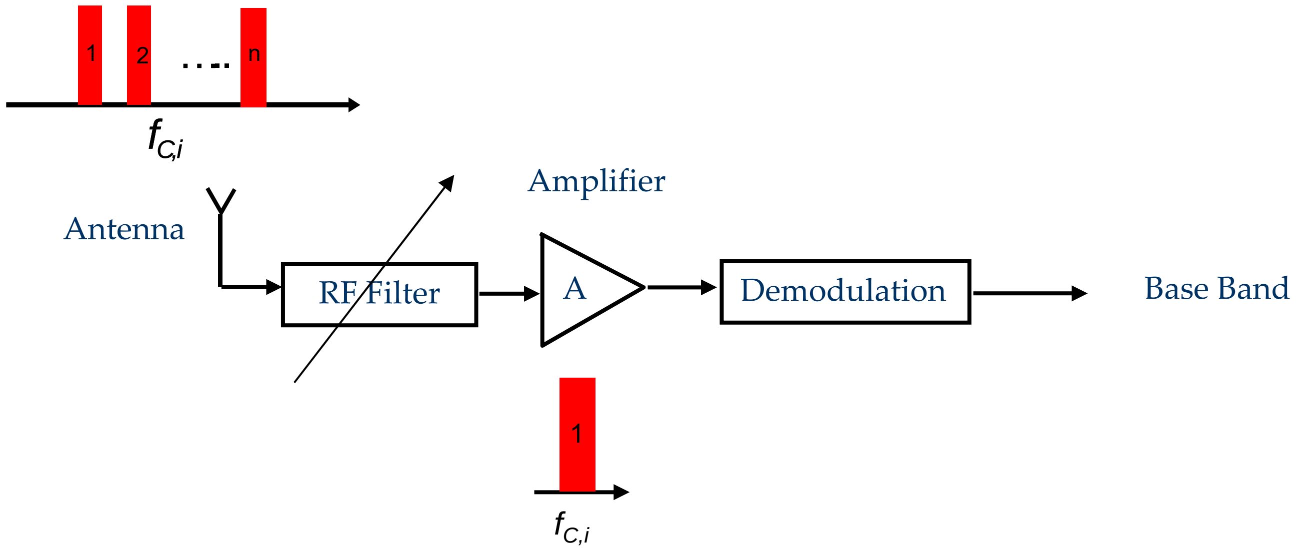
Receiver Architectures

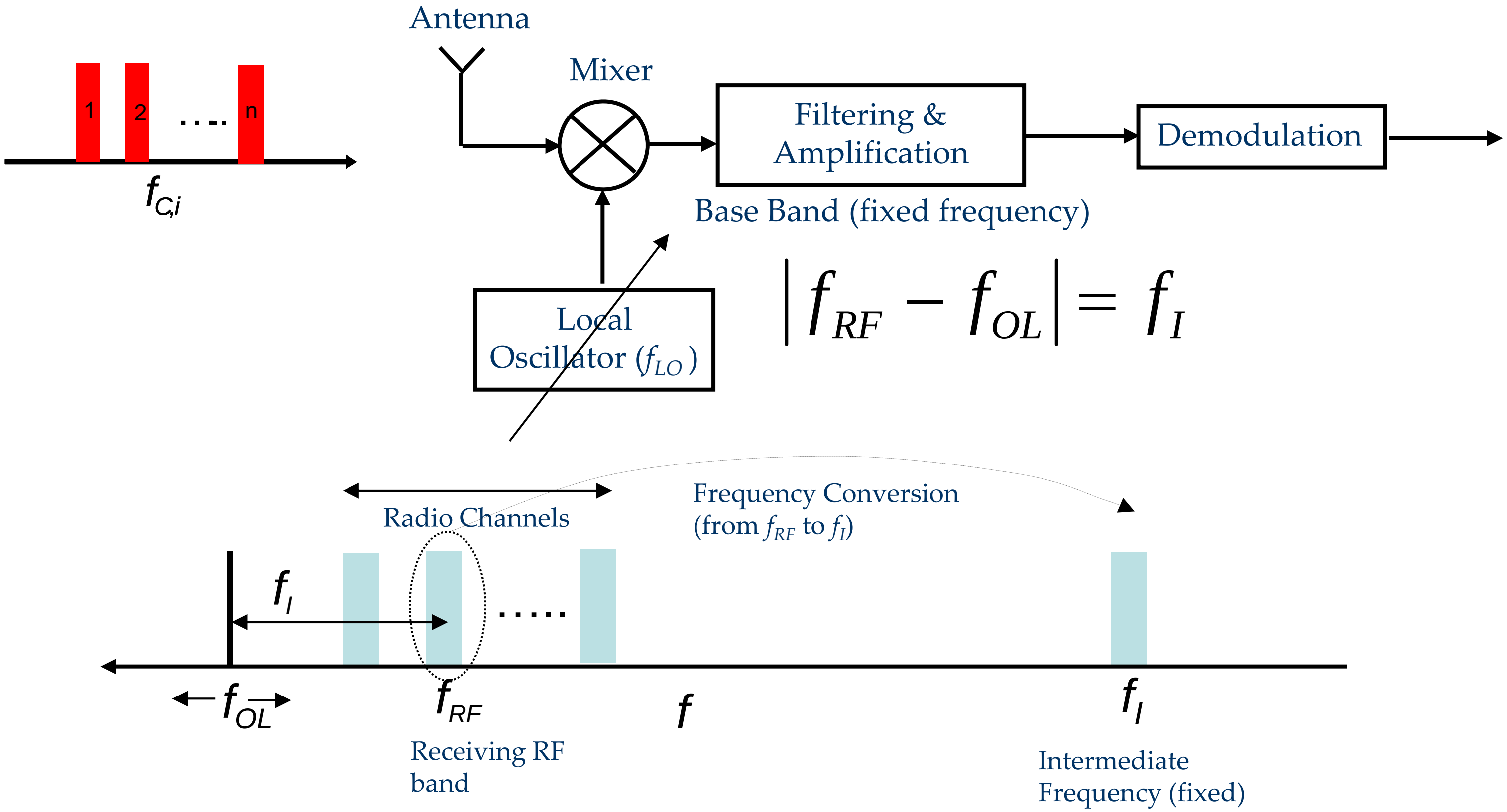
Direct Detection of radio signals



Not convenient:

- RF filter must be very selective and tunable
- Amplifier operating at RF with high gain and low noise required
- Poor performances even with expensive components

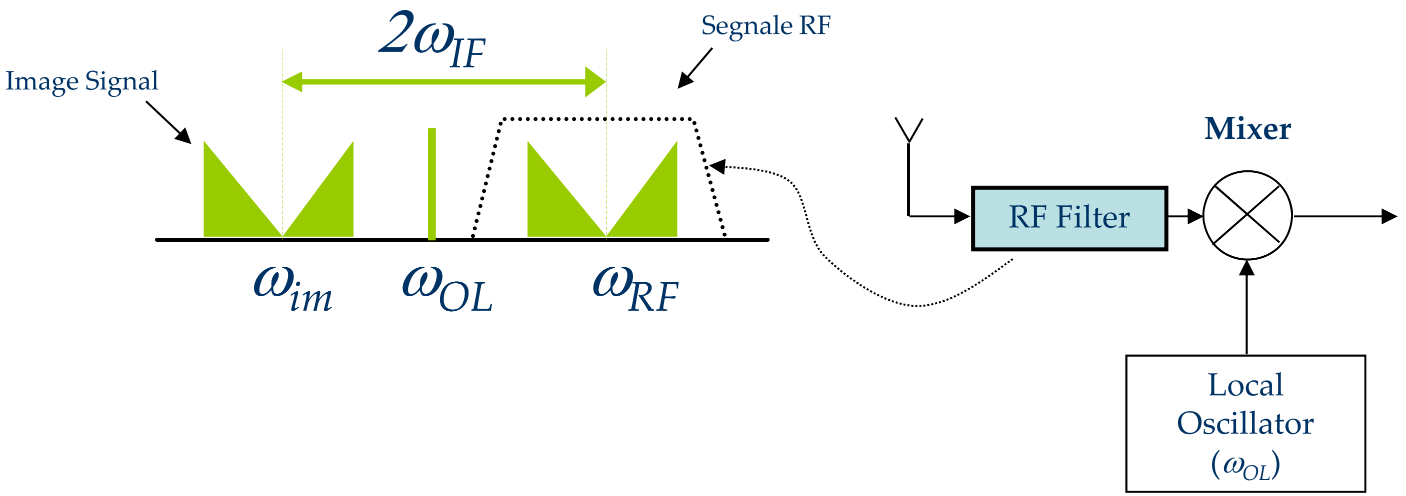
Conversion Receiver



$$\left| f_{RF} - f_{OL} \right| = f_I$$

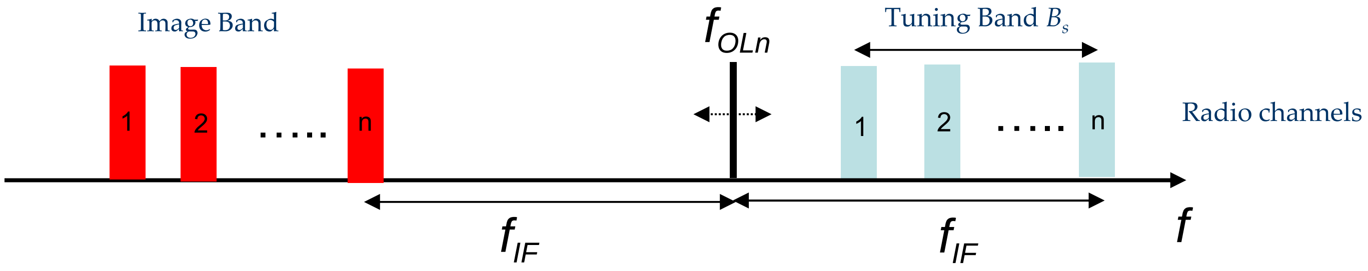
The tuning of RF channels is realized by varying the frequency f_{OL} of the local oscillator

