TSEK02: Radio Electronics Lecture 7: Noise, Receiver Architectures

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Noise, Receiver Architectures (2.3.5, 4.1, 4.2.1, 4.2.3)

- Noise: Input referred, cascaded
- Direct Detection Receiver
- Heterodyne Receiver
- Dual Downconversion Receiver
- Direct-Conversion Receiver

Noise, Receiver Architectures

- **Noise: Input referred, cascaded (2.3.5)**
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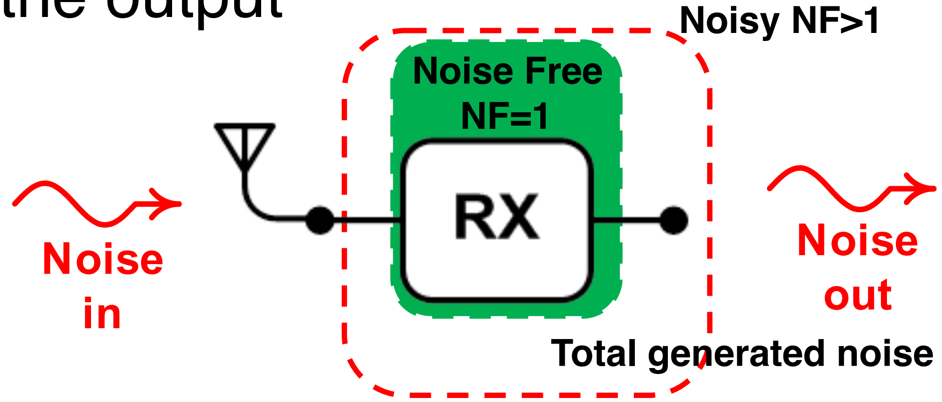
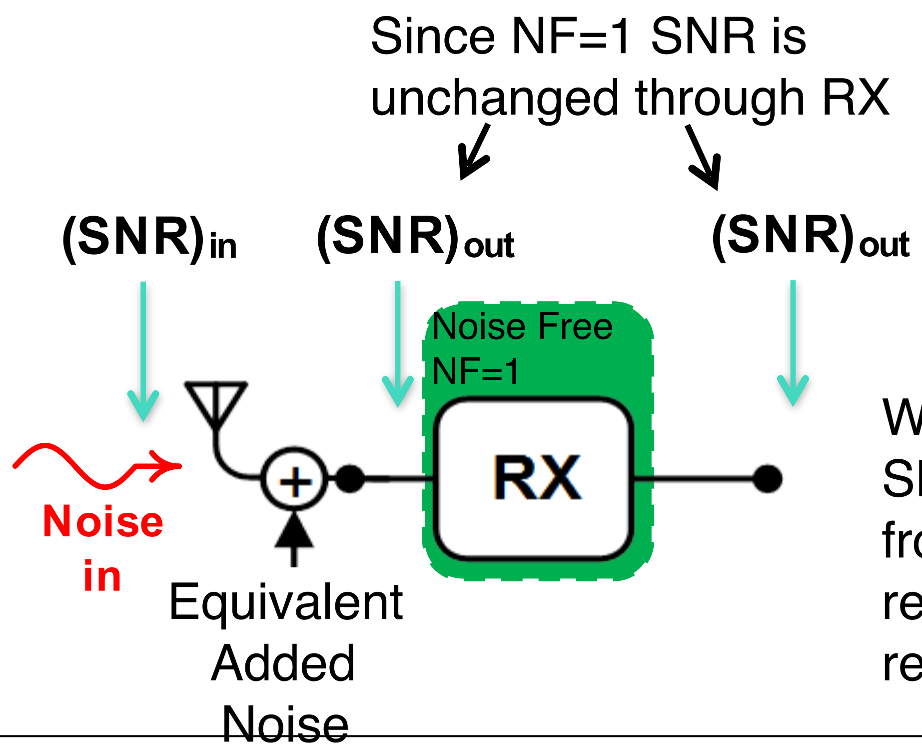
Equivalent Noise Model

- The receiver contains a lot of components, most of them are not resistors.
- Regardless of what type of noise and at which stage it is generated, all the noise power reaches the output.
- We can assume that the RX is noise free and noise is added at the output



Input Referred Noise

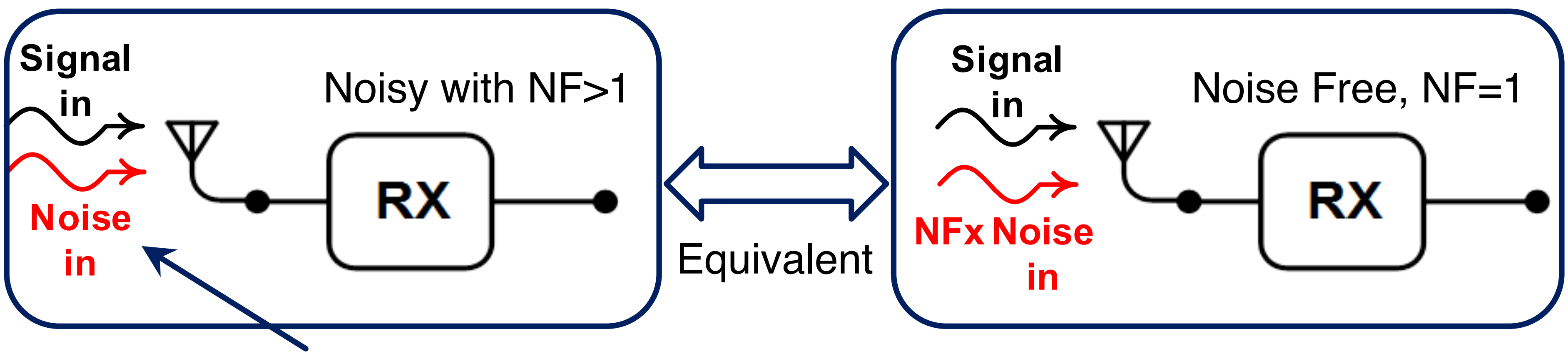
- The model with noise at the output is still inconvenient because we do not know the content of RX block at this point (gain etc.).
- Instead, put the “add” point to the input.



With this model, SNR is not changed from here on, regardless of how the receiver is made!

NF + input referred noise: summary

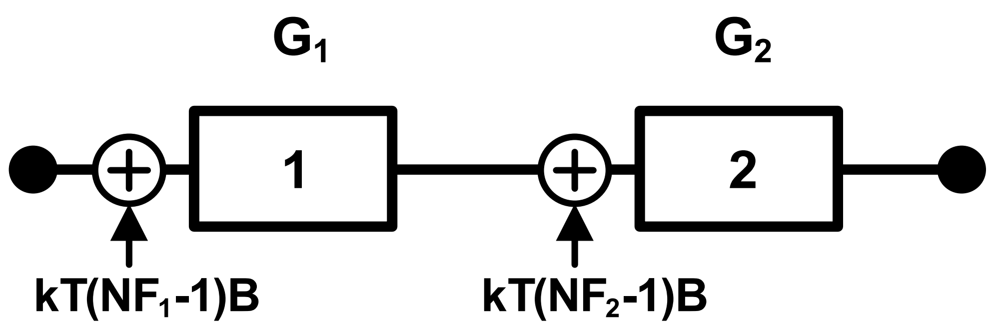
We may assume that the receiver has not generated any noise, and the input noise power is NF times larger



How much is this noise?
kTB (T is antenna temperature in K)

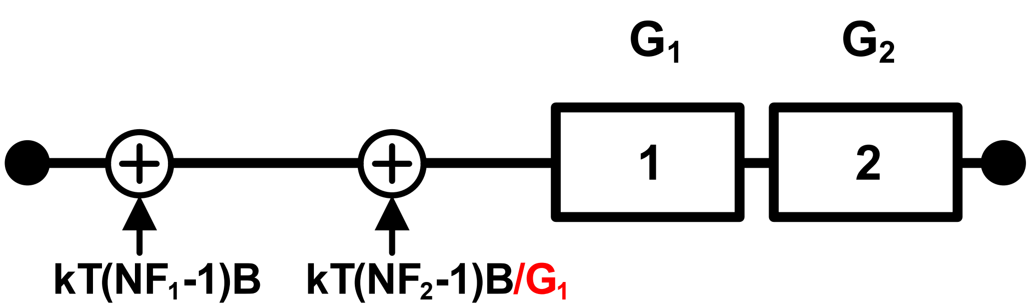
Noise Figure of Cascaded Stages

- To calculate the effective noise figure of cascaded stages:
  1. Model noise of each stage with its input-referred noise power.



