UWB Antenna and LNA Receiver Simultaneous Matching

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ABSTRACT

This paper describes a method used to design an ultra wideband (UWB) receiver antenna and low noise amplifier (LNA) simultaneously using optimization methods. In narrow band (NB) design, the impedance of the LNA or antenna is almost constant, usually matched to 50 or 75 Ohms. Thus, the antenna and LNA are designed independently. In UWB, the antenna impedance is a function of frequency, and varies greatly. Thus, the designer’s option of designing each subsystem independently is difficult.

KEYWORDS: Spiral antenna, UWB, LNA, simultaneous matching, optimization.

1. INTRODUCTION

The input frequency of a receiver LNA is frequency dependent. Several matching methods are well developed for the impedance transformation and matching. In microwaves, the preferred method is transmission lines using stubs, whether coaxial or microstrip, and in RF, the method is lumped L, T, or Pi matching networks [1]. There are other methods for wideband matching that consist of tapered TL or higher order networks or feedback [1][2][3][4]. However, these methods are not optimal since they do not take advantage of the simultaneous behavior of the antenna and receiver.

Recent standards allow operation of UWB over 3 to 10 GHz [5]. Current methods for LNA design using LC matching for NB, such as source or emitter inductance degeneration, work well over a small bandwidth as compared to the carrier center frequency. The use of resistance (ideally frequency independent impedance) is not recommended due to the thermal noise generated by these devices and large power consumption. However, the use of resistance in feedback networks might be an option to consider when properly designed with the noise figure (NF) requirements. Most UWB LNA are designed with a constant input source impedance [4]. This assumption will greatly affect the performance once the LNA is connected to the antenna.

The problem appears more severely in the antenna design. While we can theoretically make the LNA input impedance constant using resistive devices, the antenna input impedance is more difficult to control. While wideband antennas or frequency independent antennas exist, there impedance is not practically constant, mainly due to the fact that they are finite in size [6].

The list below shows the options (methods) in receiver design

1) Design LNA and Antenna assuming constant impedance for each device (narrow band design procedure)
2) Design the antenna first, then design a LNA matched to the antenna, or vice versa
3) Design the antenna and LNA simultaneously

The first method is well documented and fairly simple [3]. The second method assumes that either the antenna or the receiver is ready and is not to be modified. The designer then tries to optimize his design to the given device. The procedure can be described as follows: The antenna S parameters (or input impedance) are measured or provided by the manufacturer. The LNA topology is reviewed based on the given antenna impedance, such as common source with L match, or inductive degeneration, etc. This process requires some good experience by the designer. The designer usually uses a CAD tool that has optimization or tuning capabilities. The LNA schematics is captured and the tunable devices are identified. Then the designer uses the optimization capabilities to tune the impedance, or frequency response, of the LNA to the provided data. It is worth mentioning here that the designer has to decide which of the devices, antenna or LNA, is to be used as the reference. The process of the LNA design is usually done at the circuit level, using steady state or small signal methods, such as harmonic balance (HB), steady state, or transient SPICE. The antenna requires electromagnetic simulations. The tools
are different, and the decision how to proceed might be influenced by the available tools.

The third method might offer the best performance, but requires the most effort. First, the most influencing parameters are identified for the LNA and the antenna. The LNA consists of lumped elements. These elements are finite in number, but their values might be continuous, such as inductance in the form of spiral inductors. Antennas, such as wide band spiral or conical antennas are more complex. The antenna structure might be a planar 2 dimensional or 3 dimensional, and this will influence the design effort.

In this paper, we illustrate the second method of an UWB receiver consisting of an Archimedean spiral antenna and amplifier, and optimize a LNA using global optimization methods such that the system output is fairly constant over the operating range of 3 to 10 GHz. No effort was spent to optimize the antenna impedance so as to show how robust the LNA architecture can be.

2. ANTENNA DESIGN

The design method for the antenna can be analytic or numerical based. While analytic methods require more intelligence upfront as compared to numerical methods, they do offer a single platform, in the form of equations that can be used in the design. Thus, the antenna subsystem used in the UWB design is simply a set of equations. If the antenna can’t be described by a closed form, then numerical simulations are required.

Several antenna types are classified as wideband, such as conical, spiral, etc [6]. However, due to the ultra wideband requirements, even these types of antennas will have a great degree of variations in their antenna parameters, such as input impedance, or radiation pattern. Of course, it is possible to fit the numerical data into equations for the antenna, such as input impedance as a function of some of the geometrical shape parameters of the antenna: strip width or board dielectric, etc.

