Co-Design of Antenna and LNA for 1.7 - 2.7 GHz

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2012-08-13
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Upphovsrätt

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Abstract

In a radio frequency (RF) system, the front-end of a radio receiver consists of an active antenna arrangement with a conducting mode antenna along with an active circuit. This arrangement helps avoid losses and SNR degradation due to the use of a coaxial cable. The active circuit is essentially an impedance matching network and a low noise amplification (LNA) stage. The input impedance of the antenna is always different from the source impedance required to be presented at the LNA input for maximum power gain and this gives rise to undesired reflections at the antenna-LNA junction. This necessitates a matching network that provides the impedance matching between the antenna and the LNA at a central frequency (CF). From the Friis formula it is seen that the total noise figure (NF) of the system is dependent on the noise figure and gain of the first stage. So, by having an LNA that provides a high gain (typically >15 dB) which inserts minimum possible noise (desirably < 1 dB), the overall noise figure of the system can be maintained low. The LNA amplifies the signal to a suitable power level that will enable the subsequent demodulation and decoding stages to efficiently recover the original signal. The antenna and the LNA can be matched with each other in two possible ways. The first approach is the traditional method followed in RF engineering where in both the antenna and LNA are matched to 50 Ω terminations and connected to each other. In this classical method, the antenna and LNA are matched to 50 Ω at the CF and does not take into account the matching at other frequencies in the operation range. The second approach employs a co-design method to match the antenna and LNA without a matching network or with minimum possible components for matching. This is accomplished by varying one or more parameters of either the antenna or LNA to control the impedances and ultimately achieve a matching over a substantial range of frequencies instead at the CF alone. The co-design method is shown to provide higher gain and a lower NF with reduced number of components, cost and size as compared to the classical method.

The thesis work presented here is a study, design and manufacturing of an antenna-LNA module for a wide frequency range of 1.7 GHz – 2.7 GHz to explore the gain and NF improvements in the co-design approach. Planar micro strip patch antennas and GaAs E-pHEMT transistor based LNA’s are designed and the matching and co-design are simulated to test the gain and NF improvements. Furthermore, fully functional prototypes are developed with Roger R04360 substrate and the results from simulations and actual measurements are compared and discussed.
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<th>Description</th>
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<tr>
<td>ADS</td>
<td>Advanced Design System (A circuit design and simulation environment from Agilent)</td>
</tr>
<tr>
<td>CF</td>
<td>Central Frequency (The central frequency of the frequency range in consideration)</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>E-pHEMT</td>
<td>Enhancement mode pseudomorphic High Electron Mobility Transistor (A FET device with a heterojunction as the channel instead of a doped region)</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>IMN/OMN</td>
<td>Input / Output Matching Network (Matching networks used for impedance transformations)</td>
</tr>
<tr>
<td>IP3</td>
<td>Third Order Intercept Point (A low order polynomial used to model the nonlinearity of a device)</td>
</tr>
<tr>
<td>IRL/ORL</td>
<td>Input / Output Return Loss (A measure of difference between impedance at input / output and system impedance)</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution (Mobile communication standard)</td>
</tr>
<tr>
<td>NF</td>
<td>Noise Figure (A measure of a receiver's noise output)</td>
</tr>
<tr>
<td>P1dB</td>
<td>Compression Point (Power level at which gain of the device is reduced by 1 dB)</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio (The ratio of signal power to the noise)</td>
</tr>
<tr>
<td>S-Parameters</td>
<td>Scattering Parameters (Parameters describing the behaviour of linear networks)</td>
</tr>
<tr>
<td>TL</td>
<td>Transmission Line (A specialized cable designed for RF to carry alternating current)</td>
</tr>
<tr>
<td>VSWR</td>
<td>Voltage Standing Wave Ratio (The ratio of maximum and minimum standing waves)</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyzer (S-parameter measuring instrument)</td>
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1 Background

1.1 Introduction

The sensitivity of a radio receiver is high for a low overall noise figure (NF). The emphasis in the design of the front end of a radio subsystem is always maintaining a low NF while achieving the maximum possible gain. A Low-Noise Amplifier (LNA) is placed right after the antenna i.e. the conducting device, with an intention of boosting the received signal power while inserting the lowest possible noise. The total noise figure $F$ of a cascaded system is given by Friis’ formula as

$$F = F_1 + \frac{F_2-1}{G_1} + \frac{F_3-1}{G_1G_2} + \frac{F_4-1}{G_1G_2G_3} + \frac{F_5-1}{G_1G_2G_3G_4} + \ldots \quad (1.1)$$

where $F_n$ and $G_n$ are respectively the noise figure and gain of the $n^{th}$ stage. Since the LNA is the first stage and considering the rest of the stages together, the equation can be rewritten as

$$F_{overall} = F_{LNA} + \frac{F_{rest}-1}{G_{LNA}} \quad (1.2)$$

where $F_{rest}$ is the total noise figure of all the subsequent stages. This shows that the total noise figure of the system largely depends on the noise of the LNA and the gain of the LNA. A sufficiently high LNA gain (typically $>15$dB) with a low NF ($< 1$dB) makes the noise contribution from the stages after the LNA, negligible. Hence a LNA is a key component at the front end of a receiver and helps ensure efficient signal processing in the subsequent stages.

The antenna system used in a receiver is called an active antenna arrangement i.e. an antenna along with an active circuit. This arrangement helps avoid losses and SNR degradation resulting from the use of a coaxial cable. The active circuit is essentially an impedance matching network and a low noise amplification stage. The input impedance of the antenna is always different from the source impedance required to be presented at the LNA input for maximum power gain and this gives rise to undesired reflections at the antenna-LNA junction. This necessitates a matching network that provides the impedance matching between the antenna and the LNA at the central frequency (CF).

The antenna and the LNA can be matched with each other in two possible ways. The first approach is the traditional 50 Ω matching method followed in RF engineering where in both the antenna and LNA are matched to 50 Ω terminations and
1.2 Objectives

The objectives of the thesis are as follows;

1) To study the background of planar antenna and LNA design
2) To design and manufacture a planar antenna for 1.7 – 2.7 GHz frequency range
3) To design and manufacture a LNA for the same frequency range according to specifications
4) To design an antenna-LNA pair using traditional 50 Ω matching and manufacture a prototype
5) To co-design the antenna-LNA pair and manufacture a prototype
6) To verify the gain and NF improvements with simulations at layout level
7) To perform lab measurements for the antennas and the two versions of antenna-LNA pairs to evaluate the overall gain, sensitivity to fading, input and output reflection losses and isolation.

1.3 Thesis Outline

The thesis is presented starting with the background of antenna-LNA pairs in the front end of radio receivers, introducing the design of the LNA and the types of antennas used and finally the co-design principles are presented. Each design stage of the thesis has its relevant simulation results to draw conclusions from and information to build on the next stage. Finally, the prototype manufacturing, measurement methods and setups are explained with the relevant results.

Chapter 2 begins with the substrate properties and further discusses the design of various monopole antennas along with the antenna performance characteristics like antenna input impedance, input return loss and VSWR enabling to choose the right
antenna configuration for the co-design with LNA. A monopole antenna to be co-designed with the LNA is designed and presented with relevant simulations. Further, the design and impedance optimization of a monopole antenna for 50 \( \Omega \) input impedance is detailed for use in the classical antenna-LNA pair design. Both antenna prototypes are fabricated and measurements are performed.

The LNA is introduced in Chapter 3 with the specifications. The complete design procedure of choosing a suitable active device, deciding the required LNA topology and matching networks, down to the layout level simulations for the LNA is detailed out. The first LNA intended for use in the classical antenna-LNA pair is designed matched to 50 \( \Omega \) terminations with input and output matching networks and is presented along with simulation results for gain and NF.

Chapter 4 introduces the co-design methodology and the co-simulation of an electromagnetic (EM) design of antenna and circuit level design of LNA. The classical antenna-LNA pair design is simulated and the gain and NF results are studied and a prototype is manufactured. The co-design requires that the antenna and LNA be matched to each other for optimum power and noise. The input matching network (IMN) of the LNA is removed and various options are examined for matching the required LNA source impedance (\( Z_{\text{source}} \)) to the antenna input impedance. A co-designed pair is simulated to study the gain and NF improvements over that of the traditional design. Consequently, the prototype is manufactured and the lab measurements are carried out for both designs along with explanation of the measurement setups.

