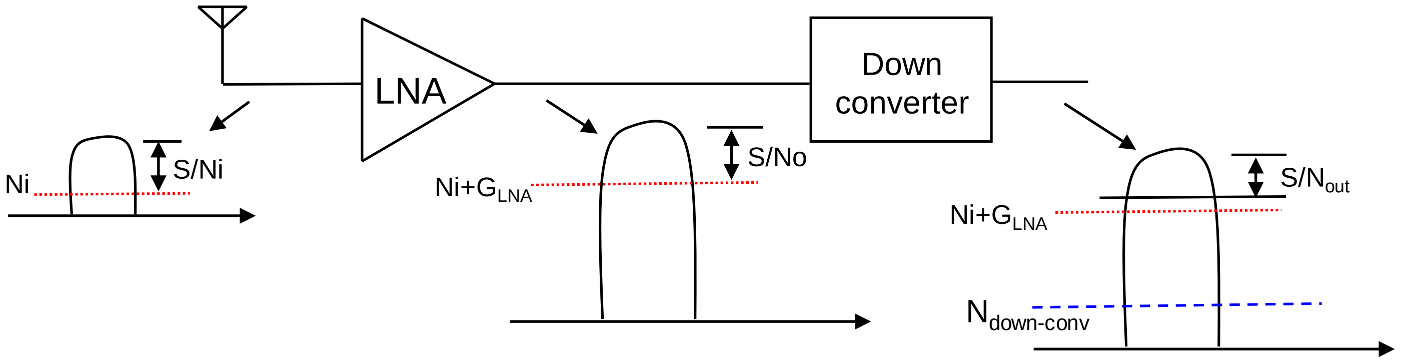
Low noise amplifier, principles

- **Low noise amplifier (LNA) design**
  - Introduction
  - 2-port noise theory, review
  - LNA gain/noise desense
  - Bias network and its effect on LNA IP3
  - LNA stability
- **References**

Why an LNA is needed in a radio receiver?

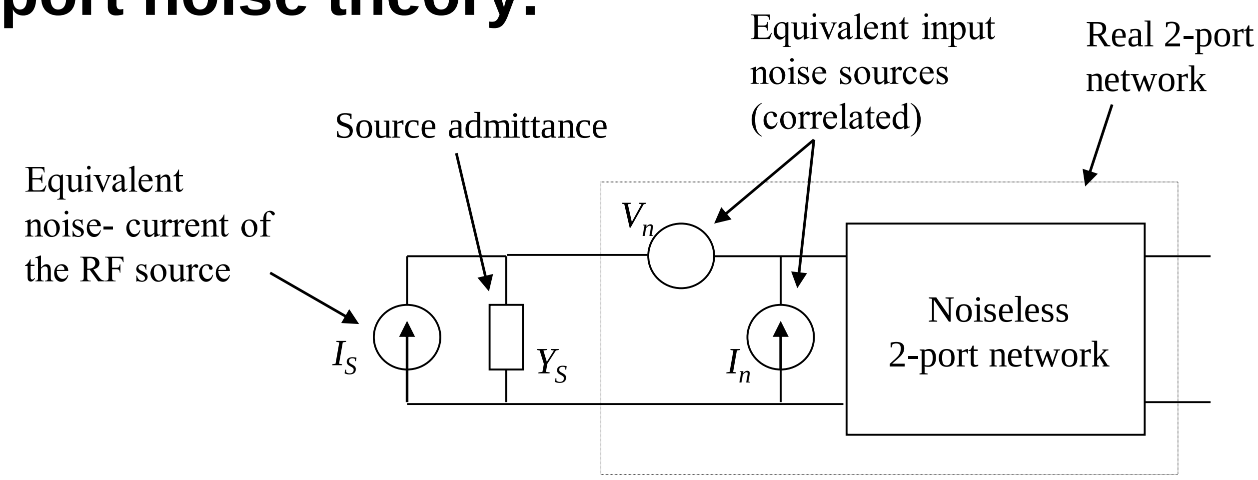


- LNA amplifies both incoming signal and noise by the same amount! So how that is going to help?

- the key is in LNA amplifying the noise enough (set by G_{LNA}) so that the noise of subsequent stages will be relatively small compared to the "overwhelming" amplified noise from the LNA. As a result, the noise added by the subsequent stages will not degrade the S/N much. In this case, the entire receiver NF will be dominated by that of the LNA itself.

- note that the LNA amplifies both incoming thermal noise and the noise generated within the LNA itself. Therefore, it is essential to design the amplifier with really low noise characteristic, hence the name LNA.

2-port noise theory:



The equivalent input noise sources , V_n and I_n, are partially correlated. I_n, can be decomposed into two components: one is proportional to V_n through some correlation admittance, Y_C, and the other component, I_u, is uncorrelated with V_n. This can be expressed as:

$$I_n = I_u + Y_C V_n$$

The *NF* is the ratio of the total noise power generated by the network and by the driving source, to the noise power generated by the driving source itself. If the network is noiseless, the S/N ratio is the same at both input and output and so the *NF* is unity.