Image Frequency

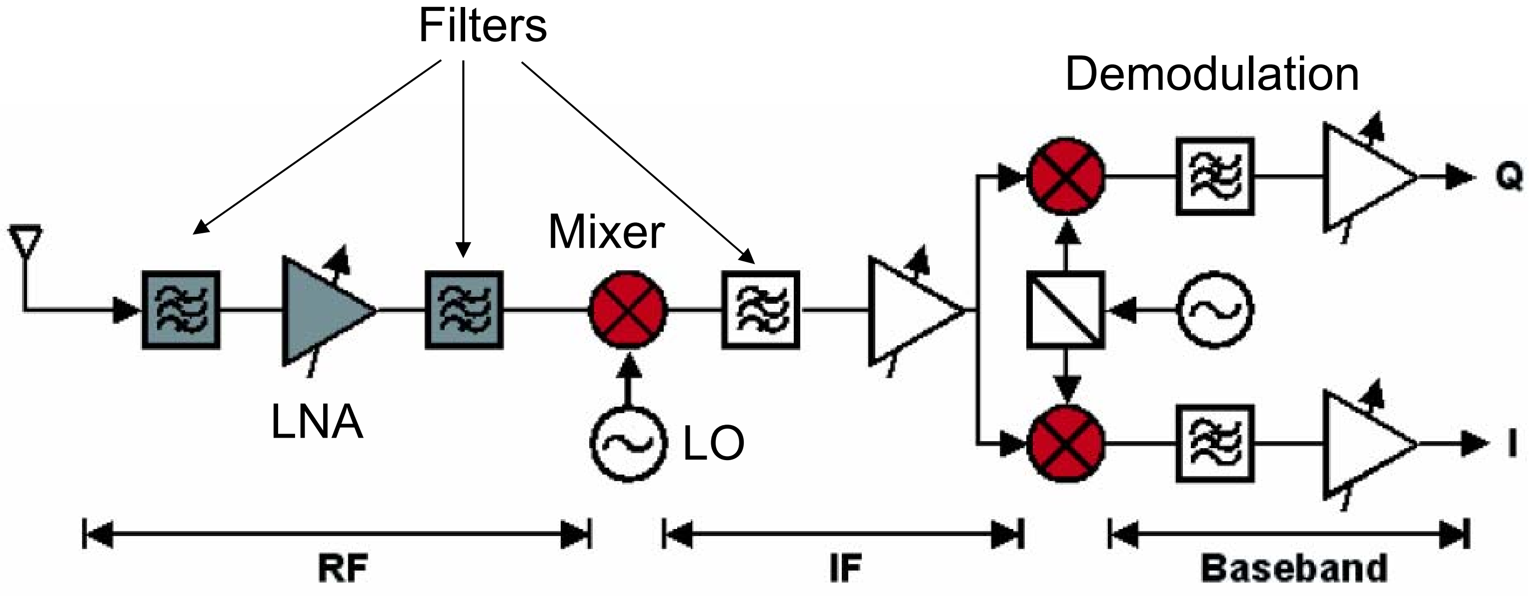


The RF filter is needed for eliminating the **image signal**

The tuning band B_s is separated from the image frequency of twice the value of the intermediate frequency. The RF filter (with passband equal to the tuning band) must suppress the image band



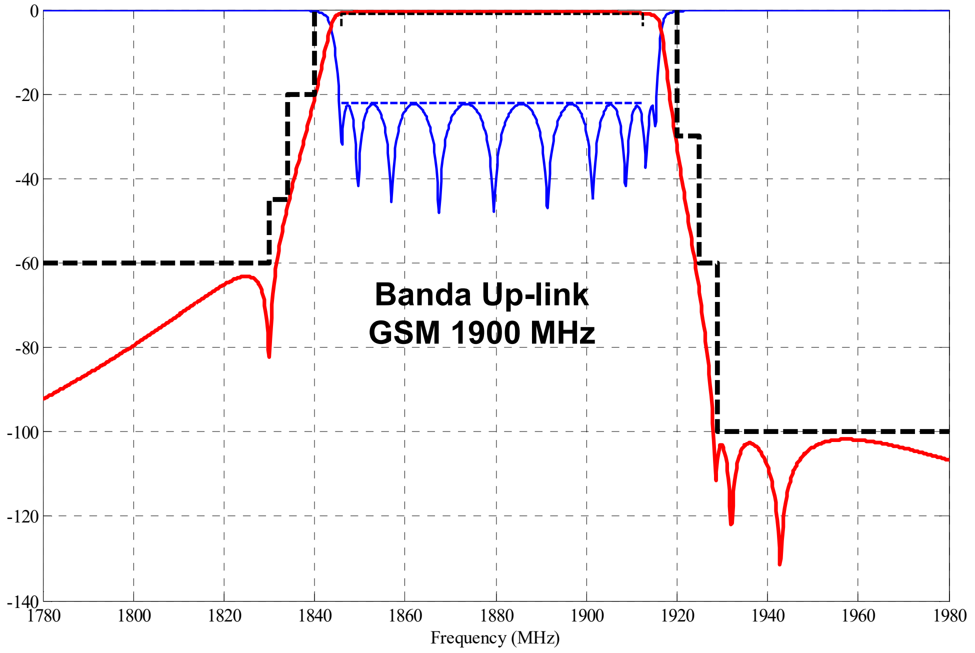
Scheme of a single conversion receiver

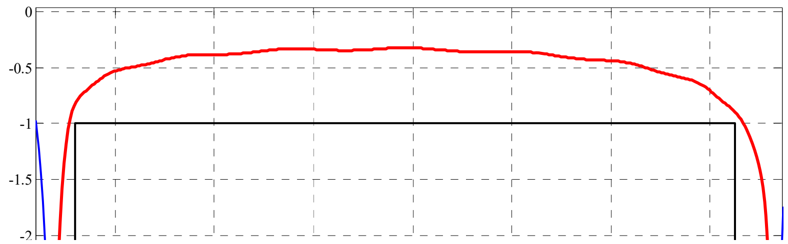


The first two filters in RF section are microwave filters (distributed parameters). The IF filter is a lumped-elements circuit.
The use of the LNA and second RF filter is not strictly necessary (see in the following)

Characteristic Parameters of RF Filter

- Selectivity (defined by means of the Transducer Gain/Attenuation Mask)
- Insertion loss in passband (dB) (Worsens the receiver S/N!)
- Physical parameters (dimensions, weight, etc)





Passband Attenuation

Considerations on microwave filters

- The passband loss is due to dissipation, so noise is generated. Out of band rejection is produced by reflection → no noise produced.
- Microwave filters are constituted by cavity resonators suitable coupled each other. As the number of cavities increases also the selectivity increases as well as the passband losses
- For a given number of resonators, the passband loss depends on the unloaded Q of the cavities (the larger are the cavities the higher is the Q and the lower is the loss)
- For a given Q, the loss increases with the decrease of B/f_0 ratio (narrow band filters → high loss)

Microwave filters technology

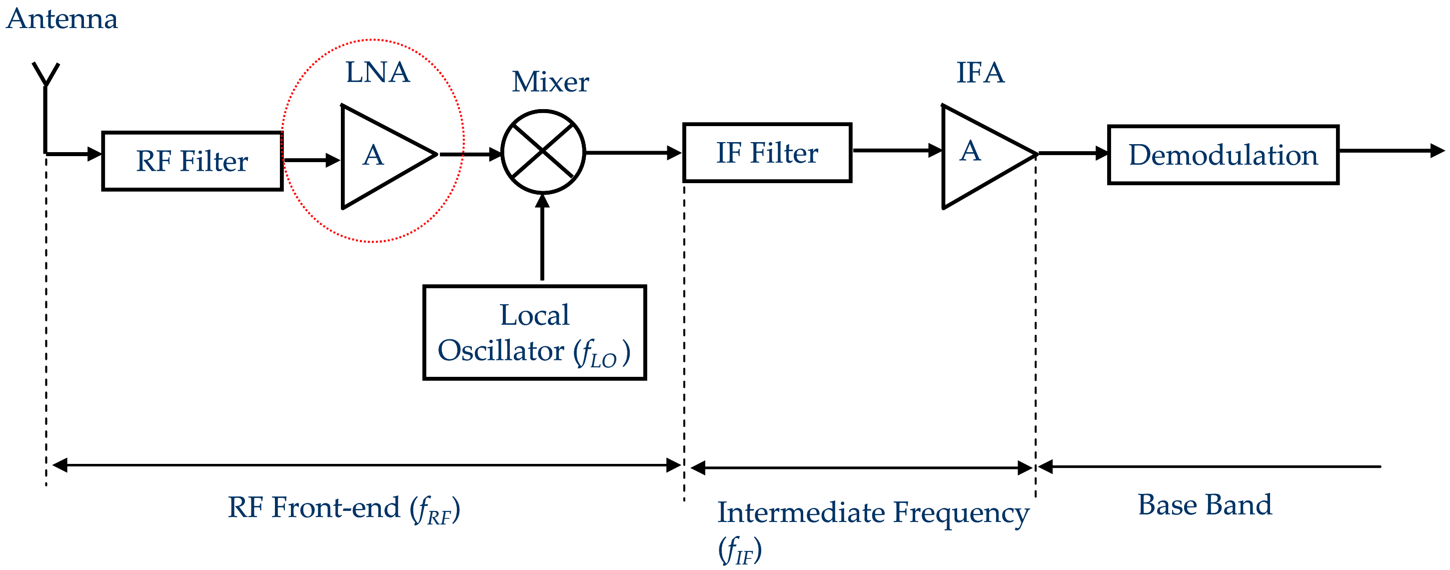
- The highest Q can be realized with 3-d cavities with dimensions related to the wavelength at the center frequency (Q values ranging from 1000 to over 10000)
- Planar technology is widely used today in microwave circuits (also in the RF front-end). The Q obtainable in this case is relatively low:100-300
- For (portable) devices operating below 2 GHz, special integrated technologies are available (SAW, FBAR) allowing a very compact implementation at expense of high losses (>5 dB)

Are the RF filters necessary?

