A Review on the Low Noise Amplifier for Wireless Application

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ABSTRACT

This proposal reviews the design aspects of a low noise amplifier (LNA) of a RF receiver for wireless communication. This LNA has an operating frequency range covering almost all the working bands of wireless communications standard like Bluetooth, GSM, and the third generation mobile communication. It is presented that this LNA is expected to have high linearity due to possibility of large interference signal tones that are present at the receiver end. But this LNA must have high linearity but not at the expense of sacrificing any other specification like gain and noise figure. This paper gives an idea of an LNA that will be of great convenience for multi-standard RF wireless communication.

General Terms

LNA design.

Keywords

Low-noise amplifiers, Multi-band receivers, Wideband RF circuits, RF Front-end, Communication System, noise figure (NF), Gain

1. INTRODUCTION

In the communication industry, one of the fastest growing medium is the wireless communication due to its cost effective and affordable option for connectivity. Also in recent years, satellite's role in telecommunication has been extended to provide a link to geographically distributed Local Area Networks (LANs) and Metropolitan Area Network [1].Here the main role played by wireless communication is to transfer information from one place to another between any electronic systems without the use of any connecting cable or wires. And through various research it is proved that wireless and radio frequency (RF) are closely associated with each other. This is because for efficiently transmitting the information, the wireless communication system requires a very high frequency signal. The frequency spectrum defined by RF is from a few KHz to around 1 GHz. This range can be extended up to 300GHz if this considered as the microwave frequencies as RF [2]. Table 1: Frequency Spectrum of RF

Table 1: Frequency spectrum of RF

f	λ	Band	Category
30−300Hz	$10^4 - 10^3$km	ELF	Extremely low frequency
300−3000Hz	$10^3 - 10^2$km	VF	Voice frequency
3−30kHz	100 − 10km	VLF	Very low frequency
30−300kHz	10−1km	LF	Low frequency
0.3−3MHz	1−0.1km	MF	Medium frequency
3−30MHz	100−10m	HF	High frequency
30−300MHz	10−1m	VHF	Very high frequency
300−3000MHz	100−10cm	UHF	Ultra high frequency
3−30GHz	10−1cm	SHF	Super high frequency
30−300GHz	10−1mm	EHF	Extremely high frequency

In order to transfer data rapidly, many industries like radar systems, television broadcasting, and hospitals etc. uses RF communication technology [3]. The frequency spectrum used by various communication standards in shown in table 2[4].

Table 2: Frequency spectrum allocated to various communication standards

Frequency Spectrum	Standards
800−900 MHz	AMPS
900 MHz and 1.8 GHz	GSM
1.9 GHz and 2.17 GHz	UMTS
2.4 GHz	WLAN
2.4 GHz	BLUETOOTH

Due to increasing demand for high rate application like wireless video, certain frequency spectrum ranging from around 900 MHz to 2.5 GHz get over crowded.

Because of this fact, many signals are subjected to interference which are caused by the out of channel signal. And one of the solution to overcome this problem is used of properly designed RF front end receiver which has the ability to suppress the interference signal and proceed with the desired channel of interest.

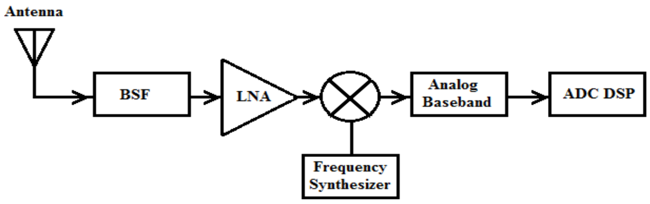


Fig. 1. RF Receiver

Proper designing of RF front end receiver also allow a circuit to have frequency characteristics that will be stable over several GHz and the impedance will be matched over a wide range of bands [5]. A typical RF receiver is shown in the fig 1 which consists of a band select filter (BSF) whose function is to suppress the out of band signals and the low noise amplifier (LNA) which amplify the weak signal [6]. The pros and cons of amplifier type used in LNA design could be put to use to find applications in different transmission requirements[7]. Hence the first block that amplifies the desired band signals without adding much noise is the LNA. The LNA is a nonlinear device that results in generation of several frequency components. This nonlinear characteristic will affect the incoming signal, thereby resulting in two issues namely Blocking and Intermodulation which will be explained in section 2 [8]. Since LNA is an indispensable component in the RF receiver, this element will be the subject of this paper. Therefore in section 3, LNA is introduced along with its parameters and is discussed for different application. And in section 4, various topologies are analyzed for designing the LNA.