The final measured results are evaluated and feasible future work options are investigated.

1.4 High Frequency Design Challenges

The design of the LNA operating at high frequencies poses certain challenges. The performance of an LNA is limited to the degrees of trade-offs achievable between the parameters – Noise figure, Gain, Power, Operating frequency, Linearity and Supply Voltage. Moreover, if the LNA shows nonlinearity it gives rise to intermodulation products resulting from the presence of unwanted signals in the neighbourhood of the desired frequency band, which hampers the quality of the reception. Cost, complexity, number of components and power consumption are the other factors considered while choosing LNA architecture. The dynamic range of the LNA can be defined as the range of signals that enable acceptable quality of reception despite interference and multipath fading and is typically 100 dB for
present day wireless receivers. The minimum detectable signal today is near power levels of -100 dBm and is limited by noise. The maximum signal power that can be efficiently decoded is limited by saturation and nonlinear characteristics of the LNA. The limited spectrum allocated also poses a challenge in the receiver design. Shannon’s theorem gives the correlation between bandwidth and rate of information and hence a limited spectrum makes compression, information coding and bandwidth-efficient modulation necessary. In turn, a narrow user bandwidth will require filtering and amplification to avoid interference with adjacent bands \[23\].

An antenna that can be integrated needs to be a planar structure. A planar structure imposes design limitations and lesser flexibility in the performance parameters as input reflection, VSWR etc. The spectral efficiency of an antenna is the bandwidth relative to its central frequency and the maximum spectral efficiency that can be achieved is limited at high frequencies. Receiver sensitivity is controlled by the antenna efficiency which is the gain of the antenna relative to directivity. Moreover, the efficiency of the antenna depends on the antenna structure and substrate used. Rogers R04360 substrate is suitable for high frequency planar antennas due to its relatively low loss tangent (Tan D = 0.003).

1.5 Antenna

An antenna is a transducer that converts electromagnetic signals to electric currents and vice versa. It serves the purpose of both transmission and reception. Several antenna types exist and based upon the application requirements, an appropriate antenna is designed which in this thesis work is a planar monopole antenna.

1.5.1 Planar Monopole Antenna

These are the most commonly and widely used antennas and are one half of a dipole antenna, mostly mounted vertically above a ground plane. The wire elements of a conventional monopole are replaced by planar elements so as to increase the impedance bandwidth and are known as planar monopole antennas. Planar monopoles are vertically polarized most of the time and nearly have an omnidirectional radiation in the horizontal plane; they are advantageous in terms of low cost, ease of fabrication. They yield very large bandwidth as the antenna feed point is not balanced but single ended which exists in most of the RF circuits now a days. They exist in different geometrical shapes such as ring, circular, elliptical, diamond, square, inverted F etc. Many techniques have been investigated to tailor and optimize the impedance bandwidth of these antennas as they are becoming popular and have been proposed for future wideband wireless applications. Over a
wide range of frequencies the radiation performance is also shown to be acceptable, where the performance is dependent on the size of the ground plane. This is similar to that of a simple dipole antenna where one element is folded into the ground plane that acts as a second radiator.

1.5.2 Microstrip Antenna

A microstrip antenna comprises of copper or gold radiating patch that can be moulded into various shapes (square, ring, disk, ellipse, etc.) on one side and the ground plane on the other side of a dielectric substrate \(^2\).

**Advantages**

1) With a simple feed design, dual frequency and dual polarizations can be achieved.
2) It is possible to fabricate the feed lines and matching networks simultaneously with the antenna structure.
3) It involves less production costs to be manufactured in large quantities and can also be merged with the microwave integrated circuits.

**Limitations**

1) They can handle low powers (~ 100mW) and mostly radiate into half space.
2) High constant dielectric substrate is favoured for fabrication which in turn results in narrow bandwidth and poor efficiency.
3) To achieve high performance arrays, complex feed structures are required that may not be suitable for wideband communication systems.

1.5.3 Antenna performance characteristics

**Bandwidth**

Bandwidth is an antenna characteristic that measures the variable frequency range in which an antenna can radiate or receive energy with an acceptable VSWR (2:1 or less) by reducing the losses in unwanted directions.

The steps involved to compute antenna bandwidth are detailed;

Narrowband or Percent bandwidth is given by

\[
\% B = \left(\frac{F_h - F_l}{F_c}\right) \times 100 \, (\%) \tag{1.3}
\]

Central frequency, \(F_c\) = \(\frac{F_h + F_l}{2}\) \tag{1.4}
Broadband or Fractional bandwidth is given by the ratio

$$B = \frac{f_u}{f_l}$$  \hspace{1cm} (1.5)

If $B > 2$, the antenna is considered as a broadband antenna.

**Impedance Bandwidth / Return Loss Bandwidth**

The impedance bandwidth of an antenna changes with frequency and in turn causes the reflected power to increase; it is a measure of the antenna in terms of return loss/voltage standing wave ratio (S11/VSWR) which is matched adequately to the input transmission line, so that $\leq 10\%$ of the incident signal is lost due to reflections and depends on many factors like the type of feed used, quality factor etc. Impedance bandwidth $B$ is given by

$$B = \frac{\text{VSWR} - 1}{Q \sqrt{\text{VSWR}}}$$  \hspace{1cm} (1.6)

where $Q$ according to Chu Harrington theory is

$$Q = \frac{1 + 3(Ko R)^2}{(Ko R)^2[1 + (Ko R)^2]}$$  \hspace{1cm} (1.7)

and $R$ is the reflector radius.

**Input Reflection**

"The ratio of reflected wave to incident wave is known as the reflection coefficient"\[22\]. A portion of the wave originating from the source and incident upon the two port device ($a_1$) will be reflected ($b_1$) and another portion will be transmitted through the two port device. A fraction of the transmitted signal is then reflected from the load and becomes incident upon the output of the two port device ($a_2$).

$$b_1 = S_{11} * a_1 + S_{12} * a_2$$  \hspace{1cm} (1.8)

If $a_2 = 0$ then

$$S_{11} = \frac{b_1}{a_1}$$  \hspace{1cm} (1.9)

which indicates a reflected wave divided by an incident wave, by definition is equal to Input Reflection Coefficient.
VSWR

If a mismatch is present between the characteristic impedance of the transmission line and the impedance terminated TL then all the power is not absorbed by the termination but a part of it is reflected down the TL. The reflected and incident signal is mixed to form a voltage standing wave pattern on the TL and the ratio of maximum to minimum voltage known as VSWR is used to describe the performance of an antenna when attached to a TL.

\[
\text{VSWR} = \frac{V_{\text{max}}}{V_{\text{min}}} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{1.10}
\]

\[
\Gamma = \frac{Z_1-Z_2}{Z_1+Z_2} \tag{1.11}
\]

where \(Z_1\) and \(Z_2\) are the mismatched impedances in \(\Omega\).

An ideal case is with a VSWR of 1:1 which means that no power is reflected back to the source which is rarely seen and in practice a VSWR of 1.2:1 is considered as the best case. If VSWR is 2, nearly 10% of the power is reflected back to the source and a VSWR < 2 indicates good impedance match and based on this criteria a conclusion is made whether the antenna is matched perfectly or not.

Antenna Gain

It is the ratio of radiation intensity in a given direction to the radiation intensity of a reference antenna in a given direction. In this case the reference antenna is the isotropic radiator which is lossless and radiates its energy equally in all directions. Its units are dBi for isotropic radiator, dBd if referenced to a dipole and is expressed in terms of dB normally.

It is computed by the expression

\[
G = e_c e_d D \tag{1.12}
\]

\[
G (\text{dBi}) = 10 \times \log \left( \frac{G_{\text{numeric}}}{G_{\text{isotropic}}} \right) = 10 \times \log (G_{\text{numeric}}) \text{ as } G_{\text{isotropic}} = 1 \text{ (or 0dB)} \tag{1.13}
\]

\(e_c\) = Conduction efficiency

\(e_d\) = Dielectric efficiency

D = Directivity of antenna
Directivity

In a specific direction the antenna radiates with greater efficiency than in the other directions within the surrounding space. It is a similar aspect as that of gain but does not take into consideration the consequences of lost power (inefficiency). If the antenna is lossless then the gain and directivity will be the same.