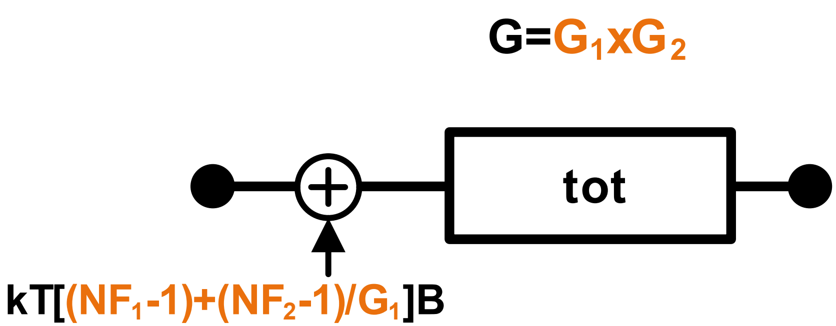
Noise Figure of Cascaded Stages

- To calculate the effective noise figure of cascaded stages:
  1. Model noise of each stage with its input-referred noise power.
  2. Slide all the added noises to the input of the first stage (note $\div G_1$).



Noise Figure of Cascaded Stages

- To calculate the effective noise figure of cascaded stages:
  1. Model noise of each stage with its input-referred noise power.
  2. Slide all the added noises to the input of the first stage (note $\div G_1$).
  3. Sum all the noise powers, and multiply gains.



Noise Figure of Cascaded Stages

- To calculate the effective noise figure of cascaded stages:
  1. Model noise of each stage with its input-referred noise power.
  2. Slide all the added noises to the input of the first stage (note $\div G_1$).
  3. Sum all the noise powers, and multiply gains.
  4. Convert back the noise power model to noise figure (note +1).

$$G = G_1 \times G_2$$

$$NF = 1 + (NF_1 - 1) + (NF_2 - 1)/G_1$$

Noise Figure of Cascaded Stages

- This can be generalized to :

$$G_{tot} = G_1 * G_2 * G_3 * \dots$$

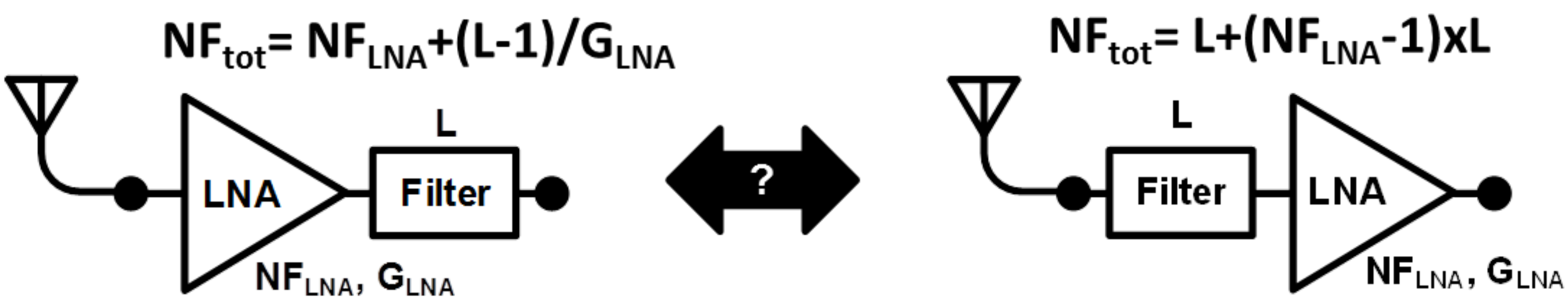
$$NF_{tot} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \dots$$

Friis' equation

- Contribution of each stage to the system noise figure reduces as we move along the chain (note ÷G).
- The system noise figure is dominated by the noise figure of the first stage if it has gain ($G_1 > 1$).
- If the first stage is lossy ($G_1 < 1$), noise figures of subsequent stages multiply by this loss.

Noise Figure of Cascaded Stages

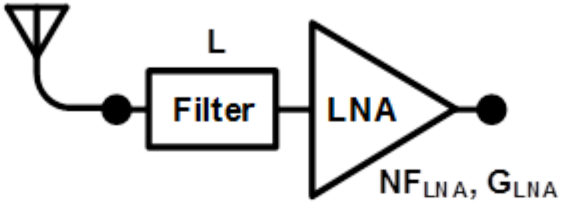
- Back to our receiver...
  - which configuration is better in terms of noise?
- filters are passive and usually lossy , i.e. L (=1/G) >1
- NF of a lossy stage is equal to its loss, i.e. NF=L
- we calculate NF of each configuration:



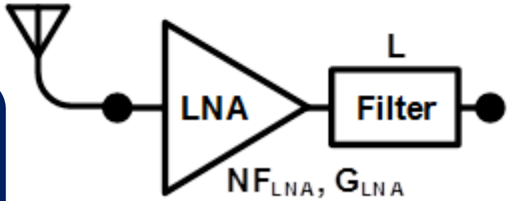
Noise Figure of Cascaded Stages

- Numerical Example,
  - $L = 1\ dB = 1.25$
  - $G_{LNA} = 10dB = 10$
  - $NF_{LNA} = 3dB = 2$

$NF_{tot}= 1.25+1x1.25= 2.5 = 4dB$



$NF_{tot}= 2+(0.25)/10=2.025 = 3dB$



1) Place those components with lowest noise figure and highest gain at earlier stages.
2) Avoid lossy components at the input.

Noise: Summary

- BER (detector) depends on SNR (receiver).
- Noise Figure (Factor) = NF = $(SNR)_{IN}/(SNR)_{OUT}$.
- Input-referred noise: reflect all noise sources to the input, make the RX noise-free (NF=1, 0 dB)
- Cascaded stages: $$NF_{tot} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \ldots$$
- Put blocks with high gain and low NF at the beginning of the RX chain.

Noise, Receiver Architectures

- Noise: Input referred, cascaded
- **Direct Detection Receiver (Ch 4)**
- Heterodyne Receiver
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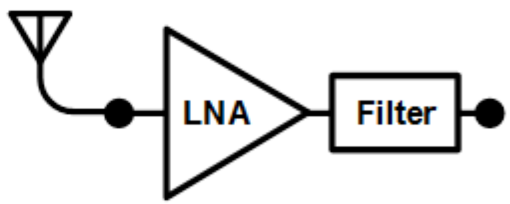
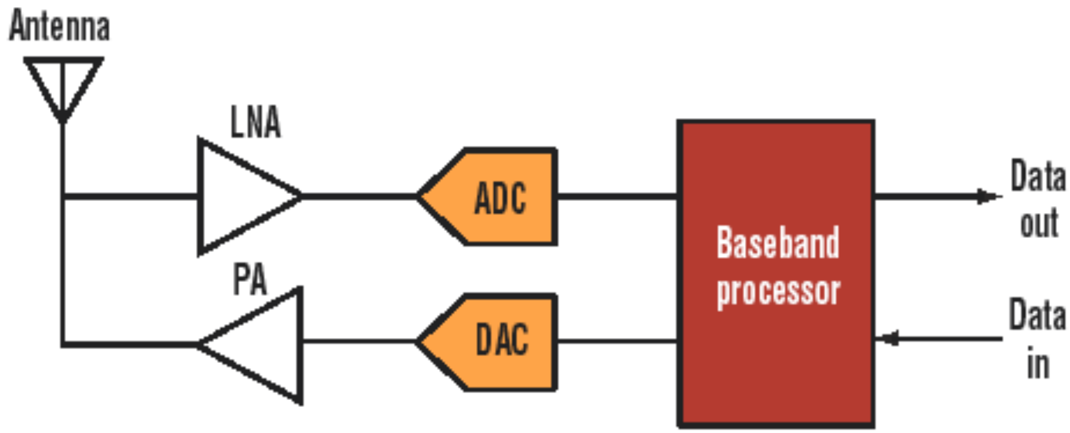
Direct Detection Receiver

- Called direct detection receiver, the architecture of the receiver shown below is the simplest.



