Wideband Low-Noise Amplifiers Aiming at Achieving Transistor $F_{\min}$

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***Abstract*—Many RF receivers operate over wide bandwidths and require wideband low-noise amplifiers (LNAs). While there are many wideband LNA topologies, only a few are able to achieve noise factors that are close to the lowest noise factors possible by a given semiconductor technology. This article complements an earlier RFIC Virtual Journal article from April 2014 by focusing on LNA topologies that are theoretically able to exhibit both wideband input and noise matching. Three broad groups of input matching strategies are identified as promising for the implementation of very-low-noise wideband amplifiers. With the focus on wideband LNA noise, this article does not consider LNA linearity, gain, and power consumption.**

***Index Terms*—Wideband LNA Design Considerations, Noise Measure; LNA Design Techniques; LNA Design Papers; Simultaneous Noise and Power Matching, Reactive Feedback, Transformer Feedback, Intrinsic Feedback, Noise Factor Sensitivity, Negative Capacitor; Nullor; Generalized Immitance Converter; Negative Impedance Converter**

I. Introduction

An excellent overview of low-noise amplifier (LNA) development, including design considerations, historic LNA papers, trends, and design techniques was published in Issue 4 of the RFIC Virtual Journal [Mak *et al.*, 2014]. This article complements [Mak *et al.*, 2014] by focusing on LNA topologies that are designed not only to operate over wide bandwidths but also achieve the transistor minimum noise factor, $F_{\min}$. In addition to noise, LNA linearity, gain, and power consumption are also important performance metrics for wideband LNAs, but these are beyond the scope of this article.

The main challenge when designing wideband very-low-noise amplifiers is achieving power and noise matching simultaneously. While a wideband power match is not necessary for excellent noise performance, failure to do so may cause in-band ripple and degraded filter (when filters are used prior to LNA) and system performance. In addition, it may be necessary to add additional stages to boost the received signal power, thereby increasing power consumption and the complexity of the receiver design. Before discussing wideband LNAs, some key design concepts are reviewed.

A. Noise matching

The concept of noise matching, which has been known since at least the 1950s [Rothe, 1954], [Rothe and Dahlke, 1956], [Haus and Adler, 1958], [Haus *et al.*, 1960], is best illustrated by LNA noise factor descriptions that are based on noise parameters. The minimum noise factor, $F_{\min}$, is one of three noise parameters that fully characterize an LNA. The other two noise parameters are the Lange invariant, N, [Lange, 1967] and the optimum signal-source admittance for minimum noise, $Y_{\text{opt}} = G_{\text{opt}} + jB_{\text{opt}}$. The equivalent noise resistance, R_{n}, is often used instead of the Lange invariant, N. The two parameters are related via $N = R_{\text{n}}G_{\text{opt}}$ [Lange, 1967], [Pospieszalski, 1989], [Boglione, 2008], [Belostotski, 2011], [Boglione, 2013]. Unlike N and $F_{\min}$, R_{n} is not invariant under lossless input impedance transformation and is therefore more cumbersome to use. In terms of the noise parameters, the noise factor is written as

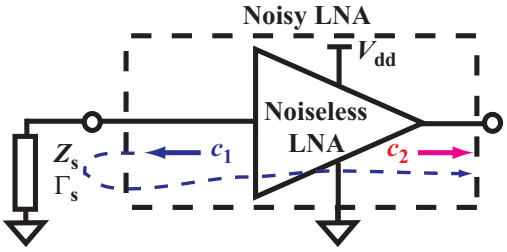

Figure 1: Noise wave representation of an LNA.

$$F = F_{\min} + \frac{N}{R_{\text{s}}R_{\text{opt}}}\left|Z_{\text{opt}} - Z_{\text{s}}\right|^2 \quad (1)$$

$$= F_{\min} + \frac{N}{G_{\text{s}}G_{\text{opt}}}\left|Y_{\text{opt}} - Y_{\text{s}}\right|^2 \quad (2)$$

where $Z_{\text{s}} = R_{\text{s}} + jX_{\text{s}}$ (or $Z_{\text{s}}^{-1} = Y_{\text{s}} = G_{\text{s}} + jB_{\text{s}}$) is the signal-source impedance, $Z_{\text{opt}} = Y_{\text{opt}}^{-1} = R_{\text{opt}} + jX_{\text{opt}}$ is LNA optimum signal-source impedance for minimum noise, and $T_0 = 290\,\text{K}$ is the IEEE reference temperature for noise measurements and simulations. To realize $F = F_{\min}$, Z_{s} should be tuned to the exact value of Z_{opt}. When this has been accomplished, the LNA is said to be noise matched. Noise matching requires an (ideally lossless) matching network to be placed between the LNA and the source of the incoming signal so that Z_{opt} is seen looking back towards the signal-source from the LNA input.

The concept of traveling noise waves [Wedge and Rutledge, 1992] is particularly useful when visualizing noise matching. The traveling-wave representation of noise contains two correlated noise waves: one emanating out of the LNA input, c_1, and one emanating out of the LNA output, c_2. As shown in Fig. 1, noise wave c_1 partially reflects off the signal source – with a reflection coefficient of $\Gamma_{\text{s}} = (Z_{\text{s}} - Z_0)\,/\,(Z_{\text{s}} + Z_0)$, where Z_0 is the characteristic impedance – and interferes with noise wave c_2 at the LNA output. If Γ_s is selected such that $Z_{\text{s}} = Z_{\text{opt}}$, the correlated portions of c_1 and c_2 will destructively interfere, and their remaining portions comprise the net LNA output noise that determines the LNA noise factor.

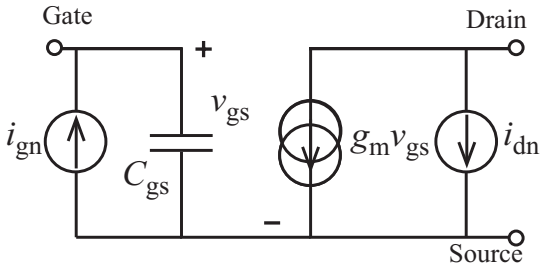

Figure 2: Simplified MOSFET small-signal model with noise sources.

When this happens, the LNA noise factor reaches its minimum of $F = F_{\text{min}}$, as desired [Belostotski, 2016].

Since MOSFET noise parameters are important when minimizing the LNA noise factor, it would be useful to review them before discussing circuit details. The noise parameters of the simplified MOSFET small-signal model in Fig. 2 are dependent on transistor gate-source capacitance, C_{gs}, and transconductance, g_{m} and are

$$\begin{cases} F_{\text{min}} = 1 + 2\frac{\omega}{\omega_T}\frac{\gamma\psi}{\alpha} \overset{l.c.}{=} 1 + 0.77\frac{\omega}{\omega_T} \\ N = \frac{1}{2}\left(F_{\text{min}} - 1\right) \overset{l.c.}{=} 0.39\frac{\omega}{\omega_T} \\ G_{\text{opt}} = \omega C_{\text{gs}}\psi \overset{l.c.}{=} 0.58\omega C_{\text{gs}} \\ B_{\text{opt}} = -\omega C_{\text{gs}}\xi \overset{l.c.}{=} -0.75\omega C_{\text{gs}} \end{cases} \tag{3}$$

where, for brevity, ω_T represents $g_{\text{m}}/C_{\text{gs}}$,

$$\psi \equiv \alpha\sqrt{\left(1 - |c|^2\right)\delta/5\gamma} \tag{4}$$

$$\xi \equiv 1 - \alpha\,|c|\,\sqrt{\delta/5\gamma} \tag{5}$$

, and

$$\alpha = (1 + 0.5\rho)\,/\,(1 + \rho)^2\,, \tag{6}$$

with $\rho \equiv V_{\text{od}}/v_{\text{sat}}L$, wherein v_{sat} is the saturation velocity, V_{od} is the gate-source overdrive voltage, and L is the channel length [Belostotski and Haslett, 2006], [Lee, 2004]. The drain and induced gate mean-squared noise currents are described by

$$\overline{i_{\text{dn}}^2} = 4kTB\gamma g_{\text{do}} \tag{7}$$

and

$$\overline{i_{\text{gn}}^2} = 4kTB\delta\frac{\omega^2 C_{\text{gs}}^2}{5g_{\text{d0}}}, \tag{8}$$

respectively, where

$$c = \overline{i_{\text{dn}}i_{\text{gn}}^*}/\sqrt{\overline{i_{\text{dn}}^2}\,\overline{i_{\text{gn}}^2}} \tag{9}$$

is the correlation coefficient, $g_{\text{d0}} = g_{\text{m}}/\alpha$ is the output conductance when the drain-source voltage V_{ds} is zero, B is the noise bandwidth, k is Boltzmann's constant, and T is the absolute temperature [Belostotski and Haslett, 2006], [Lee, 2004]. For long-channel (l.c.) transistors, $\alpha = 1$, $c = j0.395$, $\gamma = 2/3$, and $\delta = 4/3$ are the excess drain- and gate-noise coefficients, respectively. In this article, the long-channel values are used to give the reader a sense of the magnitude of some of the parameters shown in (3). Noise parameters in (3) only pertain to a stand-alone MOSFET. Addition of lossy components for matching the LNA modifies the noise parameters and increases F_{min} as will be discussed later in this article. LNA topologies that minimize the increase in F_{min} are therefore of interest.

