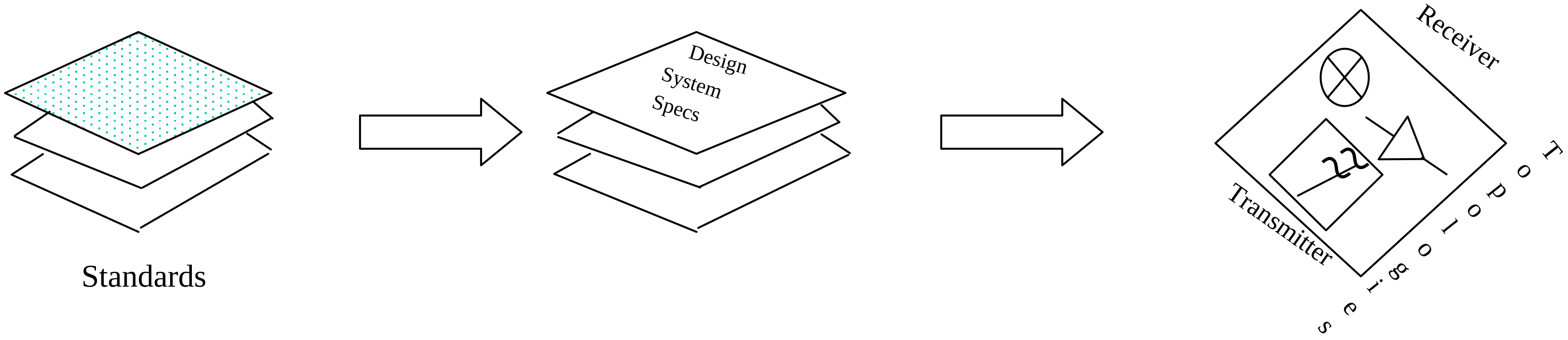
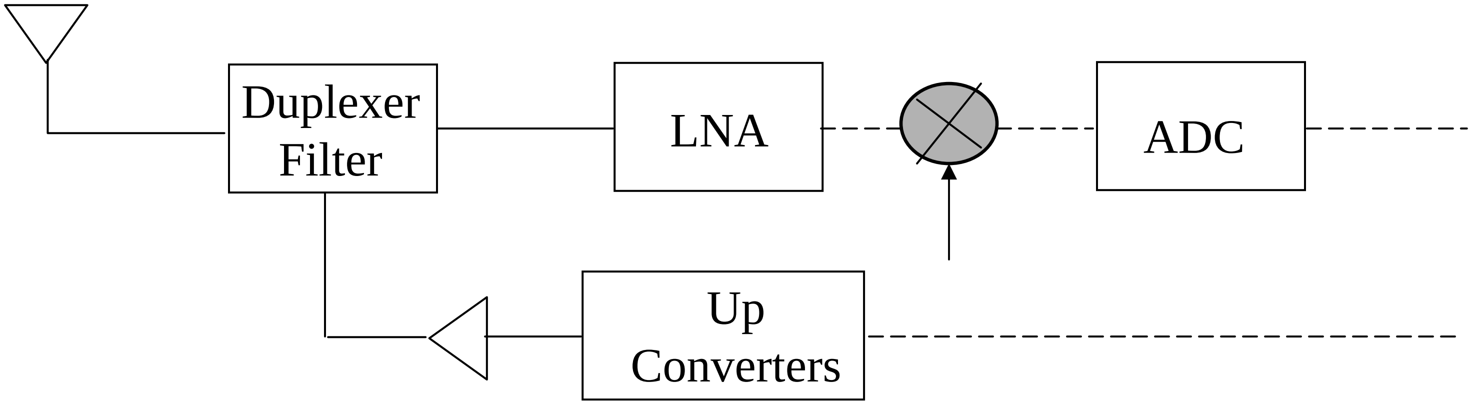
RF SYSTEM DESIGN CONSIDERATIONS