2. BLOCKING AND INTERMODULATION

In the RF receiver, the incoming signal is boost by the amplifiers before the frequency conversion process take place. This step is an important requirement in the RF receiver to prevent the mixer noise from dominating the overall front end noise performance. Therefore it is required to know the major specification of RF amplifier and some of them are noise figure, gain and third order intermodulation intercept[9]. The RF amplifier i.e. LNA must have low noise figure with high gain otherwise the weak signal is manifested by the influence of a strong in band interferer which will desensitizes the circuit. And this phenomenon is called blocking and the interferer is called blocker. In order to understand this phenomenon, let's consider an input signal which is a sum of desired signal $(A_1 \cos\omega_1 t)$ and strong interfere $(A_2 \cos\omega_2 t)$. This input signal x(t)can be expressed as

$$x(t) = (A_1 \cos\omega_1 t) + (A_2 \cos\omega_2 t), A_1 \square\ A_2 \qquad (1)$$

and for a given input $x(t)$ to the LNA, the output $y(t)$ can be written as

$$y(t) = a_1 x(t) + a_2 x^2(t) + a_3 x^3(t)$$

(2)

where a_1 is the gain of the fundamental signal and a_2, a_3 are second- and third-order nonlinearities of the LNA. Then Eq. 2 can be rewritten as

$$y(t) = \left(a_1 + \frac{3}{2} a_3 A_2{}^2\right) A_1 \cos\omega_1 + 1 \qquad (3)$$

If $a_3 < 0$, blocking will occur resulting in zero output at frequency ω_1 There exists another problem called intermodulation that occurs in nonlinear circuits. In this phenomenon, the desired input signals get corrupted when the intermodulation components fall on it. These intermodulation components are created due to the circuit nonlinearities when two strong in-band interferers appear at the input [10].in order to discuss intermodulation mathematically, let's take input interferer as $x(t) = (A_1 \cos\omega_1 t) + (A_2 \cos\omega_2 t)$. Then Eq. 2 is given by

$$\begin{aligned}
y(t) &= a_1\left[(A_1 \cos\omega_1 t) + (A_2 \cos\omega_2 t)\right] \\
&+ a_2\left[(A_1 \cos\omega_1 t) + (A_2 \cos\omega_2 t)\right]^2 \\
&+ a_3\left[(A_1 \cos\omega_1 t) + (A_2 \cos\omega_2 t)\right]^3 \\
&= \left(a_1 A_1 + \frac{3}{2} a_3 A_1^3 + \frac{3}{2} a_3 A_1 A_2^2\right)\cos\omega_1 t \\
&+ \left(a_1 A_2 + \frac{3}{2} a_3 A_2^3 + \frac{3}{2} a_3 A_2 A_1^2\right)\cos\omega_2 t \\
&+ a_2 A_1 A_2 \cos(\omega_1 + \omega_2)t + a_2 A_1 A_2 \cos(\omega_1 - \omega_2)t \\
&+ \frac{3}{2} a_3 A_1^2 A_2 \cos(2\omega_1 + \omega_2) \\
&+ \frac{3}{2} a_3 A_2^2 A_1 \cos(2\omega_1 + \omega_2) \\
&+ \frac{3}{2} a_3 A_1^2 A_2 \cos(2\omega_1 - \omega_2) \\
&+ \frac{3}{2} a_3 A_2^2 A_1 \cos(2\omega_2 - \omega_1) \quad (4)
\end{aligned}$$

As shown in Eq. 4, many frequency components are generated at the output in which frequency band of interest are $(2\omega_2 - \omega_1)$ and $(2\omega_1 - \omega_2)$. Therefore here it is considered as the third order intermodulation components (IM3) that are located at $(2\omega_2 - \omega_1)$ and $(2\omega_1 - \omega_2)$, the rest can be filtered out. These intermodulated components corrupt the signal and thus plays an important role in the RF system.