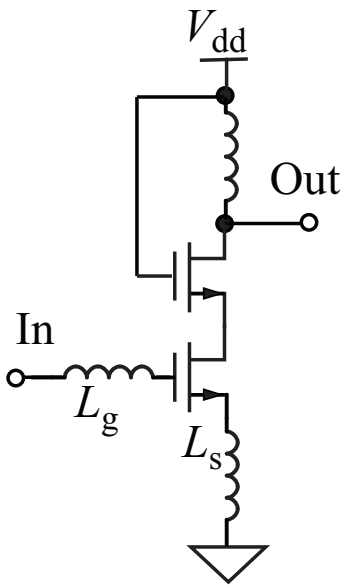

Figure 3: Simplified schematic (biasing not shown) of a source-degenerated cascode LNA.

B. Narrowband designs

We will begin by reviewing narrow band designs, as doing so will help illustrate the challenges associated with wideband designs. The main challenge in designing a very-low-noise amplifier that exhibits noise factors near transistor F_{min} is achieving simultaneous noise and power matching of the signal source and amplifier input. The inductively source-degenerated LNA shown in Fig. 3 is able to achieve very low noise figures. While there are many different methods that can be used to design LNAs, the two most common ones are described in [Shaeffer and Lee, 1997], [Nicolson and Voinigescu, 2006]. The method in [Nicolson and Voinigescu, 2006], [**?**] prescribes biasing a transistor at the technology-independent current density yielding the minimum F_{min}, $J_{\text{opt}} = 0.15\,\text{mA}/\mu\text{m}$. For a design with the characteristic impedance, Z_0 equal to $50\,\Omega$, the transistor is sized such that $G_{\text{opt}} = Z_0^{-1}$. Next, a source inductor, L_{s}, is selected to make the real part of the input impedance equal to $50\,\Omega$, while a gate inductor, L_{g}, is used to cancel out the reactive portion of the input impedance. Note that since $-B_{\text{opt}}$is not equal to ωC_{gs} when gate induced noise is included, the combination of $\omega\left(L_{\text{g}} + L_{\text{s}}\right)$ equals $1/\omega C_{\text{gs}}$ and therefore does not fully achieve noise matching.

This design strategy works well for high-frequency designs, but it results in high power consumption at low frequencies. To illustrate this behavior, assume that $C_{\text{gs}} \approx \frac{2}{3}C_{\text{ox}}WL$, with G_{opt} being expressed as in (3). Under these conditions,

$$W = \left(\frac{2}{3}\omega C_{\text{ox}}LZ_0\psi\right)^{-1} \tag{10}$$

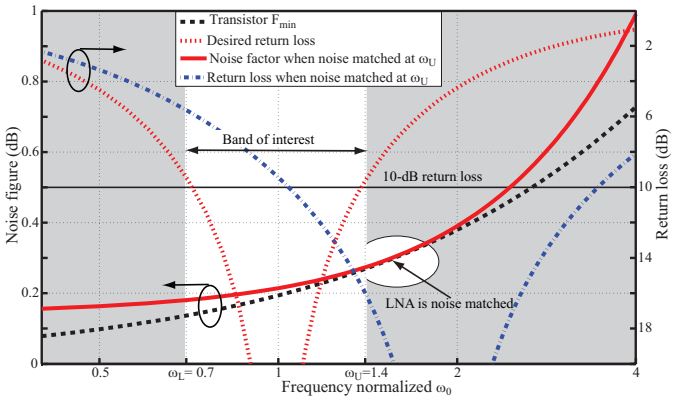

Figure 4: Demonstration of misalignment between noise matching and input power matching. The x-axis is normalized by the center frequency, ω_0. The desired band is between ω_{L} and ω_{U}, which were arbitrarily assigned values of $0.7\omega_0$ and $1.4\omega_0$, respectively. Long-channel noise parameters and g_m and C_{gs} from a 90-nm MOSFET were used in this simulation [Belostotski and Haslett, 2007c].

is needed to yield $G_{\mathrm{opt}} = Z_0^{-1}$. Therefore, the current consumption of this design becomes

$$I_{\mathrm{dc}} = J_{\mathrm{opt}} \left(\frac{2}{3} \omega C_{\mathrm{ox}} L Z_0 \psi \right)^{-1} \overset{l.c.}{=} J_{\mathrm{opt}} \left(19 C_{\mathrm{ox}} L \omega \right)^{-1}. \quad (11)$$

Substituting C_{ox} for a desired technology demonstrates a high-power consumption for a long-channel transistor that decreases with frequency.

To limit power consumption at lower frequencies, the power-constrained approach presented in [Shaeffer and Lee, 1997] is preferred. Here, the size of the MOSFET and the biasing voltages were constrained by a specific power consumption and input power matching. Because $-B_{\mathrm{opt}} \neq \omega_0 C_{\mathrm{gs}}$, the input-power-matching constraint will not permit the design to achieve transistor F_{min}. Fig. 4 demonstrates the misalignment between the input power matching and noise matching frequencies. The design procedure in [Shaeffer and Lee, 1997] produces a narrowband design when low power consumption is desired for the circuits. By contrast, when a large power consumption is chosen, C_{gs} increases and the gate inductor decreases, which results in a low input-network quality factor, $Q_{\mathrm{s}} \equiv (\omega C_{\mathrm{gs}} R_{\mathrm{in}})^{-1}$. As [Belostotski and Haslett, 2007a] demonstrated using a 10-dB return loss, the relationship between Q_{s} and the relative bandwidth, $B_{\mathrm{r}} \equiv (\omega_{\mathrm{U}} - \omega_{\mathrm{L}})/\omega_0$, is $Q_{\mathrm{s}} = 2/(3B_{\mathrm{r}})$; therefore, a low Q_{s} results in a large bandwidth. Consequently, relying on a very low Q_{s} is not sufficient for wideband LNAs, as doing so drives up power consumption.

In addition, B_{opt} behaves like a negative capacitance $(-C)$, see (3). For noise matching across a wide band of frequencies, this creates the design challenge of transferring the (typically $50\,\Omega$) output impedance of the network driving the LNA to an admittance Y_{s} near Y_{opt} that exhibits the $-C$ behavior with frequency. Fortunately, the F_{min} of a transistor decreases with decreasing frequency, and some mismatch between Y_{opt} and Y_{s} at low frequencies will not increase the noise factor of an LNA significantly. A close look at Fig. 4 reveals that the mismatch penalty is not significant (proportional to $R_{\mathrm{n}}/R_{\mathrm{s}}$ [Belostotski and Haslett, 2007a]) below the frequency at which noise matching is accomplished, whereas the penalty between the noise factor and F_{min} increases quickly (proportional to $R_{\mathrm{n}}/R_{\mathrm{s}}\omega^4/\omega_0^4$ [Belostotski and Haslett, 2007a]) at higher frequencies. As a result of the large mismatch penalty that occurs above the noise-matching frequency, wideband designs that only use a gate inductor to noise match a common-source MOSFET tend to perform this task at the upper band edge (i.e., at ω_{U}, as shown in Fig. 4). At lower frequencies, the mismatch between F and F_{min} is negligible, which results in a nearly constant overall noise factor across the wideband [Belostotski and Haslett, 2007c]. While this approach is acceptable for applications such as radio astronomy, it is less desirable for commercial systems due to the presence of large gain ripples and reduced filter rejection caused by input power mismatch. Thus, other methods that include additional components are required for wideband designs striving to achieve F_{min}, as gate-inductor-only input-matching networks are clearly insufficient for this task.