Applying the *NF* principle to the network assuming that the 2-port is matched to *YS* yields

$$NF=\frac{\overline{[I_u+(Y_c+Y_S)V_n]^2}+\overline{I_S^2}}{\overline{I_S^2}}=1+\frac{\overline{I_u^2}+\left|Y_c+Y_S\right|^2\overline{V_n^2}}{\overline{I_S^2}}$$

where I_s is the equivalent noise current of the driving source. The three independent noise sources, V_n, I_u and I_s, can be treated as a thermal noise source associated with an equivalent resistance or conductance:

$$\overline{V_n^2}=4kT\Delta fR_n\,,\quad \overline{I_u^2}=4kT\Delta fG_u\,,\quad \overline{I_S^2}=4kT\Delta fG_S$$

where $Y_c=G_c+jB_c$ and $Y_S=G_S+jB_S$

Substituting in the NF equation above, results in:

$$NF=1+\frac{G_u+\left((G_S+G_c)^2+(B_S+B_c)^2\right)R_n}{G_S}$$

Taking the partial derivative the *NF* equation with respect to the source admittance, Y_S, and setting the result to zero to find the minima yields the following two conditions to be satisfied:

$$B_{S-opt}=-B_c \quad \text{and} \quad G_{S-opt}=\sqrt{\frac{G_u}{R_n}+G_c^2}$$

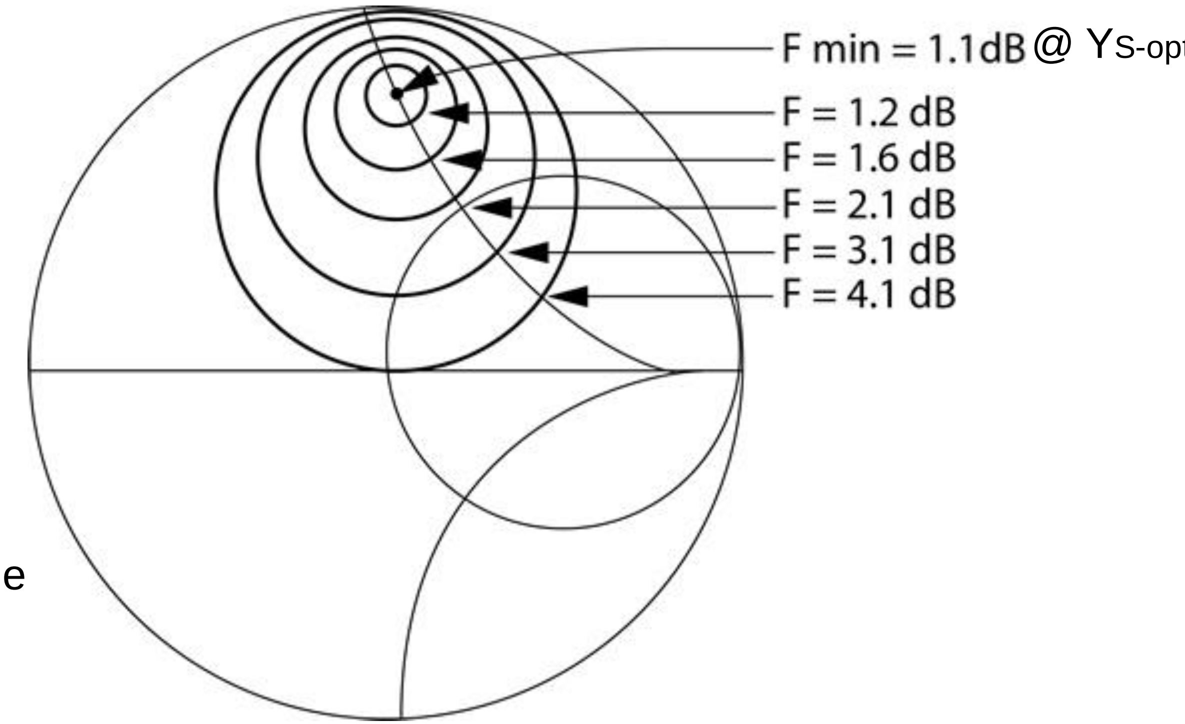
Substituting in the NF equation results in the minimum noise figure, NF_{min}

$$NF_{\min} = 1 + 2R_n\left[G_{S-opt} + G_c\right] = 1 + 2R_n\left[\sqrt{\frac{G_u}{R_n} + G_c^2} + G_c\right]$$

This result indicates that for any 2-port network, one can always find a minimum noise figure by proper choice of the driving source admittance (impedance). Any deviation of the driving source admittance from the optimum value will result in a higher *NF*. In fact, the *NF* of the 2-port can be expressed as a function of NF_{min} and any arbitrary Y_S as:

$$NF(Y_S) = NF_{\min} + \frac{R_n}{G_S}\left[(G_S - G_{S-opt})^2 + (B_S - B_{S-opt})^2\right]$$