- Filter 1 must be always used for rejecting the image band. Being this filter just at after the antenna, it degrades the overall noise figure of the receiver by the value of the passband loss. It must then exhibit a passband attenuation as low as possible (e.g. high Q requested for the cavities → 3-d technologies)
- Filter 2 is needed for rejecting the noise produced by LNA. In case this noise is very low (or when LNA is not used) it can be omitted
- Filter 2 is after LNA so its contribution to overall NF is divided by G_{LNA}. An Higher attenuation is tolerated (lower Q of the cavities, planar technology possible)

Low Noise Amplifier 1 (LNA)

- The task of LNA is to rise the power level of the signal coming from the antenna to the level requested by the mixer for the proper operation.
- Even if it introduces additional noise, the overall S/N ratio of the receiver can be increased with a good LNA
- Inexpensive systems may not use a LNA (it depends on the mixer employed)

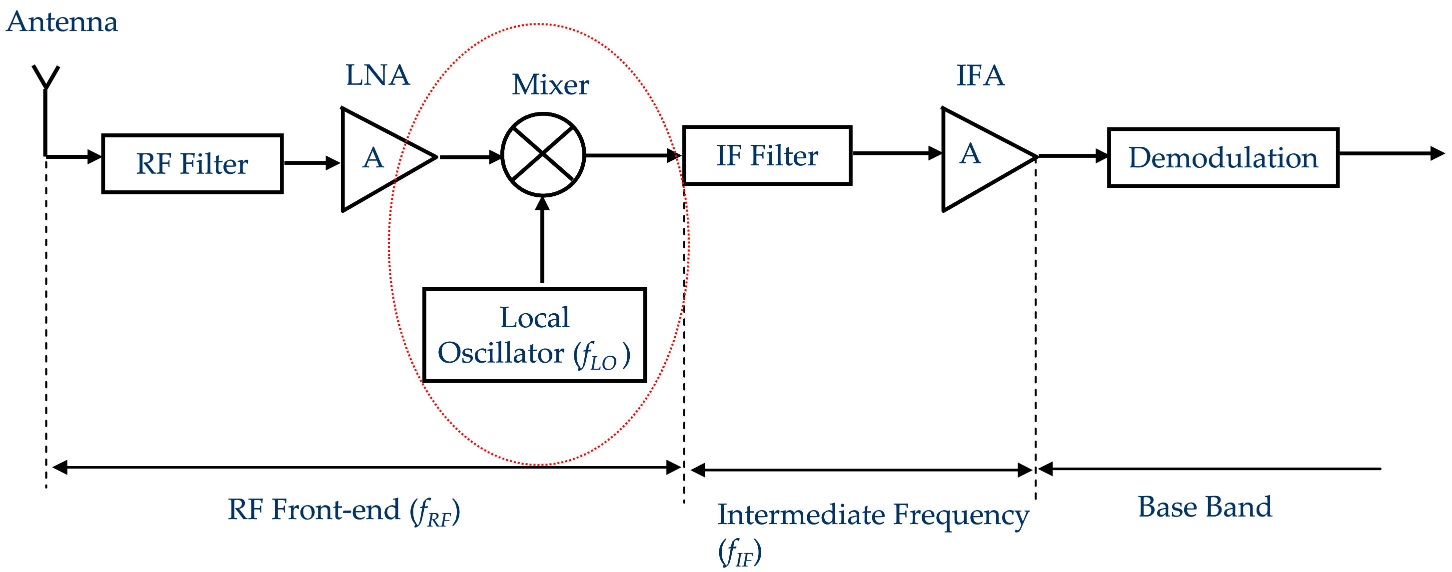


Characteristic parameters of LNA

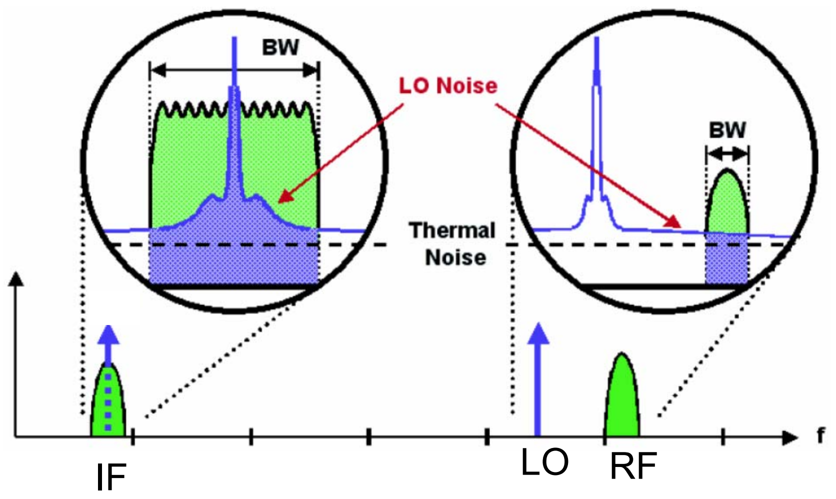
- Transducer Power Gain (in dB)
- Noise Figure (degradation of S/N ratio from input to output)
- Maximum power level at output (linearity)
- Input and output matching
- Biasing (Voltage and Current. DC power required)
- Temperature range (especially when operating in unconditioned environment)

Mixer

- Its task is the translation of the RF signal to intermediate frequency (IF)
- At microwave frequencies is not realized through analogical multiplication but exploiting the non linearity of particular components (diodes or transistors)
- It affects the receiver performances: add noise (T_{SSB}) and degrades linearity (IIP3)



Degradation produced by local oscillator

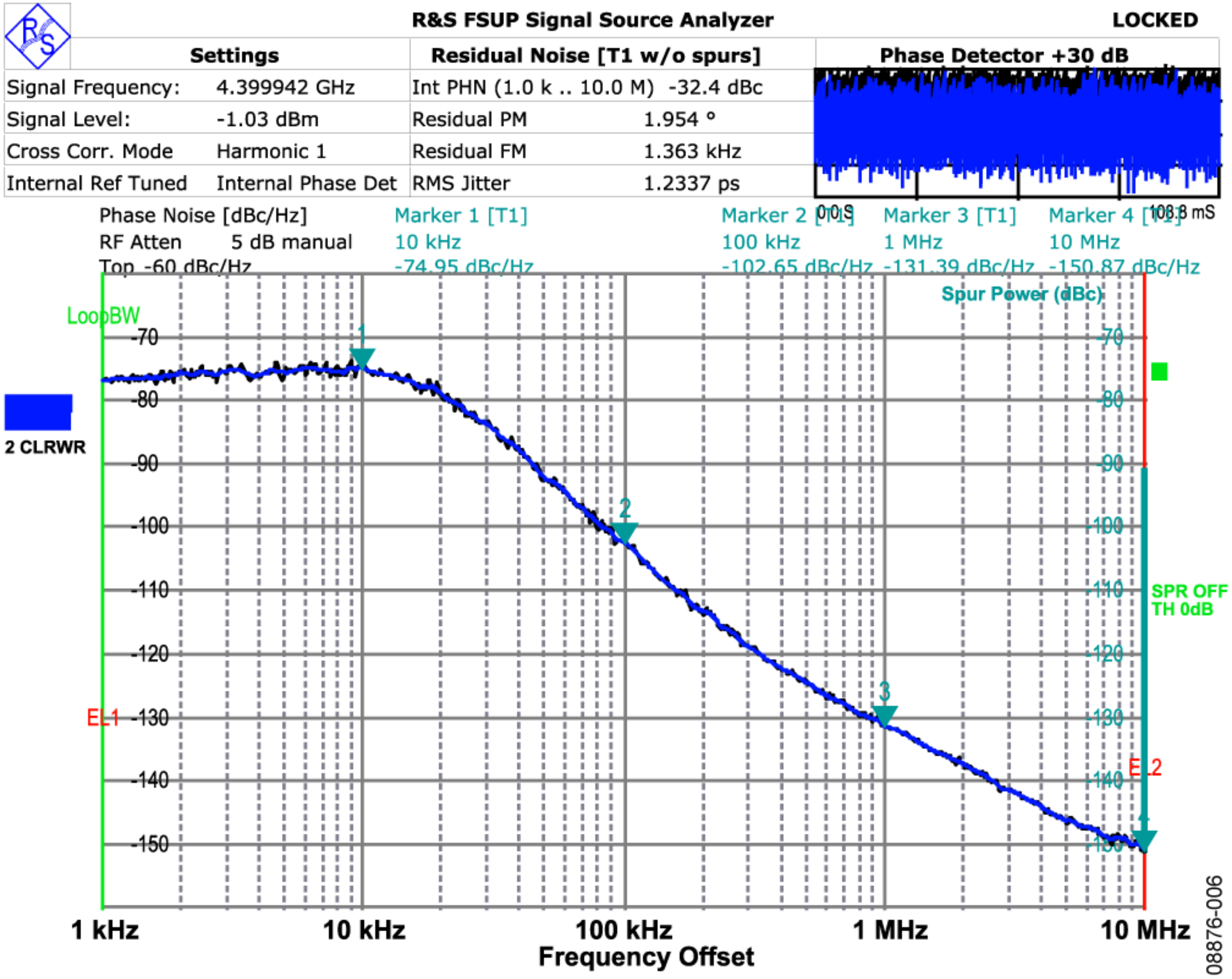


The spectrum of LO is not an ideal straight line. The fluctuations of the instantaneous phase produce a broadening of the line called “**phase noise**”

- The noise spectrum around LO is transferred at IF around the translated signal degrading the SNR.
- Oscillators used in receivers must satisfy strict requirements concerning the phase noise (characterized by C/N ratio at a specified distance from f_0)
- The degrading effects of phase noise can be relaxed by increasing the gain of the stages before the mixer.