C. Noise measure

At this point, the question: "how do these additional circuits affect noise?" may be raised. A cascade of stages is one well-known amplifier arrangement, the noise factor, F_{12}, of which can be estimated using Friis' formula [Friis, 1944]

$$F_{12} = F_1 + \frac{F_2 - 1}{G_1} \quad (12)$$

where F_1 and F_2 are the noise factors of the first and second stages in the cascade, respectively, and G_1 is the available gain of the first amplifier. When the noise factor of a transistor is reduced to near unity by applying degenerative feedback, the network noise factor becomes determined by the second stage of the cascade. Therefore, in more complicated situations wherein feedback is used or transistors are cascaded, another performance metric is required. Such a metric was proposed by Haus and Adler [Haus and Adler, 1958], [Adler and Haus, 1958], [Haus and Adler, 1959], who developed a single measure that incorporates noise factor and gain in order to identify the noise performance of amplifiers.

Considering (12), we note that switching the positions of the two amplifiers in the chain gives us

$$F_{21} = F_2 + \frac{F_1 - 1}{G_2}. \quad (13)$$

Moreover, if $F_{12} < F_{21}$, (12) and (13) give

$$\frac{F_1 - 1}{1 - G_1^{-1}} < \frac{F_2 - 1}{1 - G_2^{-1}}. \quad (14)$$

This suggests that the lowest noise factor for a cascade can be achieved by placing the amplifier with the lowest $(F-1)/\left(1-G^{-1}\right)$ at the front, rather than the amplifier with the lowest F. Haus and Adler refer to the term

$$M \equiv \frac{F - 1}{1 - G^{-1}} \quad (15)$$

as "noise measure," with the noise measure of a cascade being expressed by

$$M_{12} = M_1 + (M_2 - M_1)\,\frac{G_2 - 1}{G_1 G_2 - 1}. \tag{16}$$

The important conclusion of [Haus and Adler, 1958] is that when a two-port amplifier is comprised of an arbitrary number of two-port amplifier stages with lossless interconnections, the noise measure of the resultant amplifier cannot be less than the noise measure of the best amplifier in the network. Furthermore, if interconnections are lossy, the resultant noise measure cannot be less than that in the lossless case. Another important result is that the minimum noise measure of a circuit is invariant to a lossless network, which embeds the active devices. However, lossy or active-circuit embedding adds noise and can only degrade the minimum noise measure.

The results of Haus and Adler's work indicates that, for a network consisting of more than one active circuit, the lower limit on the minimum noise factor will be determined by the minimum noise factor of the best active circuit. Any lossy passive components will increase the lowest noise factor of the network. Keeping the outcomes of [Haus and Adler, 1958] in mind, we can now investigate different wideband design strategies.

II. Wideband amplifiers

Common-gate LNAs [Zhuo *et al.*, 2005], [Sanghyun Woo *et al.*, 2009], [Shim *et al.*, 2007], [Jeong *et al.*, 2011] are popular due to their input impedance, $Z_{\text{in}} = 1/\left[g_{\text{m}}\left(1 + j\omega/\omega_{\text{T}}\right)\right] \approx 1/g_{\text{m}}$, being relatively low (i.e., close to 50Ω) and resistive at frequencies much lower than ω_{T}. While it is easy to show that common-gate and common-source transistors have identical noise-parameter values, common-gate LNAs do not achieve transistor F_{min} because in such designs the input-power-matching condition (i.e., $Z_{\text{s}} = 1/g_{\text{m}}$) does not coincide with the noise-matching condition as the common-gate LNA relies on ωC_{gs} is much less than g_m, which from (3) implies that noise matching is not possible since $G_{opt} \ll g_m = Z_s^{-1}$. Resistive shunt-feedback LNAs [Lin *et al.*, 2014], [Chang and Hsu, 2010], [Zhan and Taylor, 2006] are also able to achieve very wide bandwidths, but the addition of the feedback resistor increases their noise factor well beyond F_{min}, as would be expected based on the discussion in Section I-C.

Noise-canceling LNAs [Bruccoleri *et al.*, 2001], [Bruccoleri *et al.*, 2004], [Blaakmeer *et al.*, 2006], [Blaakmeer *et al.*, 2008], [Jussila and Sivonen, 2008], [Ho and Saavedra, 2010], [El-Nozahi *et al.*, 2011], [Mak and Martins, 2011], [Murphy *et al.*, 2012], [Chen and Liu, 2012] were developed to alleviate the noise penalty associated with the design choices in common-gate and shunt-feedback LNAs by embedding them in a network of one or more additional active devices. As discussed in Section I-C, the fundamental limit on the noise performance of such circuits is determined by the individual sub-circuit noise- and S-parameters. Prior work by Haus and Adler [Haus and Adler, 1958], [Haus and Adler, 1959] indicate that noise-canceling LNAs cannot achieve noise factors approaching the technology F_{min}. Nevertheless, noise-canceling LNAs are popular because they are broad band, some are capable of providing differential outputs, and they enable the cancellation of circuit intermodulation components [Blaakmeer *et al.*, 2008].

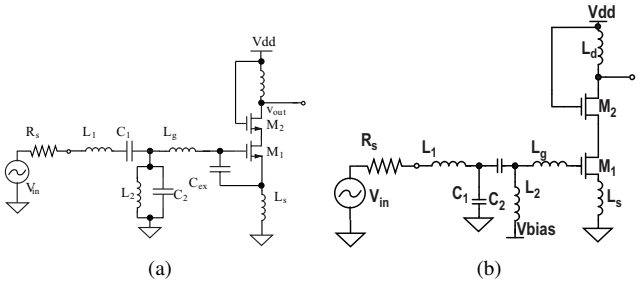

Figure 5: (a) Filter-synthesis approach for input power matching [Bevilacqua and Niknejad, 2004], [Ismail and Abidi, 2004]. (b) LNA with simultaneous wideband noise and input power matching as proposed in [Zailer *et al.*, 2020].

The following sections provide an overview of circuits that provide wideband input power matching, and are also capable of noise matching, at least in theory.

A. LNAs with wideband reactive input-matching networks

The input impedance (looking into the transistor gate) of the inductively degenerated common-source MOSFET in Fig. 3 is

$$Z_{\text{in}} = \left(j\omega C_{\text{gs}}\right)^{-1} + \omega_{\text{T}} L_{\text{s}} + j\omega L_{\text{s}}. \tag{17}$$

Considering this R-C-L impedance as a part of a bandpass filter, the filter synthesis method can be used to identify matching components, which are placed ahead of the amplifier to complete the wideband impedance match. An example is shown in Fig. 5(a) [Bevilacqua and Niknejad, 2004], [Ismail and Abidi, 2004]. Although this method does not provide noise matching explicitly, the wideband nature of the input-matching network means that noise matching can be expected somewhere within the band. For the lowest noise in the band, the input impedance network should be over-designed slightly to extend the input-power-match bandwidth beyond the upper band edge so that noise matching is satisfied at this point, as discussed in Section I-B.