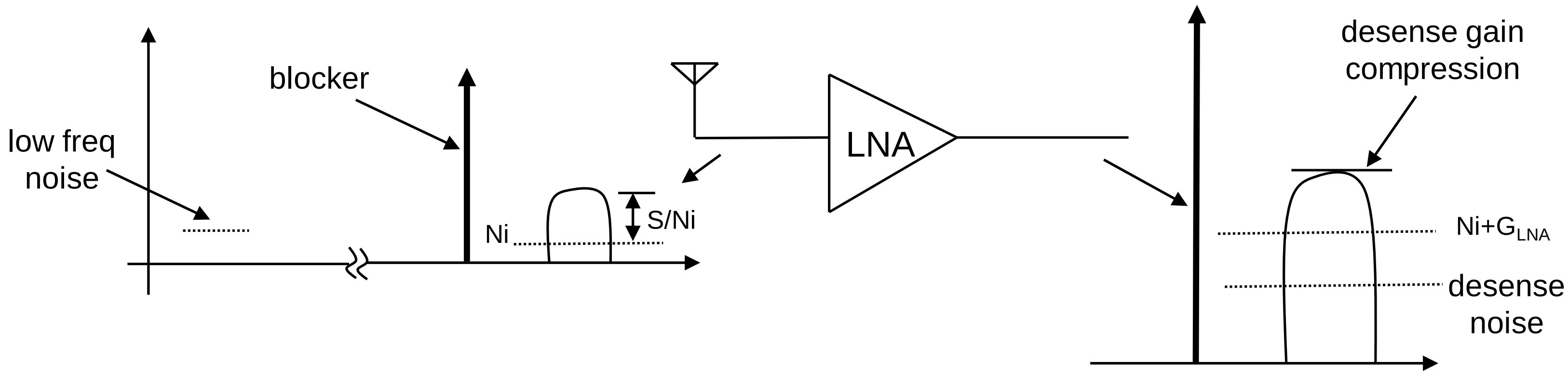
which are the famous noise circles that can be represented on a Smith Chart. In the following sections, the 2-port noise theory will be applied to the design of low noise amplifiers, which can be treated as a 2-port network.



example

The NF contours (circles) are centered around $Y_{S\text{-opt}}$ and plots the NF in the admittance domain as a function of Y_S. This shall give the designer an idea on how to trade-off NF vs power match. Please note that any changes to the circuit (active or passive) changes Ys-opt and NFmin values. We will discuss later in class how to manipulate circuit to get simultaneous NFmin and power match

LNA linearity and desensitization:



In the presence of a blocker, the forward gain of the LNA might actually compress even if the desired signal is actually very small. The gain compression due to a blocker is caused by LNA 3rd order nonlinearity. Furthermore, due to LNA second order nonlinearity, the large blocker will mix with low frequency noise, generated within the LNA, and get upconverted to fall right on the desired band degrading the overall S/N. **The desensitization of LNA is defined as the blocker level that causes the LNA dynamic range to drop by 1dB (either by gain compression or by noise floor rising, whichever is smaller).**

LNA gain desensitization due to blocker

The LNA output voltage can be written as a function of the input voltage as

$$V_o = a_1 V_i + a_2 V_i^2 + a_3 V_i^3 + \ldots$$

a1 represents the small signal forward gain. Let us assume also that *a1*, *a2*, and *a3* are frequency independent. Now, let us assume that the input to the LNA is composed of a desired signal *V1* and the blocker *V2* as follows

$$V_i = V_1 \cos\omega_1 t + V_{blk} \cos\omega_2 t$$

Substituting the *Vi* into the LNA function and gathering terms at the desired signal frequency ω1 we get

$$V_o = a_1 V_1 \cos\omega_1 t + \frac{3}{2} a_3 V_1 V_{blk}^2 \cos\omega_1 t + \ldots$$

Where the second term comes from 3rd order nonlinearity. Thus, the actual gain of the LNA in presence of a blocker is

$$a_1^{'} = a_1\left(1 + \frac{3}{2}\frac{a_3}{a_1} V_{blk}^2\right)$$

The blocker level that degrades (compresses) the LNA gain by 1dB can then be calculated as:

$$20\log\left(1+\frac{3}{2}\frac{a_3}{a_1}V_{blk}^2\right)=-1\text{dB}\Rightarrow V_{blk}=0.27\sqrt{\frac{|a_1|}{|a_3|}}$$

As seen, the blocker level causing 1dB gain desense is set by the ratio of coefficients a_1 and a_3. The more is the 3^{rd} order distortion in the LNA, the less blocker level it can handle.

Note that we assumed that a_1 and a_3 are of opposite signs, which will result in gain compression in the presence of a blocker. If a_1 and a_3 have the same sign, gain expansion will occur.