Example of phase noise measurement

The graph shows the carrier-to-noise ratio (CNR) of a VCO operating at 4.4 GHz



R&S FSUP Signal Source Analyzer **LOCKED**

Settings		**Residual Noise [T1 w/o spurs]**	
Signal Frequency:	4.399942 GHz	Int PHN (1.0 k .. 10.0 M)	-32.4 dBc
Signal Level:	-1.03 dBm	Residual PM	1.954 °
Cross Corr. Mode	Harmonic 1	Residual FM	1.363 kHz
Internal Ref Tuned	Internal Phase Det	RMS Jitter	1.2337 ps

Phase Noise [dBc/Hz]
RF Atten 5 dB manual
Top -60 dBc/Hz

Marker 1 [T1]	Marker 2 [T1]	Marker 3 [T1]	Marker 4 [T1]
10 kHz	100 kHz	1 MHz	10 MHz
-74.95 dBc/Hz	-102.65 dBc/Hz	-131.39 dBc/Hz	-150.87 dBc/Hz

Typical Microwave Mixer parameters

- Conversion Loss (dB) (5-15 dB)
- NF_{SSB} (5-15 dB)
- Linearity (Input Intercept point IP3: 0-10 dBm)
- Local Oscillator Power (0-10 dBm)
- Spurious signals at output
- Matching at the ports (<15 dB)
- Isolation LO-IF and LO-IF (depends on the actual implementation)
- Phase noise of LO: CNR>100 dB for $\Delta f \approx$100KHz-1MHz

Characterizing parameters of a receiver

- **Sensitivity**: ability to response to a weak signal. It is expressed as the level of the input signal (dBm) determining a specified value of a quality parameter (SNR, BER, EVM, etc)
- **Selectivity**: ability to reject the unwanted signals on the adjacent frequency channels (>70 dB typical)
- **Spurious response rejection**: ability to reject signals outside the receiving band. It depends on the filters and on the value of IF and OL frequencies
- **Intermodulation rejection**: with two or more large signals at input possible intermodulation products are generated inside the receiver (and converted at IF)

- **Equivalent noise temperature** quantify the overall noise produced by the receiver referred to the input
- **Frequency stability** it refers to the LO frequency. Instability produces phase noise which impact on the quality of dem. signal
- **LO Isolation**: possible leak through the mixer could allows the LO signal reaching the antenna an be radiated into the free space. To be avoided

Receiver Sensitivity

Analog receiver:

Minimum power level (S) at the receiver input for a specified input SNR. It has:

$$SNR = \frac{S}{KT_{eq}B}$$

T_{eq}=Equivalent noise temp. of the receiver

B = Signal band

Digital receiver:

Minimum signal power (S) at the receiver input for a specified BER in base band.

BER determines E_b/N_0 at mixer output, which can be back propagated at the receiver input, allowing the evaluation of the input SNR

Dynamic Range

It quantifies the range of power allowed at the receiver input.

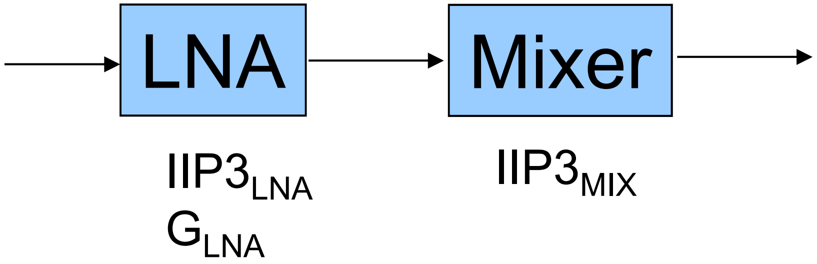
The minimum power is defined by the sensitivity (S).

The maximum power is conventionally assumed as the mean power of a 2-tone signal producing a IM3 power (referred to the input) equal to the receiver sensitivity (S):

$$DR_{dB} = \frac{2}{3}\left(IIP_{3,dBm} + 3 - S_{dBm} \right)$$

IIP3=3th order Intercept power at input of the receiver

Overall IIP3 of the receiver



The intercept at input of each stage (IIP3) is equal to the intercept at output (IP3) divided the gain.
For the chain in the figure it has:

$$\left(\frac{1}{IIP_3}\right)^2 = \left(\frac{1}{IIP_{3,LNA}}\right)^2 + \left(\frac{G_{LNA}}{IIP_{3,mix}}\right)^2$$

Note: all the quantities are natural (not dB!)

For a chain with n stages:

$$\left(\frac{1}{IIP3}\right)^2 = \left(\frac{1}{IIP3_1}\right)^2 + \left(\frac{G_1}{IIP3_2}\right)^2 + \left(\frac{G_1G_2}{IIP3_3}\right)^2 + \ldots \left(\frac{G_1G_2\ldots G_{n-1}}{IIP3_n}\right)^2$$

Spurious responses

Spurious responses are any undesirable signal that produces an output in base band (overlapping and degrading the desired information)
Spurious may arise both externally and internally to the receiver. Those external can be controlled with the filters (it could be difficult for broad band receiver)
The most critical spurious are however those generated internally to the receiver. These are typically produced inside the mixer, exploiting its intrinsic non linearity. Given f_{IF} and f_{LO} the IF and LO frequencies, the frequencies f_{RF} converted at IF satisfy the following condition:

$$mf_{RF} - nf_{LO} = \pm f_{IF} \quad \Rightarrow \quad f_{RF} = \frac{nf_{LO} \pm f_{IF}}{m} \qquad n, m = 1, 2, 3....$$

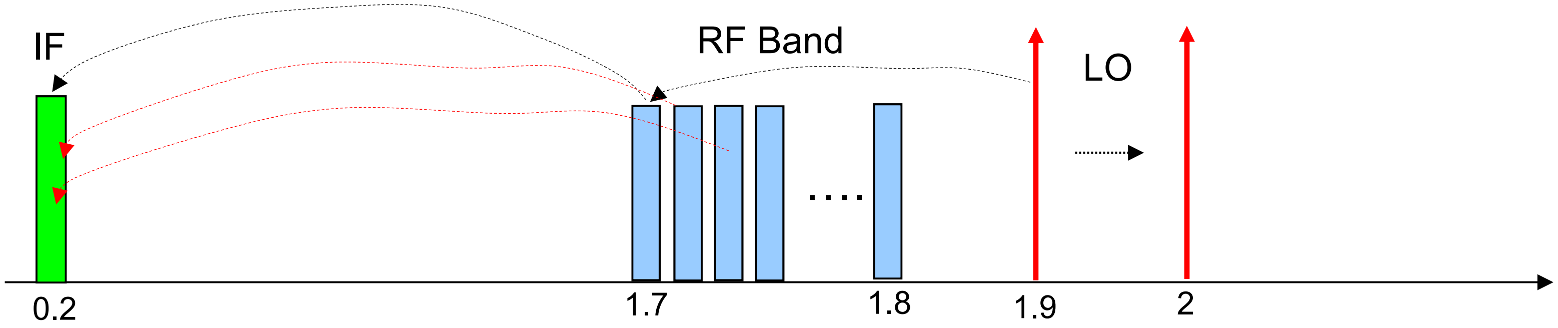
With m=n=1 the wanted and the image frequencies are obtained (the second one is rejected by filter 1). Among all the other values of m,n the most critical ones are those producing frequencies inside the receiver band and then converted to f_{IF}. (note that the IF filter don’t remove these spurious because they fall inside its passband).

Note that spurious can be also generated when two high level carrier close each other are present at the receiver input . The finite IIP3 of the receiver is responsible in this case of the spurious generation.

Example

Receiver band: 1700-1800 MHz
Channel band: 1 MHz (101 ch.)
IF frequency: 200 MHz

Local Oscillator:1900-2000 MHz
Image band (rejected): 2100-2200



Let consider the spurious generating from the first 8 harmonics of LO=1.991: $f_{rf}=(n\cdot 1.991\pm 0.2)/m$. In addition to $f_{RF}=1.791$ (tuned channel 92), three other frequencies in the RF band are converted at f_{IF} with the following values of m and n:

n=7, m=8: $f_1=1.7171$, $f_2=1.7671$; n=6, m=7: $f_3=1.7351$

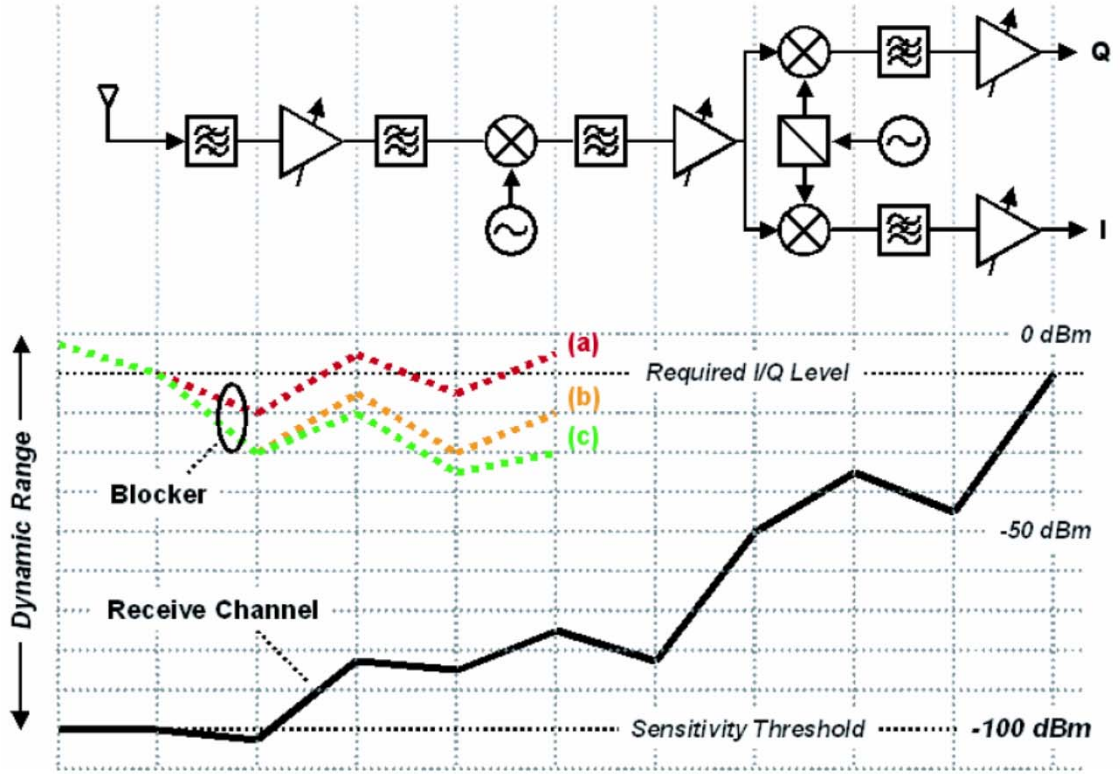
These frequencies fall in channels 18, 68 and 36 which then represent spurious signals for the received channel (92).

It can be however observed that these spurious signals are produced by high order harmonics (6,7,8) of local oscillator and RF, the level of which is extremely low in the real mixers

Blockers

When a receiver operates in a highly crowded frequency spectrum, it may happen that high power unwanted signals fall just outside the receiver band (but far away the image band). These signal may degrade the receiver performances for several reasons.

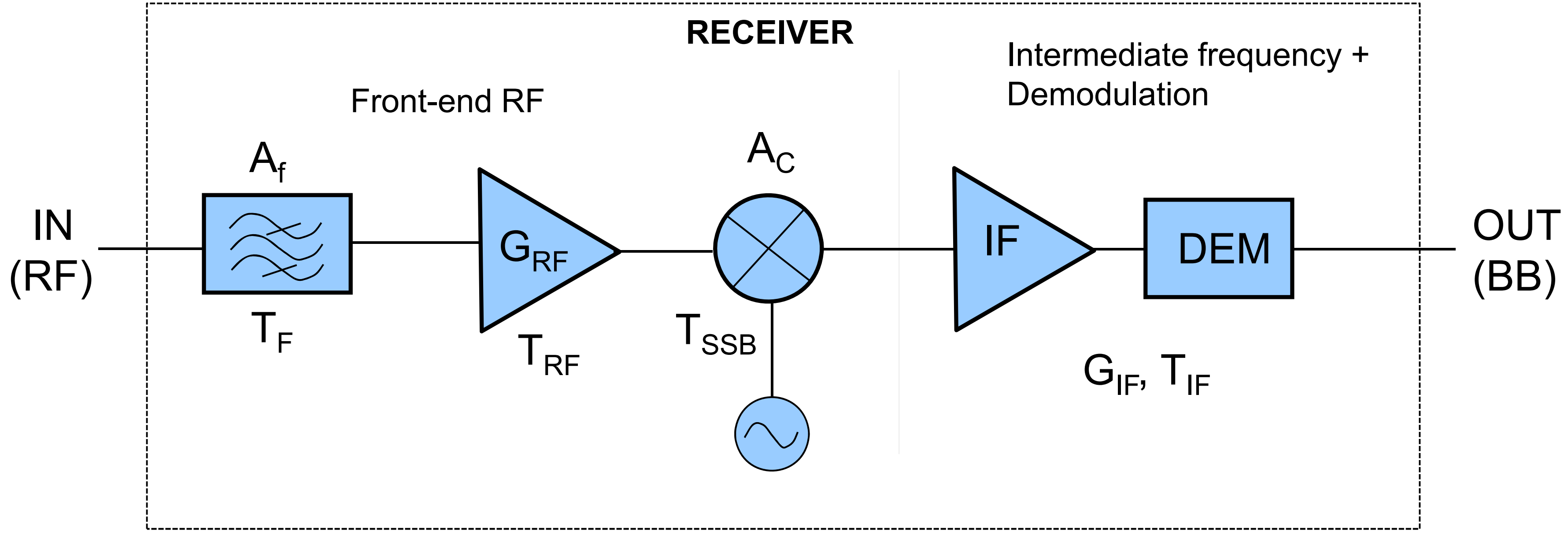
A possible scenario is shown in the next picture:

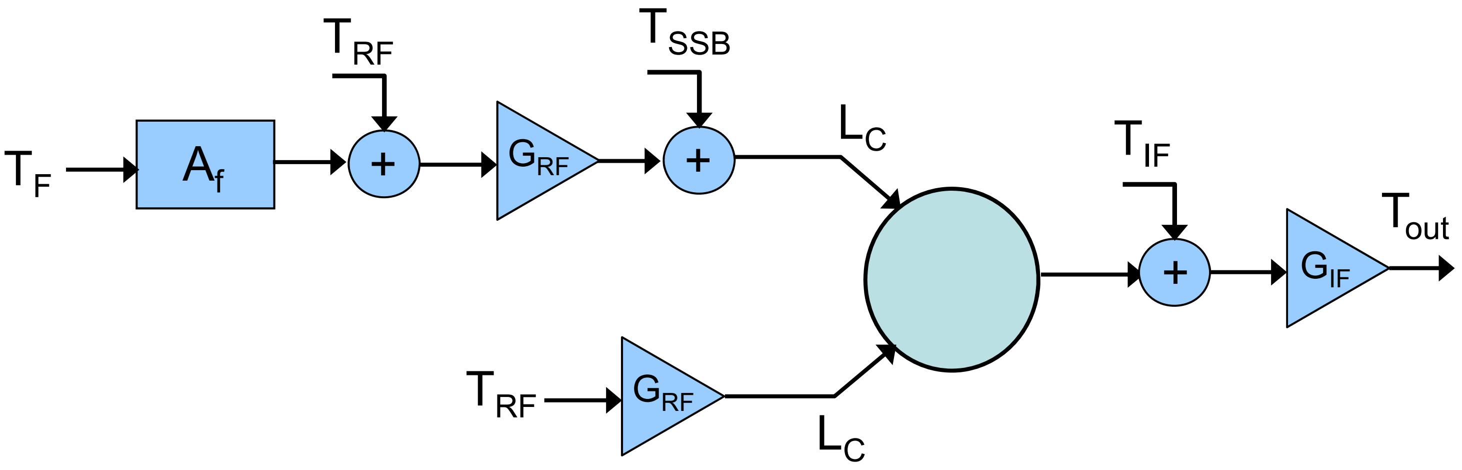


It can be observed that the RF front-end could operate with a the disturbing signal after the image filter larger than the channel signal (several tens of dB). Moreover the blocker may saturate the LNA or the Mixer, reducing the gain for the channel signal and producing also IMD with the signal itself.

The final rejection of the blocker is provided by the IF filter

Evaluation of the receiver Noise





Equivalent noise temperature of the receiver

The equivalent noise temperature of a receiver is obtained by dividing the noise temperature at output for the overall gain between BB and antenna:

$$T_{REC} = T_{out} \frac{L_C A_f}{G_{RF} \cdot G_{IF}}$$

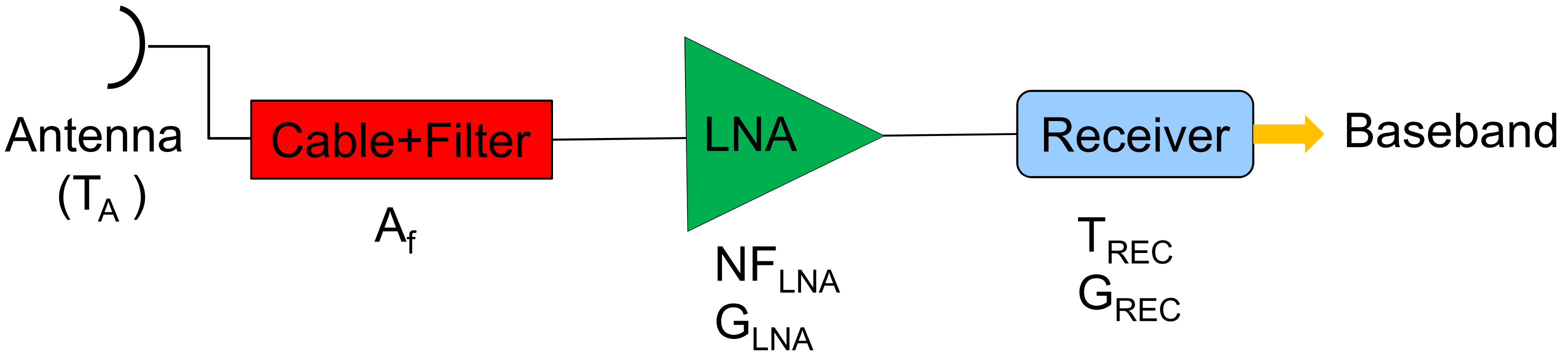
From the scheme in the previous slide, assuming $A(f_{IF}) \approx \infty$, it is obtained:

$$T_{out} = G_{IF} \cdot \left[\frac{T_{RF} \cdot G_{RF}}{L_C} + \frac{\left[\frac{T_F}{A_f} + T_{RF} \right] G_{RF} + T_{SSB}}{L_C} + T_{IF} \right]$$