- This approach results in many practical limitations.
- Just of academic interest, at least at high frequency.

SDR – Software Defined Radio



1. In the ideal software-defined radio, the antenna connects directly to the LNA and ADC, or the PA and DAC. The processor handles all radio functions, filtering, up/downconversion, modulation/demodulation, and digital baseband.

- No filters, can receive/transmit at any frequency and handle any modulation and speed.

Quality Factor (Q)

- Quality factor of a filter is a quantitative measure of how much loss the filter exhibits
  - Lower quality factor indicates more losses
  - Practical filters (especially on-chip filters) have high losses and therefore low Q
- It can be shown that the quality factor is inversely proportional to the fractional bandwidth of the filter:

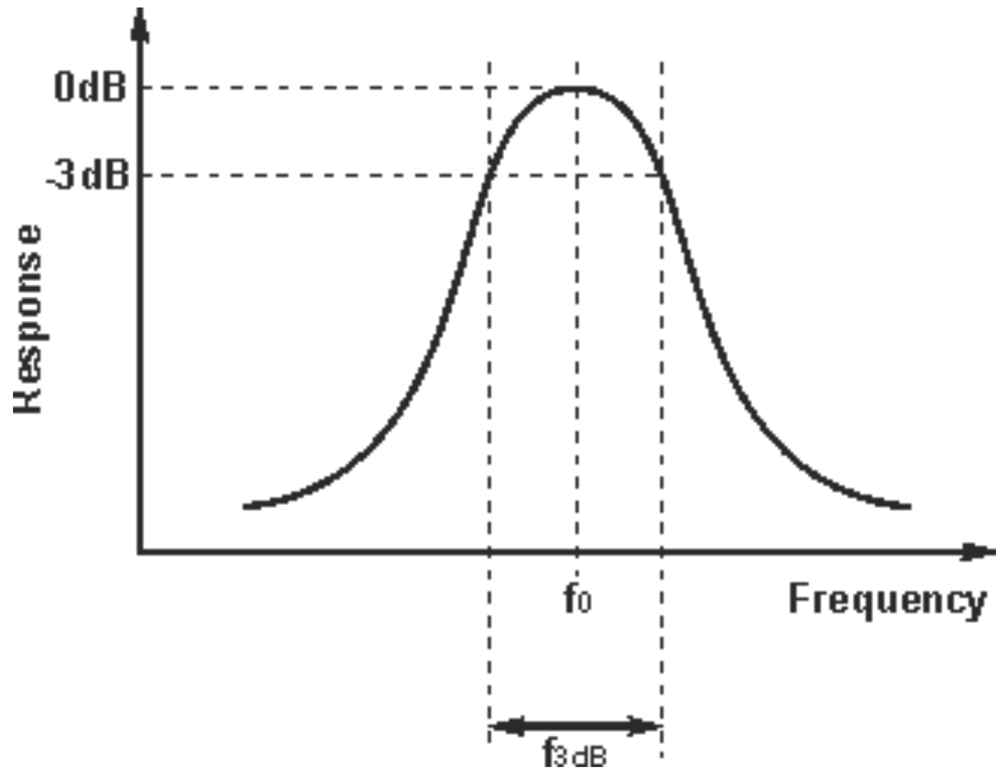
$$\Delta f = \frac{BW}{f_c}$$

- f_c is the center frequency, BW is the -3 dB limit.

To have a small BW at high f_c,
a filter with very high Q is needed

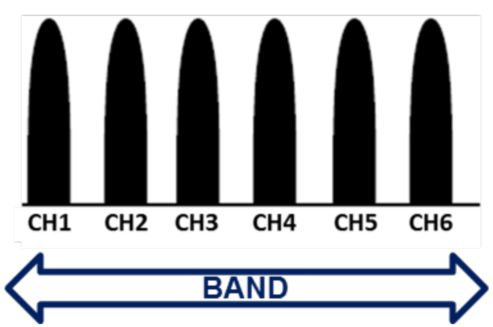
Quality Factor (Q)

- $Q = f_0 / f_{3dB}$

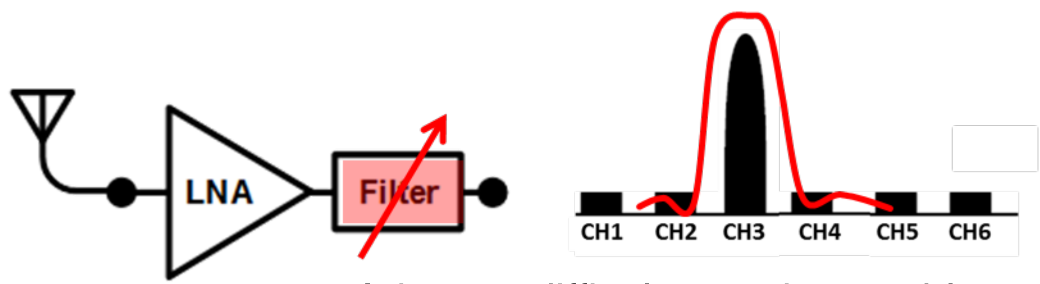


Channel Selection

- Most communication systems divide the frequency band into several narrower channels
- The receiver should select each channel for detection
  - Need for very sharp filter response (high Q-filter)
  - Need for variable filter (tunable filter)



Practical filters have low Q so their fractional bandwidth cannot be reduced too much



It is very difficult to make tunable filters in practice

The problems of channel selection:

- Problem: We need to limit the bandwidth for better channel selection and limit the noise (improve the SNR).

- Problem: We need to filter signals at different frequencies (channels).

The problems of channel selection:

- Problem: We need to limit the bandwidth for better channel selection and limit the noise (improve the SNR).
- Solution: Reduce the center frequency, so that much lower BW can be achieved with the same fractional bandwidth.

- Problem: We need to filter signals at different frequencies (channels).
- Solution: Use a fixed filter and move the signal frequency instead!

Noise, Receiver Architectures

- Noise: Input referred, cascaded
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Frequency Conversion

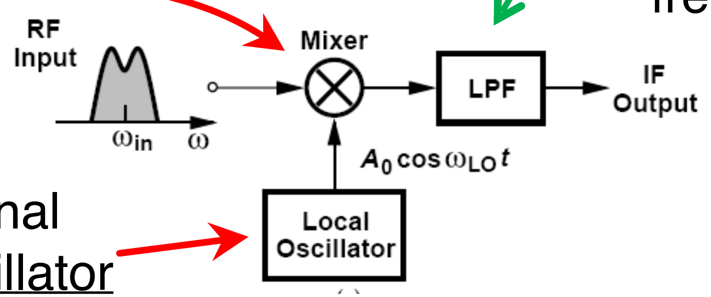
- The frequency of a signal can be shifted by multiplying it with another sinusoidal signal:

$x(t) = A \cos \omega_{in} t, \quad s(t) = \cos \omega_{LO} t$

$x(t) * s(t) = ½A^* \cos(\omega_{in} - \omega_{LO})t + ½A^* \cos(\omega_{in} + \omega_{LO})t$

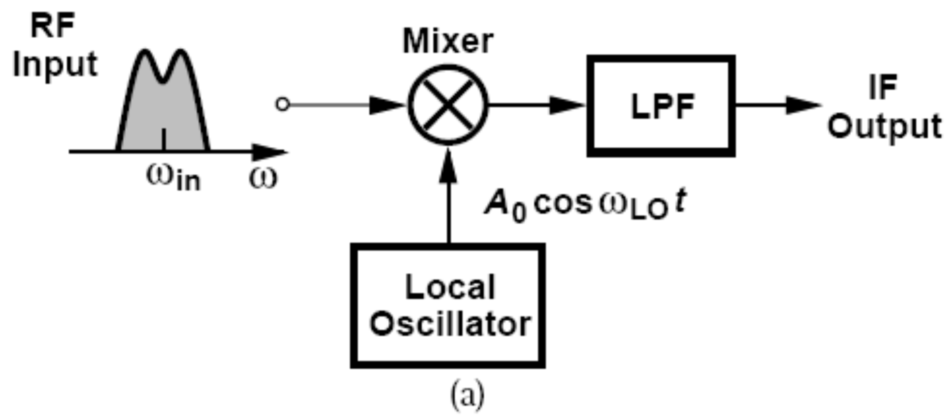
low-pass filter removes the high frequency signal