However, over-designing is not always possible and setting $-B_{\text{opt}} = B_{\text{in}}$, where $B_{\text{in}} = \Im\{1/Z_{\text{in}}\}$, is therefore desired. In an attempt to set $-B_{\text{opt}} = B_{\text{in}}$ within the band for simultaneous wideband noise and input matching, authors in [Zailer *et al.*, 2020] investigated both the mismatch between transistor F and F_{min} (expressed as $\Delta F = F - F_{\text{min}}$) and the sensitivity of ΔF to ω

$$S_{\text{f}} \equiv \frac{\partial \Delta F}{\partial \omega}\frac{\omega}{\Delta F}. \tag{18}$$

Coincidence $\Delta F = 0$ and $S_f = 0$ occurs when $\psi^2 + \xi^2 = \xi$, which results in

$$\alpha = |c|\,\sqrt{5\gamma/\delta} \overset{l.c.}{\rightarrow} 0.62 \tag{19}$$

from the definitions of ψ and ξ,. Simultaneous noise and power matching is achieved when transistor bias is selected such

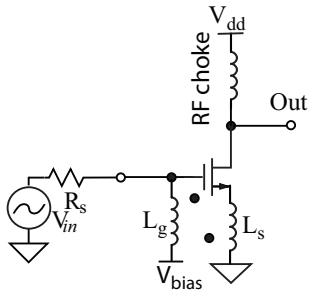

Figure 6: LNA with transformer feedback.

that $\alpha = 0.62$. Paper [Zailer *et al.*, 2020] also investigated a matching strategy that permitted the input resistance at the transistor gate to deviate from $50\,\Omega$, which provided an additional degree of design freedom. Given the flexibility in designing the input network and selecting R_s, the design of the LNA in Fig. 5(b) was achieved by: (a) selecting an inductor with the highest Q in-band for $L_{\rm g}$ from the design kit, (b) selecting a high-Q kit inductor, L_2, and (c) targeting a return loss of at least 12 dB. This design strategy enabled the LNA to achieve its minimum noise factor throughout the operating range. Nevertheless, these passive matching components contribute noise, and $F_{\rm min}$ for the LNA remains higher than that of the transistor.

B. Wideband LNAs with feedback

Feedback elements can also be used to realize input matching. For example, shunt feedback amplifiers [Zhan and Taylor, 2006] demonstrate wide input bandwidth. However, such amplifiers use lossy feedback elements and do not come close to achieving $F_{\rm min}$. In contrast, reactive, low-loss feedback may permit wide input matching without increasing the LNA noise factor significantly beyond $F_{\rm min}$. Examples of such designs were presented in [Reiha and Long, 2007], [Cui and Long, 2020], [Xiaoyong Li *et al.*, 2005], wherein a transformer formed between the MOSFET source inductor and gate inductor (Fig. 6) was used to provide negative feedback. The noise factor of the LNA in the circuit depicted in Fig. 6 is

$$F = 1 + \frac{1}{n+1}\frac{\gamma}{\alpha} + \frac{\omega^2}{\omega_T^2}(n+1)\left(\frac{\gamma}{\alpha} + \frac{\delta\alpha}{5} - 2|c|\sqrt{\frac{\gamma\delta}{5}}\right), \tag{20}$$

where n is the transformer turns ratio, the transformer coupling coefficient is assumed to be 1, the impedance matching condition forces $R_{\rm s}g_m = n^2/(n+1)$, and losses in the transformer are ignored. From (6), a minimum in F exists when $n \overset{l.c.}{=} \omega_T/\omega - 1$. While no physically realizable n can make $F = F_{\rm min}$, by focusing on setting feedback factors to set the input impedance to $50\,\Omega$ across a wideband in a more reproducible way than the LNA with source degeneration and series gate matching, the LNAs in designs following [Reiha and Long, 2007], [Cui and Long, 2020] have achieved excellent bandwidths (3.1 to 10.6 GHz and 22 to 32 GHz) and very low noise figures (2.1 dB and 1.7 dB) while consuming 9 mW and 17.3 mW of power.

To reduce the number of lossy reactive components at the LNA input, the parasitic feedback through transistor gate-drain capacitance, $C_{\rm gd}$, can also be employed to tune the power and the noise match independently [Hu and Yang, 2005], [Hu, 2006], [Belostotski *et al.*, 2006], [Belostotski and Haslett, 2007a], [Belostotski and Haslett, 2007c], [Belostotski and Haslett, 2007b]. Since feedback through $C_{\rm gd}$ is always present, and measurements of transistor noise parameters naturally take $C_{\rm gd}$ into account, using $C_{\rm gd}$ for feedback does not impact $F_{\rm min}$. When an inductively source-degenerated LNA is loaded with a dc-blocking capacitor, $C_{\rm L}$, and a load resistor, $R_{\rm L}$, as shown in Fig. 7(a), the input impedance of the transistor can be described by

$$Z_{\rm in}^{-1} = Z_{\rm gs}^{-1} + Y_{\rm gd}, \tag{21}$$

where

$$Z_{\rm gs} = (sC_{\rm gs})^{-1} + sL_{\rm s} + g_{\rm m}L_{\rm s}/C_{\rm gs} \tag{22}$$

and $Y_{\rm gd}$ is the result of $C_{\rm gd}$ feedback. When the load is implemented by a common-gate transistor such that $R_{\rm L} = 1/g_{\rm m}$, the model of the resultant $Z_{\rm in}$ is as illustrated in Fig. 7(b) [Belostotski *et al.*, 2006]. This configuration forms two resonant networks: $Z_{\rm gs}$ resonates at high frequency, and $Y_{\rm gd}$ resonates at low frequency. By adjusting $C_{\rm L}$, the location of the low-frequency resonance can be tuned. This arrangement, which is conceptually very simple and resembles a narrowband circuit, does not require any additional components to be connected to the transistor input to form feedback networks. The wideband LNA design then uses a standard narrowband source-degenerated LNA design method to implement the narrowband LNA noise match at the upper frequency range (see Section I-B and Fig. 4). Since LNAs that utilize $C_{\rm gd}$ feedback exhibit an additional low-frequency resonance at the LNA input due to $Y_{\rm gd}$, adjusting the LNA load capacitor, $C_{\rm L}$, will enable wideband input power matching. Such LNAs have been shown to achieve very low noise factors over wide bandwidths [Belostotski and Haslett, 2007b], [Beaulieu *et al.*, 2016], [Hu, 2004]. [Belostotski and Haslett, 2007b], [Beaulieu *et al.*, 2016] demonstrated noise noise figures of <0.2 dB over 55% relative bandwidth (from 0.8 to 1.4 GHz), while GaAs LNA in [Hu, 2004] reported return loss of greater than 10 dB and noise figures of 1.3dB in the band between 8 and 20 GHz.

C. LNAs with negative capacitance for wideband noise and power matching

As discussed in Section I-B, the realization of simultaneous noise and power matching over a wide frequency range in an LNA design is complicated by the fact that a negative capacitance (–C) is required at the MOSFET input to achieve the MOSFET minimum noise factor, $F_{\rm min}$. This –C element is often approximated using an inductor over a narrow band of frequencies. While there are examples of LNAs that have employed negative capacitance [Chang *et al.*, 2008], [Jang *et al.*, 2019], [Jacob and Sievenpiper, 2016], these examples do not use the –C for noise matching, but rather, they tend to use the –C for power matching or for neutralizing capacitance $C_{\rm gd}$. When used for power matching, the –C circuit spoils the LNA noise factor, and it does not contribute to noise

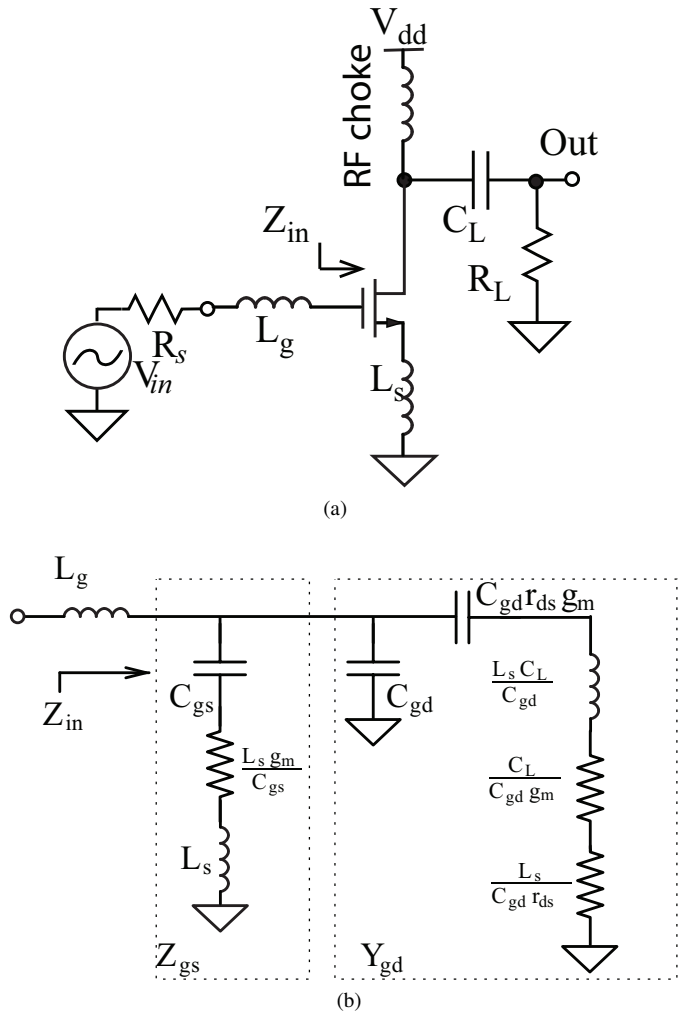

Figure 7: (a) Example of an LNA topology that makes use of intrinsic feedback through $C_{\rm gd}$. (b) Approximate input-impedance model of the LNA in (a) with $R_L = 1/g_{\rm m}$.

