Guidelines for the Power Constrained Design of a CMOS Tuned LNA


Center for Integrated Systems, Stanford University
Outline

• Motivation
  ✧ Optimization Technique
  ✧ Four Noise Parameters

• Intrinsic MOSFET Noise Characteristics

• Tuned Low Noise Amplifier Analysis
  ✧ Input Stage
  ✧ Cascode Stage
  ✧ Matching Element

• Conclusions
Motivation
(Importance of the LNA in RF Systems)

\[ NF \triangleq \frac{(S/N)_{in}}{(S/N)_{out}} \]

\[ NF_{tot} = 1 + (NF_1 - 1) + \frac{NF_2 - 1}{A_1} + \cdots + \frac{NF_n - 1}{A_1 \cdots A_{n-1}} \]

When the LNA provides sufficient gain

\[ NF_{tot} \approx NF_{LNA} \]
Motivation (Continue)
(Noise Optimization)

• Classical Noise Optimization
  ✧ Given device with fixed geometries and characteristics.
  ✧ Adjust the source impedance to optimize the noise figure.

• CMOS Noise Optimization
  ✧ Freedom in tailoring device geometries.
  ✧ Enable simultaneous optimization of the power, input matching, and noise figure.
  ✧ Ambiguous optimization procedure due to the poor noise modeling.
Motivation (Continue)

(Four Noise Parameters)

\[
NF = 1 + 2R_n (G_{opt} + G_c) + \frac{[(B_s - B_{opt})^2 + (B_s - B_{opt})^2]R_n}{G_s} \\
= NF_{min} + \frac{(Y_s - Y_{opt})^2 R_n}{G_s}
\]

✧ **NF\textsubscript{min}**: Best achievable noise performance
✧ **Y\textsubscript{opt}**: Source admittance yielding \(NF_{min}\)
✧ **R\textsubscript{n}**: Sensitivity of \(NF\) when \(Y_s\) differs from \(Y_{opt}\)

shorter \(L\) yields lower \(NF_{min}\)  
scaled by \((1/W)\)  
scaled by \(W\)
Motivation (Continue)
(Tuned LNA Architecture)

\[ Z_{in} = s(L_g + L_s) + \frac{1}{sC_{gs}} + \omega_T L_s \]

\[ NF = 1 + \gamma g_{\text{do}} \chi \frac{G_s}{G_s^2 + B_s^2} \left( \frac{\omega_0}{\omega_T} \right)^2 \]

\[ \chi = 1 + 2|\epsilon G_s \kappa + [G_s^2 + (B_s + \omega_0 C_{gs})^2] \kappa^2 \]

\[ \kappa \triangleq \frac{\omega_T}{\omega_0^2 C_{gs}} \sqrt{\frac{\delta g_s}{\gamma g_{\text{do}}}} \]

✧ Shorter \( L \) yields lower \( NF \).
✧ Power/Noise matching conditions are different from the MOSFET.
Motivation (Continue) (MOSFET Noise)

- **Flicker (\(1/f\)) Noise**
  - Dominant up to few MHz range.
  - Significant in mixer circuits (Up-conversion Error).

- **Shot Noise**
  - Dominant in the subthreshold region.

- **Thermal Noise** (Velocity Fluctuation Noise)
  - Dominant in high frequencies (LNA).
  - Drain noise + Induced gate noise.
Intrinsic MOSFET Noise
(Thermal Noise Simulation Method)
Intrinsic MOSFET Noise (Continue)
(Noise Parameters for 0.25µm MOSFET)

\[
\gamma = \frac{\overline{\sigma_d^2}}{4kT\Delta f \cdot g_{d0}} \\
\delta = \frac{\overline{\sigma_g^2}}{4kT\Delta f \cdot \Re[Y_{GS}]} \\
c = \frac{\sqrt{\overline{\sigma_g^2} \overline{\sigma_d^2}}}{\sqrt{\overline{\sigma_g^2} \overline{\sigma_d^2}}}
\]

Classical Values:
- \( \gamma = 1.0 \) (Linear)
- \( \delta = 2/3 \) (Saturation)
- \( c = 0.395 \) (Saturation)

✧ Good agreement with Toshiba 0.25µm nMOSFET

Integrated Circuits Lab
Center for Integrated Systems
Stanford University
Tuned LNA
(Power Matching)

\[ G_{m1} = \frac{1}{2} \frac{1 + \Gamma_B}{e^{j\beta l} + \Gamma_B e^{-j\beta l}} \left( \frac{1}{s C_p || Z_A} \right) \frac{1}{s C_{gs1}} \frac{g_{m1}}{Z_B Z_A} \]

When \( Z_C = R_s \)

\[ G_{m1} = \frac{1}{2\sqrt{\omega T L_s R_s}} \frac{g_{m1}}{s C_{gs1}} \]

\( W_1 = 328 \mu m \)
\( W_2 = 263 \mu m \)
\( I_{D,0} = 5mA \)
\( f = 4GHz \)

\( S_{N,s} \)
\( S_{M1} + S_{M2} \)

Real Part of \( Z_A [\Omega] \)

Output Noise Power \([A^2/Hz]\)

Noise Figure [dB]

Real Part of \( Z_A [\Omega] \)
Tuned LNA (Continue)
(Power Matching)

✧ Optimum $L_s$ is bias dependent and linearly scaled by the current specification.

✧ The achievable noise figure is independent of the current specification and quite close to the intrinsic $NF_{min}$. 

---

Integrated Circuits Lab
Center for Integrated Systems
Stanford University
Tuned LNA (Continue)
(Power Constrained Noise Figure)

Select $L$ → Select $V_{GS}$ & $V_{DS}$ → Select $W$

Noise Figure [dB]

$NF \approx 1 + \frac{\gamma g_{d0}}{G_s} \left( \frac{\omega_0}{\omega_T} \right)^2 + G_s \frac{\delta \zeta}{g_{d0}}$
Tuned LNA (Continue)
(Cascode Stage)

✧ Cascode device noise is not significant.
✧ Drain noise is dominant in $M_2$.
✧ $W_1 = W_2$ is OK.
Conclusions

• Tuned LNA can achieve near \( NF_{\text{min}} \) at optimum \( V_{gs} \).
• Simultaneous choice of \( V_{gs} \) and width of input stage is most critical in design: optimum \( V_{gs} \) is usually 0.1~0.3V above \( V_{th} \).
• Cascode stage is not significant. \( W_1=W_2 \) is OK.
• Overall \( NF \) is affected by \( L_s \) : optimum \( L_s \) exists.
• Optimal choice of \( L_s \) can achieve the noise figure quite close to the intrinsic \( NF_{\text{min}} \).