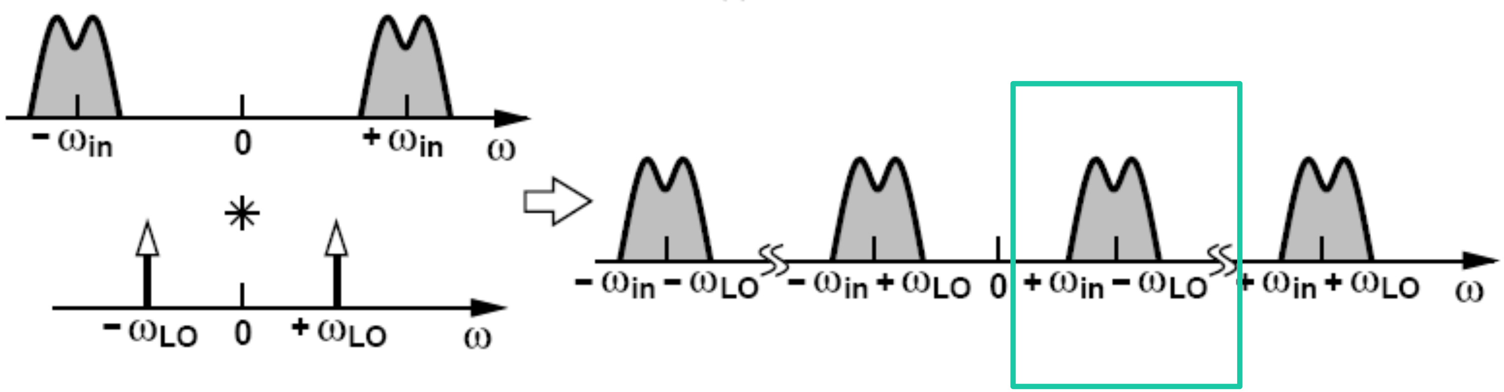
multiplication is performed by a mixer



the other sinusoidal signal comes from a local oscillator

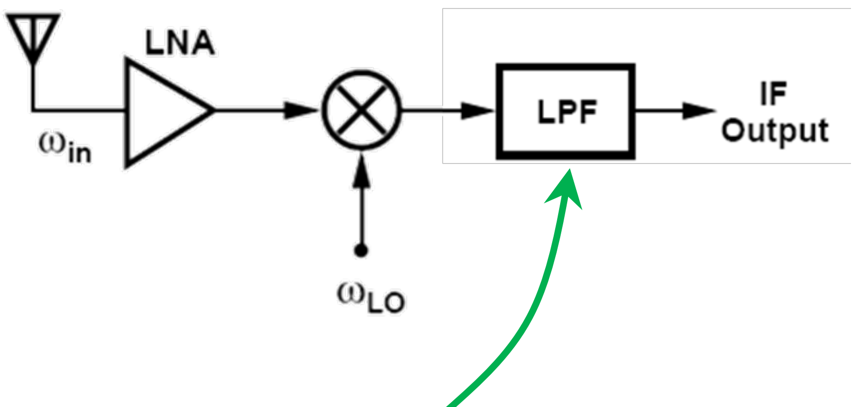
Frequency Conversion





Heterodyne Receiver – improved sensitivity

- By down-converting the radio-frequency signal (RF) to a lower intermediate frequency (IF), much better selectivity can be achieved and SNR is improved

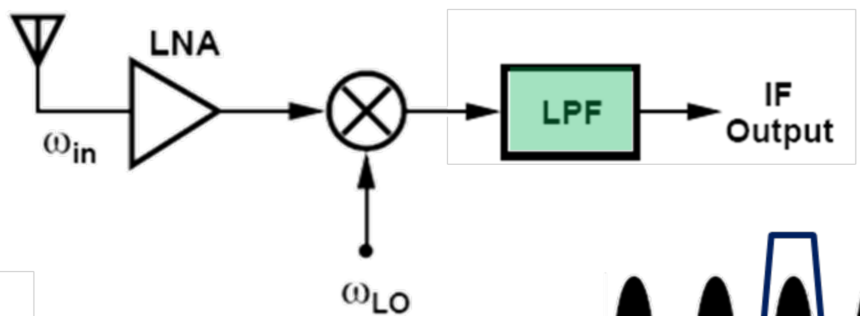


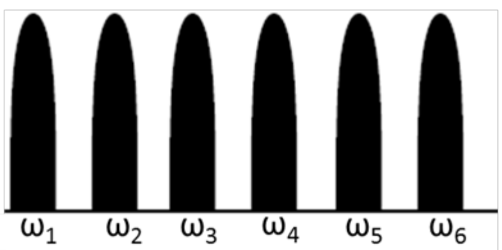
Bandwidth (B) of this filter
determines the noise power (kTB)

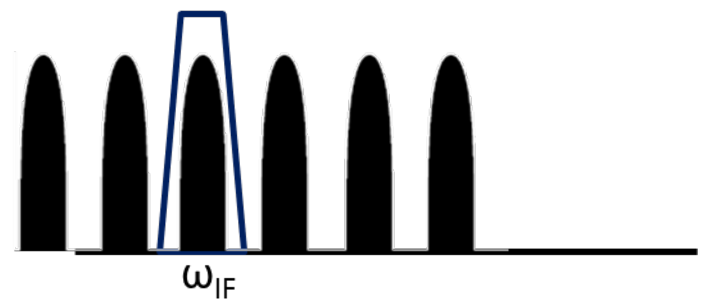
Heterodyne Receiver – Channel Selection

- By changing ω_{LO}, different ω_{in} will down-convert to the same IF.

The IF filter is always at a fixed frequency!







Variable LO frequencies can be made with a synthesizer

$\omega_{LO1} = \omega_1 - \omega_{IF}$
$\omega_{LO2} = \omega_2 - \omega_{IF}$
$\omega_{LO3} = \omega_3 - \omega_{IF}$

Example 4.6

A dual-mode receiver is designed for both 802.11g and 802.11a. Can this receiver operate with a single LO?

Solution:

Figure 4.12(a) depicts the two bands. We choose the LO frequency halfway between the two so that a single LO covers the 11g band by high-side injection and the 11a band by low-side injection [Fig. 4.12(b)]. This greatly simplifies the design of the system but makes each band the image of the other. For example, if the receiver is in the 11a mode while an 11g transmitter operates in close proximity, the reception may be heavily corrupted. Note that also the IF in this case is quite high, an issue revisited later.