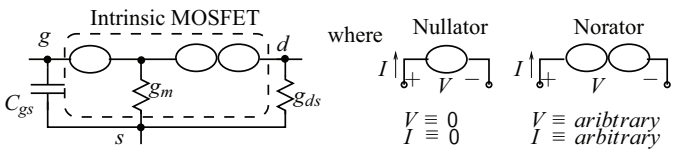

Figure 8: A small-signal MOSFET nullor model.

matching when it is used to neutralize $C_{\rm gd}$. To create a –C element that can be embedded within an LNA, it is convenient to replace a noiseless version of the MOSFET controlled-current-source model in Fig. 2 with the nullor small-signal representation in Fig. 8 to make use of the concept of nullor equivalences in circuit analysis [Bruton, 1980]. A two-nullor generalized immittance converter (GIC) comprised of nullators and norators is shown in Fig. 9(a) [Bruton, 1980]. Many possible circuits can be constructed from the GIC configured as a negative impedance converter (NIC) in Fig. 9(a) by identifying MOSFET nullor models within it (see Fig. 8). For example, the two-MOSFET circuit in Fig. 9(b) synthesizes the NIC, and is capable of synthesizing a negative capacitance

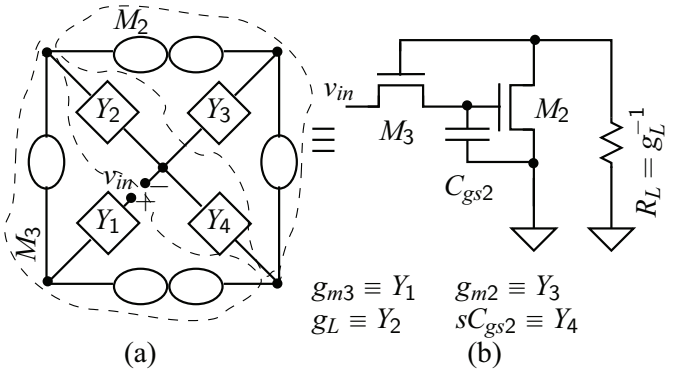

Figure 9: (a) The two-Nullor GIC configured as an NIC (b) MOSFET based representation of the GIC (biasing not shown).

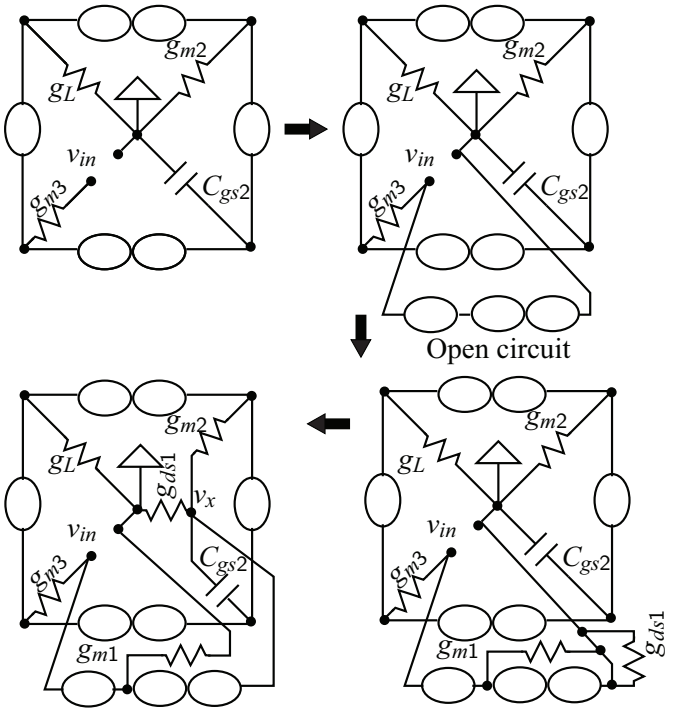

Figure 10: GIC equivalences.

for small signals. However, since the input is applied to the source terminal of M3, this circuit topology will likely yield unsatisfactory noise factors, similar to those observed in common-gate LNAs. To improve the noise factor, the nullor equivalence [Bruton, 1980] is used to transform the GIC in Fig. 9(a) to the equivalent GIC of Fig. 10. Note that the nullator and norator definitions are depicted in Fig. 8. Using these definitions, it is easy to show that they can be connected in series to produce an open circuit. Therefore, adding such networks to the GIC in Fig. 9(a) will not affect it, as shown in the first step in Fig. 10. Furthermore, the other transformations also do not affect the GIC. The last transformation in Fig. 10 is possible because currents flowing through $g_{\rm m2}$ and $C_{\rm gs2}$ are independent of the voltage, $v_{\rm x}$. Further use of equivalences can continue until a suitable circuit topology is found. With the three transformations shown in Fig. 10, the resultant nullor-equivalent representation can be implemented with three

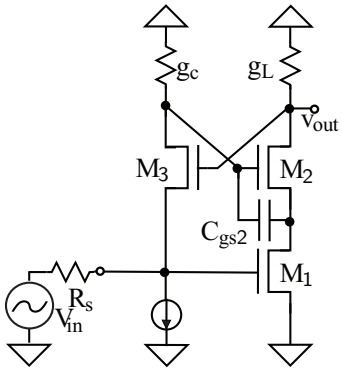

Figure 11: An example of a –C LNA.

MOSFETs (including a common-source MOSFET at the input, as in Fig. 11), and thus has the potential for enabling lower noise factors. With the GIC configured as an NIC, the small-signal –C, synthesized by M2-M3 at the input to M1, provides simultaneous power and noise matching over a broad-band frequency range. Unlike shunt feedback LNAs, the circuit in Fig. 11 has a non-zero conductance, (i.e., $g_c = 1/R_c$). In addition to providing a DC current to M3, g_c is required for stability and an adequate output match. Transistor M_3 draws very low current and contributes a low amount of noise at the input node. Using this NIC, the 65-nm CMOS LNA in [Belostotski *et al.*, 2012] was able to achieve a 1-dB noise figure, while it was also noise and power matched with $S_{11} < -10\,\text{dB}$ across a 10MHz to 2.8GHz frequency range, consumed the total power in all sections of 40 mW, and demonstrated voltage gain of 32dB and IIP3 of -13.6dBm. However, the addition of M_3 and the current source, which was implemented with a large resistor to ensure a low impact on noise, inevitably increased the LNA F above the MOSFET F_{min}.

III. Conclusions

This article has reviewed several wide-band LNA circuit topologies that theoretically permit simultaneous noise and power matching over at least part of the desired pass band. Circuits that require a lower number of components at the LNA input are more likely to have noise factors that approach the transistor F_{min}. Since wideband LNAs require more than one passive element for input power matching, those that employ reactive or intrinsic feedback through C_{gd} are better able to achieve low noise factors due to the reduced number of circuit elements at the LNA input. A short example of how the nullor equivalence can be used identify new LNA topologies was also provided at the end of this article.

References

[Adler and Haus, 1958] R. Adler and H. Haus. Network realization of optimum amplifier noise performance. *IRE Transactions on Circuit Theory*, 5(3):156–161, 1958.
Editor comment: follows [Haus and Adler, 1958] by elaborating on the detailed development of the network realizations that achieve optimum noise measured.

