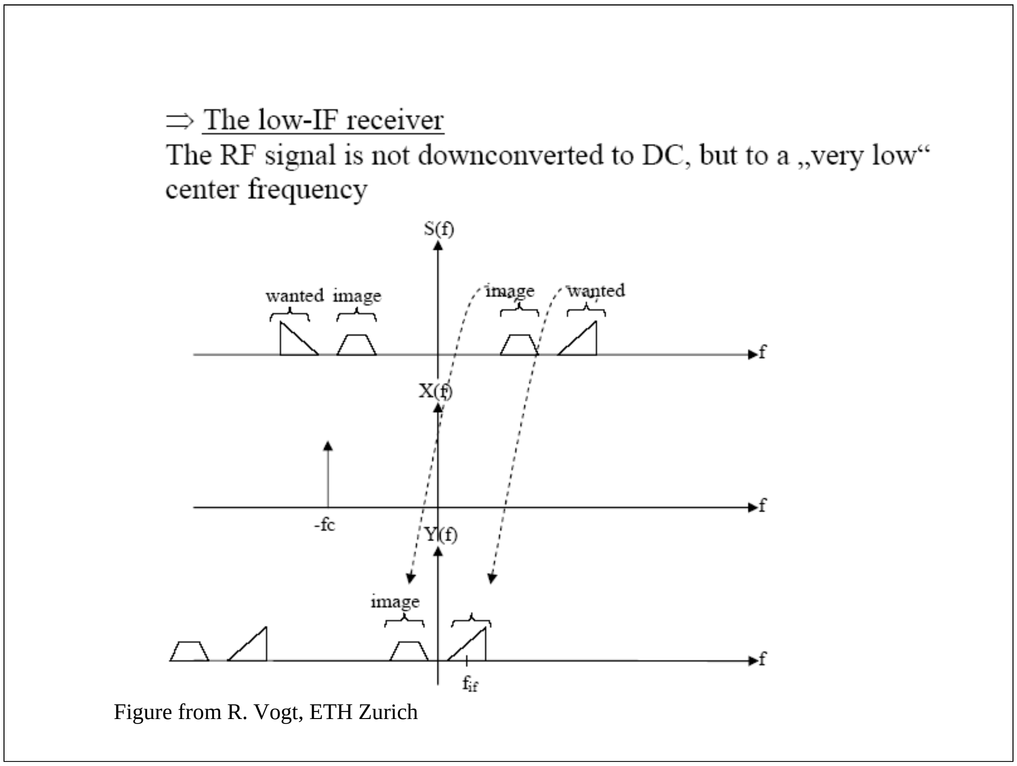
$$V_i = (A+\varepsilon\cos\omega_m t)(a\cos\omega_c t + b\sin\omega_c t)$$

Then, the LNA output contains a

$$(a^2+b^2)A\varepsilon\cos\omega_m t$$

term at baseband that will corrupt the desired signal.

These are some reasons why minimizing second-order distortion is very important in direct conversion receivers.



⇒ 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

A low IF receiver architecture eliminates the DC offset problem and reduces the 1/f noise problem. Filtering can be done on chip with analog or digital filters.

Additional reading

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