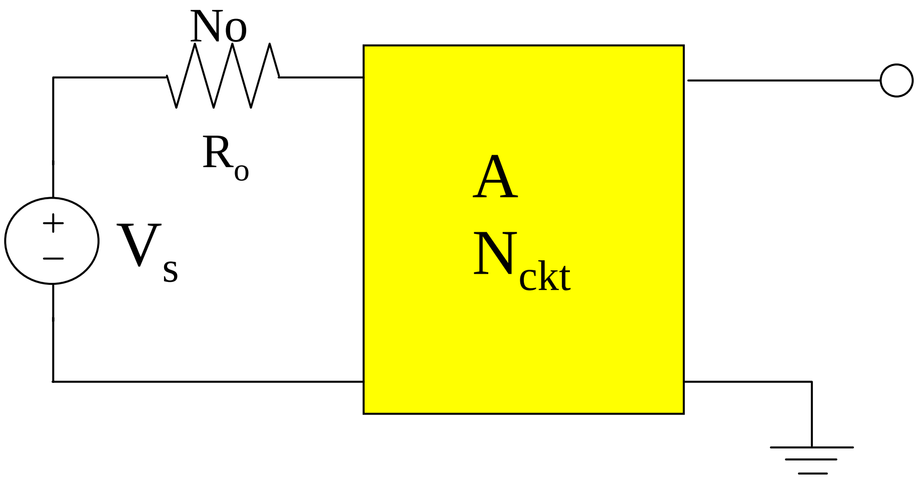
Transceiver Building Blocks



How do you assign specifications to each building block?

- Each block shares part of the total specification of the system and of its total budget.
- Main specs involve noise, power gain, minimum signal power (sensitivity) and linearity (distortion).
- Let us discuss these parameters (specs) one by one and identify their trade-offs.

Noise Performance



Output
Noise = $A^2 N_o + N_{ckt}$

Where $N_{out} = A^2 N_o + N_{ckt}$ is the output noise density, N_o is the noise from the input source resistance, A is the voltage gain, and N_{ckt} is the circuit generated noise density.

Observe that the input-referred noise density is

$$N_{inp,ref} = \frac{N_{out}}{A^2} = N_o + \frac{N_{ckt}}{A^2}$$

$$N_{inp,ref} \downarrow \text{for } \; A \uparrow$$

Signal to Noise Ratio (S/N) is a key parameter in the system and circuit design. A figure of merit to evaluate S/N is the so called noise factor (F). F measures the amount of noise produced by an RF device relative to the ambient thermal noise at its input, and is defined as the ratio

$$F = \frac{N_{out}}{N_{in}} = \frac{N_{out}}{A^2 N_o} = \frac{A^2 N_o + N_{ckt}}{A^2 N_o}$$

$$F = 1 + \frac{N_{ckt}}{A^2 N_o}$$

Note that F can be also expressed as a function of $N_{inp,ref}$ as

$$F = \left(\frac{N_{out}}{A^2}\right)\frac{1}{N_o} = \frac{N_{inp,ref}}{N_o}$$

The noise figure (NF) is often defined as the noise factor in units of dB.

$$NF = 10\ log\ F$$

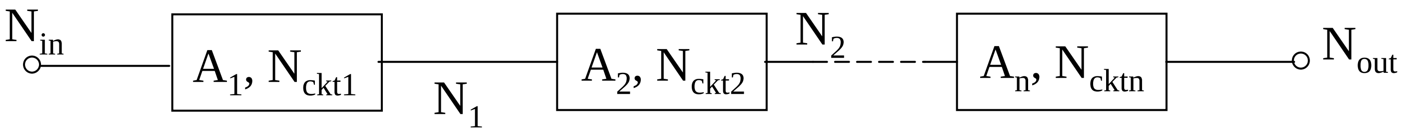
NF is often used to characterize the S/N at the output and input port. Thus one can rewrite F as

$$F = \frac{N_{out}}{A^2 N_o}(1) = \frac{N_{out}}{A^2 N_o}\frac{S_i A^2}{S_o} = \frac{N_{out} S_i}{N_o S_o}$$

$$F = \left(\frac{\frac{S_i}{N_o}}{\frac{S_o}{N_{out}}}\right) = \frac{SNR_i}{SNR_o}$$

Where S_i and S_o are the input and output signal power, respectively.