[Beaulieu *et al.*, 2016] A. J. Beaulieu, L. Belostotski, T. Burgess, B. Veidt, and J. W. Haslett. Noise performance of a phased-array feed with CMOS low-noise amplifiers. *IEEE Antennas and Wireless Propagation Letters*, 15:1719–1722, 2016.
Editor comment: an antenna array equiped with CMOS LNAs operating from 0.7 to 1.5 GHz. Array beam-equivalent noise measurements, using an ambient load as a hot load and the sky as a cold load, show array beam-equivalent noise temperatures as low as 20 K.

[Belostotski and Haslett, 2006] L. Belostotski and J. W. Haslett. Noise figure optimization of inductively degenerated CMOS LNAs with integrated gate inductors. *IEEE Trans. Circuits Syst. I*, 53(7):1409–1422, July 2006.
Editor comment: noise figure optimization techniques for inductively degenerated cascode CMOS LNAs with on-chip lossy gate inductors. Seven different optimizations techniques are discussed.

[Belostotski and Haslett, 2007a] L. Belostotski and J. W. Haslett. Noise figure optimization of wide-band inductively-degenerated CMOS LNAs. In *IEEE MSCAS*, pages 1002–1005, Montreal, Canada, 5-8 August 2007.
Editor comment: design and measurement results of a wide-band inductively-degenerated 0.18-μm CMOS LNA targeted for the square kilometer array (SKA) radio telescope. The LNA operating from 0.7 to 1.4 GHz achieves noise figures better than 0.57 dB, S_{21}>15 dB, input return loss of > 16 dB, OP1dB = 6 dBm, and OIP3 = 14.5 dBm while consuming 50 mW of power from a 1.5-V supply.

[Belostotski and Haslett, 2007b] L. Belostotski and J. W. Haslett. Sub-0.2 dB noise figure wide-band room-temperature CMOS LNA with non-50 Ω signal-source impedance. *IEEE J. of Solid-State Circuits*, 42(11):2492–2502, November 2007.
Editor comment: noise figure optimization procedure and C_{gd} feedback that result in reduced noise figure and wide bandwidth. The 90-nm CMOS LNA achieves NF of 0.2 dB from 0.8 to 1.4 GHz, S_{11} < -11 dB, gain of > 17 dB, OP1dB = dBm, OIP3 = 12 dBm, OIP2 = 22 dBm while consuming 43 mW of power.

[Belostotski and Haslett, 2007c] L. Belostotski and J. W. Haslett. Wide band room temperature 0.35-dB noise figure LNA in 90-nm bulk CMOS. In *IEEE Radio and Wireless Symposium*, pages 221–224, Long Beach, 7-11 January 2007.
Editor comment: bandwidth constrained LNA noise figure optimization and broad-banding technique as well as the importance of substrate shielding. The LNA demonstrated NF=0.35 dB, power consumption of 45 mW, OP1dB of -5.3 dBm, OIP3 of 7.5 dBm, and S21 ranging from 20.5 dB to 16.3 dB across the band from 0.7 to 1.4 GHz.

[Belostotski *et al.*, 2006] L. Belostotski, J. W. Haslett, and B. Veidt. Wide-band CMOS low noise amplifier for applications in radio astronomy. In *IEEE International Symposium on Circuits and Systems*, pages 1347–1350, Kos, 21-24 May 2006.
Editor comment: a variation on a well-known source-degenerated LNA topology is introduced that allows tuning of the power match centre frequency independently from the frequency at which the LNAs noise figure approaches its minimum noise.

[Belostotski *et al.*, 2012] L. Belostotski, A. Madanayake, and L. T. Bruton. Wideband LNA with an active -C element. *IEEE Microwave and Wireless Components Letters*, 22(10):524–526, October 2012.
Editor comment: active -C element, which draws 170 μA, is described for noise matching. The LNA is power- and noise- matched, achieves minimum noise figure of 1 dB, voltage gain of 32 dB, and IIP3 of -13.6 dBm.

[Belostotski, 2011] L. Belostotski. On the number of noise parameters for analyses of circuits with MOSFETs. *IEEE Trans. Microw. Theory Techn.*, 59(4):877–881, April 2011.
Editor comment: discusses the applicability of the inequality relating F_{min} and Lange invariant N to MOSFETs. This work shows that by using N, the number of noise parameters for modeling of intrinsic MOSFETs can be reduced by one.

[Belostotski, 2016] L. Belostotski. No noise is good noise: Noise matching, noise canceling, and maybe a bit of both for wide-band LNAs. *IEEE Microwave Magazine*, 17(8):28–40, August 2016.
Editor comment: compares and contrasts noise-matched to noise-cancelling LNAs.

[Bevilacqua and Niknejad, 2004] A. Bevilacqua and A. M. Niknejad. An ultrawideband CMOS low-noise amplifier for 3.1-10.6-GHz wireless receivers. *IEEE J. Solid-State Circuits*, 39(12):2259–2268, Dec 2004.
Editor comment: an input three-section band-pass Chebyshev filter is presented. A 3.1-10.6-GHz LNA achieves a power gain of 9.3 dB with an input match of -10 dB over the band, a minimum noise figure of 4 dB, and an IIP3 of -6.7 dBm while consuming 9 mW.

[Blaakmeer *et al.*, 2006] S.C. Blaakmeer, E.A.M. Klumperink, D.M.W. Leenaerts, and B. Nauta. A wideband noise-canceling CMOS LNA exploiting a transformer. In *IEEE Radio Frequency Integrated Circuits Symposium*, pages 1–4, San Francisco, 11-13 June 2006.
Editor comment: a broadband LNA incorporates single-ended to differential conversion and a noise-canceling technique. The LNA achieves a voltage gain of 19dB, an input match from 2.5 to 4.0 GHz, and NF between 4 and 5.4 dB, while consuming only 8mW.

[Blaakmeer *et al.*, 2008] S. C. Blaakmeer, E. A. M. Klumperink, D. M. W. Leenaerts, and B. Nauta. Wideband balun-LNA with simultaneous output balancing, noise-canceling and distortion-canceling. *IEEE J. of Solid-State Circuits*, 43(6):1341–1350, June 2008.
Editor comment: a noise-canceling and distortion-canceling LNA that exploits a combination of a common-gate stage and an common-source stage. The LNA demonstrates 15-dB gain, NF < 3.5 dB, IIP2 > 20 dBm and IIP3 > 0 dBm between 0.3 to 3.5 GHz.

[Boglione, 2008] L. Boglione. An original demonstration of the $T_{\min}/T_o \leq 4N$ inequality for noisy two-port networks. *IEEE Microwave and Wireless Components Letters*, 18(5):326–328, 2008.
Editor comment: demonstration of the inequality relating F_{min} and the Lange invariant N.

[Boglione, 2013] L. Boglione. Considerations on the $4NT_{\rm o}/T_{\rm m}$ ratio and the noise correlation matrix of active and passive two-port networks. *IEEE Transactions on Microwave Theory and Techniques*, 61(12):4145–4153, 2013.
Editor comment: discussion on relations between F_{min} and the Lange invariant N.

[Bruccoleri *et al.*, 2001] F. Bruccoleri, E. A. M. Klumperink, and B. Nauta. Generating *all* two-MOS-transistor amplifiers leads to new wide-band LNAs. *IEEE J. of Solid-State Circuits*, 36(7):1032–1040, July 2001.
Editor comment: a methodology for generates all 2-MOS-transistor wide-band amplifiers is used to identify a noise-canceling LNA. The LNA shows NF between 4.3 and 4.9 dB for gains from 6 to 11 dB across 50 to 900 MHz.

[Bruccoleri *et al.*, 2004] F. Bruccoleri, E. A. M. Klumperink, and B. Nauta. Wide-band CMOS low-noise amplifier exploiting thermal noise canceling. *IEEE J. of Solid-State Circuits*, 39(2):275–282, February 2004.
Editor comment: a feedforward noise-canceling technique for simultaneous noise and impedance matching, while canceling the noise and distortion contributions of the matching device. The LNA achieves NF < 2.4 dB across 0.15 to 2 GHz, the voltage gain of 13.7 dB, IIP2 = 12 dBm, and IIP3 = 0 dBm.

[Bruton, 1980] L.T. Bruton. *RC-Active Circuits: Theory and Design*. Printice Hall, 1980.
Editor comment: seminal work on RC active circuits.