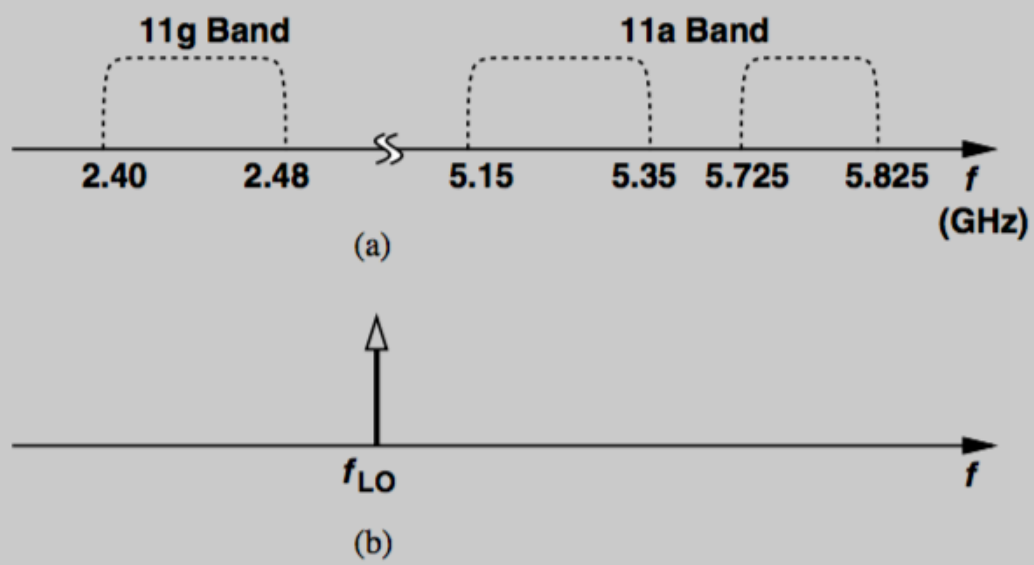


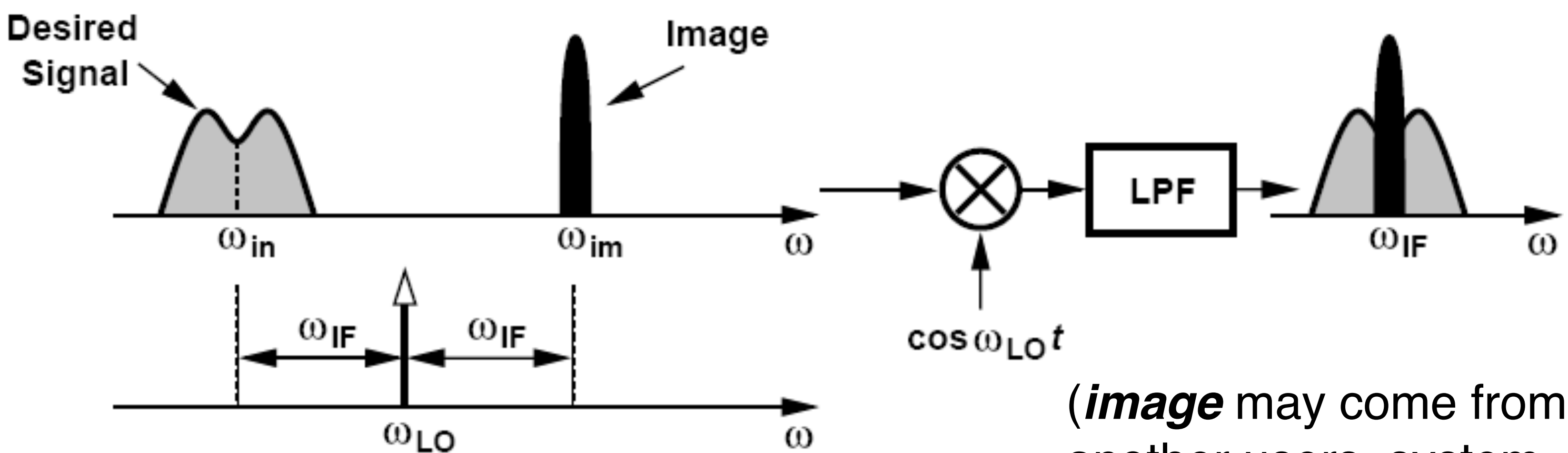
Figure 4.12 *(a) 11g and 11a bands, (b) choice of* f_{LO}.

Choice of Intermediate Frequency

- By lowering the signal frequency to an intermediate frequency (IF), we can reduce the bandwidth and therefore improve the SNR (better filtering).
- The lower we chose this intermediate frequency, the better performance we can get.
- What limits us from choosing very low IF?

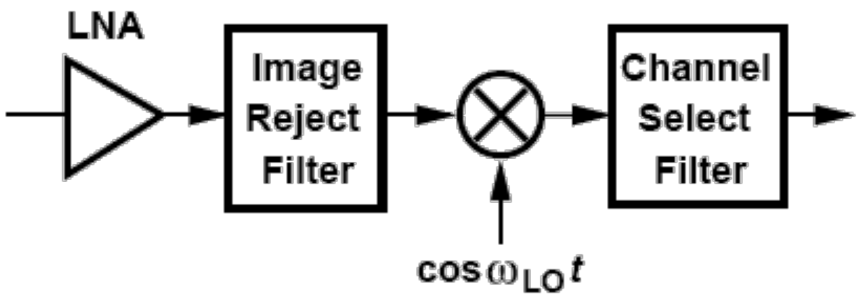
Image Frequency

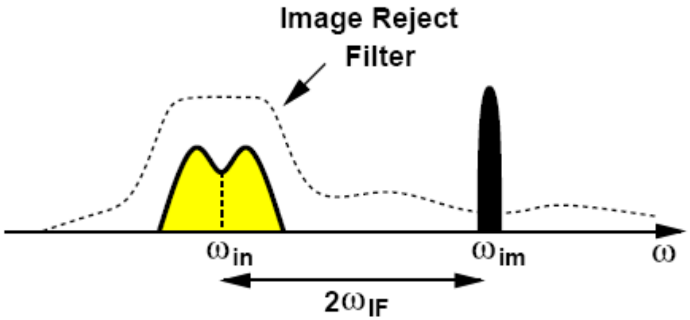
- A closer look at the down-conversion process:
  - We need an ω_{LO} which is ω_{IF} away from the desired signal
  - This ω_{LO} may down-convert signals to the same ω_{IF}



(***image*** may come from another users, system, etc.)

Image Reject Filtering



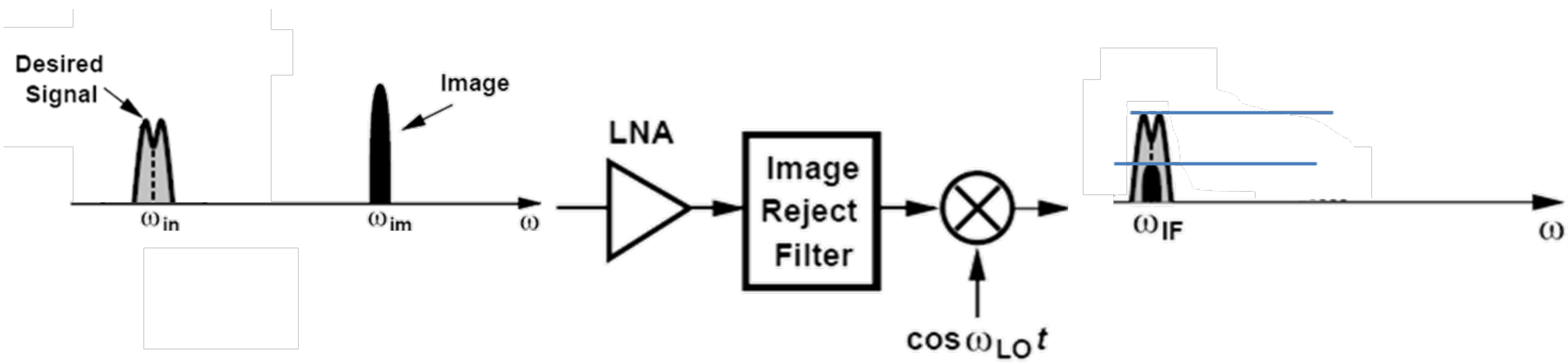


Note that the image reject filter is at high frequency, i.e. has limited selectivity.

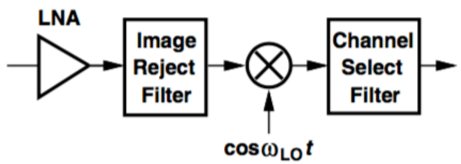
Typically after the LNA, not to degrade the NF.

Image Rejection Ratio

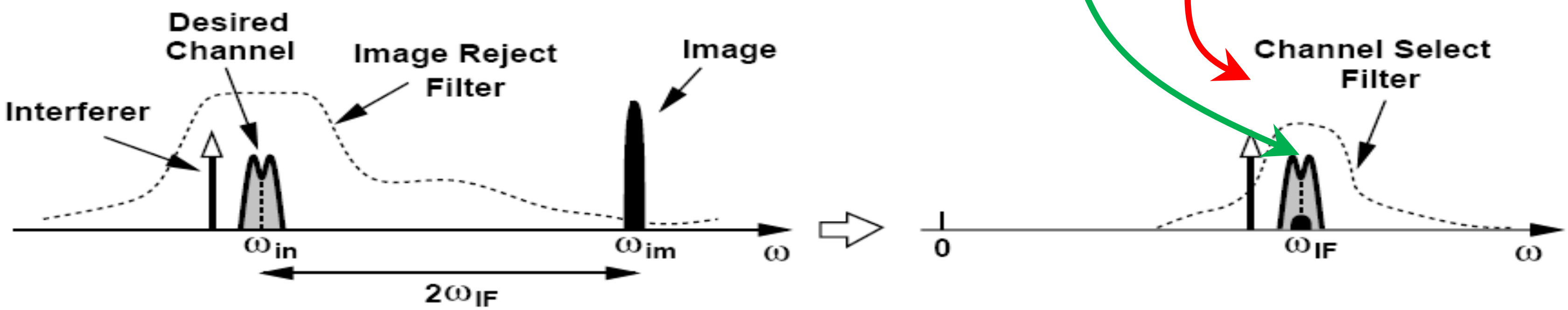
- Image Rejection Ratio, IRR = (Power of the received signal)/(Power of the image signal) at the IF port.
- Since IRR is a ratio, it is often expressed in dB.