NOISE FIGURE OF CASCADE SYSTEMS



N_{in}, N_1, . . N_{out} are the noise at the input, output block 1, … and the output block n, respectively. Note that $N_{in} = N_o$.

$$N_1 = A_1^2 N_{in} + N_{ckt1} = N_o A_1^2 + N_{ckt1}$$

$$N_2 = N_1 A_2^2 + N_{ckt2} = A_2^2 A_1^2 N_o + A_2^2 N_{ckt1} + N_{ckt2}$$

.

.

$$\begin{aligned} N_{out} &= A_n^2 A_{n-1}^2 \cdots A_2^2 A_1^2 N_o + A_n^2 A_{n-1}^2 \cdots A_2^2 N_{ckt1} \\ &\quad + A_n^2 A_{n-1}^2 \cdots A_3^2 N_{ckt2} + \cdots + A_n^2 N_{ckt_{n-1}} + N_{ckt_n} \end{aligned}$$

Thus, the input referred noise due to N_1, N_2, . . N_n becomes

$$N_{inp,ref} = \frac{N_{out}}{A_1^2 A_2^2 \cdots A_n}$$

Observe that we have assumed that the input noise of the ith stage comes from the input resistance of ith stage and this quantity is "N_o" for all stages, thus $N_{inp,ref}$ can be expressed as:

$$N_{inp,ref} = \left(1 + \frac{N_{ckt1}}{A_1^2 N_o} + \frac{N_{ckt2}}{A_1^2 A_2^2 N_o} + \cdots + \frac{N_{cktn}}{A_1^2 A_2^2 \cdots A_n^2 N_o}\right) N_o$$

and

$$F_{total} = \frac{N_{inp,ref}}{N_o} \qquad ; \qquad F_1 = 1 + \frac{N_{ckt1}}{A_1^2 N_o}$$

Furthermore notice that

$$F_2 = 1 + \frac{N_{ckt2}}{A_2^2 N_o}$$

Then

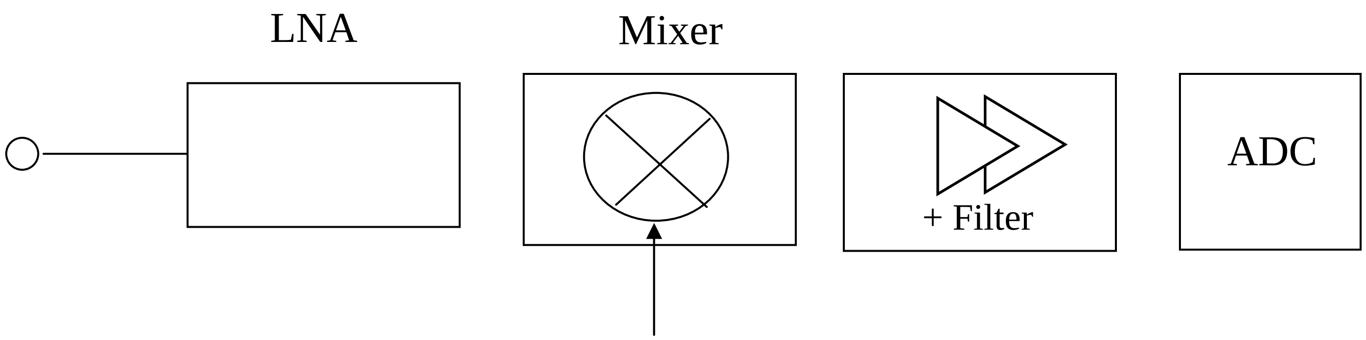
$$N_{ckt2} = (F_2 - 1)A_2^2 N_0$$

Similarly for N_{ckt3}, . . N_{cktn}, then the noise factor can be expressed as:

$$F_{total} = F_1 + \frac{F_2 - 1}{A_1^2} + \frac{F_3 - 1}{A_1^2 A_2^2} + \cdots + \frac{F_n - 1}{A_1^2 A_2^2 \cdot\cdot A_{n-1}^2}$$

Note that A_i^2 can be related to power gains, G_i, for a certain resistance i.e., $\mathrm{R_s} = 50\Omega$.