[Chang and Hsu, 2010] P. Chang and S. S. H. Hsu. A compact 0.1-14-GHz ultra-wideband low-noise amplifier in 0.13-μm CMOS. *IEEE Trans. Microw. Theory Techn.*, 58(10):2575–2581, Oct 2010.
Editor comment: inductorless LNA using the resistive-feedback and current-reuse techniques for wideband and high-gain characteristics. The LNA has maximum gain of 12.4 dB, minimum NF of 2.7 dB across 0.1 to 14 GHz.

[Chang *et al.*, 2008] T. Chang, J. Chen, L. A. Rigge, and J. Lin. ESD-protected wideband CMOS LNAs using modified resistive feedback techniques with chip-on-board packaging. *IEEE Transactions on Microwave Theory and Techniques*, 56(8):1817–1826, 2008.
Editor comment: a modified resistive feedback structure for designing wideband LNAs. One LNA operates from 0.2 to 9 GHz with 10 dB of power gain and a minimum NF = 4.2 dB. Another LNA operates form 0.2 to 3.2 GHz with 15.5 dB of power gain and a minimum NF = 1.76 dB.

[Chen and Liu, 2012] Ke-Hou Chen and Shen-Iuan Liu. Inductorless wideband CMOS low-noise amplifiers using noise-canceling technique. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 59(2):305–314, February 2012.
Editor comment: gain-enhanced noise-canceling technique. A common-soure LNA with resistive shunt feedback achieves a maximum power gain of 10.5 dB, a bandwidth of 10 GHz, a NF of 2.7 to 3.3 dB, and an IIP3 of -3.5 dBm. A common-gate LNA achieves a maximum power gain of 10.7 dB, a bandwidth of 5.2 GHz, a NF of 2.9 to 5.4 dB, and an IIP3 of -6 dBm.

[Cui and Long, 2020] B. Cui and J. R. Long. A 1.7-dB minimum NF, 22-32-GHz low-noise feedback amplifier with multistage noise matching in 22-nm FD-SOI CMOS. *IEEE Journal of Solid-State Circuits*, 55(5):1239–1248, 2020.
Editor comment: a low-noise feedback amplifier with inter stage noise matching is presented. Minimum noise figure (NF) is below 1.98$\pm$0.25 dB from 22 to 32 GHz, the peak gain is 21.5 dB, maximum IIP3 = -13.4 dBm when dissipating 17.3 mW.

[El-Nozahi *et al.*, 2011] M. El-Nozahi, AA Helmy, E. Sanchez-Sinencio, and K. Entesari. An inductor-less noise-cancelling broadband low noise amplifier with composite transistor pair in 90 nm CMOS technology. *IEEE J. of Solid-State Circuits*, 46(5):1111–1122, May 2011.
Editor comment: a composite NMOS/PMOS cross-coupled transistor pair to increase the amplification while reducing the noise figure. Measurements show a conversion gain of 21 dB across 2 to 2300 MHz frequency range, an IIP3 of -1.5 dBm at 100 MHz, NF between 1.4 dB and 1.7 dB.

[Friis, 1944] H. T. Friis. Noise figures of radio receivers. *Proceedings of the IRE*, 32(7):419–422, July 1944.
Editor comment: introduced the concept of cascaded noise figure.

[Haus and Adler, 1958] H. A. Haus and R. B. Adler. Optimum noise performance of linear amplifiers. *Proceedings of the IRE*, 46(8):1517–1533, 1958.
Editor comment: established noise measure as a single quantitative measure of amplifier spot noise performance.

[Haus and Adler, 1959] H. A. Haus and R. B. Adler. *Circuit Theory of Linear Noisy Networks*. John Wiley & Sons, Inc., 1959.
Editor comment: presents a single quantity (noise measure) to characterize LNA performance on the basis of the signal-to-noise ratio.

[Haus *et al.*, 1960] H. A. Haus, W. R. Atkinson, W. H. Fonger, W. W. Mcleod, G. M. Branch, W. A. Harris, E. K. Stodola, W. B. Davenport, Jr., S. W. Harrison, and T. E. Talpey. Representation of noise in linear twoports. *Proceedings of the Institution of Radio Engineers*, 48(1):66–74, January 1960.
Editor comment: a tutorial paper, written by the Subcommittee on Noise, IRE 7.9, to provide the theoretical background for some of the IRE Standards on methods of measuring noise.

[Ho and Saavedra, 2010] S.S.K. Ho and C.E. Saavedra. A CMOS broadband low-noise mixer with noise cancellation. *IEEE Transactions on Microwave Theory and Techniques*, 58(5):1126–1132, May 2010.
Editor comment: provides an example of using LNA noise-cancelling technique in a design of a broadband mixer.

[Hu and Yang, 2005] R. Hu and M. S. C. Yang. Investigation of different input-matching mechanisms used in wide-band LNA design. *International Journal of Infrared and Millimeter Waves*, 26(2):221–245, February 2005.
Editor comment: analyzes of different input-matching mechanisms used in designing the wide-band amplifiers and thier impact on noise. Feedback through C_{gd} is identified as a promising matching method.

[Hu, 2004] R. Hu. An 8-20-GHz wide-band LNA design and the analysis of its input matching mechanism. *IEEE Microwave and Wireless Components Letters*, 14(11):528–530, November 2004.
Editor comment: input matching thought C_{gd}. A GaAs LNA achieves 100 K noise temperature and 10 dB return loss from 8 to 20 GHz.

[Hu, 2006] R. Hu. Wide-band matched LNA design using transistor's intrinsic gate-drain capacitor. *IEEE Transactions on Microwave Theory and Techniques*, 54(3):1277–1286, March 2006.
Editor comment: a wide-band feedback mechanism provided by the transistor C_{gd} is analyzed. A bandwidth broadening mechanism using double feedback is also proposed for the future design of matched ultra-wide-band LNA.

[Ismail and Abidi, 2004] A. Ismail and A. Abidi. A 3-10-GHz low-noise amplifier with wideband LC-ladder matching network. *IEEE J. Solid-State Circuits*, 39(12):2269–2277, December 2004.
Editor comment: Reactive matching is extended to wide bandwidths using the impedance property of LC-ladder filters. A SiGe LNA operating from 3 to 10 GHz delivers 21-dB peak gain, 2.5-dB noise figure, and IIP3 = -1 dBm.

[Jacob and Sievenpiper, 2016] M. M. Jacob and D. F. Sievenpiper. Gain and noise analysis of non-Foster matched antennas. *IEEE Transactions on Antennas and Propagation*, 64(12):4993–5004, 2016.
Editor comment: an non-Foster circuit is used to overcome the gain-bandwidth limitations of passive small antennas, but at the cost of increased noise generated by the active matching circuit.

[Jang *et al.*, 2019] J. Jang, H. Kim, G. Lee, and T. W. Kim. Two-stage compact wideband flat gain low-noise amplifier using high-frequency feedforward active inductor. *IEEE Transactions on Microwave Theory and Techniques*, 67(12):4803–4811, 2019.
Editor comment: shunt peaking with a self-biased active inductor and a cross-coupled capacitor for wideband operation. A feedforward path creates a negative capacitance. The 65-nm LNA has a gain of 26.7 dB, a bandwidth of 4.1 GHz, a NF of 3 dB, and IIP3of -14.2 dBm.

[Jeong *et al.*, 2011] C. J. Jeong, W. Qu, Y. Sun, D. Y. Yoon, S. K. Han, and S. G. Lee. A 1.5V, 140μA CMOS ultra-low power common-gate LNA. In *IEEE Radio Frequency Integrated Circuits Symposium*, pages 1–4, 2011.
Editor comment: design guidelines for ultra-low power common-gate LNA. A 2.2 GHz common-gate LNA demonstrates 13.9 dB power gain, 5.14 dB NF, and -9.3 dBm IIP3, while dissipating 140 μA from a 1.5 V supply.

[Jussila and Sivonen, 2008] J. Jussila and P. Sivonen. A 1.2-V highly linear balanced noise-cancelling LNA in 0.13-μm CMOS. *EEE Journal of Solid-State Circuits*, 43(3):579–587, March 2008.
Editor comment: current-to-voltage combiner realizes a highly linear, balanced noise-cancelling LNA. The LNA exhibits a NF of 3.0 dB at 2.1 GHz with an IIP3 of 10.5 dBm.