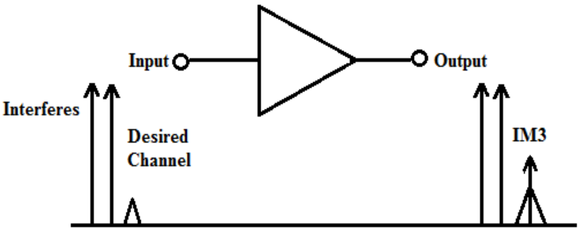


Fig. 2. IM3 Corrupted Desired Weak Channel

The nonlinearity of RF system is characterized by Input Third-order Intercept Point (IIP3) [11].for an RF system with cascaded blocks, IIP3 of the last stage will dominate the overall IIP3 of the system as they experience larger amplitude signal while noise figure. But for wireless environment, LNA must be able to suppress the interferers and provide good performance in terms of linearity and high IIP3 is desired for an LNA to be in RF receiver but not at the expense of gain and noise figure

3. LOW NOISE AMPLIFIER

The first real signal processing element just after the antenna that determine the noise performance and linearity of the overall system in a RF receiver is low noise amplifier (LNA) which makes it one of the most important and sensitive block of a RF receiver that can improve the performance of the circuit[12-14].

3.1 LNA Parameters

Noise figure, gain, bandwidth, linearity, impedance matching and power consumption are the major specifications of LNA [15-17]. Amplification of weak signal received from the antenna is the main function of the LNA in the RF receiver and then extract that signal from the undesirable environment, thereby enabling signal processing by blocks advancing down the receiver chain. The gain of the LNA is either expressed in terms of voltage or power respectively as

$$A_v = \frac{V_{out}}{V_{in}} \tag{5}$$

$$S_{21} = \frac{P_{out}}{P_{in}} \tag{6}$$

Both equations (5) and (6) are expressed in decibels. Bandwidth is a frequency range in which gain lies within the 3 dB of its peak values. In the recent years, wideband LNA is becoming more popular than its counter narrow band LNA because wideband LNA transceiver increasingly tends to be multi-standard

Noise figure (NF) of LNA is defined as the measures of degradation in the signal-to-noise ratio (SNR) that is caused by the various components in a RF signal chain. When several devices are cascaded, the overall noise figure of the system can be obtained from the Friis' Formula [18] as

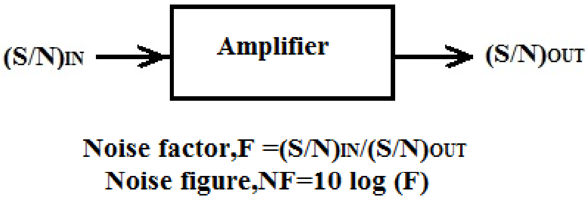


Fig. 3 Noise figure of an amplifier

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + ... + \frac{F_n - 1}{G_1 G_2 G_3 ... G_{n-1}} \tag{7}$$

Where F_n and G_n are noise figure and power gain of the n^{th} device respectively. It is clear from Eq. 7, that the1st device in the chain has the most significant impact on the overall noise figure. But the first component in the RF receiver is LNA. Therefore, the total noise of the RF receiver can be reduced only when the LNA have the lowest possible noise.

In a wireless standard, the input extends over a wide range. For example, in GSM standard, antenna received signal that lies between -110 and -20 dBm. For this reason the LNA in the RF receiver must be able to receive and process this signal simultaneously providing linear processing. But at high input power, the gain trends to saturate, as a result linearity comes into picture. Therefore, it is necessary for the LNA to be linear up to powers beyond which the highest power is likely to enter it. The power at which the gain of the LNA drops 1dB below its steady linear value is called 1dB compression point or input IP1 (dB).

A common place where possibility of having strong blocker is in the channel, next to be one which has to be processed. In GSM, the blocker as strong as -15dBm interferes with the main power tone, resulting to the generation of intermodulation products (IP3). The main effect of IP3 is that it saturates the LNA and blocks the receiver. Intermodulation measurement is carried out by applying two tones to the input such that one is desired and the other one is blocker. According to the preferred communication standard, the spacing between the two tones is defined. For example, 1MHz in Global System for mobile communication [19], 200MHz for Ultra Wideband like Bluetooth [20-22], 2MHz in Wideband Code Division Multiple Access (WCDMA) [23] and so on. An important feature of linear LNA is that it can alternate the performance of the other blocks making low power consumption [24].