EXAMPLE



If the NF and gain of the blocks are:

LNA:	20dB gain,	3dB NF	(A_1, NF_1)
Mixer:	10dB gain,	10 dB NF	(A_2, NF_2)
VGA + Filter:	80dB gain,	20 dB NF	(A_3, NF_3)

$$F_{total} = F_1 + \frac{F_2 - 1}{A_1^2} + \frac{F_3 - 1}{A_1^2 A_2^2}$$

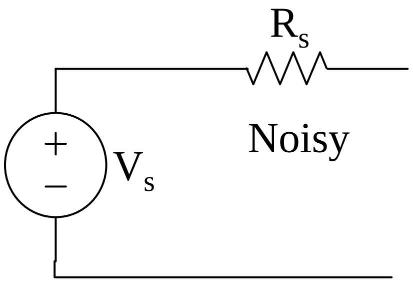
$$F_{total} = 1.99526 + \frac{9}{100} + \frac{99}{100.10} = 2.18426$$

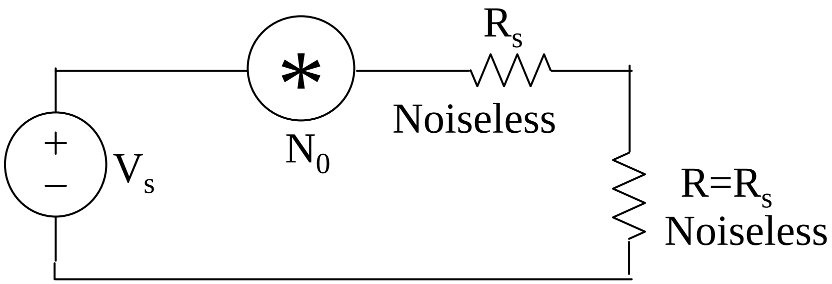
$$NF_{total} = 3.39\ dB$$

Notice that the additional blocks have deteriorated the LNA NF by about 0.4 dB.

Exercise. Repeat the NF_{total} calculation with a new LNA with NF of 2.55 dB and a gain of 12 dB. How is the NF_{total} compared with previous case?

Input Noise Power Density (N_o)





$$N_o = kT_o = \left(1.38\times10^{-23}\ J/K\right)\left(290K\right) = 400.2\times10^{-23}\,J = -203.4dBW/Hz$$

N_o is in watts per hertz, and can be expressed in dBm for room temperature (290°K), and a BW of 1Hz as

$$N_o\left(N_{in}\right)_{dBm} = -174\ dBm$$

Thus, the minimum power signal that can be detected properly by a receiver is $(N_{in})_{dBm}$; with a signal having the same power as the input noise. The available noise power is defined as

$$P_{N_O} = kT_o\,\Delta f = N_o\Delta f$$

or

$$N_o = \frac{P_{N_O}}{\Delta f}$$

SENSITIVITY

This parameter is specified for each communication standard. Sensitivity ($S_{\min}$) is the minimum signal power applied to the receiver input terminals that yields the required output signal-to-noise ratio.

$$\left(S_{\min}\right)_{dBm} = \left(N_{in}\right)_{dBm} + \left(NF\right)_{dB} + \left(10\log BW\right)_{dB} + \left(\text{Prediction S/N}\right)_{dB}$$

- N_{in} is the input noise power density (N_o) produced on the source resistor feeding the receiver. This might come from the input resistor of an input signal generator used for lab testing or from the equivalent resistance from the antenna.

$$N_{in} = kT_o \text{ watts} \times \text{Hz}$$

$$N_{in} = N_o$$

$$\left(N_{in}\right)_{dBm} = -174dBm$$

- Noise Figure $(\mathrm{NF})_{\mathrm{dB}}$

$$(NF)_{dB} = (S/N)_{\substack{\mathrm{dB}\\ \mathrm{input}}} - (S/N)_{\substack{dB\\ output}}$$

$(NF)_{dB}$ is the overall noise figure of the receiver.