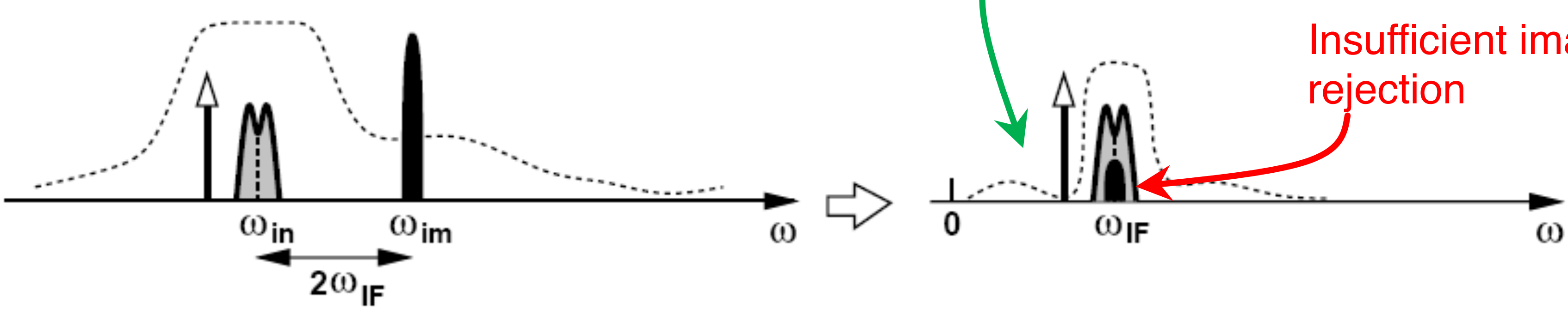
Trade-off in choice of IF



- High IF



- Low IF



Example 4.7

An engineer is to design a receiver for space applications with no concern for interferers. The engineer constructs the heterodyne front end shown in Fig. 4.15(a), avoiding band-select and image-select filters. Explain why this design suffers from a relatively high noise figure.

(Continues)

Example 4.7 *(Continued)*

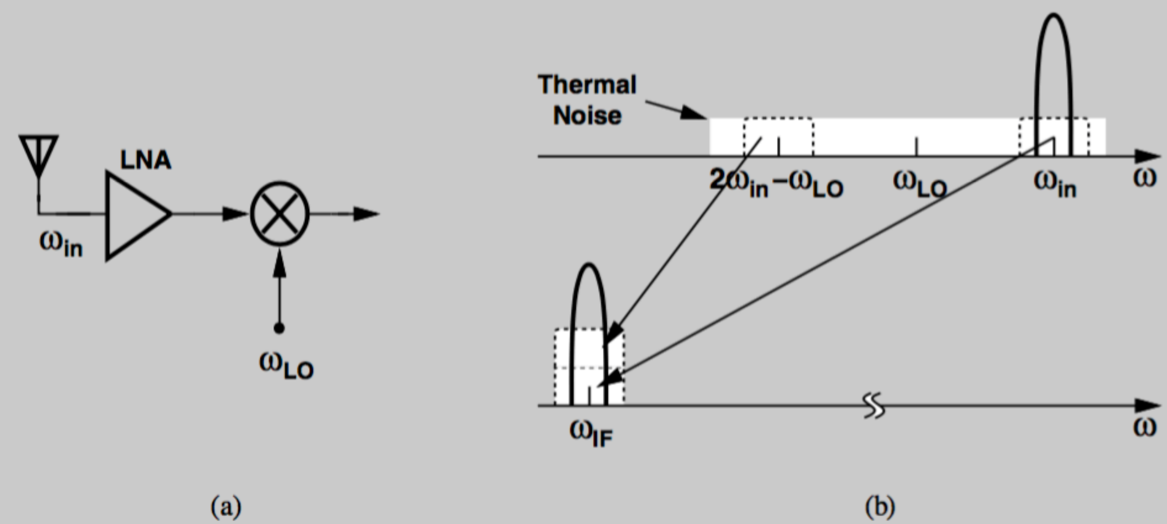


Figure 4.15 *(a) Receiver for space applications, (b) effect of noise in image band.*

Solution:

Even in the absence of interferers, the thermal noise produced by the antenna and the LNA in the image band arrives at the input of the mixer. Thus, the desired signal, the thermal noise in the desired channel, and the thermal noise in the image band are downconverted to IF [Fig. 4.15(b)], leading to a higher noise figure for the receiver (unless the LNA has such a limited bandwidth that it suppresses the noise in the image band). An image-reject filter would remove the noise in the image band. We return to this effect in Chapter 6.