** Similar analysis to calculate P1dB due to signal-only as well as IIP3 with two equal tones leads to [4]

$$V_{1dB}=0.383\sqrt{\frac{|a_1|}{|a_3|}} \quad , \; V_{IM3}=1.155\sqrt{\frac{|a_1|}{|a_3|}}$$

Which leads to the famous 9.5dB difference between an amplifier P1dB and IIP3

LNA NF desensitization due to blocker

The LNA dynamic range can also be degraded due to presence of a blocker by increasing the noise floor of the desired band. This happens when low frequency noise generated within the LNA and its bias mixes with the large blocker and gets upconverted to RF, aliasing on the desired band. The mechanism is strictly due to second order nonlinearities.

Let us assume the input to the LNA is composed of a small desired signal V_1 and a large blocker V_{blk}:

$$V_i = V_1 \cos \omega_1 t + V_{blk} \cos \omega_2 t$$

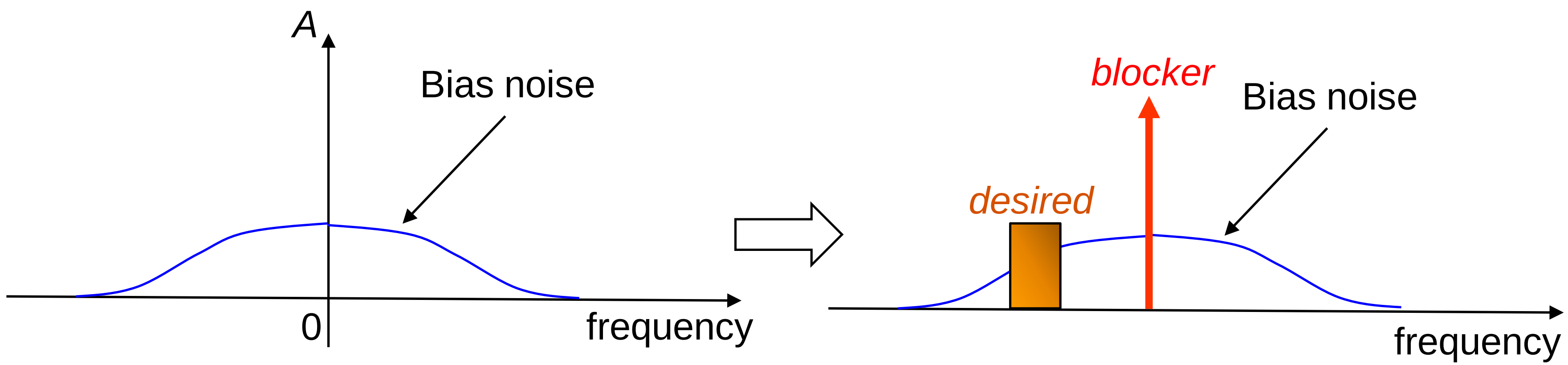
Let us represent the low frequency noise by a sinusoidal signal, $V_3 \cos \omega_3 t$, with frequency $\omega_3 << (\omega_1, \omega_2)$. Therefore

$$V_i = V_1 \cos \omega_1 t + V_{blk} \cos \omega_2 t + V_3 \cos \omega_3 t$$

Substituting into the LNA gain equation, neglecting powers beyond the 2nd results in

$$V_o = a_1 V_1 \cos \omega_1 t + a_2 V_{blk} V_3 \cos(\omega_2 \pm \omega_3) t + \ldots$$