Radiation pattern or Antenna pattern

It is the graphical gain representation of the radiation properties of an antenna in all directions as a function of space. It is represented in 2D and 3D forms and the antenna patterns are plotted as “azimuth” in reference to horizontal and “elevation” in reference to vertical patterns and are known as “principal plane patterns”. The x-y plane represents azimuth plane (θ =90°) and the elevation plane or y-z plane (φ = 90°).

On viewing this pattern one can get an understanding of how the antenna radiates in various directions.

Lobes

The regions of a pattern where the gain has local maxima are called lobes.[10] They are represented in patterns of Polar and Cartesian (rectangular) coordinate form and the various lobes are self-explanatory from the Figure 1.1. If the gain of an antenna is given as a single value then it is considered to be the main lobe or main beam gain.

3-dB beamwidth

The angular measure between the points in the main lobe either in vertical or horizontal plane pattern where the gain is 3dB lesser than the maximum gain is the 3 dB beamwidth of an antenna.
Fading

Fading is the attenuation caused in the amplitude or relative phase with time at the receiver side for one or more frequency components of the signal.

**Slow Fading or Shadowing:** This type of fading occurs due to variation in the moving or constant obstacles in and around the receiver end.

**Multipath Fading:** Within the channels multipath structure, the transmitted channel special characteristics are preserved at the receiver. The received signal strength changes with time as the gain of the channel is prone to fluctuations caused by multipath.

### 1.6 Low-Noise Amplifier

Noise figure is an important design consideration for an RF or microwave amplifier besides gain and stability. Often in receiver applications it is important to have a preamplifier with as low a noise figure and high a gain as possible since the first stage of a receiver front end has the dominant effect on the noise performance of the whole system, as seen in section 1.1. Though it’s desired to have both minimum noise figure and maximum gain, generally it is not possible and hence there exists a compromise between the achievable gain and lowest NF.

![Figure 1.2: Basic microwave LNA diagram](image)

A good LNA is by and large expected to provide a high amplification. For this reason, the active device in the LNA is a pseudomorphic High Electron Mobility Transistor (pHEMT) biased for the right drain current, $I_{DS}$ and drain voltage, $V_{DS}$ as specified in the manufacturer datasheet and is achieved by a passive dc bias network, usually a resistor network. It is important to select the correct dc operating point and proper dc bias network topology to obtain optimum performance.
Figure 1.2 shows the diagram of a basic microwave amplifier \[^1\]. The input matching network (IMN) transforms the generator impedance $Z_1$ (usually 50 $\Omega$) to the source impedance $Z_{\text{source}}$ (i.e. source reflection coefficient $\Gamma_{\text{source}}$). The output matching network (OMN) transforms the terminating impedance $Z_2$ (usually 50 $\Omega$) to the load impedance $Z_{\text{load}}$ (i.e. load reflection coefficient $\Gamma_{\text{load}}$). The reflection coefficients $\Gamma_{\text{source}}$, $\Gamma_{\text{load}}$ and S-parameters of the transistor determine the transducer power gain, operating power gain and available power gain of the amplifier \[^1\].

**Stability of the LNA:** The stability of a LNA is its resistance to oscillate and is a function of the LNA S-parameters, matching networks and terminations at source and load. In a two port network oscillations occur when either the input or output port represents a negative resistance i.e. if $|S_{11}| > 1$, the transistor presents a negative resistance at the input and if $|S_{22}| > 1$, the transistor presents a negative resistance at the output. A two port network is said to be unconditionally stable at a given frequency if the real parts of $Z_{\text{in LNA}}$ and $Z_{\text{out}}$ are greater than zero for all passive source and load impedances. If a two port network is not unconditionally stable, it is potentially unstable. That is, some passive source and load terminations can produce input and output impedances with a negative real part \[^1\].

The necessary and sufficient conditions for a two port network to be unconditionally stable are

$$K > 1 \quad (1.14)$$

and

$$|\Delta| < 1 \quad (1.15)$$

where the stability factor $K$ is given by

$$K = \frac{(1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2)}{2|S_{12}S_{21}|} \quad (1.16)$$

and

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \quad (1.17)$$

Microwave transistors produced by manufacturers are either unconditionally stable or potentially unstable with $K < 1$ and $|\Delta| < 1$. Such a potentially unstable transistor can be made unconditionally stable by resistively loading the transistor. A stabilising resistor at the drain of the transistor will be used in this thesis to achieve unconditional stability of the LNA \[^1\].
2 Monopole Antenna

2.1 Substrate and Antenna Specifications

2.1.1 Substrate Specifications

The initial step in the design process is the selection of an appropriate substrate and it depends on the target application. Various parameters are to be considered while choosing a substrate like dielectric constant, loss tangent, thickness etc. The application has the restriction of compact size and was met by choosing a substrate with high dielectric constant as these physical parameters are inversely related. The substrate consists of two conductor (cond) layers for the antenna design as shown in Figure 2.1 in which “cond” is employed for the feed line, antenna patch and LNA whereas “cond2” is employed for the ground plane of the antenna and LNA. The substrate utilized is ROGERS “RO4360” and is chosen based on various properties better than the predecessors from ROGERS [21].

![Figure 2.1: Rogers RO4360](image)

The RO4360 has greater dielectric constant than its predecessor RO4350B and the conductor layer is copper in both the cases. The thickness is almost half of RO4350B and is preferred for the current application. The properties can be seen in Table 2.1.

<table>
<thead>
<tr>
<th>RO4360</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric constant</td>
<td>6.15</td>
</tr>
<tr>
<td>Loss Tangent @ 2GHz</td>
<td>0.003</td>
</tr>
<tr>
<td>Substrate Thickness</td>
<td>0.305 mm</td>
</tr>
<tr>
<td>Copper Thickness</td>
<td>18 μm</td>
</tr>
<tr>
<td>Copper Conductivity</td>
<td>$5.8 \times 10^7$ S/m</td>
</tr>
</tbody>
</table>

Table 2.1: RO4360 substrate properties
2.1.2 Monopole antenna requirement specifications

The antenna requirement specifications are given in Table 2.2.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>1.7 – 2.7 GHz</td>
</tr>
<tr>
<td>Central Frequency</td>
<td>2.2 GHz</td>
</tr>
<tr>
<td>Characteristic Impedance</td>
<td>50 Ω</td>
</tr>
<tr>
<td>Input reflection</td>
<td>&lt; -10 dB</td>
</tr>
<tr>
<td>VSWR</td>
<td>&lt; 2</td>
</tr>
</tbody>
</table>

Table 2.2: Requirement specifications of a monopole antenna

2.2 Design of Monopole Antennas

The design process of an inverted F antenna and a square monopole antenna are discussed in this section.

2.2.1 Inverted F Antenna

The improved version of a monopole antenna is an inverted F antenna that can be thought of as a tilted whip, the antenna is tapped at the appropriate impedance point along its width to obtain the impedance matching. It has few advantages like compact size, reduction in backward radiation and good efficiency.

Figure 2.2: Layout and current distribution of an Inverted F antenna

To obtain good efficiency an appropriate ground plane is required as the currents in the ground leg will be high. The ground plane considered is of width 80 mm, length 50 mm and it has variable lengths, widths for various arms, feed and planar patch are shown in Figure 2.2 along with current distribution. It can be seen that less current is
flowing in the ground plane and high current distribution is flowing through the feed probe and the upper arm of the antenna. The simulated results in Figure 2.3 shows that VSWR < 2 in the 2.1 - 2.4 GHz range, the input reflection is around -25 dB as it is designed in a way that it resonates at the central frequency. Due to the narrow bandwidth limitation, various feeding techniques and tailoring methods are tried so as to increase the bandwidth. The desired VSWR and input reflection throughout the frequency range couldn’t be achieved upon employing these methods.

![Figure 2.3: Layout and current distribution of an Inverted F antenna](image)

The radiation pattern in Figure 2.4 consists of a main lobe and side lobes that show how it radiates in space.

![Figure 2.4: Far field Radiation Pattern of an Inverted F antenna](image)
2.2 Design of Monopole Antennas

2.2.2 50 Ω Square Monopole Antenna

The wire element of a conventional monopole is replaced by a planar element which is a square radiator in this case as seen in Figure 2.5. The band coverage of 50 Ω antenna when compared with the inverted F antenna shows good improvements in terms of VSWR and input reflection and matches the thesis requirements. The radiating element dimensions $L$ sets the bandwidth of the antenna and a suitable feed gap separation $g$ is required to acquire maximum impedance.