In the RF receiver, LNA is placed either just after the antenna or follows a Band pass filter (BPF). So to avoid reflection of signals on the transmission line/cable, impedance matching is important [25, 26]. In general, the noise figure of the LNA is determined by input impedance matching and the linearity is affected by output impedance matching if a low output load (50Ω) is driven [27]. Trade-offs of parameters is decided depending upon the desired standard for which the LNA is designed.

3.2 LNA Specification

LNA specifications are generally divided into two parts; one is wideband LNAs and narrow-band LNAs. A narrow-band LNA must contribute top performance at that particular frequency for which stable performance over frequencies ranging several hundreds of MHz

For GSM standard, to reduce distortion and interference, the gain of the LNA is made moderate. Since linearity cannot be compromised, the noise figure is also made moderate nearly 2dB [28-31]. On the other hand, unlike GSM, in GPS (Global Positioning System) the gain and noise figure of LNA is given more priority than the linearity. For example, LNA for GPS standard, the gain and NF must be around 20 dB, respectively. And linearity is kept as secondary option [32]. Likewise, for Personal Communication Service (PCS) standard, LNA must be highly linear with moderate gain [33]. For the WCDMA standard, linearity is the most important specification where IIP3~0 dBm with power consumption less than 5mA [34]. LNA for WLAN (wireless local area network) standard can have moderate gain and noise figure with higher power consumption of nearly 10mA [35].

Some relevant LNAs for various wireless communication standards are compared in TABLE II. LNAs in the table below are presented in terms of their application, starting from CDMA to UWB standards and also in terms of their performance.

Every standard has its basic requirement other than the linearity. LNA in [37] has much higher IP1dB than GPS LNA in [32] but comparable to the PCSI900 LNA in [29] and WCDMA LNA in [24]. Highest IP1dB is observed in [19].

In terms of size, LNA in [36] and [37] has the smallest size when compared to the LNA in the literature. Power consumption is also less for LNA in [37], consuming less than 4.5mA

The most area occupying region in LNA is the impedance matching circuitry. At the same time, successful matching is achieved in very narrow bands. LNAs [22][36] and [37] almost attains good matching.

After analyzing TABLE III, it can be concluded that if the relation between gain and control current is inversed, then this will give best gain at lowest power dissipation.

Table 3: Comparison between various LNA for different communication standards

References paper	**[29]**	**[32]**	**[36]**	**[22]**	**[24]**	**[37]**
Frequency (GHz)	1.9	1.23	0–2	3–5	0.88	0–2
Applications	PCS1900	GPS	Wideband	UWB	CDMA	Wideband
Noise figure (dB)	1.8	0.8	2.4	2.3	1.2	6.8
S11 (dB)	-22	-11	Less than -10	Less than -9	-10	Less than -13
S12	Not mention	Less than -31 dB	Less than -36 dB	Less than -20 dB	Not mention	Less than -28 dB
S22 (dB)	-10	-11	Less than -8	Less than -10	-10	Less than -10
IP1 dB	-11 dBm	-24 dBm	Not mention	Not mention	Not mention	-12.5 dBm
Bandwidth F_L	1.7 GHz	1.0 GHz	0 Hz	2.0 GHz	Not mention	0 Hz
F_H	2.1 GHz	1.4 GHz	1.6 GHz	4.6 GHz		3.5 GHz
Area	1.3 mm^2	.66 mm^2	.08 mm^2	.9 mm^2	Not mention	.022 mm^2
Passives	3	8	8	9	8	0
Peak gain (dB)	15	20	13.7	9.8	16.2	0
Dissipation (mW)	25	9	35	12.6	31.2	12.6
Consumption (mA)	25	6	14	Not mention	12	4.2
Technology	.5 µmCMOS	.25 µmCMOS	.25 µmCMOS	.18 µmCMOS	.25 µmCMOS	.35 µmBiCMOS

4. LNA DESIGN METHODOLOGY

Designing the LNA of a RF receiver is the most crucial part which must satisfy two conditions. And the first condition is to match input impedance with the source impedance and the second condition is to design a LNA that must have low noise figure with high gain. There are few topologies for designing the LNA which are discussed in this section

4.1 Resistive Matching

In a resistive matching type LNA as shown in fig. 4 two resistors R_1 and R_2 are connected in parallel are connected to the input of the MOSFET.