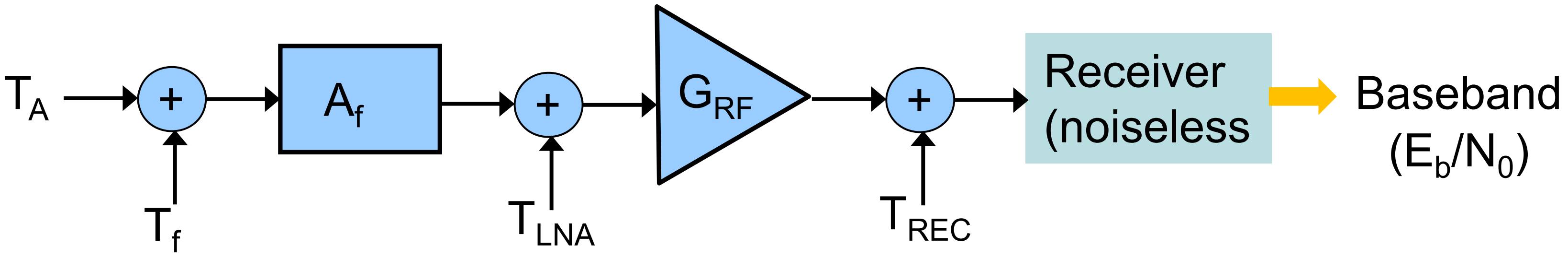
Then:

$$\boxed{\begin{aligned} T_{REC} &= T_{RF} \cdot A_f + \left[T_F + A_f T_{RF} \right] + \frac{A_f T_{SSB}}{G_{RF}} + \frac{L_C A_f T_{IF}}{G_{RF}} \\ &= T_F + 2 A_f T_{RF} + \frac{A_f \left(T_{SSB} + L_c T_{IF} \right)}{G_{RF}} \end{aligned}}$$

System noise temperature



The system noise temperature is the overall noise in baseband (N_{BB}) reported at the antenna input: $N_{SYS}=N_{BB}\cdot A_f/(G_{LNA}\cdot G_{REC})$



$$T_f = T_0\left(10^{A_f/10}-1\right), \qquad T_{LNA} = T_0\left(10^{NF_{LNA}/10}-1\right)$$

$$\boxed{T_{SYS} = T_A + T_f + A_f T_{LNA} + \frac{A_f}{G_{LNA}} T_{REC}}$$

If S is the power received from the antenna, the SNR_{sys} is defined as:

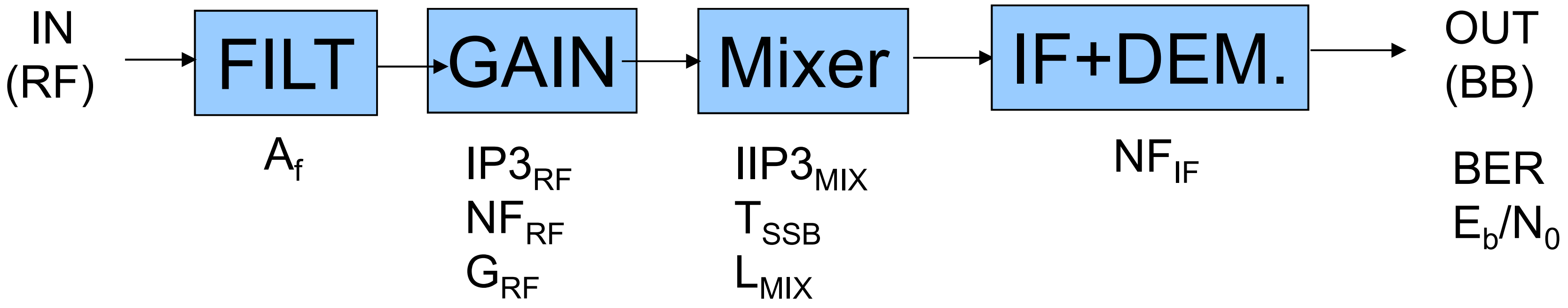
$$\boxed{SNR_{SYS} = \frac{S}{KT_{SYS}B} = \frac{E_B}{N_0}\frac{R}{B}}$$

Note: E_B/N_0 is the same in baseband

Receiver Budget Analysis

- The purpose of a budget analysis is to determine the individual specifications of the receiver blocks. This analysis is dependent on several key system parameters.
- Sensitivity and dynamic range of a receiver are the two main parameters that define the range of input RF power that must be received
- Bit error rate (BER) is the measures that define the acceptable quality of the received signal.
- Sensitivity defines the lowest input RF signal that must be detected and distinguished by the receiver with acceptable quality
- Dynamic range defines the entire range of input RF power from the sensitivity threshold up to the maximum detected signal.
- The budget analysis assumes suitable criteria to determine the requirements of various receiver blocks. This typically involves calculations for gain, noise figure, filtering, intermodulation products (IM), and input 1dB compression power.
- CAD programs often offer specific tools for carrying out the budget analysis at system level

Budget evaluation (example)



IN (RF) → FILT → GAIN → Mixer → IF+DEM. → OUT (BB)

A_f

$IP3_{RF}$
NF_{RF}
G_{RF}

$IIP3_{MIX}$
T_{SSB}
L_{MIX}

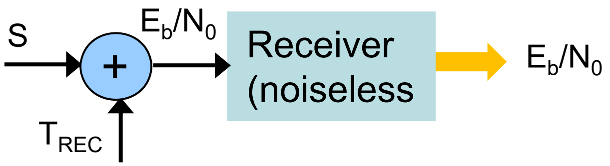
NF_{IF}

BER
E_b/N_0

Assigned parameters:
- Sensitivity S (dBm) for a given BER (→ E_b/N_0)
- Dynamic Range D (=P_{max}-S)
- Data rate R (MBit/sec) and signal band B (MHz)

Constraint on the minimum input power

Representing the receiver with its equivalent noise temperature (T_{REC}) it has:



S

T_{REC}

+

E_b/N_0

Receiver (noiseless)

E_b/N_0

$$SNR = \frac{S}{\left(KT_{REC}\right)\cdot B} = \frac{E_b}{N_0}\frac{R}{B}$$

We know the expression for T$_{REC}$:

$$T_{REC} = T_F + 2A_f T_{RF} + \frac{A_f\left(T_{SSB} + L_{mix} T_{IF}\right)}{G_{RF}}, \qquad T_F = 290\left(10^{A_f/10} - 1\right), \quad T_{RF} = 290\left(10^{NF_{RF}/10} - 1\right)$$

The budget equation is then:

$$\underset{\substack{\uparrow\\ \text{Ass.}}}{\left(\frac{E_b}{N_0}\right)_{dB}} + \underset{\substack{\uparrow\\ \text{Ass.}}}{\left(\frac{R}{B}\right)_{dB}} = \underset{\substack{\uparrow\\ \text{Ass.}}}{S\Big|_{dBm}} - 10\log\left(KB\right) - 10\log\left(T_F + 2\underset{\substack{\uparrow\\ \text{Var.}}}{A_f}\,\underset{\substack{\uparrow\\ \text{Var.}}}{T_{RF}} + \frac{A_f\left(\underset{\substack{\uparrow\\ \text{Var.}}}{T_{SSB}} + L_{MIX}\underset{\substack{\uparrow\\ \text{Var.}}}{T_{IF}}\right)}{\underset{\substack{\uparrow\\ \text{Var.}}}{G_{RF}}}\right)$$

For the assigned parameters values there are several combinations of the variables which satisfy the budget equation. Selecting criteria must take into account other possible constraint as costs, dimensions, availability etc. Some of the above variable however impact on the budget equation resulting from the large signal behavior of the receiver (see the next slide)

Constraint on the maximum input power

In this case, using the sensitivity and the dynamic range, we can derive IIP3 from S and DR: IIP3=(3/2)DR-3+S. Using the formula giving the overall IIP3 of the cascade of several stages we obtain (linear blocks have infinite IP3):

$$\left(\frac{1}{IIP3}\right)^2 = \left(\frac{\frac{1}{\overset{\text{Var.}}{A_f}}}{\frac{IP3_{RF}}{\underset{\text{Var.}}{G_{RF}}}}\right)^2 + \left(\frac{\frac{1}{\overset{\text{Var.}}{A_f}}\overset{\text{Var.}}{G_{RF}}}{\underset{\text{Var.}}{IIP3_{mix}}}\right)^2 = \left(\frac{1}{10^{\frac{(3/2)DR_{dB}+S_{dBm}}{10}}}\right)^2$$

Note that G_{RF} and A_f also appear in the previous budget equation so the same value must be used.