![Figure 2.5: Square Planar Monopole antenna](image)

$L_1, L_2$ → Lengths of radiating element  
$g$ → Feed gap  
$d$ → Diameter of the probe  
$h$ → Length of the probe

**Effect of feed gap ‘g’, diameter ‘d’ and length ‘h’ of the feeding probe**

1) The feed gap ‘g’ between the radiator and ground plane plays a major role in the design of the square monopole antenna. Optimization in feed gap value alters the lower frequency range.

2) The diameter ‘d’ value is considered as per the line calculator value and when it’s increased, the upper frequency value decreases which might not produce the desired results.

3) Length of the probe ‘h’ is altered and can be viewed under various design steps below; a drop in input reflection can be seen as well as the lower frequency value depends on it.
**Ground plane effects on square monopole antenna**

A common problem which occurs in monopole antennas is the performance degrading due to the ground plane; large ground plane covers more band and provides less input reflection. The size of the main radiator decreases than the usual. After observation, the maximum bandwidth occurred when the ground plane size is 50 * 80 mm.

**Design calculations**

The length of the radiating planar element is designed using the lower frequency limit of 1.7 GHz, where L, r are the length and radius of the square radiator, F is resonant frequency, p is probe length and k is correction factor where L, r, p are in cm.

\[
 f_l = \frac{7.2}{(L+r+p) \times k} \quad (2.1) \\
 L = 0.24 F \lambda \quad (2.2) \\
 F = \frac{\left(\frac{L}{p}\right)}{\left(1+\frac{F}{\lambda}\right)} \quad (2.3) \\
 r = \frac{L}{2\pi} \quad (2.4)
\]

The lengths and widths of the feed line for a characteristic impedance of 50 Ω quarter wave transmission line are calculated using the line calculator available in Agilent ADS tool. The designed ground plane is large in this case of length 50 mm and width 80 mm; it reduced the size of the main radiator and the integration of antenna-LNA pair was fabricated on the same ground plane. The optimum feed gap between the radiator and the ground plane varies between 1.9 – 2.5 mm for various designs shown in Figure 2. 6

![Images](a)(b)
2.2 Design of Monopole Antennas

Figure 2.6: Square monopole antenna design steps (a) Main radiator (b) Varied main radiator size (c) Increased main radiator width and decreased probe length (d) Decreased main radiator length and increased probe length (e) Decreased probe length, square main radiator (f) Beveled main radiator with increased length (g) Beveled square monopole antenna.
Table 2.3 shows various lengths of the radiator, diameter, length of the probe and feed gap used for various designs in

Table 2.3: Various length of the radiating element, feed gap, diameter and length of the feeding probe.

<table>
<thead>
<tr>
<th>Design</th>
<th>$L_1$ (mm)</th>
<th>$L_2$ (mm)</th>
<th>g (mm)</th>
<th>h (mm)</th>
<th>d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>16</td>
<td>17.1</td>
<td>2.43</td>
<td>25</td>
<td>0.46</td>
</tr>
<tr>
<td>b</td>
<td>14.47</td>
<td>28</td>
<td>2.42</td>
<td>25</td>
<td>0.46</td>
</tr>
<tr>
<td>c</td>
<td>14.47</td>
<td>28</td>
<td>2.5</td>
<td>16.57</td>
<td>0.46</td>
</tr>
<tr>
<td>d</td>
<td>17.43</td>
<td>28</td>
<td>2.5</td>
<td>25</td>
<td>0.46</td>
</tr>
<tr>
<td>e</td>
<td>19.38</td>
<td>28</td>
<td>2.5</td>
<td>22.66</td>
<td>0.46</td>
</tr>
<tr>
<td>f</td>
<td>16.50</td>
<td>25</td>
<td>1.93</td>
<td>22.66</td>
<td>0.46</td>
</tr>
<tr>
<td>g</td>
<td>17.45</td>
<td>27</td>
<td>2.5</td>
<td>22.16</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Figure 2. 6: Square monopole antenna design steps (a) Main radiator (b) Varied main radiator size (c) Increased main radiator width and decreased probe length (d) Decreased main radiator length and increased probe length (e) Decreased probe length, square main radiator (f) beveled main radiator with increased length (g) beveled square monopole antenna.

shows the step by step design process upon tailoring of square radiator, feed line, and feed gap. Figure 2.7 shows how input reflection varies w.r.t. the designs (a) antenna operating in the range of 1.7-2.7 GHz with input reflection < -10dB and VSWR < 2 at 2.2 -2.5 GHz. (b) covers the whole band but the input reflection is in the range of -6dB to -9dB that is acceptable upto a mark but the VSWR >2 (c) the feed gap, main radiator and the length of the feed line is tailored so as to see how it effects the Input Reflection, VSWR. A drop is observed at 1.8 GHZ which is around -7dB but the VSWR >3. (d) the placement of the radiator on the ground plane is varied which gives an Input Reflection < -10dB and VSWR > 2 in the 1.8 – 2.5 GHz band. (e) the main radiator was tailored accordingly to make it in the shape of the square that resulted an improvement in the input reflection and VSWR which covered the entire band but there was some deviation from the prerequisites. (f) beveling technique was applied to the antenna, so as to match it with the requirements. In relation with the placement of the antenna and size but could not acquire the band coverage as expected. (g) The final design matched with the desired requirements upon minor
changes in lengths of the radiator and placement of the feed gap, the Input Reflection < -10 dB and the VSWR is in the range < 2 throughout the band requirement.

Figure 2.7: Input reflection comparison of various designed antennas (a – g)

Figure 2.8 shows the current distribution taking place among the 50 Ω square monopole antenna at 1.7-2.7 GHz. It can be seen that more current is flowing through the probe into the main radiator. The radiation pattern shows how the antenna radiates energy to and fro from the space.
Chapter 2 Monopole Antenna

The designed 50 Ω square monopole antenna has an impedance of 39 Ω. It is calculated using the equation 2.5, the plot of impedance against frequency can be viewed in Figure 2.9

\[ Z_{in} = Z_0 \left( \frac{1 + S(1,1)}{1 - S(1,1)} \right) \]  

(2.5)

![Impedance plot for 50 Ω square monopole antenna](image)

Figure 2.9: Impedance plot for 50 Ω square monopole antenna

2.2.3 Impedance Matched 50 Ω Square Monopole Antenna

![Impedance matched square monopole antenna](image)

Figure 2.10: 50 Ω impedance matched square monopole antenna with impedance plot.

The designed antennas in Figure 2.6 are the 50 Ω square monopole antennas. The antenna in Figure 2.10 is the impedance matched 50 Ω square monopole, that is designed upon tailoring the ground plane width by 2 mm, radiator length \( L_1 \) to 16.5 mm, \( L_2 \) is altered to 25 mm. Feed gap is reduced to 1.93 mm and the length of the probe to 22.66 mm which resulted an impedance of 50 Ω with an imaginary part as it’s hard to get an ideal 50 Ω match. The impedance plot is calculated using the equation 2.5 and is plotted in Figure 2.10. As the main aim of the thesis is to make a comparison between the integrated classical design and the co-designed approach,
the 50 Ω square monopole antenna and the impedance matched 50 Ω square monopole are designed.

![Graphs showing Input Reflection and VSWR](image)

**Figure 2.11:** Input Reflection and VSWR for a 50 Ω impedance matched antenna.

The input reflection is within the desired frequency band, in the range <-10 dB and can be seen in Figure 2.11. The VSWR is in an acceptable range i.e., below 2 throughout the frequency band, the antenna designs can be used for the integrated design upon consideration of the simulated results.

### 2.2.4 Measured Results

The prototypes are fabricated at the ITN department PCB lab under the supervision of Magnus Karlsson and Gustav Knutson, Linkoping University.

**50 Ω square monopole antenna**

The Figure 2.12 shows the front view of a large radiator along with the feed line whereas the rear view shows how the ground plane is mounted to the feed line with the help of a SMA connector.

![Prototype images](image)

**Figure 2.12:** Front and rear view of the 50 Ω antenna prototype.
The antenna in Figure 2.6 (g) results in VSWR < 2 and input reflection < -10 dB, whereas the measured antenna prototype results show some deviation from the simulated results illustrated in Figure 2.13. Within 1.4 – 2.3 GHz range the prototype performs better than the simulated results and 2.3 – 3.0 GHz band performs well in the simulation environment. The measured input reflection is below -10 dB within the whole band and can be utilized to integrate it with the classical antenna – LNA pair.