The noise at ω_3 falls on ω_1 band if $\omega_2 \pm \omega_3 = \omega_1$



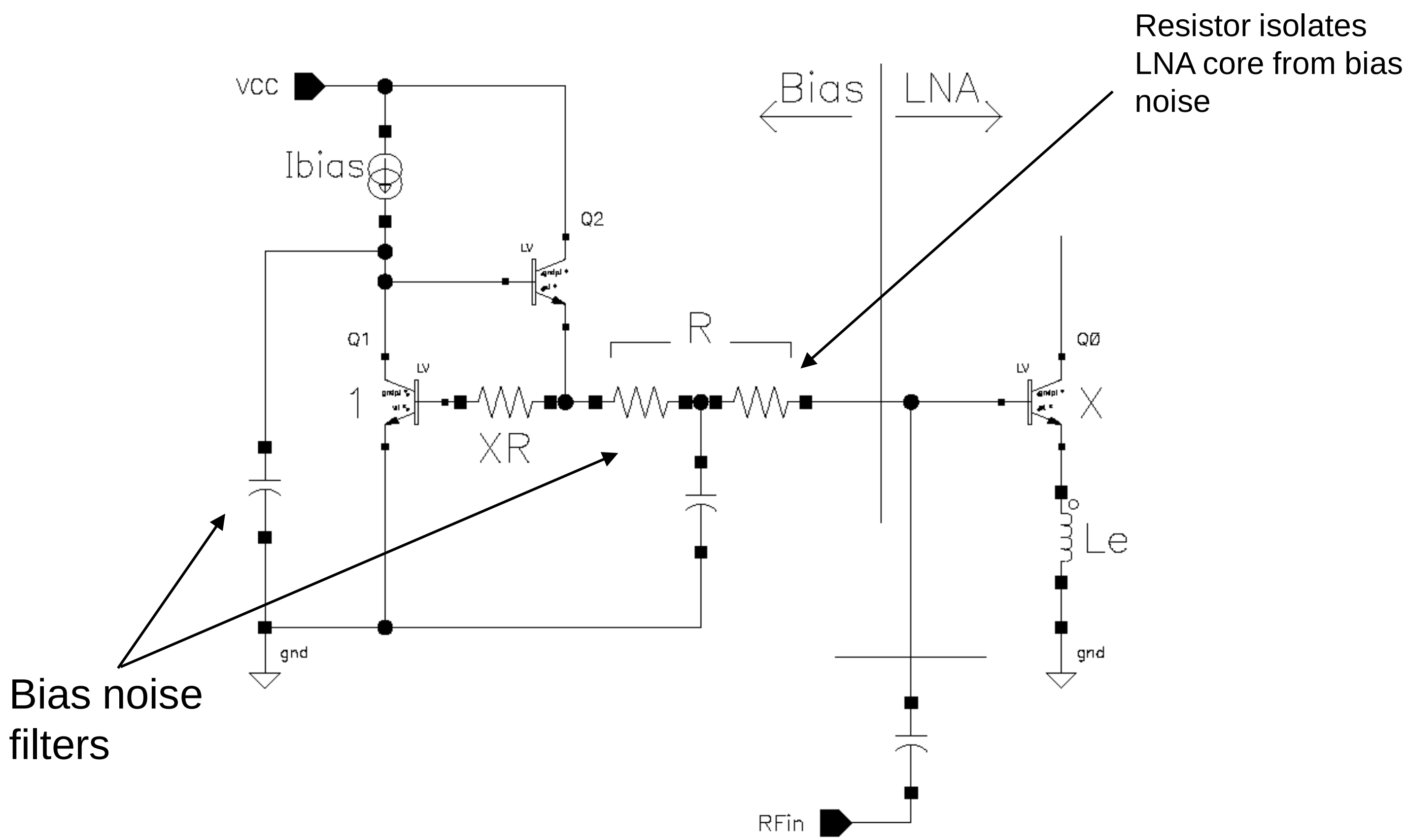
How can one reduce the LNA noise desense?

By investigating the derived desense equation, one can see that the desense performance can be improved by:

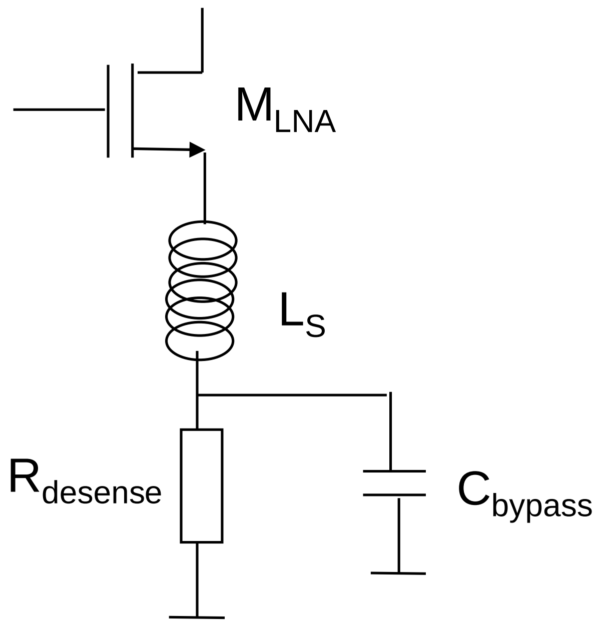
1) Decrease the low frequency noise level, V_3, at bandwidth ω_3.
2) Decrease the LNA second order distortion

The circuit generating bias current to the LNA tend to be quite noisy at low frequency (especially if it is PTAT). It is important to “shield” or ultimately suppress noise generated by bias circuit before it reaches the LNA and desensitize it with large blocker.

Because the bias circuit is quite noisy, its noise is filtered out by an RC filter, whose 3dB corner is set based on blocker offset. The bias noise is further isolated from the LNA core via a relatively large resistor (which forms an impedance divider with the LNA input impedance)