In case of available equations describing the antenna behavior, either analytical or numerical, the optimization time can be greatly reduced for the overall system. While this is desired, it might not be available; however, it is worthwhile if the designer spends time upfront to investigate this requirement.

2.1. Antenna Analysis

Several methods are used for antenna analysis, including integral equation based methods or differential equations methods [7]. Differences are: required fields (near or far, or both), run time constraints, resource allocations (such as computer memory requirements), etc.

In this paper, attempts were made to optimize output voltage to be of constant level over the operating band. An antenna can be described by an electrical model that consists for RLC components; however, the model might be very complex. The radiation resistance is responsible for antenna power transmission in the far field, while the admittance describes the near field reactive energy that is required to satisfy the EM boundary conditions. For our purposes, then, we only need the antenna input impedance (or S-Parameters) and these can be easily obtained using any of the numerical methods, whether integral or differential based.

Figure 1 shows the spiral antenna, with output feed at the center

![Figure 1. Archimedean Spiral Antenna](image)

Figure 2 shows the spiral antenna input impedance. The real part of the impedance changes between 10 to 500, while the imaginary part ranges between 130 and -500. Several options can be taken to reduce the impedance variations including larger separations between the traces to reduce coupling.
3. LNA DESIGN

A LNA is usually a class A, small signal, linear, low noise amplifier that is recommended to be used as the first component after the antenna. The LNA might be preceded by a filter to remove other signals that might block the amplifier (drive it into the nonlinear region). However, some tuned amplifiers might not require a bandpass filter. The LNA technology (bipolar, FET, silicon, GaAs, etc) influences the design. Some of the most important factors are unity gain frequency, $f_t$, the input impedance; mostly capacitive for CMOS, and resistive for bipolar. Other factors are the amplifier type, whether common source (CS), common drain (CD), or common gate (CG). Most FET LNA’s are a cascode consisting of a CS with CG as its load [2]. Other important forms are single ended or differential amplifiers.

The circuit below shows a top level LNA showing most important components. The biasing network is not shown for simplicity. The LNA has a frequency selective feedback network (voltage sample-current sum) consisting of a resistor, capacitor, and inductor, such as that suggested by [9] from drain to gate, as well as a degeneration inductor at the source, an inductor at the gate forming a series LC network, and a cascaded two tank circuits tuned circuits as the load.

The following parameters were used in the constrained optimization as follows:
1) Inductance and capacitance of the two tuned tank circuits. Initially, the two resonant frequencies were spread apart to provide two maxima between 3 and 10 GHz.
2) Channel width of the two transistors. Initially, the channel width is obtained using common analysis procedures for narrow band designs,
3) The inductor at the gate of the CS transistor and the degeneration inductor at the source. The initial values can be obtained using the procedure for step 2
4) The feedback series RLC network for the CS transistor.
5) The input compensation parallel resonant circuit

3.1. LNA Analysis

The LNA can be analyzed using several circuit methods. These include a SPICE based simulation, whether small signal or transient, a Harmonic Balance simulation, usually good for relatively non-linear circuits, or a steady state simulation, such as SPECTRE. Other simulations based on measurements are S-Parameters, mostly used in microwave design.

4. OPTIMIZATION METHODS AND CIRCUIT PARAMETER FITTING

There are several optimization methods, classified according to their principle of operation. Some are listed below [5]:
1) Steepest Descent, including gradient based methods
2) Linear Optimization
3) Monte Carlo based Simulated Annealing and Quantum Annealing
4) Monte Carlo Genetic algorithms, Ant Colony, and Particle swarm [10]

The execution time for the algorithm is minimal compared to that of the circuit or EM structure. However, some methods are more efficient than others and generally converge faster. These algorithms will require less execution time. The steepest descent methods are very fast but suffer from local minima traps. Nonetheless, they can be combined with a Monte Carlo based method to search over large space and escape local minima.

A circuit model can also be obtained using optimizations. This consists of fitting a model to a computed circuit response by varying certain parameters. A model obtained this way describes the circuit well and can be used in the design procedure instead of the actual circuit. For example, the antenna impedance function can be described by an equation as a ratio of two polynomials. The procedure to obtain the polynomial coefficients can be a fitting or optimization one. This can decrease the execution time by several hundred times.