Figure 2.13: VSWR and Input Reflection of the 50 Ω antenna prototype.

**Impedance matched 50 Ω square monopole antenna**

The front and rear view of the impedance matched 50 Ohm antenna with a small radiator and increased feed line can be seen in the Figure 2.14, mounted to the ground plane with an SMA connector.

Figure 2.14: Front and rear view of the Impedance matched antenna prototype.

The prototype VSWR results shown in Figure 2.15 match with the prerequisites, within the lower band of 1.7 – 1.98 GHz, VSWR > 2 which means that more power is reflected from the antenna than expected. Practically a VSWR of 3 is accepted in real time applications, so this might not cause any major problems for the integrated
The measured prototype results within the 2.1 – 2.8 GHz band show improvement than the simulated results.

The measured prototype results of the antenna with small radiator shows improvement in input reflection when compared with the simulated results within the range 2.1 – 2.7 GHz. The 1.7 – 1.98 GHz band has an input reflection < -10 dB and VSWR > 2 that do not match with the requirement specifications. The peaks and drop outs in the measured results observed are due to imperfections caused in fabrication, soldering process.
3 Low-Noise Amplifier

3.1 LNA Specifications

The LNA is designed for maximum gain and minimum NF while maintaining gain linearity, gain flatness and stability. The following specifications are applicable to the co-designed antenna-LNA pair as well. Table 3.1 shows the specifications of the LNA presented.

<table>
<thead>
<tr>
<th>LNA parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency range</td>
<td>1.7 – 2.7 GHz</td>
</tr>
<tr>
<td>Noise figure</td>
<td>&lt; 1 dB</td>
</tr>
<tr>
<td>Gain</td>
<td>&gt; 10 dB</td>
</tr>
<tr>
<td>OIP3</td>
<td>&gt; +20 dBm</td>
</tr>
<tr>
<td>P1dB</td>
<td>&gt; +15 dBm</td>
</tr>
<tr>
<td>Input return loss</td>
<td>&gt;15 dB</td>
</tr>
<tr>
<td>Output return loss</td>
<td>&gt;15 dB</td>
</tr>
<tr>
<td>Stability factor</td>
<td>&gt;1</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>5 V</td>
</tr>
</tbody>
</table>

Table 3.1: LNA specifications

The LNA is designed to be unconditionally stable as explained in section 1.5. The other important figures of merit for the LNA are good input and output impedance matching, isolation between input and output and low power consumption.

3.2 Selection of Active Device

The active device is selected based on the specifications. Avago Technologies’ ATF58143 microwave transistor’s datasheet provides the following electrical specifications at 2 GHz, VDS = 3 V, IDS = 30 mA;

- 16.5 dB associated gain
- 0.5 dB noise figure
- 19 dBm P1dB
- 30.5 dBm OIP3

ATF58143 is an enhancement mode PHEMT having a very low noise figure (typically 0.6 dB), high dynamic range and high gain with high linearity, suitable for wireless applications in 450 MHz to 6 GHz frequency range, housed in a 4-lead surface mount plastic package. Moreover, an enhancement mode device requires only a single positive bias (Gate voltage VGS) and eliminates the need for the negative gate voltage
3.3 Bias Point Selection

associated with depletion mode devices. This feature simplifies the bias network and enables overall LNA design to be compact \cite{24}.

The manufacturer provides both the electrical model of the transistor and the S-parameter files (.S2P files) for different bias points in Touchstone format. The S-parameter files can be used in ADS simulations for impedance matching, gain and noise calculations. However, for low frequency simulations (DC simulation for bias point) the electrical model of the transistor is most suited. The electrical model of ATF58143 transistor is shown in Figure 3.1.

![ATF58143 ADS Model](image)

Figure 3.1: Low frequency electrical model of ATF58143

So the next task is to bias the transistor referring the characterization data from the datasheet, according to best possible NF-gain combinations. Since the central frequency of the design is 2.2 GHz, noise figure and gain data specified at that frequency is considered to select the suitable bias point.

### 3.3 Bias Point Selection

As can be seen in Table 3.2, from the datasheet the bias point of \( V_{DS} = 3 \) V, \( I_{DS} = 30 \) mA provides a noise figure \( F_{\text{min}} = 0.45 \) dB and associated gain \( G_a = 17.33 \) dB at 2 GHz. Since these figures were desirable than those with other bias points, this bias point is chosen.

![Table 3.2: ATF58143 parameters for 3V, 3 mA bias](image)

Table 3.2: ATF58143 parameters for 3V, 3 mA bias \cite{24}
To maintain a drain current of $I_{DS} = 30$ mA with a drain to source voltage of $V_{DS} = 3$ V, the appropriate gate voltage $V_{GS}$ has to be determined.

Figure 3.2: $V_{DS}$ vs. $I_{DS}$ for different $V_{GS}$ values

By performing a DC simulation of the transistor with sweeping $V_{DS}$ for different $V_{GS}$ values, the bias point curves as shown in Figure 3.2 are obtained and it is seen that $V_{GS} = 515$ mV will hold the transistor in the desired bias point specified for optimum gain and noise figure.

### 3.4 Bias Network Design

A resistive passive bias network is designed to maintain the bias point of $V_{DS} = 3$ V, $I_{DS} = 30$ mA and $V_{GS} = 515$ mV with a $V_{DD} = 5$ V supply, as shown in Figure 3.3. The four resistor values are calculated using applying KVL in the bias network.

\[
R_1 = \frac{V_{GS}}{I_{BB}} \quad (3.1)
\]

\[
R_2 = \frac{(V_{DS} - V_{GS}) \times R_1}{V_{GS}} \quad (3.2)
\]

\[
R_3 = \frac{V_{DD} - V_{DS}}{I_{DS} + I_{BB}} \quad (3.3)
\]

\[
R_4 = \frac{V_{GS}}{I_{GS}} \quad (3.4)
\]

where $I_{BB}$ is the current through $R_1/R_2$ voltage divider network and is chosen to be ten times the expected gate leakage current. $I_{BB}$ is chosen as 400 µA. $I_{GS}$ is the maximum gate current and is obtained from ATF-58143 transistor datasheet as 0.2 mA. Hence
the resistor values are obtained as $R_1 = 1.275 \, k\Omega$, $R_2 = 6.975 \, k\Omega$, $R_3 = 56 \, k\Omega$ and $R_4 = 2.6 \, k\Omega$. The DC values are annotated in order to verify the currents and voltages.

With ideal components and non-standard resistor values, a bias point of $V_{DS} = 3.3 \, V$, $I_{DS} = 29.7 \, mA$ and $V_{GS} = 512 \, mV$ is resulted. Though these component values will be replaced by real components in the final layout level simulations, the values provide an indication of required real component values. The DC Feed and DC Block components ensure that the RF signals and DC voltages of the LNA do not interfere.

### 3.5 Matching Networks

A simple S-parameter simulation of the transistor will provide indicators to the $Z_{\text{opt}}$, $Z_{\text{source}}$ and $Z_{\text{load}}$ values with 50 $\Omega$ terminations. The matching networks that translate these impedances to 50 $\Omega$ are designed using the Smith chart tool in ADS, with lumped L and C components. Since the matching networks also need to serve the purpose of DC block, the design is carried out with an intention of having a series capacitor element close to the transistor. A LNA is distinguished from an ordinary RF power amplifier by the fact that the matching is primarily done for a lower NF. However, since a LNA with high gain is preferred, a trade off between NF and power gain is inevitable and hence a source impedance in between $Z_{\text{opt}}$ and $Z_{\text{source}}$ is chosen and the L-C network is designed as shown in Figure 3.4. The $Z_{\text{opt}}$ and $Z_{\text{source}}$ values at the CF of 2.2 GHz are determined as $33.9+j14.95 \, \Omega$ and $17.9+j0.65 \, \Omega$ respectively. An impedance is chosen in between as $25+j7 \, \Omega$. 
A similar procedure is repeated for the OMN for a $Z_{\text{load}}$ value of 66.4-j14.45Ω. The L-C networks thus designed at 2.2 GHz are used in the schematic shown in Figure 3.5 to verify the matching at the central frequency.