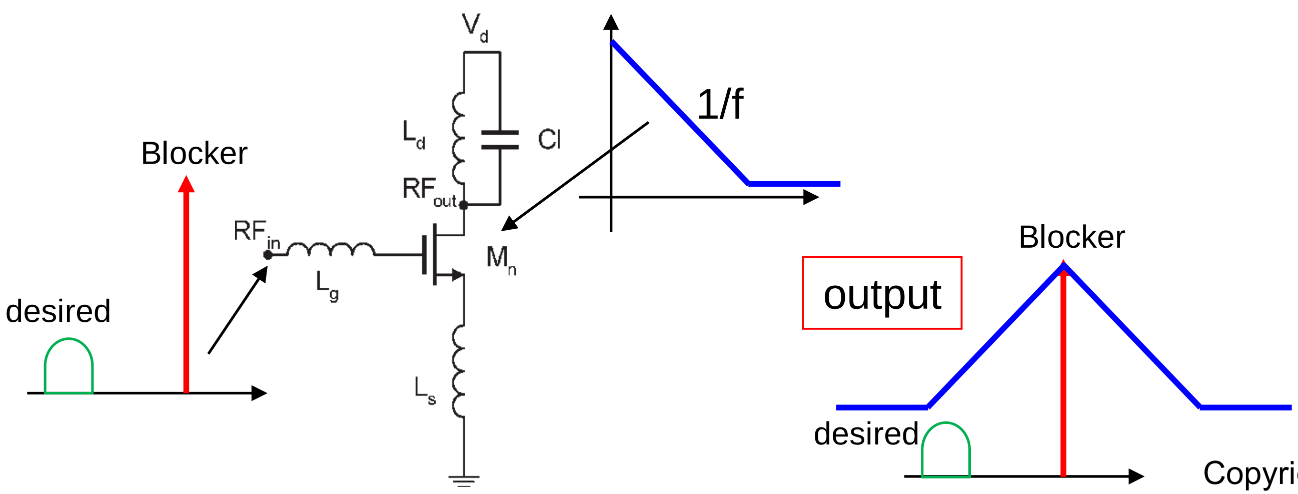
Another source of low frequency noise is that generated within the LNA core itself. This low frequency noise usually gets amplified by the relatively large DC gain of LNAs. Therefore, reducing the low-frequency LNA gain results in improving the LNA noise desense.



Isolating the bias noise is not enough to prevent noise desensitization due to a blocker. This is because the low frequency noise generated within the LNA core itself mixes with the blocker causing the desense. To improve this, one must do the following:

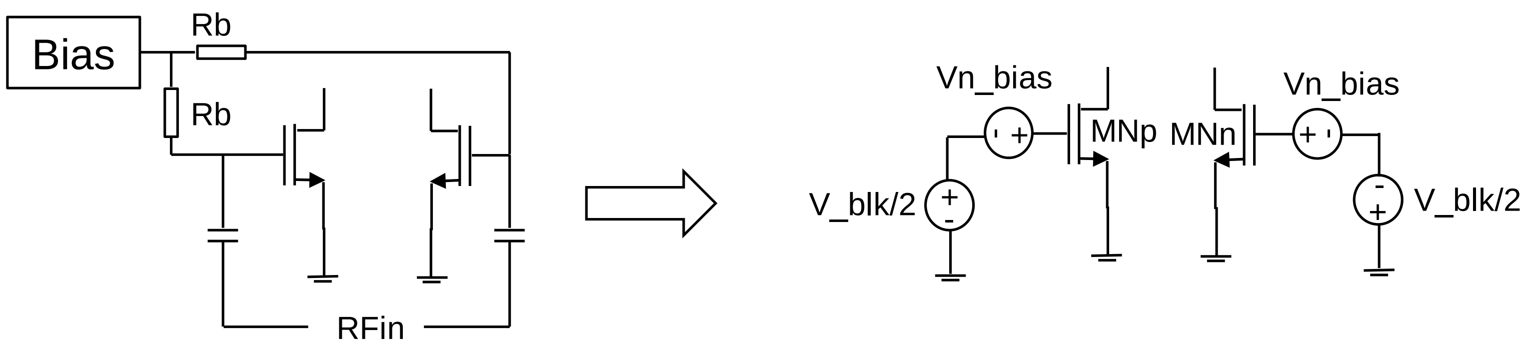
1. reduce the low frequency noise of the LNA core
2. Improve the LNA second order non-linearity.

The second order non-linearity of single-ended LNA's is hard to control but can slightly be improved by increasing the bias current or playing with the device channel length (velocity saturation tend to improve second order distortion). Degeneration also helps. The low frequency noise (especially flicker noise) can be improved by increasing device area (especially channel length).



Would differential LNAs be more immune to bias noise desense?

One would think that for a differential LNA topology, bias noise is "common-mode", hence should make it more immune to noise desense. However this is incorrect. The reason is because although bias noise is indeed common-mode but the blocker is differential. Hence the circuit acts as a "single-balanced mixer" in which the differential blocker up-converts this common-mode bias noise to RF to appear differentially at output. Mathematically it can be proven as follows:



The bias noise is represented as a common-mode noise in series with the gate of each side of the differential input transistors. The blocker is placed differentially with a half circuit representation as shown above.

