CMOS Wideband Noise Canceling LNAs and Receivers: A Tutorial

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Thanks to Indrajit Das
Outline

- Preliminaries
- Introduction to wideband noise canceling (NC) LNAs and receivers
- Review of feedback and feedforward models for NC
- Macro models of MOSFETs and resistors
- Equivalent models of NC circuits and simulations
- Conclusions
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• Preliminaries

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Preliminaries: Noise in Electronics

Preliminaries: Noise factor

\[ \text{SNR}_i = \frac{P_i}{N_i}; \quad \text{SNR}_o = \frac{P_o}{N_o} = \frac{\text{Gain}.P_i}{\text{Gain}.N_i+N_A}; \]

Noise factor = \( \frac{\text{SNR}_i}{\text{SNR}_o} = \frac{P_i}{N_i} \cdot \frac{N_o}{P_o} = 1 + \frac{N_A}{\text{Gain}.N_i} > 1 \)

If expressed in dB, Noise factor is referred as Noise figure and is always > 0 dB.

Preliminaries: Noise factor of a cascaded system

\[ F_{cas} = \frac{P_i}{P_o} \cdot \frac{N_o}{N_s} = \frac{1}{G_1 G_2} \cdot \frac{G_1 G_2 N_s + G_2 \cdot N_{A1} + N_{A2}}{N_s} \]

\[ F_{cas} - 1 = \frac{N_{A1}}{G_1 N_s} + \frac{N_{A2}}{G_1 G_2 N_s} \]

\[ = (F_1 - 1) + \frac{F_2 - 1}{G_1} \]

N. Nallam, "CMOS Wideband Noise Canceling LNAs and Receivers: A Tutorial", 2016 APMC, New Delhi, India.
Preliminaries: Noise figure of the receiver

Only the signals whose amplitudes are greater than the noise floor of the Rx can be detected.

\[ P_{Rx} \]

\[ (\text{NF})_{Rx} \text{ is dominated by } (\text{NF})_{LNA} \]

1. $Z_{in}$ looking into the pin of the chip (i.e., including the pad and package parasitics) should be 50 $\Omega$.

2. Output matching is not needed as the track length from the LNA output to the mixer input is $\ll \lambda$.

3. Large gain, large IIP3 and small NF are needed.
Why wideband?

Modern radio receivers need to support multiple wireless standards which span across the frequency spectrum!

Two ways of supporting:

Multiple Narrowband radios

Wideband radio

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Common Gate (CG) Wideband LNA

\[
NF_{CG} = 1 + \frac{\gamma}{g_m R_s} + \frac{R_s}{R_L} (1 + \frac{1}{g_m R_s})^2
\]
Resistive Shunt Feedback (RSF) Wideband LNA

\[ \frac{v_{out}}{v_{in}} \approx 1 - g_m R_f \]

\[ R_{in} = \frac{1}{g_{m1}} \]

\[ NF_{RSF} = 1 + \frac{4R_s}{R_f} + \gamma g_{m1} R_s + \gamma g_{m2} R_s \]  \hspace{1cm} (2)

Wideband Noise Canceling LNAs†


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Wideband Noise Canceling LNAs†


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Noise canceling Condition is

\[ r_m = \alpha R_s \]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Wideband_NoteCancelButton.png}
\caption{(a)}
\end{figure}


Wideband Noise Canceling Receiver†

Noise canceling Condition is
\[ r_m = \alpha R_s \]

Voltage Measurement Path
\[ (\alpha = -g_m R_{aux}) \]

Current Measurement Path
\[ (r_m = R_m) \]

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Add a feed forward amplifier to nullify the noise of main amplifier at the output [13].
Feedforward Noise Canceling

Add a feed forward amplifier to nullify the noise of main amplifier at the output [13].

\[
\begin{align*}
\gamma_1 &= \frac{1}{A_m}, \quad X_1 = \gamma_1 N_m \\
Y_A &= A_{aux} (\gamma_1 N_m) \\
Y &= A_m X + N_m \\
Z &= Y - Y_A = A_m X + N_m (1 - A_{aux} \gamma_1) \\
&\text{If, } A_{aux} = \frac{1}{\gamma_1}, \quad Z = A_m X
\end{align*}
\]

Noise Cancelling Condition is \( A_{aux} = A_m = \frac{1}{\gamma_1} \)
Feedback Noise Reduction

\[ e = \frac{X}{1+A_m\beta} \]

\[ Y = \frac{A_mX}{1+A_m\beta} \]
Feedback Noise Reduction

\[ e = \frac{x}{1 + A_m\beta} \]

\[ e = -\beta N_m \frac{1}{1 + A_m\beta} \]

\[ Y = \frac{N_m}{1 + A_m\beta} \]

\[ Y = \frac{A_m X}{1 + A_m\beta} \]
Feedback-Feedforward Noise Canceling

\[ e = \frac{X}{1 + A_m \beta} - \frac{\beta N_m}{1 + A_m \beta} \]  

\[ Y = \frac{A_m X}{1 + A_m \beta} + \frac{N_m}{1 + A_m \beta} \]
Feedback-Feedforward Noise Canceling

\[ e = \frac{X}{1+A_m\beta} - \frac{\beta N_m}{1+A_m\beta} \]

\[ Y = \frac{A_m X}{1+A_m\beta} + \frac{N_m}{1+A_m\beta} \]

**Condition for Noise Cancellation:**

\[ A_{aux} = \frac{1}{\beta} \]