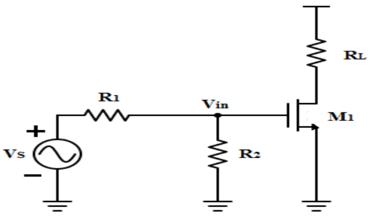


Fig 4 Resistive matching topology

From the fig. 4, it is clear that V_{in} will be half of the V_s i.e. $V_{in} = \frac{V_s}{2}$ which means poor performance since the signal power become half before entering the LNA.

And due to the presence of R_1, thermal noise is added to the input of the LNA. In such type of LNA, there will be four sources of noise and they are

Due to R_1 (source resistance) given as

$$\overline{\upsilon^2_{nR_1}} = 4KTBR_1$$

Due to R_2 (termination resistance) given as

$$\overline{\upsilon^2_{nR_2}} = 4KTBR_2$$

Due to induced drain current which is expressed as

$$\overline{i^2_{nd}} = 4KTB\gamma g_{do}$$

Due to R_L (load resistance)

$$\overline{i^2{}_{nL}} = 4KTBG_L$$

Where K, T and B are Boltzmann's constant, absolute temperature and the noise bandwidth respectively. And γ is a process parameter and g_{do} the drain-source conductance when $V_{ds} = 0$. G_L is the load transconductance.

Using the four noise sources, total output noise current of the circuit can be obtained which is given by the expression

$$\overline{i^2{}_n} = \overline{i^2{}_{nd}} + \overline{i^2{}_{nL}} + \left(\overline{v^2{}_{nR_1}} + \overline{v^2{}_{nR_2}}\right) g_m{}^2 \quad (8)$$

Also, the noise figure of a circuit is related to its noise sources by the relation as

$$Noise\ figure = \frac{Total\ Output\ Noise}{Total\ noise\ due\ to\ different\ sources} \quad (9)$$

Using Eq. 9, the noise figure of the resistive matching type LNA can be obtained as

$$F = 1 + \frac{R_2}{R_1} + \frac{\gamma}{g_m R_1} + \frac{G_L G_2}{g^2{}_m} \quad (10)$$

Equation 10 clearly explained that total noise figure for this topology will be always greater than 3dB which is not practically applicable for any LNA design.

4.2 Shunt-series feedback amplifier

Main advantage of this topology is that it does not show the problem that the previous topology has i.e. problem related to attenuation of half power before entering to the input of the actual circuit. Fig. 5shows a shunt-series feedback amplifier which consists of a feedback resistor R_f. The noise figure for such type of LNA (designed based on shunt-series feedback) is given as

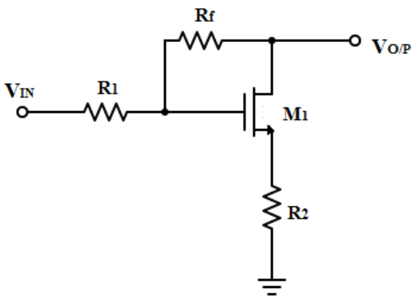


Fig. 5Shunt-series feedback topology

$$F = 1 + \frac{R_1}{R_f}\left(1 + \frac{1}{g_m R_1}\right)^2 + \frac{\gamma}{g_m R_1} \quad (11)$$

From Eq. 11 we get, for getting low noise figure, R_f and $g_m R$ must be large but the main worry is R_f generate noise. Due to this reason, this topology is also of least option for designing an LNA.

4.3 Common gate amplifier

A common gate topology is shown in fig. 6whose noise figure is obtained by taking into account the effect of drain current. The main issues with this topology is that it add noise in the shunt along with the input noise current and this is because here the drain current is introduced into the input.

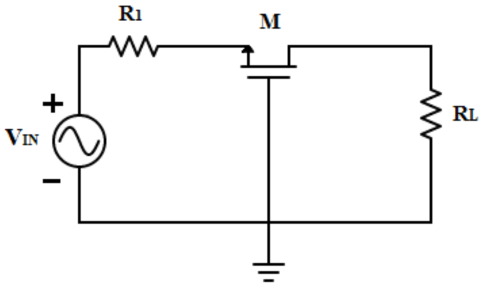


Fig. 6Common gate amplifier

Therefore by definition,

$$F = \frac{\overline{i^2{}_{ns}} + \overline{i^2{}_{nd}}}{\overline{i^2{}_{ns}}} \quad (12)$$