- Bandwidth BW

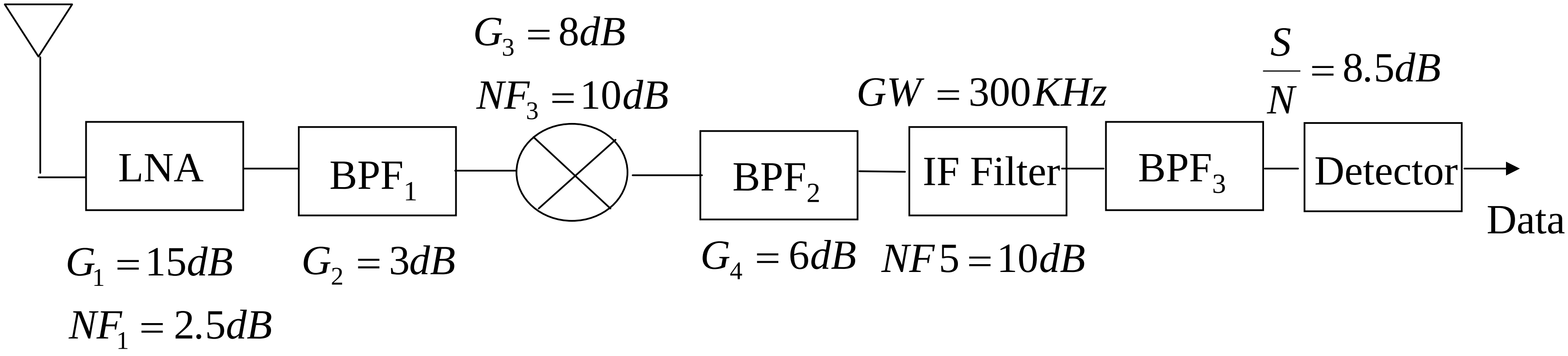
The maximum attainable sensitivity depends on the bandwidth of the modulated signal, since a narrower receiver bandwidth will distort the demodulated signal, causing intersymbol interference and increasing the bit error rate (BER) in digital communications and degrading fidelity and intelligibility of analog signals.

The BW is mainly determined by IF filter and the commercial SAW resonators.

Predetection Signal-to-Noise Ratio

This term is the SNR needed for a specified BER. For FM analog detection, the required (signal + noise+ distortion)/(noise + distortion) in dB is often specified as the performance criterion.

EXAMPLE: Consider the following receiver architecture with the individual specs shown for each flock. G’s represent the power gains.



LNA

BPF$_1$

BPF$_2$

IF Filter

BPF$_3$

Detector

Data

$G_1 = 15dB$

$NF_1 = 2.5dB$

$G_2 = 3dB$

$G_3 = 8dB$

$NF_3 = 10dB$

$G_4 = 6dB$

$GW = 300KHz$

$NF5 = 10dB$

$\frac{S}{N} = 8.5dB$

The noise factor for the first 5 building blocks can be expressed as:

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \frac{F_5 - 1}{G_1 G_2 G_3 G_4}$$

Substituting the parameters (not in dBs)* in the above expression yields:

$F_{total} = 2.42$ and $NF = 3.8\ dB$

In the sensitivity (TOTAL) expression, the BW term yields:

$$10\,log\left(3 \times 10^5\right) = 54.8\ dB\ Hz$$

$$\left(S_{min}\right)_{dBm} = -174 + 3.8 + 54.8 + 8.5 = -106.9\ dB_m$$

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* $F = 10^{NF/10}$; $G_i = 10^{\frac{G_i(B)}{10}}$

References

[1] W. F. Egan, “ *Practical RF System Design*”, John Wiley & Sons 2003

[2] W. Shen, A. Emira, and E. Sánchez-Sinencio, “CMOS RF Receiver System Design: A Systematic Approach” *IEEE Transaction on Circuits and Systems I: Regular Papers:* Volume: 53, Issue 5, pp. 1023-1034, May 2006.

[3] A. Emira, A. Valdes-Garcia, Xia Bo, A.N. Mohieldin, A.Y. Valero-Lopez, S.T. Moon, C. Xin, and E. Sánchez-Sinencio, “Chameleon: A Dual Mode 802.11b/Bluetooth Receiver System Design” *IEEE Transaction on Circuits and Systems I: Regular Papers:* Volume: 53, Issue 5, pp. 992-1003, May 2006.