For NF matching the $Z_{\text{opt}}$ impedance must be used in the design of the IMN and the conjugate match $Z_{\text{load}}$ if source impedance is $Z_{\text{opt}}$, must be used to design the OMN. However, in the LNA matching, a source impedance in between $Z_{\text{opt}}$ and $Z_{\text{source}}$ is (as a trade-off between NF and power gain) used for the design of IMN. The $Z_{\text{load}}$ specified for gain matching and the $Z_{\text{load}}$ for conjugate match for NF, was observed to be almost equal and hence was used in the design of the OMN.

**Determining the value of stabilising capacitor $C_{\text{stab}}$**

The LNA stability is achieved by $R_{\text{stab}}$ resistor loading. The drawback is that a high $R_{\text{stab}}$ value causes a significant drop in the LNA gain. Hence, to stabilise the LNA without sacrificing the gain, a stabilizing capacitor $C_{\text{stab}}$ is used at the drain as can be seen in Figure 3.5. The value of $C_{\text{stab}}$ is determined by sweeping its value from 0.2 pF to 1.6 pF while maintaining a constant $R_{\text{stab}}$ value of 6.8 Ω. As shown in Figure 3.6, the LNA is stable with sufficient gain, at an optimum value for $C_{\text{stab}}$ chosen as 1 pF.
3.6 LNA topology and configuration

The LNA is implemented in a common source topology with a passive bias using a resistor network comprising of R1, R2, R3 and R4. The capacitors C3, C4, C5 and C6 provide bias stability. Instead of using radial stubs with quarter wavelength lines to isolate the RF signal from the bias network, two inductors L2 and L3 are used as RF chokes or DC feed. L-C networks are used as IMN (Capacitors C1 and C2 with inductor L1) and OMN (Capacitors C7 and C8 with inductor L4) which match the LNA impedances to 50 Ω terminations at source and load. The capacitors C2 and C7 have the added function of DC blocking so that the bias network is isolated from the RF section of the LNA. The LNA is designed to be unconditionally stable using the resistor $R_{stab}$ and a capacitor $C_{stab}$ at the transistor drain. The complete LNA using ATF58143 transistor and a 5 V supply is shown in Figure 3.7.

![Figure 3.6: Dependence of LNA stability on $C_{stab}$ capacitor](image)

**3.6 LNA topology and configuration**

![Figure 3.7: ATF58143 LNA with passive bias and matching networks](image)
Table 3.3 gives the component values for the LNA based on the circuit in Fig 3.4.

<table>
<thead>
<tr>
<th>Transistor</th>
<th>Resistor</th>
<th>Capacitor</th>
<th>Inductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATF58143</td>
<td>R1</td>
<td>C1</td>
<td>L1</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>C2</td>
<td>L2</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>C3</td>
<td>L3</td>
</tr>
<tr>
<td></td>
<td>R4</td>
<td>C4</td>
<td>L4</td>
</tr>
<tr>
<td></td>
<td>Rstab</td>
<td>C5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C8</td>
<td></td>
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Table 3.3: LNA component values

3.7 Complete LNA on Layout Level

The layout of the 50 Ω LNA as shown in Figure 3.8: 50 LNA board layout

is designed in ADS Momentum with substrate definitions for R04360 substrate as given in Table 2.1. The layout component is created by simulating the layout with a mesh density of 30 CpW for the ‘cond’ layer (used for the RF signal sections) and 15 CpW for pc1 layer (used for ground).
3.8 Simulation Results

The layout component generated from ADS Momentum simulation as shown in Figure 3.8: 50 LNA board layout

is populated with real components (with parasitics), S-parameter model of the transistor, terminations and supply voltage of 5 V. The 50 Ω matched LNA simulation is performed in ADS for the frequency range 1.4 GHz to 3 GHz using the S-parameters simulations Design Guide for amplifiers. One of the most important performance parameters of a LNA is its stability. As discussed in section 1.5, stability factor $K$ indicates the unconditional stability. The simulated $K$ values for the LNA are shown in Figure 3.9. The stability factor is $K = 1.091$ at 1.7 GHz and higher for the rest of the range of frequencies. Hence the LNA can be assumed to operate without oscillations as long as the terminations are 50 Ω.

Any other source or load impedances that can be used without oscillations are determined using the source and load reflection coefficients from the source and load stability circles presented by the simulation agent.

![Figure 3.9: Stability factor of the LNA](image)

Figure 3.10: Simulated gain and noise figure of the 50 Ω matched LNA shows the simulated power gain and noise figure for the LNA. The gain ranges from 16.74 dB to 11.38 dB and the NF is well below 1 dB for the 1.7 GHz to 2.7 GHz frequency range.
Figure 3.10: Simulated gain and noise figure of the 50 Ω matched LNA

Figure 3.11: Simulated input and output return loss of the 50 matched LNA

As observed from the input and output reflection plots in Figure 3.11, the LNA has acceptable matching around the central frequency.

Figure 3.12: LNA S11 on Smith chart

It is interesting to note the LNA $S_{11}$ on a Smith chart as shown in Figure 3.12, since the 50Ω matched LNA is used for the design of the classical antenna-LNA pair as will
be described in section 4.2. Later, the IMN of the LNA is removed to investigate the possibilities of co-design with antenna. This is accomplished by plotting the antenna $S_{11}$ and LNA $S_{11}$ and using a microstrip line of tuneable width and length while observing the matching between the both $S_{11}$, to obtain gain and NF improvements and is detailed out in section 4.3.
4 Co-Design of Antenna and LNA

4.1 Co-Design Methodology

In common RF engineering practice, LNA designers and antenna designers work independently. The link between antenna and the LNA is the conventional characteristic impedance in RF systems, 50 $\Omega$ in communication applications and 75 $\Omega$ in TV signal systems \[18\]. Figure 4.1 shows the traditional method of 50 $\Omega$ matching between the antenna and LNA at a particular frequency. As discussed in section 1.5, the matching network IMN$_{LNA}$ transforms the $Z_{\text{source}}$ of the LNA to 50 $\Omega$. Similarly the antenna matching network IMN$_{\text{ant}}$ transforms the input impedance of the antenna ($Z_{\text{in ant}}$) to 50 $\Omega$ impedance. This matching eliminates unwanted reflections at the antenna-LNA junction and reduces loss of power transferred to the LNA, at the matching frequency.

![Traditional antenna-LNA matching](image)

The drawback of the 50 $\Omega$ matching approach is that when a wider frequency band of operation is desired, this approach is unlikely to attain simultaneous noise and gain matching throughout the entire band. The concept of co-design can be utilized to achieve a wider range of matching between the antenna and the LNA, to a greater extent than by the 50 $\Omega$ matching technique.

The basic idea of having matching networks for the antenna and the LNA is to have the input impedance of the antenna ($Z_{\text{in ant}}$) equal to the $Z_{\text{source}}$ of the LNA which ensures a VSWR of 1:1 at the antenna – LNA junction and thereby maximum power transfer. It is known that $Z_{\text{in ant}}$ is a function of the antenna $S_{11}$ ($S_{11}^{\text{ant}}$) and $Z_{\text{source}}$ of the LNA is a function of $S_{11}$ of the LNA ($S_{11}^{\text{LNA}}$). Hence the essential condition for optimum power matching is;
Similarly, a zero reflection matching between $Z_{\text{ant}}$ and optimum impedance of the LNA ($Z_{\text{opt}}$) ensures the best noise matching for minimum noise figure. This implies that the condition for noise matching is:

$$S_{11}^{\text{ant}} = S_{11}^{\text{LNA}}$$

(4.1)

Considering an example for illustration, a plot of $S_{11}^{\text{ant}}$ and $S_{11}^{\text{LNA}}$ for the 50 $\Omega$ matching technique produces a result as shown in Figure 4.2. In the example, for a frequency range of 1.7 GHz to 2.7 GHz, it can be noted that both the impedances are equal to 50 $\Omega$ at a selected frequency, the central frequency 2.2 GHz.