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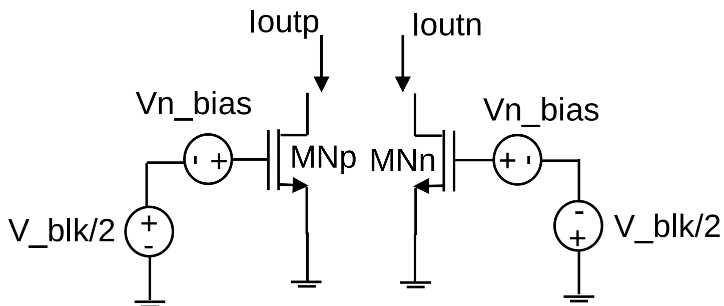


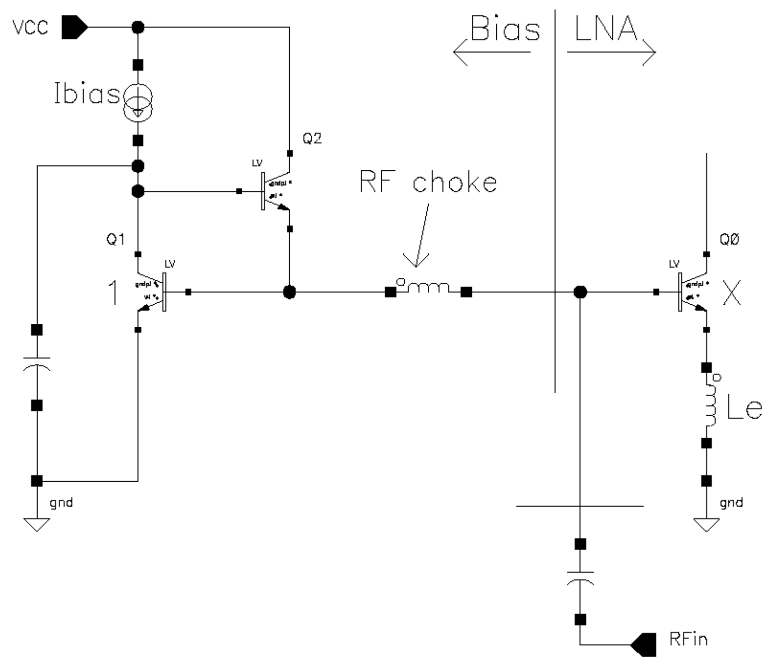
Taking only the terms due to second order nonlinearity to calculate the noise desense:

$$I_{outP} = \alpha_2 \left(V_{n\_bias} + 0.5V_{blk}\right)^2 = \alpha_2 V_{n\_bias} V_{blk}$$
$$I_{outN} = \alpha_2 \left(V_{n\_bias} - 0.5V_{blk}\right)^2 = -\alpha_2 V_{n\_bias} V_{blk}$$

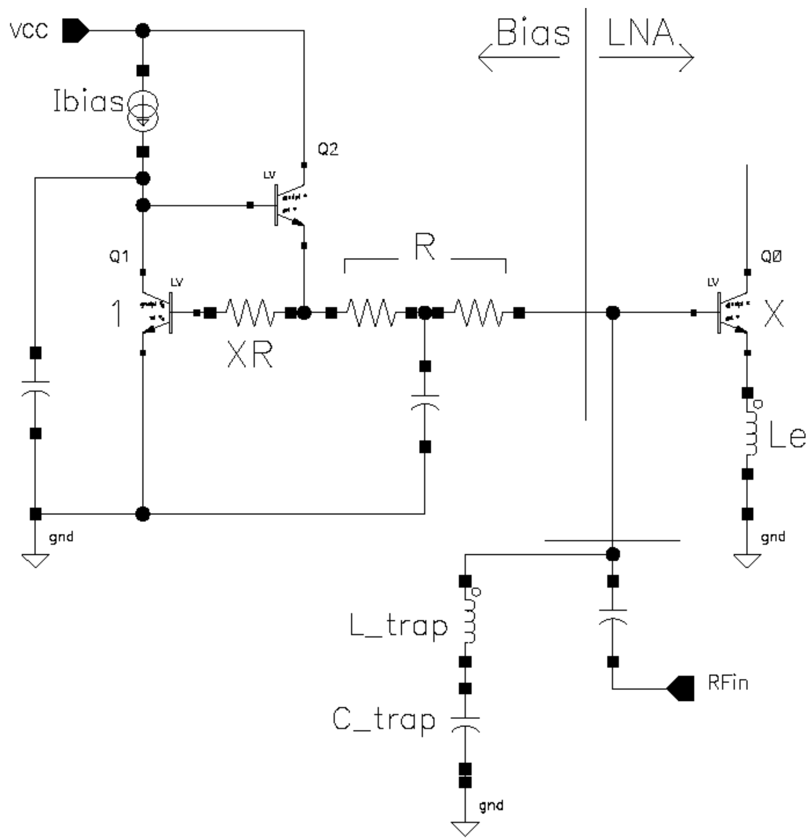
As seen, the differential blocker up-converts this common-mode noise to RF and shows up differentially at the output. Hence, differential circuits are not immune from bias-noise desensitization

LNA bias impedance and its impact on IP3 & P1dB:

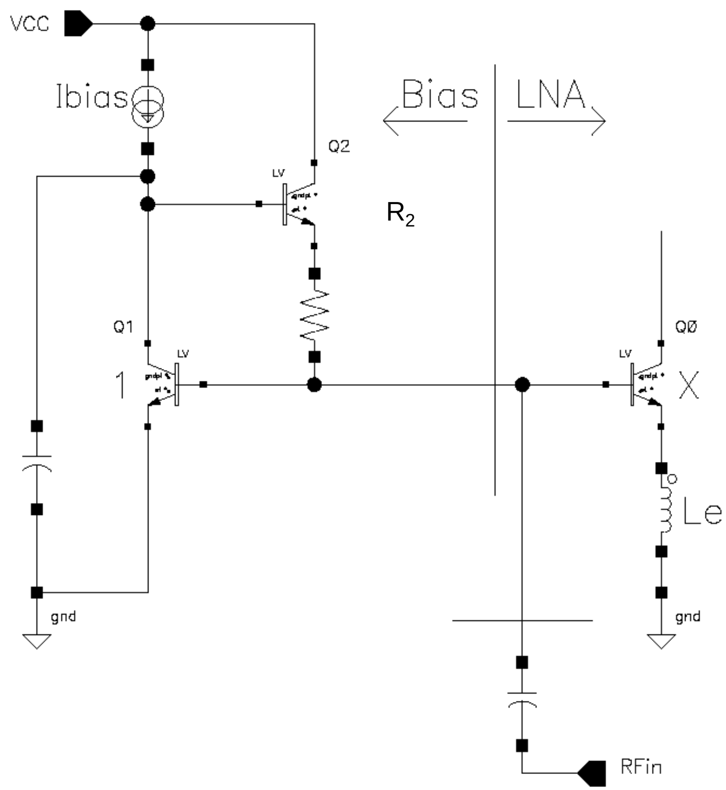
The classical resistive isolation of the LNA from the bias imposes some degradation of the LNA large signal performance. As the input RF signal gets larger and larger, the r.m.s. bias voltage and corresponding bias current to charge device input cap of the LNA device increases. Since the DC bias voltage/current of the LNA device is provided by the bias circuit, this results in a significant voltage drop across the biasing resistor causing “de-biasing” of the LNA input device and a premature compression. Furthermore, for wide signal bandwidth, the RC delay can cause memory effects. For high compression LNAs, a biasing choke is used, which has low frequency impedance to provide the required base current, but acts like open at RF.



The bias network has also an impact on the LNA IP3. It is has been shown that for good IP3, the LNA impedance looking into the LNA input much be very low at the tone spacing frequency of the IP3 two tone test [5]. This can be achieved by an off-chip series resonance network (L_trap, C_trap) that acts like a short at the tone spacing frequency (for example 10MHz for the two tone frequency of 2150, 2160MHz).



The problem with the trap network is that it is difficult to integrate. An alternative is to design the biasing network of the LNA to have a low impedance at the tone spacing, for good IP3, and a high impedance at RF to prevent loading. An example is shown below. The Q_2, R_2 feedback results in low frequency impedance looking into the LNA. At high frequency, the loop gain collapses and so the impedance becomes high at RF. Noise is of concern in such circuits, so careful design is needed.



LNA stability:

Stability of an LNA is affected by the forward gain, reverse isolation, input and output terminations. Therefore, a metric called the "K_f" factor is used to determine the LNA stability. If the K_f is >1 for all frequencies, then the LNA is "unconditionally stable". This means that the LNA is stable for all impedance terminations at input and/or output. The K_f is given by:

$$K_f = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |S_{11}S_{22} - S_{21}S_{12}|^2}{2|S_{21}||S_{12}|}$$

The unconditional stable requirement of an LNA is crucial even if it is driven by a 50Ω source in the RF passband. This is because although the duplexer has a pass band impedance of 50Ω, its impedance outside the band is far from that and is almost an open circuit.

The stability of the LNA is tested in the lab by connecting a variable transmission line at both input and output ports and monitor any oscillation at the spectrum analyzer. The K_f can be simulated using SpectreRF.

Note that the K_f factor is not enough to guarantee LNA stability because it is based on the S-parameters, which are small signal sims by definition. A large signal sets of simulations are also needed to ensure stability.

References:

[1] H. Rothe, “Theory of Noisy Fourpoles,” Proc. IRE, Vol. 44, pp. 811-818, June 1956.

[2] H. Fukui, “The Noise Performance of Microwave Transistors,” IEEE Transactions on Electron Devices, Vol. ED-13, pp. 329-341, March 1966.

[3] H. Hillbrand, P. Russer, “An Efficient Method for Computer Aided Noise Analysis of Linear Amplifier Networks,” IEEE Trans. on Circuits and Systems, pp-235-238, April 1976.

[4] R. G. Meyer, A. K. Wong, “Blocking and Desensitization in RF Amplifiers,” IEEE JSSC, Vol. 30, No. 8, August 1995, pp. 944-946.

[5] Vladimir Aprin, Charles Persico, “Effect of Out-of -Band Terminations on Intermodulation Distortion in Common-Emitter Circuits,” IEEE BCTM, 1997.