Noise, Receiver Architectures

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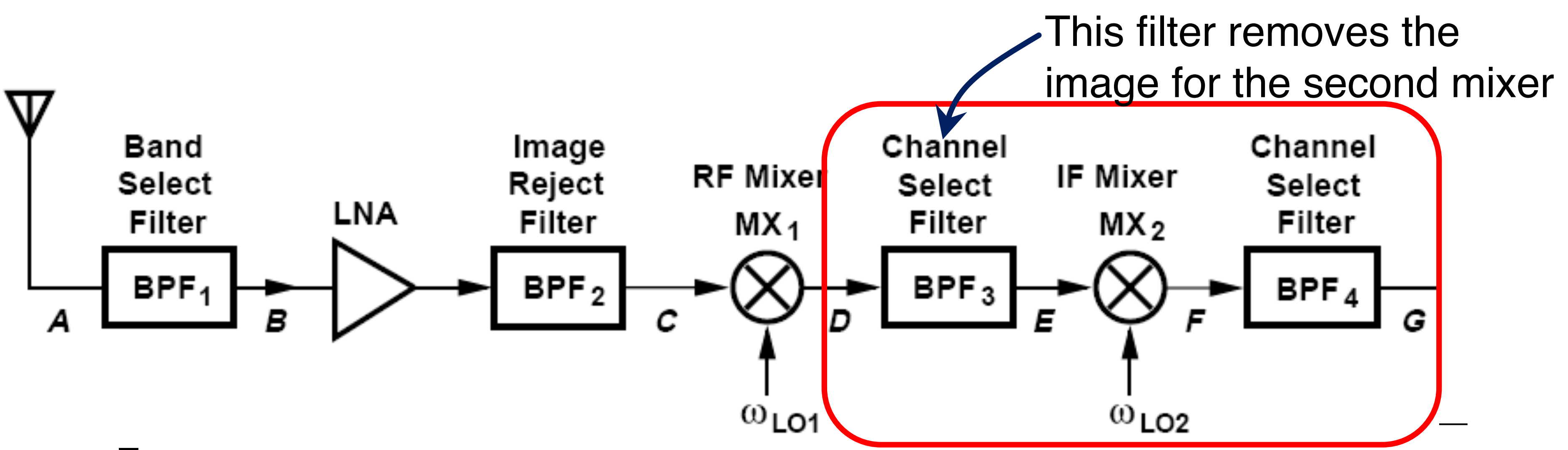
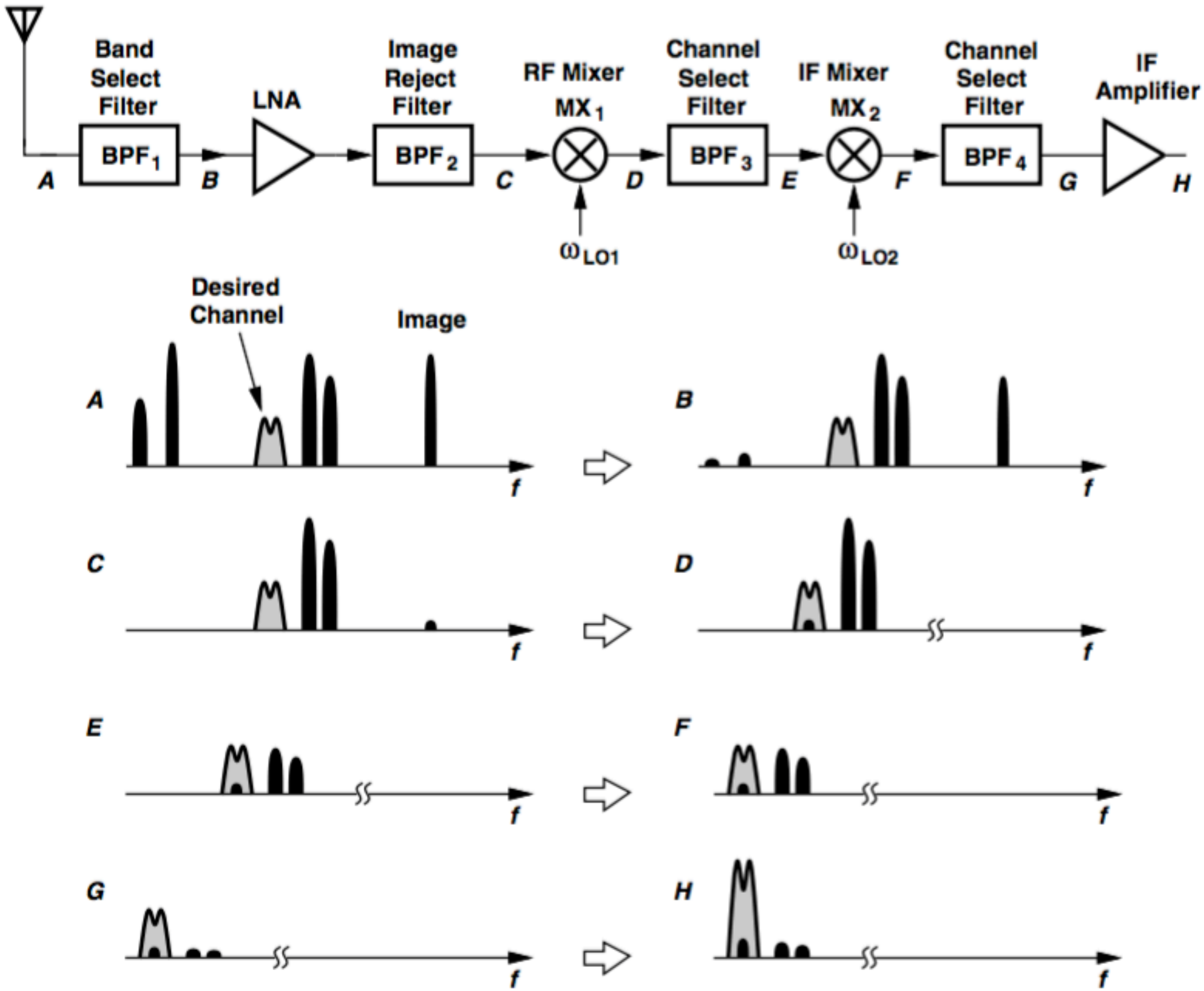
Dual Downconversion Architecture

- In order to avoid the problem of image and channel selectivity, down-conversion of the signal may be performed in two steps:
  - the image signal is removed in the first step (high IF)
  - in-band interference is removed in the second stage (low IF)



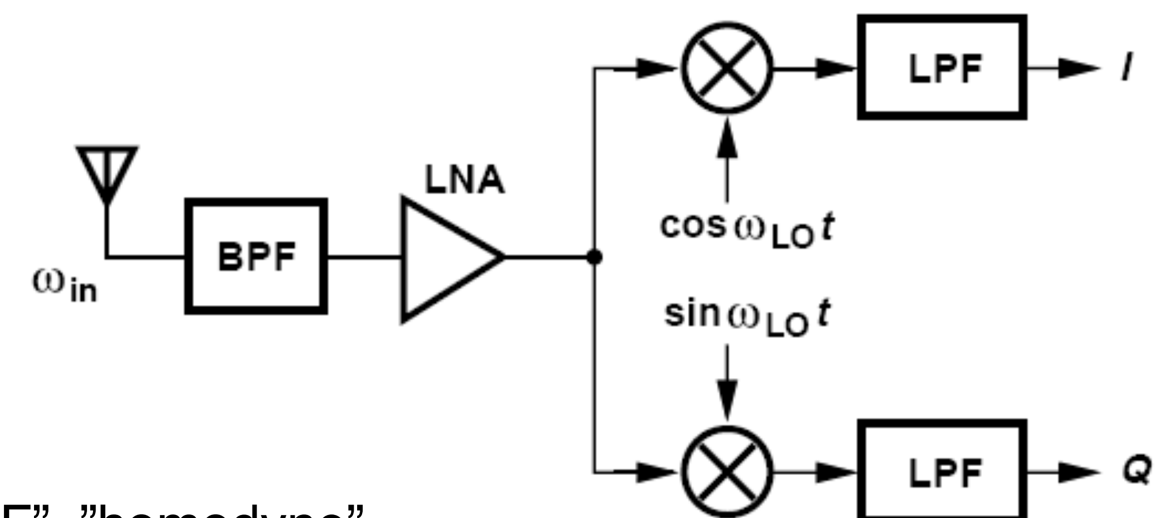

Band Select Filter
BPF1
LNA
Image Reject Filter
BPF2
RF Mixer MX1
ωLO1
Channel Select Filter
BPF3
IF Mixer MX2
ωLO2
Channel Select Filter
BPF4
IF Amplifier
A
B
C
D
E
F
G
H
Desired Channel
Image
f

Noise, Receiver Architectures

- Noise: Input referred, cascaded
- Direct Detection Receiver
- Heterodyne Receiver
- Dual Downconversion Receiver
- **Direct-Conversion Receiver (4.2.3)**

Direct-Conversion Receivers

- Absence of an image greatly simplifies the design process.
- Channel selection is performed by on-chip low-pass filter.
- Mixing spurs are considerably reduced in number.
- Suitable for ICs, few external components.



aka ”zero-IF”, ”homodyne”

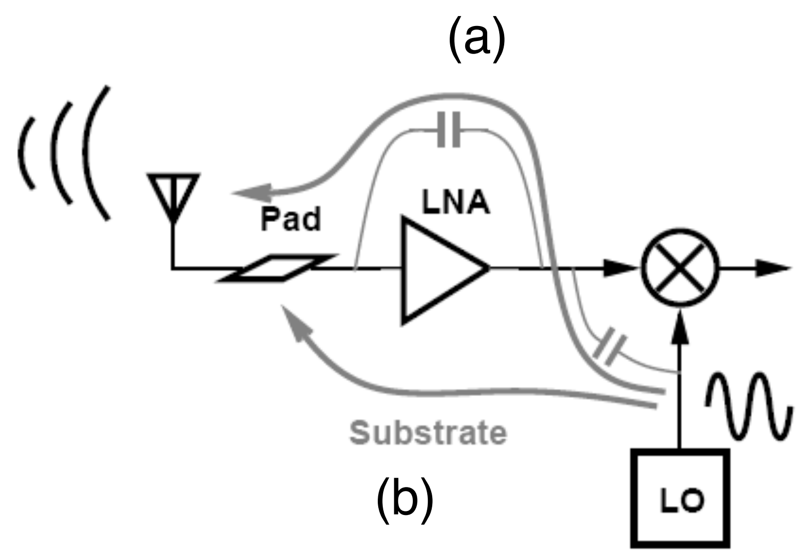
Direct-Conversion Receivers: LO leakage

- LO couples to the antenna through:

(a) device capacitances between LO and RF ports of mixer and device capacitances, or resistances between the output and input of the LNA.