![Figure 4.2: 50 $\Omega$ matching technique example at 2.2 GHz](image)

This example is only for illustration of the concept and is rarely realised in practice because it is extremely difficult to have a purely resistive impedance of 50 $\Omega$ at any frequencies. As a result, the point marked by the arrow on the Smith chart in Figure 4.2 rarely occurs in the centre of the Smith chart in practical cases. As can be seen in Figure 4.2, the 50 $\Omega$ matching plot has poor matching at other frequencies other than the CF. As a consequence, this method is suitable only for a fixed frequency of operation or a narrow band. To achieve better matching throughout the entire range of frequencies the concept of co-design can be implemented. Though exact matching of impedances might not be always possible, a uniform matching between the impedances will result in better gain (or NF, depending on whether $S_{11}^{\text{LNA}}$ or $S_{\text{opt}}^{\text{LNA}}$ is being matched) for the entire frequency range on consideration.
Co-design is performed by removing the input matching networks of the antenna and the LNA as shown in Figure 4.3. A microstrip line of proper length and width replaces the IMN_{LNA} and changes Z_{source} of the LNA in such a way as S_{11}^{LNA} is as close to S_{11}^{ant}.

For the same example considered for the 50 Ω matching approach, the co-design method can bring about much better matching as shown in Figure 4.4.

It has to be noted that the uniform matching, as illustrated in the example, might not necessarily be always possible. However, the parameters that can be tweaked for the antenna and the LNA provide a greater degree of freedom in matching the impedances.

The LNA S_{11}^{LNA} can be controlled by the one or more of the following techniques;

1) Introducing a properly designed microstrip line at the LNA input
2) Adding inductances at the transistor source

The antenna $S_{11}^{\text{ant}}$ can be varied by varying the following parameters of the antenna by ensuring that the VSWR is maintained between 1 and 2.

1) The length of the antenna feed line (as explained in section 1.4) can be varied with substantial impact on $S_{11}^{\text{ant}}$
2) The feed gap of the antenna
3) Shape/size of the antenna patch (modifying by chopping to introduce more edges)
4) Dimensions of the antenna ground plane

4.2 Classical Design Approach

4.2.1 Co-Simulating the Antenna and LNA

The classical antenna-LNA pair consists of the 50 $\Omega$ matched LNA presented in Chapter 3 and the 50 $\Omega$ input impedance antenna presented in section 2.2.4. Since the antenna and LNA are matched to 50 $\Omega$ at 2.2 GHz, both designs can be directly interfaced. However, while co-simulating the antenna and LNA, the antenna impedance needs to be presented at the input of the LNA instead of a regular 50 $\Omega$ termination. A direct connection on schematic level will not produce the right results since the LNA is a circuit level design and the antenna is an EM design. Hence for co-simulating the designs, RefNetDesign termination component in ADS is used for file based input termination of the LNA. The RefNetDesign provides an impedance reference of the antenna’s input impedance referenced from a file with simulation data. The figures Figure 4.5, Figure 4.6 and Figure 4.7 shows the method of referencing an EM simulation’s impedance to a circuit. More information is available at the ADS help section for RefNetDesign termination\(^{[19]}\).

![Figure 4.5](codesign_refdesantenna_50ohm.ds)
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![Figure 4.6: Sub-network for loading the simulation dataset (codesign_datasetloadantenna_50ohm.ds)](image)

Figure 4.6: Sub-network for loading the simulation dataset (codesign_datasetloadantenna_50ohm.ds)

![Figure 4.7: RefNetDesign termination used in top level design for S-parameter based termination](image)

Figure 4.7: RefNetDesign termination used in top level design for S-parameter based termination

The design codesign_datasetloadantenna_50ohm.ds in Figure 4.6 is the top level sub-network with a one-port design file that reads in the S-parameter data file created by the design saved as codesign_refdesantenna_50ohm.ds in Figure 4.5 where 50ohm_square is the black box symbol created from the Momentum simulation of the antenna. Finally, in a design file that contains the circuit under test (i.e. LNA) the RefNetDesign termination component as shown in Figure 4.7, is placed at the pin (LNA input port) where the S-parameter based termination of the antenna input impedance is to be applied.

### 4.2.2 Classical design PCB layout

The Figure 4.8 shows the 50 Ω matched antenna and LNA placed together on layout.
4.2 Classical Design Approach

4.2.3 Simulation Results

The classical antenna-LNA design is co-simulated for a frequency range 1.4 GHz to 3.0 GHz. The classical antenna-LNA pair design is unconditionally stable from 1.55 GHz.

![Stability of the classical antenna-LNA design](image1)

![Simulated gain and NF of the classical design](image2)
The classical design has a gain that ranges from 15.32 dB at 1.7 GHz to 10.93 dB at 2.7 GHz with a peak gain of 16.73 dB at 1.9 GHz. The noise figure is above 1 dB from 1.6 GHz to 2.1 GHz and is the lowest at 0.8 dB at 2.5 GHz. The input reflection is the minimum at 2 GHz and the best output matching is seen at 1.8 GHz.

### 4.2.4 Classical Antenna-LNA pair measurement

The Classical Antenna-LNA prototype is manufactured following the key steps of the PCB fabrication process, lumped components are soldered on to the LNA. A measurement setup is prepared and with the help of a VNA ZVM from Rhode Schwarz (10MHz - 20GHz), the gain and isolation of the prototypes are measured. The measurement setup consists of 3 stages in which the forward transmission, reverse transmission are measured. The gain and isolation could not be measured with the available equipment. So the forward transmission of stage 3 and stage 1 or 2 is measured and a subtraction method is applied to achieve the gain and similar process is applied to reverse transmission so as to obtain isolation results of the prototype. The distances and power levels are varied in all the 3 stages to observe how gain and isolation varies in short (18 cm) and long (29 cm) distances under power levels ranging from 0 to -20 dBm respectively. It is to be noted that all the power, forward, reverse transmission and isolation levels are negative values.

Stage 1 setup comprises of a 39 Ω antenna on the right side, a 50 Ω antenna on the left side of the VNA and the forward, reverse transmission are measured.
In stage 2 the inverse of stage 1 is setup with a 50 Ω antenna on the right side, 39 Ω antenna on the left side and the forward transmission, reverse transmission are measured.

![Diagram of 50 Ω Antenna to 39 Ω Antenna with 18 cm distance]

In stage 3, a 50 Ω antenna is placed on the right side and the 39 Ω antenna in stage 2 is replaced by a classical antenna – LNA design on the left side. The forward and reverse transmission are measured in this case, similar to that of stage 1 or stage 2. The Subtraction method is applied to the forward, reverse transmission of stage 1 w.r.t. that of stage 3 and the resultant gain, isolation of the classical antenna – LNA designed prototype are obtained.

![Diagram of 50 Ω Antenna to Classical Antenna - LNA with 18 cm distance]

4.2.5 Measured results and comparison

**Setup 1**

The front and rear view of the classical antenna – LNA prototype can be viewed in Figure 4.12 where an impedance matched 50 Ω square monopole antenna is integrated with 50 Ω LNA.

![Image of Antenna - LNA prototype]

Figure 4.12: Front and rear view of the antenna - LNA prototype

Stage 3 setup is implemented with a distance of 18 cm between the modules and the measured forward transmission is plotted in Figure 4.13 against frequency for various power levels of 3,5,10,15 dBm. The measured forward and reverse transmission of 3 dBm power level is for stage 1, i.e., between the antenna modules, it is considered as a reference stage to calculate the gain and isolation of the prototype. The forward
transmission behaviour is almost similar for all power levels. The reverse transmission behaves similar for 3, 15 dBm power levels in the range of 15 - 70 dB, and for 5, 10 dBm it varies in the range 50 - 70 dB.

The measured gain plotted for 5, 10 dBm power levels can be seen in Figure 4.14. It is in the range of 20 - 7 dB and does not match with the simulated results. The measured isolation for various power levels when compared with the simulated result is less in the 1.7 - 2.5 GHz range and has a peak in the range 2.6 - 2.7 GHz.

**Setup 2**

The prototype results plotted in Figure 4.15 are for a distance of 29 cm between the modules. A similar setup as of the setup 1 is followed and the forward, reverse transmission levels are measured. The forward transmission plot for 3 dBm power level (stage 1) is 20 - 65 dB and for 5, 10, 15 dBm power levels it is identical and is in
the range 55 - 80 dB. The reverse transmission levels are almost similar for all power levels.

Figure 4.15: Forward and Reverse Transmission for different power levels in setup 2.

The gain obtained is in the range of 5 - 5 dB within 1.4 – 2.75 GHz band, a peak in gain around 25 dB is observed at 2.8 GHz; the isolation range for 5,15 dBm power levels are plotted in comparison to the simulated results that are close to each other and can be seen in Figure 4.16.