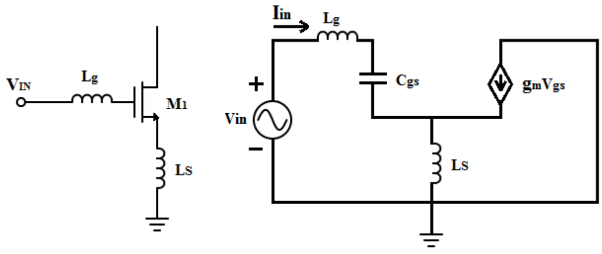
$$= 1 + \frac{4KTB\gamma g_{do}}{4KTBR_1} \quad (13)$$

$$\approx 1 + \frac{\gamma}{\alpha} \quad (14)$$

Here γ and α constants whose values are $2/3$ in saturation region and unity respectively. After putting the values of γ and α in Eq. 14, we have $F \approx 2.2dB$ and this value of F will increases for short channel devices.

4.4 Inductive source degeneration topology

One of the most widely used topology for designing LNA is inductive source degeneration because of its good noise matching technique as compared to the above three discussed topologies. Fig. 7shows an inductive source degeneration topology. The main target of this configuration is to remove the capacitive reactance at the input by adding an inductive feedback to the source so that 50Ω matching can be achieved at the input.



(a) (b)

Fig.7 (a) Inductive source degeneration topology and (b) its small signal model.

From the fig.7,

$$V_{in} = I_{in} j\omega L_g + \frac{I_{in}}{j\omega C_{gs}} + j\omega L_s\left(I_{in} + g_m V_{gs}\right) \quad (15)$$

$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{g_m L_s}{C_{gs}} + \left\{\omega\left(L_g + L_s\right) - \frac{1}{\omega C_{gs}}\right\} \quad (16)$$

In the Eq. 15, $\frac{g_m L_s}{C_{gs}}$ is the real part which is responsible for providing 50Ω at the input. Therefore to make $Z_{in} = \frac{g_m L_s}{C_{gs}}$, we must select the value of L_g such that at the resonant frequency it cancel out C_{gs} .That is

$$Z_{in} = \frac{g_m L_s}{C_{gs}} = 50\Omega \text{ when } \omega\left(L_g + L_s\right) = \frac{1}{\omega C_{gs}} \quad (17)$$

4.5 Cascode inductive source degeneration

A cascode is a two stage amplifier which is a combination of common source and common gate. And the main goal of using cascode configuration is it enhance the input –output isolation, thereby suppressing the Miller effect at the output. Other advantages of cascode over other single amplifier stage are higher gain, higher input and output impedance.

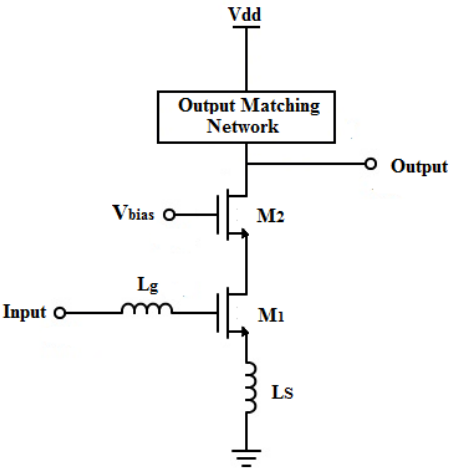


Fig. 8 cascode source inductive degeneration topology

Now we can conclude that cascode configuration is best option over other topologies. So a LNA design using cascode configuration with inductive load will provides sufficient gain without adding significant noise and also provides good stability by using cascode stage (common gate). It has also a good property it provides better matching in comparison to other topologies.

5. CONCLUSION

The main motive of this paper is to update the various state of the art of low noise amplifier used in the RF receiver for wireless communication. An exclusive review of various LNA results to the conclusion that an LNA to be in RF receiver must have five major specifications, that is, gain, linearity, impedance matching, noise figure and power consumption. Various topology for designing the LNA is also discussed here where cascode inductive source degeneration topology is the most widely used topology because provide good matching and low noise figure as compared to other topology. The LNA's specification for wireless communication is defined depending on different standard,. Most of the LNAs are narrow-band structures and this is because, wideband LNAs provide bandwidths of the order of GHz at the expense of increased noise and power consumption with moderate gain. Now we can state that to design LNA for a RF receiver, the LNA must exhibits following properties (a) competitive performance in terms of gain, noise, linearity etc. (b) small size (c) large bandwidth and (d) easy to control gain over a wide ranges.

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