[Lange, 1967] J. Lange. Noise characterization of linear twoports in terms of invariant parameters. *IEEE J. Solid-State Circuits*, 2(2):37–40, June 1967.
Editor comment: a representation of noisy twoports in terms of parameters invariant under lossless transformation. This publication introduced the invariant N parameter.

[Lee, 2004] T. H. Lee. *The Design of CMOS Radio-Frequency Integrated Circuits*. Cambridge Univeristy Press, New York, 2004.
Editor comment: a popular text describing the development of most common RF circuits.

[Lin *et al.*, 2014] Y. Lin, C. Wang, G. Lee, and C. Chen. High-performance wideband low-noise amplifier using enhanced π-match input network. *IEEE Microw. Wireless Comp. Lett.*, 24(3):200–202, March 2014.
Editor comment: an enhanced π-match input network is used to achieve wideband input impedance matching as well as high and flat gain. The LNA achieves NF of 2.3 $\pm$ 0.1 dB for frequencies from 3 to 10 GHz.

[Mak and Martins, 2011] Pui-In Mak and R.P. Martins. A 0.46-mm^2 4-dB NF unified receiver front-end for full-band mobile TV in 65-nm CMOS. *IEEE J. of Solid-State Circuits*, 46(9):1970–1984, September 2011.
Editor comment: a gain-boosting current-balancing noise-cancelling LNA, a current-reuse mixer, and a direct injection-locked LO generator to implement a mobile TV receiver. The receiver exhibits 4-dB NF, 17-to-35-dB gain, and IIP3 = -3.4 dBm.

[Mak *et al.*, 2014] P.-I. Mak, D. Leenaerts, H. C. Luong, and J. R. Long. Low-noise amplifiers. *IEEE RFIC Virtual Journal*, April 2014.
Editor comment: the latest developments in integrated LNAs. The article discusses 29 papers with the most significant contributions and provided curated commentary about their key features and performance.

[Murphy *et al.*, 2012] D. Murphy, A Hafez, A Mirzaei, M. Mikhemar, H. Darabi, M.F. Chang, and A Abidi. A blocker-tolerant wideband noise-cancelling receiver with a 2dB noise figure. In *IEEE International Solid-State Circuits Conference (ISSCC)*, pages 74–76, San Francisco, 19-23 February 2012.
Editor comment: a hybrid frequency-translational, noise-cancelling (FTNC) receiver. The LNA demonstrates a sub-2dB NF from 80 MHz to 2.7 GHz and tolerates 0dBm blockers.

[Nicolson and Voinigescu, 2006] S. T. Nicolson and S. P. Voinigescu. Methodology for simultaneous noise and impedance matching in W-band LNAs. In *IEEE CSICS*, pages 279–282, November 2006.
Editor comment: a step-by-step methodology for simultaneous noise and input impedance matching in CMOS and SiGe W-band LNAs.

[Pospieszalski, 1989] M.W. Pospieszalski. Modeling of noise parameters of MESFETs and MODFETs and their frequency and temperature dependence. *IEEE Transactions on Microwave Theory and Techniques*, 37(9):1340–1350, Sept. 1989.
Editor comment: a simple noise model of a microwave MESFET (MODFET, HEMT, etc.) is described.

[Reiha and Long, 2007] M. T. Reiha and J. R. Long. A 1.2 V reactive-feedback 3.1-10.6 GHz low-noise amplifier in 0.13 μm CMOS. *IEEE J. of Solid-State Circuits*, 42(5):1023–1033, May 2007.
Editor comment: Transformer feedback reduces the noise figure, stabilizes the gain, and sets the terminal impedances over the desired bandwidth. The LNA demonstrates 15.1 dB gain, 2.5$\pm$0.43 dB NF across the entire 3.1 to 10.6 GHz band.

[Rothe and Dahlke, 1956] H. Rothe and W. Dahlke. Theory of noisy fourpoles. *Proceedings of the IRE*, 44(6):811–818, June 1956.
Editor comment: equivalent circuits are derived for two-port networks. Noise parameters are described.

[Rothe, 1954] H. Rothe. The theory of noisy four–poles. *IEEE Transactions on Electron Devices*, 1(4):258–259, December 1954.
Editor comment: one of the first discussions of noise parameters.

[Sanghyun Woo *et al.*, 2009] Sanghyun Woo, Woonyun Kim, Chang-Ho Lee, Kyutae Lim, and J. Laskar. A 3.6mw differential common-gate CMOS LNA with positive-negative feedback. In *IEEE International Solid-State Circuits Conference*, pages 218–219,219a, 2009.
Editor comment: a differential g_m-boosted common-gate LNA with a positive-negative feedback technique. The LNA exhibits a maximum voltage gain of 21dB, a minimum NF of 2dB, an IIP3 of -3.2dBm in a 300-to-920MHz band.

[Shaeffer and Lee, 1997] D. K. Shaeffer and T. H. Lee. A 1.5-V, 1.5-GHz CMOS low noise amplifier. *IEEE J. Solid-State Circuits*, 32(5):745–759, May 1997.
Editor comment: a detailed analysis of the LNA architecture, a discussion on the effects of induced gate noise in MOS devices, and different optimization methods. A 1.5-GHz low LNA shows a gain of 22 dB and NF of 3.5 dB.

[Shim *et al.*, 2007] Y. Shim, C. Kim, J. Lee, and S. Lee. Design of full band UWB common-gate LNA. *IEEE Microwave and Wireless Components Letters*, 17(10):721–723, 2007.
Editor comment: an example of a wide-band common-gate LNA. The LNA operating form 3.1 to 10.5 GHz achieves maximum gain of 16 dB, and NF between 3.8 to 4.0 dB.

[Wedge and Rutledge, 1992] S. W. Wedge and D. B. Rutledge. Wave techniques for noise modeling and measurement. *IEEE Transactions on Microwave Theory and Techniques*, 40(11):2004–2012, November 1992.
Editor comment: a noise wave approach is applied to analysis, modeling, and measurement of two-ports.

[Xiaoyong Li *et al.*, 2005] Xiaoyong Li, S. Shekhar, and D. J. Allstot. G_m-boosted common-gate LNA and differential colpitts VCO/QVCO in 0.18-μm CMOS. *IEEE Journal of Solid-State Circuits*, 40(12):2609–2619, 2005.
Editor comment: a transformer g_m-boosted common-gate LNA, differential Colpitts voltage-controlled oscillators (VCO), and a quadrature Colpitts voltage-controlled oscillator (QVCO). G_m-boosting loosens the link between noise factor and input matching.

[Zailer *et al.*, 2020] E. Zailer, L. Belostotski, and R. Plume. Wideband LNA noise matching. *IEEE Solid-State Circuits Letters*, 3:62–65, 2020.
Editor comment: selection of transistor size and biasing that simultaneously minimize $F - F_{min}$ and reduce the sensitivity of $F - F_{min}$ to frequency. A 0.13-μm CMOS LNA exhibits gain of 10dB, NF < 2.5dB from 4 to 8 GHz.

[Zhan and Taylor, 2006] J.-H. C. Zhan and S. S. Taylor. A 5GHz resistive-feedback CMOS LNA for low-cost multi-standard applications. In *IEEE International Solid-State Circuits Conference*, pages 721–730, San Francisco, February 2006.
Editor comment: an example of a resistive-feedback broadband LNA. The 90-nm CMOS LNA achieves NF between 1.9 and 2.6 dB and a gain of 25 dB in a 0.5-to-8.2GHz band.

[Zhuo *et al.*, 2005] W. Zhuo, X. Li, S. Shekhar, S. H. K. Embabi, J. P. de Gyvez, D. J. Allstot, and E. Sanchez-Sinencio. A capacitor cross-coupled common-gate low-noise amplifier. *IEEE Transactions on Circuits and Systems II: Express Briefs*, 52(12):875–879, 2005.
Editor comment: a capacitor cross-coupled g_m-boosting scheme for a common-gate LNA. The 0.18-μm CMOS achieves NF of 3.0 dB at 6.0 GHz, IIP3 = 11.4 dBm while drawing 3.6 mA from a 1.8-V supply.