Figure 4.16: Gain and Isolation levels for different power levels of setup 2 in comparison with the simulated results.

The gain and isolation results shown in Figure 4.17 are a comparison between the simulated, setup1 and setup2 results. Upon observation, the simulated results are comparatively better than the prototype results within the 1.7 – 2.7 GHz band.
The drops and peaks in gain, isolation are due to the soldering problems, imperfections in fabrication process and the transistor bias network did not work as expected due to which more power was required to drive the transistor into desired bias state. The spacing between the metal layers in the LNA prototype is very narrow, so this might also have caused the design to not work as expected and hence the results had much variation from the simulation results.

### 4.3 Co-Design of Antenna and LNA

#### 4.3.1 Co-Design and layout preparation

As explained in section 4.1, to perform the co-design of the antenna and LNA, the IMN of the LNA is removed and only the DC blocking capacitor is left. The resulting LNA layout is shown in Figure 4.18. In order to investigate the possibilities of a matching with the antenna presented in section 2.2.2 (39 Ω input impedance), the LNA $S_{11}$, $S_{\text{opt}}$ and antenna $S_{11}$ are plotted in Figure 4.19.
It is observed that a fair matching between all plotted S-parameters is possible with a suitably designed microstrip line at the input of the LNA. The proper length and width of the microstrip line is found out by sweeping these dimensions and observing the plots. At a width of $W = 1.033$ mm and length $L = 8.288$ mm, the matching as shown in Figure 4.20, is obtained. Observing the gain and NF of the design, simultaneously, it is inferred that this particular matching provides the highest gain and lowest NF.
The LNA layout is modified with this microstrip line (MLIN) component at the input as shown in Figure 4.21.

To optimize the bias network and stability of the co-designed LNA, a few of the lumped component and resistor values are modified as shown in the Table 4.1 (the component numbering in reference to LNA circuit in section 3.6).
4.3 Co-Design of Antenna and LNA

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Table 4.1: LNA component values for co-designed antenna-LNA pair

Figure 4.22: Co-designed antenna-LNA pair PCB layout

Figure 4.22 shows the PCB layout for the co-design PCB. Since the LNA input has to be close to the antenna feed point and at the same time the whole design had to accommodate above the antenna’s ground plane (any extra ground plane would change the antenna characteristics), the LNA is placed tilted but with no difficulties in prototype manufacturing.

4.3.2 Simulation results

The LNA shown in Figure 4.21 is co-simulated with the 39 Ω input impedance antennas in section 2.2.2 using the method described in section 4.2.1.
As shown in Figure 4.23 the co-designed version is unconditionally stable from 1.7 GHz with $K = 1.001$. Figure 4.26 shows that the gain peaks at 1.9 GHz with 17.23 dB and the noise figure is less than 1 dB for the entire frequency range with the lowest NF of 0.68 dB occurring at 2.3 GHz.
**Comparison of co-designed and classical design simulation results**

The co-design brings about clear improvements in gain and NF as seen in Figure 4.27 with higher gain than the classical design for the entire operation range and a lower NF than classical design version with noise figure less than 1 dB for the whole range of frequencies. It is interesting to note that the classical design has superior input matching at 2 GHz and better input matching than co-design for frequencies up to 2.9 GHz. The co-design version has better output matching for frequencies above 2 GHz.

**4.3.3 Co-Designed Antenna-LNA pair measurement**

The measurement setup is similar to the classical design measurement setup; the classical antenna-LNA module in stage 3 is replaced by the co-designed antenna-LNA module in stage 4. The distances varied are 13, 24 cm and different voltage levels considered are 5, 5.5, 6 volts. Instead of power levels as of the previous setup, the voltage levels are varied and the power in this setup is kept constant at 3 dBm.
The subtraction method is applied with stage 4 to that of the stage 2 to obtain the gain and isolation levels of the prototype.

### 4.3.4 Measured results and comparison

#### Setup 1

The front and rear view of the prototyped co-design antenna – LNA pair can be seen in Figure 4.28 that consists of a impedance matched 50 Ω square monopole antenna, 50 Ω LNA integrated and mounted on the ground plane.

![Figure 4.28: Front and rear view of the Co-design prototype](image)

The forward transmission behaves similar when the voltage levels are varied as 5, 5.5, 6 V at 3dBm power and is in the range 0 - 30 dB. 3dBm, 5V plot represents the stage 2 setup that is considered as a reference stage in this setup. The reverse transmission levels are in an acceptable range within 40 - 90 dB and can be seen in Figure 4.29.

![Figure 4.29: Forward and reverse transmission for different voltage levels in setup 1.](image)
The measured gain plotted against frequency in Figure 4.30 shows little deviation from the simulated result, at few frequencies the measured gain and isolation are proven to be better than the simulated results within the required band.

![Figure 4.30: Gain and Isolation levels for different power levels of setup 1 in comparison with the simulated results.](image)

**Setup 2**

The distance between the modules in setup 2 is 24 cm and the measured forward transmission at 5V is for stage 2 i.e., between the antenna modules and can be seen in Figure 4.31

![Figure 4.31: Forward and Reverse Transmission for different voltage levels in setup 1.](image)

The measured gain and isolation results in Figure 4.32 are in hand with the simulated results and the dropouts, peaks occurred at several frequencies are due to the multipath reflections because of the closed measurement setup, soldering problems and the bias network did not draw sufficient current as expected.
Figure 4.32: Gain and Isolation levels for different power levels of setup 1 in comparison with the simulated results.

Figure 4.33 shows the comparison drawn between the simulated gain, isolation and the measured gain, isolation for 13 and 24 cm separation distance between the modules.

Figure 4.33: Gain and Isolation levels for setup 1, 2 in comparison with the simulated results

The co-designed antenna - LNA pair results are proven to be better than the classical antenna – LNA pair in the simulation environment. Since the classical antenna – LNA pair had problems while manufacturing the prototype, the conclusion on which design has yielded better results with the prototypes is yet to be made after the improvements are performed.
5 Conclusion

Planar antennas working in the 1.7 - 2.7 GHz frequency range were designed and manufactured on Rogers R04360 substrate. Low-Noise Amplifier for the same frequency range using a pHEMT device was designed, simulated and manufactured on Rogers R04360 substrate. Two versions of functional modules of an antenna-LNA pair were designed, simulated and manufactured. All the design (circuit and layout) and simulations were carried out by an interactive process using the schematic capture and RF simulation EDA tool Advanced Design System (ADS) from Agilent Technologies. The process included design of schematics with ideal components, layout generation using Momentum and EM simulations on layout level with real components (with parasitics).

The manufactured prototypes were tested in the lab for conformity with simulated results, using a Vector Network Analyzer. For the lack of a Noise Figure Analyzer in the measurements lab, noise figure of the manufactured prototypes were not measured.

Monopole antennas are better suited for co-design applications since they have a wider range of acceptable operation. Co-design of antenna and LNA provides clear improvements over gain and NF of a classical design version. However, the input reflections were observed to be slightly higher than the co-designed antenna-LNA pair, for frequencies upto 2 GHz.

Since the work focussed on the gain and NF improvements, the area optimization was not considered. So it could be interesting to miniaturize the co-design layout for space saving. The noise figure of the LNA could be further reduced by using distributed microstrip lines instead of lumped L and C components. The measurement results suffer from interference and fading, so to analyse the results with more accuracy, measurements could be performed in an anechoic chamber though the existing measurement results correspond to non-ideal real life situations of antenna operations.

It could be interesting to extend the procedure to use different integrated antenna designs tailored to the frequency range. The ground plane size of the antenna is a major obstacle in miniaturization. Hence to reduce the size of the design, different antenna architectures could be investigated.
# Appendix

## A.1 Individual contributions

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<td>Co-design of antenna and LNA on S-parameter model level</td>
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References


[17] “APPLICATION NOTE AN058, ANTENNA SELECTION GUIDE” BY RICHARD WALLACE, TEXAS INSTRUMENTS.


[20] “APPLICATION NOTE 1375 ATF-58143 E-pHEMT GaAs FET LOW NOISE AMPLIFIER DESIGN FOR 900 MHZ APPLICATIONS”, AVAGO TECHNOLOGIES.


[23] “CHALLENGES AND TRENDS IN RF DESIGN”, BEHZAD RAZAVI, HEWLETT-PACKARD LABORATORIES.