**Overall Gain at NC condition:**

\[ \frac{Z}{X} = \frac{Y}{X} + \frac{Y_A}{X} = \frac{A_m}{1+A_m\beta} + \frac{1/\beta}{1+A_m\beta} = \frac{1}{\beta} \text{ or } A_{aux} \]
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Macro Model of a MOSFET

Macro Model of a MOSFET in CG configuration

Macro Model of a MOSFET in CS configuration

(a) (b) (c) CG configuration (d) CS configuration

Macro Model of a Resistor

\[ i_x = i_y \]

\[ v_x \quad i_x \quad R_f \quad i_y \quad v_y \]

(a)

Macro Model of a Resistor

\[ i_x = i_y \]  \hspace{5cm} (5)

\[ i_x = \left( \frac{v_x}{R_f} \right) - \left( \frac{v_y}{R_f} \right) + i_n \]  \hspace{5cm} (6)

Macro Model of a Resistor

\[ i_x = i_y \]

\[ v_x \]

\[ R_f \]

\[ y \]

\[ i_n \]

\[ (v_x) - \left( \frac{v_y}{R_f} \right) + i_n \]

Macro Model of a Resistor

(a) $i_x = i_y$

(b) $i_x = \left( \frac{v_x}{R_f} \right) - \left( \frac{v_y}{R_f} \right) + i_n$

(c)†


Macro Model of a Resistor

\[ i_x = i_y \]

(a)

\[ \dot{i}_x = \left( \frac{v_x}{R_f} \right) - \left( \frac{v_y}{R_f} \right) + \dot{i}_n \]

(b)

\[ v_x \rightarrow \dot{i}_n \rightarrow i_n \rightarrow \frac{1}{R_f} \rightarrow i_y \rightarrow v_y \]

(c)

\[ v_x \rightarrow \dot{i}_n \rightarrow i_n \rightarrow \frac{1}{R_f} \rightarrow i_y \rightarrow v_y \]

(d)

\[ v_x \rightarrow \dot{i}_n \rightarrow i_n \rightarrow \frac{1}{R_f} \rightarrow i_y \rightarrow v_y \]

\[ \sum \]

\[ \dot{i}_n \]


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Equivalent Model of a Common Gate LNA

Figure 1: (a) A CG amplifier, and (b) a feedback model of it.

\[ v_e = \frac{1}{1+g_mR_s} v_{in} - \frac{R_s/R_L}{1+g_mR_s} v_n \]

\[ v_{out} = \frac{g_mR_L}{1+g_mR_s} v_{in} + \frac{1}{1+g_mR_s} v_n, \text{ where } v_n = i_n R_L \]
Equivalent Model of a NC Common Gate LNA

Noise canceling condition: \[ A_{aux} = \frac{R_L}{R_s} \]
Simulation of CG NC-LNA

\[ V_{dd} = 1.8 \text{ V} \]

\[ \beta = \frac{R_s}{R_L} = \frac{1}{7} \]

\[ A_{aux} = \frac{1}{\beta} = 7 \]

Simulation of CG NC-LNA

\[ A_{aux} = \frac{1}{\beta} = 7 \]

\[ \frac{v_{out}'}{v_{in}} = \left| \frac{1}{\beta} \right| = 7 \]

Equivalent Model of the NC RSF LNA

\[ v_e = \frac{1}{1+g_mR_s} v_{in} + \frac{R_s/R_f}{1+g_mR_s} v_n \]

\[ v_{out} = \frac{1-g_mR_f}{1+g_mR_s} v_{in} + \frac{1+R_s/R_f}{1+g_mR_s} v_n \]

Simulation of RSF NC-LNA

\[ \beta = \frac{R_s}{R_f} = \frac{1}{5} \]

\[ V_{dd} = 1.8 \text{ V} \]

\[ \text{Gain of amplifier at NC} = \frac{1}{\beta} = 5 \]

NC condition: \( A_{aux} = 1 + \frac{1}{\beta} = 6 \)
Simulation of RSF NC-LNA

Noise cancellation occurs at $|A_{aux}| = 1 + \frac{1}{\beta}$ instead of $\frac{1}{\beta}$ due to the bidirectional nature of $R_f$.

$|A_{aux}| = 1 + \frac{1}{\beta} = 6$

Gain of the auxiliary amplifier ($|A_{aux}|$)

(a)

Noise voltage in nV/$\sqrt{\text{Hz}}$

(b)

$\frac{|v_{out}'|}{|v_{in}|} = \frac{1}{\beta} = \frac{R_s}{R_f} = \frac{1}{5}$
Equivalent Model of a Wideband Receiver

\[ v_e = \frac{1}{1+\frac{R_s}{R_{in}}} v_{in} - \frac{-R_s/r_m}{1+\frac{R_s}{R_{in}}} v_n \]

\[ out_n = \frac{-r_m/R_{in}}{1+\frac{R_s}{R_{in}}} v_{in} + \frac{1}{1+\frac{R_s}{R_{in}}} v_n, \text{ where } v_n = -i_n r_m \]
Simulation of the Wideband NC Receiver

\[ g_m = 20 \text{mS} \]

Simulation of a Wideband NC Receiver

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Conclusions

- Shown that the NC is a feedback-feedforward technique

- In a NC amplifier/receiver, if the feedback factor of the main amplifier/receiver is $\beta$, then the gain of the auxiliary amplifier/receiver ($A_{aux}$) needed to cancel the noise of the main amplifier/receiver is equal to $|1/\beta|$

- Under this noise canceling condition, the overall gain of the NC-wideband amplifier/receiver is equal to $|1/\beta|$

References