In the design of the receiver also other constraints need to be taken into account, like the spurious and blocker suppression, the image band suppression, etc.
All these constraints result into additional budget equations which have to be satisfied by all the involved variables.
The budget analysis must be repeated for each possible configuration of the receiver (moving or changing the order of the blocks and also removing blocks)

Double conversion receivers

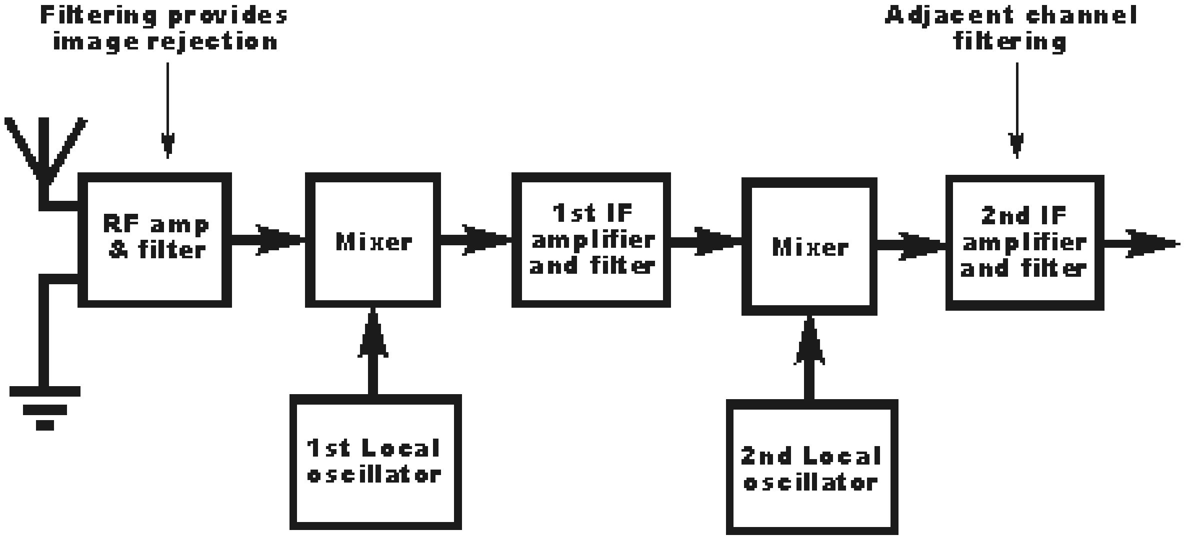
When choosing the intermediate frequency for a conversion receiver a trade-off is needed concerning the value of the IF:

- ***High IF:*** The use of a high IF means that the difference between the wanted frequency and the unwanted image is much large and it is possible to achieve a good performance even with a simple image filter (high level of rejection is provided).
- ***Low IF:*** The advantage of choosing a low IF is that the IF filters and amplifiers works at low frequency and are easier to realize. The use of a low IF enables the performance to be high, while keeping the cost low.

Accordingly there are two conflicting requirements which cannot be easily satisfied using a single intermediate frequency.

A possible solution for easing the fulfillment of both requirements at the same time is the double conversion topology

Double conversion receivers



(fixed)

(variable)

The basic concept behind the double conversion radio receiver is the use of a high intermediate frequency to achieve high levels of image rejection, followed by a low intermediate frequency to provide the levels of performance required for the adjacent channel selectivity and amplification.

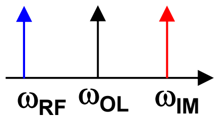
Comments on the frequency-conversion receiver

- It allows most of the signal amplification at IF (more easy than at RF being f_{IF} fixed and much smaller than f_{RF})
- Channel filtering at IF (IF filters more compact and not to be tuned)
- Flexibility in the choice of components (LNA, Mixer, Filters) allows to fit more easily the requirements (Gain, Noise, etc)
- High complexity and integration not completely possible (RF filter)

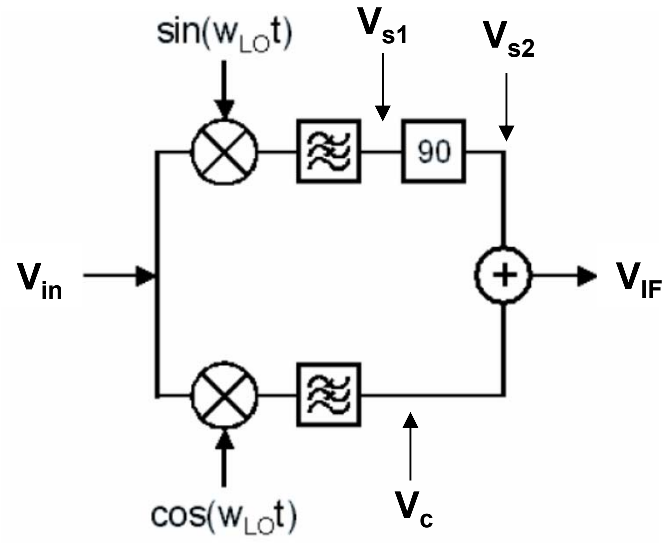
Image reject receivers

- The major drawbacks of heterodyne receiver is the image frequency interference.
- In many application the suppression of image band requires filters with very high attenuation (60-90 dB), resulting in cumbersome devices, expensive and not integrable at all.
- In order to reduce the suppression requirements a particular type of mixer can be used, which allow an intrinsic suppression of the image frequency (image reject mixer).
- The receivers using such mixers (Image Reject Receivers) have relaxed requirements for the image filter (up to 35 dB less that the classical receivers).

Image reject mixer



$$V_{in} = V_{RF}\cos(\omega_{RF}t) + V_{IM}\cos(\omega_{IM}t)$$



$$V_{s1} = V_{RF}\cos(\omega_{RF}t)\sin(\omega_{OL}t) + V_{IM}\cos(\omega_{IM}t)\sin(\omega_{OL}t) = \frac{1}{2}V_{RF}\sin((\omega_{OL}-\omega_{RF})t) - \frac{1}{2}V_{IM}\sin((\omega_{IM}-\omega_{OL})t)$$

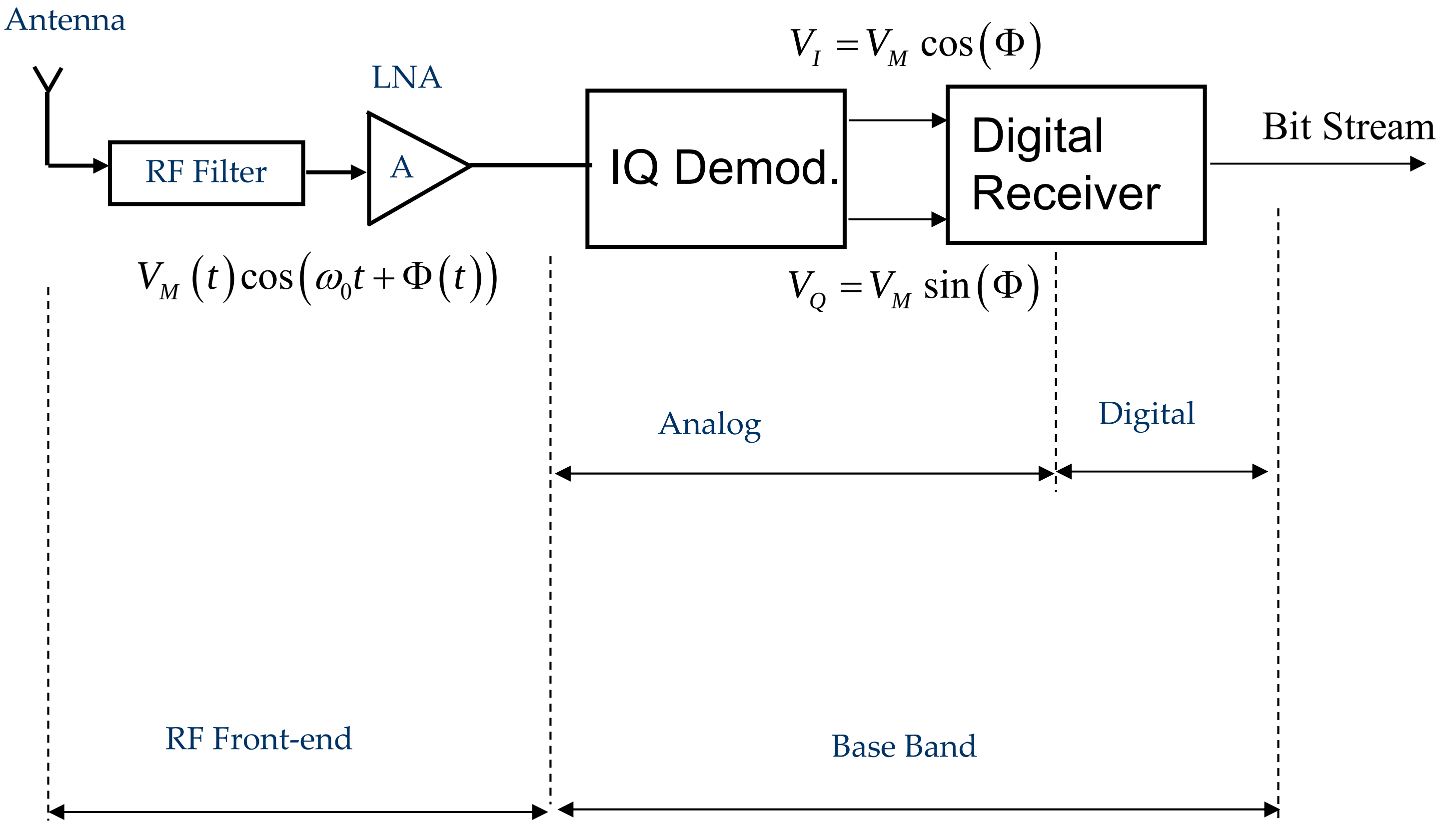
$$V_{s2} = \frac{1}{2}V_{RF}\cos((\omega_{OL}-\omega_{RF})t) - \frac{1}{2}V_{IM}\cos((\omega_{IM}-\omega_{OL})t)$$

$$V_c = V_{RF}\cos(\omega_{RF}t)\cos(\omega_{OL}t) + V_{IM}\cos(\omega_{IM}t)\cos(\omega_{OL}t) = \frac{1}{2}V_{RF}\cos((\omega_{OL}-\omega_{RF})t) + \frac{1}{2}V_{IM}\cos((\omega_{IM}-\omega_{OL})t)$$

$$V_{IF} = V_c + V_{s2} = \frac{1}{2}V_{RF}\cos((\omega_{OL}-\omega_{RF})t) \cancel{- \frac{1}{2}V_{IM}\cos((\omega_{IM}-\omega_{OL})t)} + \frac{1}{2}V_{RF}\cos((\omega_{OL}-\omega_{RF})t) \cancel{+ \frac{1}{2}V_{IM}\cos((\omega_{IM}-\omega_{OL})t)} =$$