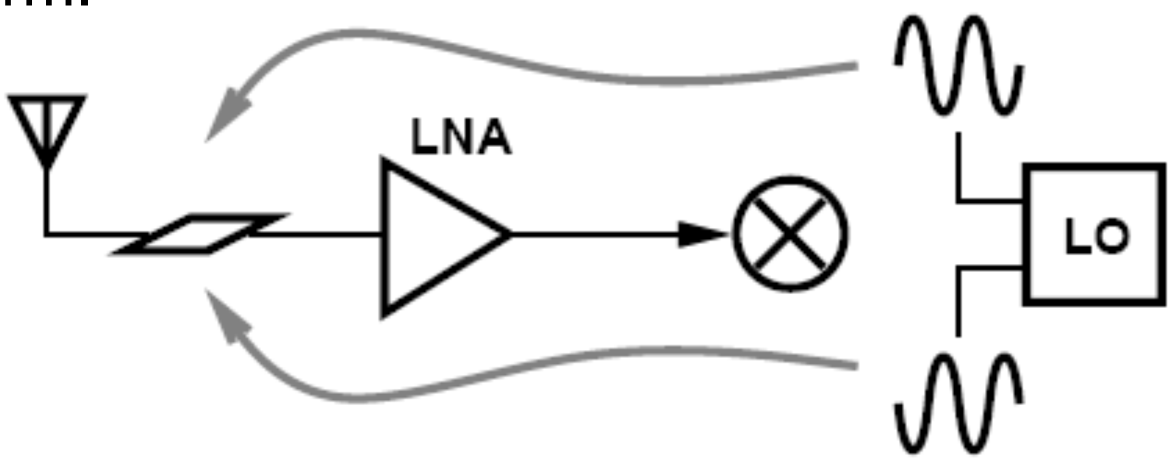
(b) the substrate to the input pad, especially because the LO employs large on-chip spiral inductors.

- Desensitize other receivers.



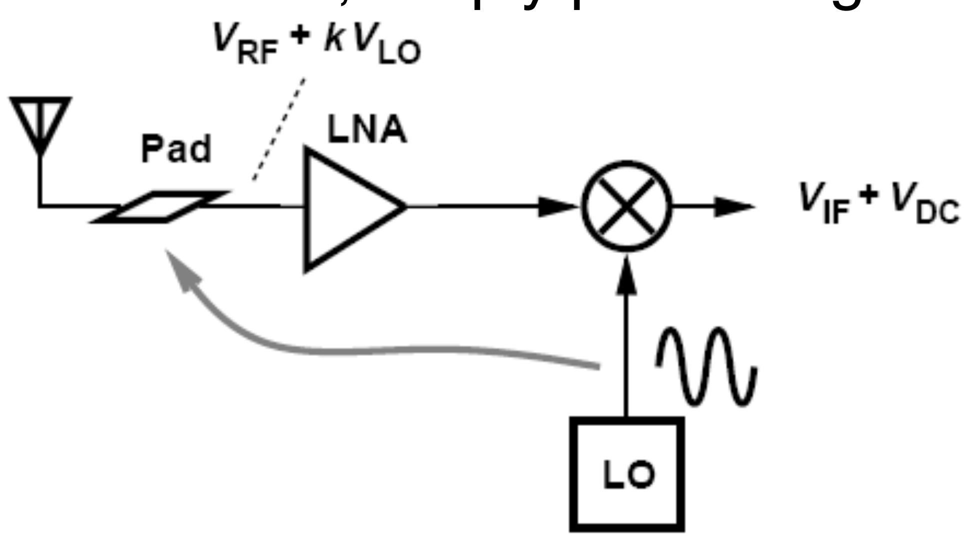
Direct-Conversion Receivers: LO leakage

- LO leakage can be minimized through symmetric layout of the oscillator and the RF signal path.
- => LO leakage arises primarily from random or deterministic asymmetries in the circuits and the LO waveform.



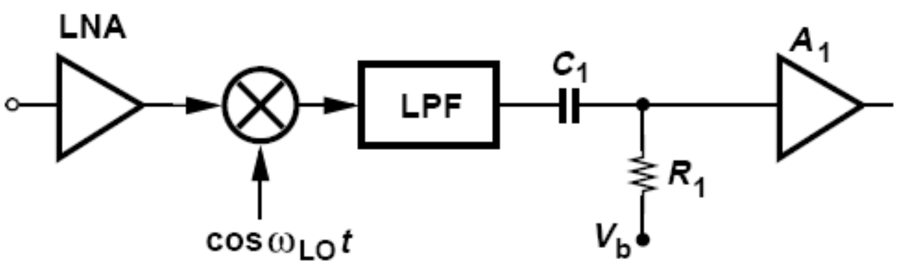
Direct-Conversion Receivers: DC offsets

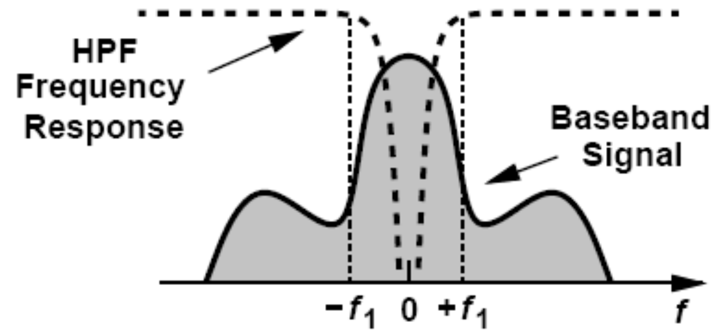
- A finite amount of in-band LO leakage appears at the LNA input. Along with the desired signal, this component is amplified and mixed with LO.
- May saturate baseband circuits, simply prohibiting signal detection.



Direct-Conversion Receivers: DC offsets

- Cancellation: high-pass filters.
- Will also remove a fraction of the signal's spectrum near zero frequency, introducing ISI

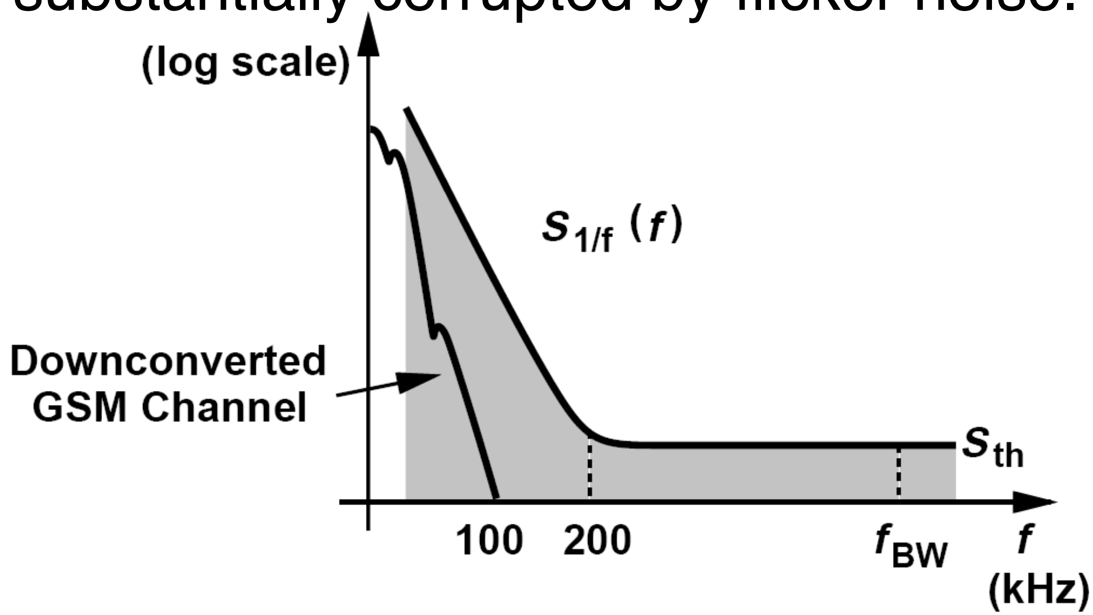




- Many other solutions (circuit, architectures) also exist for this problem.

Direct-Conversion Receivers: Flicker noise

- Since the signal is centered around zero frequency, it can be substantially corrupted by flicker noise.



- Fix: lower 1/f noise, NF optimization of RX chain.

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