The optimization procedure starts at some initial parameters, then some of these parameters are changed by the optimization algorithm (randomly or using descent methods). The new response of the system is computed based on these new parameters, then the optimization algorithm iterates over several thousand iterations until it converges or until it reaches the maximum iteration limit (set by the user).

5. HIGH LEVEL MODELLING

An amplifier consists of several components. A SPICE simulation requires extensive models at RF frequencies; a transistor consists of more than 30 parameters in BSIM3. A Verilog AMS or Verilog A can be used to describe the behavior of the LNA at a high level. Of course, while most of the processing power is spent on the EM simulation, nonetheless, the circuit level demands execution time. Measurements of S Parameters (might be obtained by simulations) for the transistors and the antenna can be used to speed the execution. One can use the S-Parameters and if two devices are connected in series, the S-Parameters can be converted to ABCD Parameters and the system overall response is computed.

As mentioned above, if a circuit model is available for the antenna, it can be described at a high level (lumped elements analyzed by Kirchoff’s laws rather than EM structures analyzed by Maxwell equations) and the design process can proceed in a similar fashion to the circuit level description.

6. UWB SYSTEM DESIGN

The UWB receiver system consists of the antenna and the LNA. For our design, we used a spiral UWB antenna and a cascode LNA. The antenna structure was not optimized any further for the purposes of showing the capabilities of the LNA architecture and the optimization methods.

The antenna was analyzed using Microwave Office EMSIGHT software, which is geared towards planar structures using integral equations. The antenna impedance was calculated over the required frequency range and is shown in Figure 2 above. Once calculated, the results can be stored and no further EM analysis is required, since we are not modifying the antenna shape. The antenna is connected to the LNA. The antenna can be modeled at the circuit level as a current source in parallel (Thevenin equivalent) with the antenna impedance. Once in this form, the EM solver is not needed any more and this greatly reduces the optimization execution time. The LNA elements that affect the system response, in the form of voltage gain, power gain, etc. are identified. This is a simple process in advanced CAD tools such as Microwave Office. Further, the values of the elements can be constrained with upper and lower limits.

Narrow band matching between two constant impedances is performed using simple matching networks; however, these networks are usually frequency dependent, such as inductance or transmission line sections. Wideband matching between two systems can be done using more elaborate networks such as Chebyshev or tapered transformers. None of these methods give good results since each of the two devices (antenna and LNA) have impedances varying as a function of frequency.

As explained above, the optimization method might be selected due to several factors such as available tools, or previous design decisions based on ready made device (such as the antenna in this case). In the case of optimization of the antenna and the LNA, the above procedure can be used as well. However, since the antenna and LNA analysis methods are different (different solvers used), the tool optimization interface might require some more effort. While it is straightforward to implement optimization based on a single cost function, the process gets more complicated when different solvers are required to produce the optimization cost function. For example, in a LNA design, the output voltage gain might be set as the optimization goal. The optimizer will vary some of the parameters and produce the cost function to
be used by the optimizer. Now, if the goal is the voltage gain, Noise Figure, and input impedance, then the analysis solver will change some circuit parameters, obtain corresponding objective values, then these values are mapped into a common global performance measure to be used by the optimizer.

When different solvers are required to produce the system performance, such as EM solver for the antenna and SPICE solver for the LNA circuit, the optimization algorithm will vary the parameters as for the case above. However, the new parameters are sent to two different analysis solvers. The output of these solvers might not be the same form, for example one can be impedance while the other S-Parameters. These two outputs are then combined to form a common optimization goal.

For complex systems, the designer has to be aware of the time requirements for each solver. Thus, if EM analysis requires ten folds more time than the circuit analysis, then more parameter changes might be used for the circuit. This way, the antenna will be modified once as compared to hundreds of circuit modifications.

7. RESULTS

Figure 4 below shows the narrow band cascode LNA output for a 50 Ohm matched source and 1 micro Amp AC current source sweeping the frequency range (-86 dBV). The peak gain at the resonance frequencies is obvious.

Figure 5 shows the same narrow band LNA output when connected to the spiral antenna. The variations over the frequency range is about 20 dB.

Figure 6 shows the UWB LNA output when connected to the spiral antenna. The receiver has a 6 dB ripple in the passband from 3 to 10 GHz.

8. CONCLUSIONS

An UWB receiver antenna has a non-constant output impedance over the operating range. The antenna acts as the source impedance for the receiver LNA. Most previous work considered a constant impedance source. The proposed LNA architecture and design method
presented here is shown to be robust to be used for UWB receivers with real broadband antennas.

REFERENCES