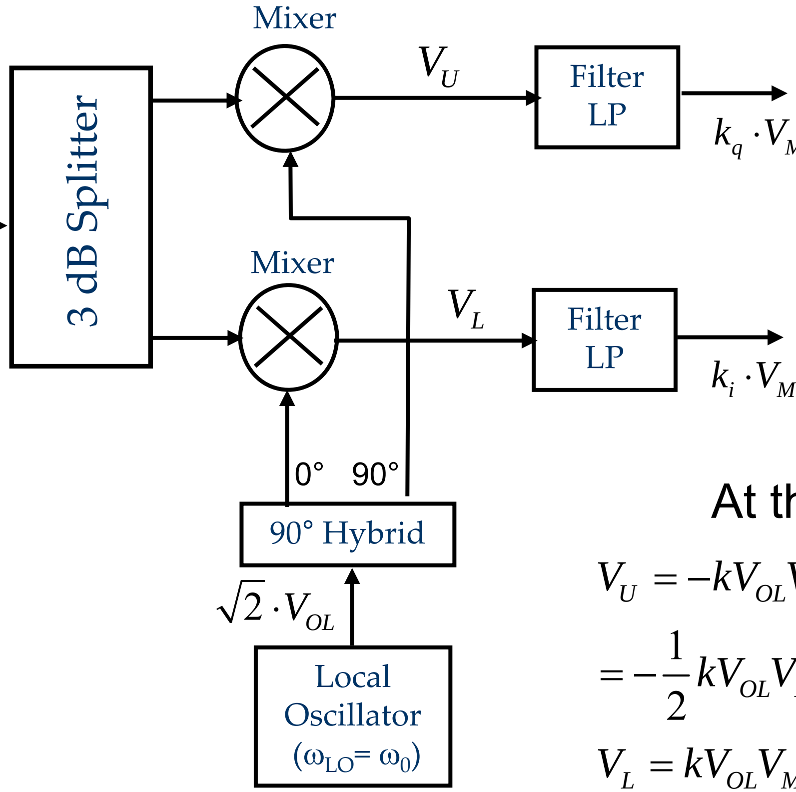
$$\boxed{V_{IF} = V_{RF}\cos((\omega_{OL}-\omega_{RF})t)}$$

Direct-conversion Receiver (zero IF)



IQ Demodulator

$\sqrt{2}\cdot V_M(t)\cos\left(\omega_0 t+\Phi(t)\right)$



3 dB Splitter

Mixer

Mixer

V_U

V_L

Filter LP

Filter LP

0°   90°

90° Hybrid

$\sqrt{2}\cdot V_{OL}$

Local Oscillator ($\omega_{LO}=\omega_0$)

$k_q\cdot V_M(t)\sin\left(\Phi(t)\right)$

$k_i\cdot V_M(t)\cos\left(\Phi(t)\right)$

At the hybrid out:

$$V_{OL,i}=V_{OL}\cos\left(\omega_0 t\right)$$

$$V_{OL,q}=-V_{OL}\sin\left(\omega_0 t\right)$$

At the mixers out:

$$V_U=-kV_{OL}V_M\cos\left(\omega_0 t+\Phi\right)\sin\left(\omega_0 t\right)=$$

$$=-\frac{1}{2}kV_{OL}V_M\left(\cos\left(2\omega_0 t+\Phi\right)+\sin\left(\Phi\right)\right)$$

$$V_L=kV_{OL}V_M\cos\left(\omega_0 t+\Phi\right)\cos\left(\omega_0 t\right)=$$

$$=\frac{1}{2}kV_{OL}V_M\left(\cos\left(2\omega_0 t+\Phi\right)+\cos\left(\Phi\right)\right)$$

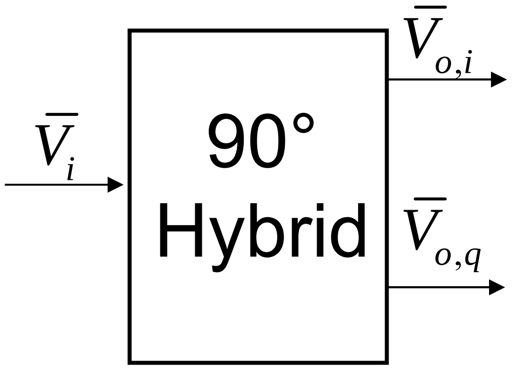
The LP (low pass) filters remove the components at $2\omega_0$ (and all the others produced by the actual nonlinearities). The two output signals are then proportional to I and Q components of the modulated RF signal

Pro & Cons of direct-conversion receiver

- Reduced complexity (cheaper and more compact)
- Easier to integrate (but not the RF Filter)
- More susceptible to noise and distortion
- DC offset voltage at the mixer output due to spurious signal from antennas
- Offset voltage at the mixer output not easy to eliminate (it overlaps with the useful signal)

Hybrid splitter

The hybrid splitter is a passive 3 port device which is characterized by the following properties (all the ports are connected to the reference load R_0):



$$\overline{V}_{o,i} = \frac{1}{\sqrt{2}}\overline{V}_i, \qquad \overline{V}_{o,\mathrm{q}} = -j\frac{1}{\sqrt{2}}\overline{V}_i$$

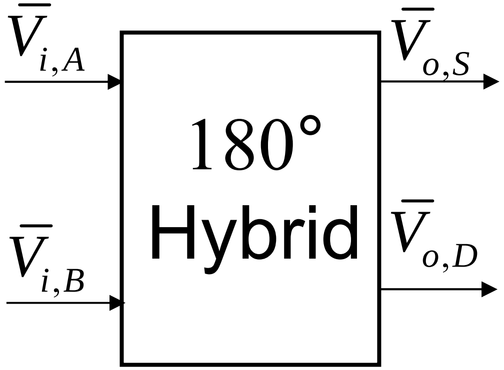
All the signals are voltage phasors (carrier f_0)

The input signal is split into 2 equal signals carrying half of the overall power.
The two out signals have a phase difference of 90°.
All the ports are matched (no reflected power).

Hybrids with 0° and 180° of phase difference are also possible.

Hybrid combiner

An hybrid combiner is a passive 4 port device which is characterized by the following properties (all the ports are connected to the reference load R_0):



$$\bar{V}_{o,i} = \frac{1}{\sqrt{2}}\left(\bar{V}_{i,A} + \bar{V}_{i,B}\right)$$

$$\bar{V}_{o,q} = \frac{1}{\sqrt{2}}\left(\bar{V}_{i,A} - \bar{V}_{i,B}\right)$$

All the signals are voltage phasors (carrier f_0)

Note that $|V_{o,S}|^2$ is proportional to the sum of the input signals power only when the signals are equal. In this case $V_{o,D}=0$.

When the signal are statistically defined we get the following result:

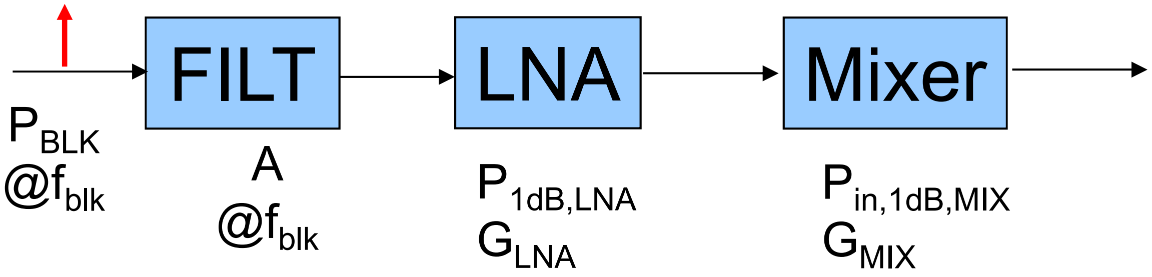
$$P_{o,\mathrm{i}} = \frac{1}{2}\frac{\left|\bar{V}_{o,i}\right|^2}{R_0} = \frac{1}{2}\left(\frac{\left|\bar{V}_{i,A} + \bar{V}_{i,B}\right|^2}{2R_0}\right) = \frac{1}{2}\left(\frac{\left|\bar{V}_{i,A}\right|^2}{2R_0} + \frac{\left|\bar{V}_{i,B}\right|^2}{2R_0} + \frac{\left\langle V_{i,A}\cdot V_{i,B}\right\rangle}{R_0}\right) = \frac{1}{2}\left(P_{i,A} + P_{i,B} + P_{cross}\right)$$

For uncorrelated signals $P_{cross}=0$, then:

$$\boxed{P_{o,\mathrm{i}} = \frac{1}{2}\left(P_{i,A} + P_{i,B}\right)}$$

The output power is 3dB less than the sum of the input powers

Example



P_{BLK} @f_{blk}

FILT

A @f_{blk}

LNA

$P_{1dB,LNA}$ G_{LNA}

Mixer

$P_{in,1dB,MIX}$ G_{MIX}

Let consider a blocker with power P_{BLK} at the receiver input, at a frequency f_{blk} outside the band of the receiver. We want to found the filter attenuation $A(f_{blk})$ so that the power of the blocker at LNA output and mixer input is lower than P_{1dB} of the two devices by at least BO (all the quantities are in dB). It is assumed that all the devices parameters above specified are about independent on frequency.
The power at LNA output results:

$$P_{out,LNA} = P_{BLK} - A + G_{LNA}$$

Imposing that $P_{out,LNA}$ is lower than $P_{1dB,LNA}$-BO and $P_{in1dB,MIX}$-BO the condition on A is found:

$$A \geq P_{BLK} + BO + G_{LNA} - \min\left(P_{1dB,LNA}, P_{in1dB,MIX}\right)$$