Design and Optimisation of Low Noise Amplifier in Superhetrodyne GPS Receiver Front End

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Abstract: The Global Positioning System (GPS) as it was developed for military purposes originally by the USA has become the most valuable tool for military purposes today. GPS can be used for different applications such as military, science, sports, transportation and many more. Each particular application needs a specific performance from GPS receiver. In this report the architecture of the Superhetrodyne GPS receiver front end will be discussed. The receiver includes all analogue signal paths including Low Noise Amplifier, Radio Frequency Filter, Mixer, Local Oscillator and IF Filter. Specific attention will be paid to the Low Noise Amplifier (LNA). The design issues related to LNA will be discussed as well. These issues include gain, noise figure and linearity. The discussion also includes the technological constraints for design of LNA. What particular technology is going to be used for this design? Normally LNA is designed using discrete elements, but for this particular application enhancement mode (pHEMPT) technology is used.

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1 Introduction

The Global Positioning System (GPS) is a constellation of 24 satellites in six orbits. They circle the earth twice each day at an inclination angle of approximately 55 degrees to the equator. The satellites continuously transmit coded positional and timing information at high frequencies (in the 1500MHz range) [1].

GPS receivers on the ground pick up the signals and use the coded information to calculate a position on an earth coordinate system. A receiver determines a position by calculating the time it takes for the radio signals transmitted from each satellite to reach the receiver. Multiplying the time by the speed of light determines how far the unit is from each of the satellites: Distance = Rate x Time. Time is determined using an ingenious code matching technique within the GPS receiver. The location of each satellite is encoded in its transmitted signal. With these data, the receiver can triangulate to calculate its location on Earth.

1.1 GPS system and its working

Space Segment: This segment is based on the constellation of satellites usually in the Medium Earth Orbit (MEO). These satellites orbit the Earth at a distance of about 20,000 km from earth's surface [2]. Satellites in this constellation use two microwave frequencies for transmission of ranging signals.

Control Segment: This segment is based on a system of ground monitors to maintain a GPS system and it is responsible for providing upload facilities and to synchronize the atomic clock on board the satellite [3].

User Segment: This segment is comprised of a user receiver. The atomic clock on board the satellite generates a unique digital code sequence and the satellite transmits that code to the ground segment. Additionally a user segment GPS antenna picks up the sequence and the GPS receiver matches the sequence with its own sequence generated inside the receiver [4]. These sequences are used to calculate the total time; the signals have taken to travel from space segment to the ground segment. The calculated time is then converted into the distance as the microwaves travel with the same speed as light (300,000 km/sec). A GPS receiver can view at least four satellites at the same time and knows the exact location of these satellites. The receiver clock is synchronized with the GPS time standard.

2 GPS receiver Introduction

We no longer have to do what people used to do few years before to find a location. If you have to go somewhere you do not need to get map references. Now things have become simpler and faster. If you want to trace a particular place just buy £100 tom-tom and it will take you exactly where you want. When people discuss GPS they actually mean the GPS receiver. The GPS receiver actually uses the process called trilateration to calculate a particular position or place. How does it work? Let us take this example.

Let us say that you are at a location and you do not know where you are. You ask someone and they tell you that you are about 100 KM away from A. You can be within a circle the radius of which is 100 km. Now if you enquire from somebody else the location he tells you that you are about 130 km from B so it means you are now in a circle the radius of which is about 130 km. Similarly a third person tells you that you are at 95 km from C. Here you are in a circle whose radius is 95 km. Now you will know the exact location which is shown as D below, because the third circle will intersect at only one point. So this is how GPS receiver determines the location by using four satellites. The satellites functionality matches the analogy discussed in the above example.

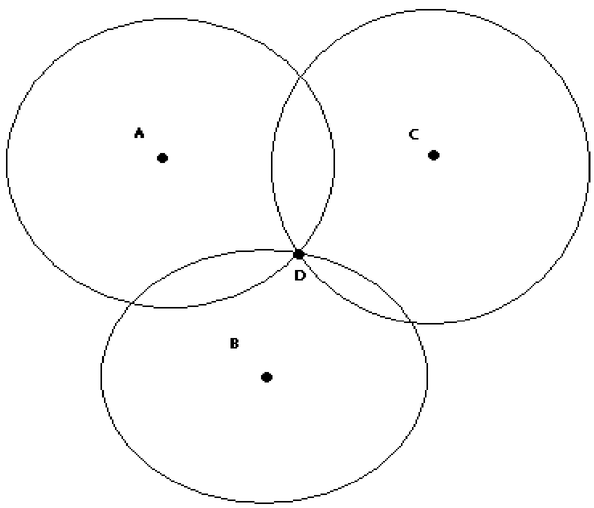


Figure 2.1: Working of GPS to find the distance

2.1 GPS Receiver Architecture

RF signals have very small wavelength and they are shorter then ordinary signals like audio signals. Even a moderate RF signal has a very short wavelength. As the value of frequency changes the values of reactive components like capacitors and inductors also change because they are frequency dependant. The practical circuits do not contain only capacitors or only inductors but they contain both of them. At microwave frequencies their effects are very sensitive. So when we are designing an RF circuit it is very different from the ordinary circuit.

As discussed earlier the amount of gain we shall have at various blocks of the GPS receiver is always a trade off. High gain at early stages of the receiver will help in getting better performance from the receiver [5]. If we get high gain at active antenna and LNA then of course it will help a lot to reduce the noise figure by minimizing the contribution of noise to the mixer. On the other hand if the gain is low then it will improve the linearity and power consumption, as these blocks will consume power as well. For a GPS receiver front end non linearity is not a big problem. As the signal is coming from far away, so its strength is very low. Therefore for our design we would rather get better gain then get better linearity.

In the receiver technology section we shall discuss the GPS receiver components overview.

In this section we shall focus on the following GPS receiver components:

- Antenna
- Low noise amplifiers
- RF Filters
- Mixers
- Oscillators
- IF Filter
- IF Amplifier

As the ADC part of the receiver is beyond the scope of our study, because our main focus will be on the RF part of the receiver, we shall not discuss the digital part of the receiver.

Before we look in depth at the GPS receiver we must first look at its basic architecture. The idea here is to understand the basic architecture of how different components of the receiver are attached to get the desired functionality.

Below is the basic architecture of the GPS receiver.

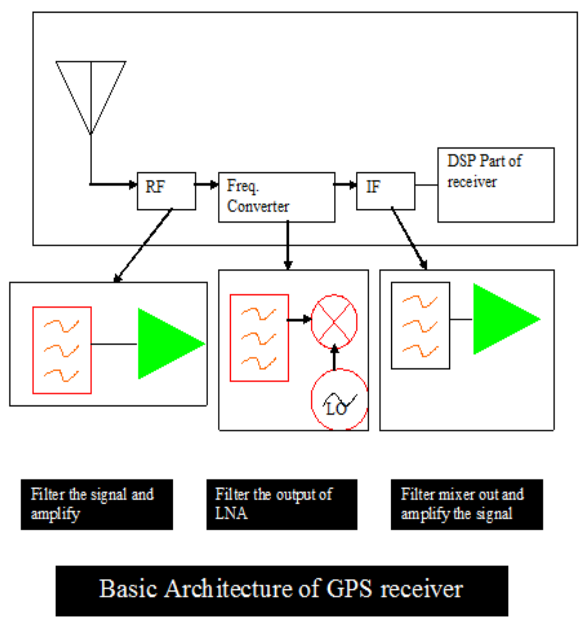


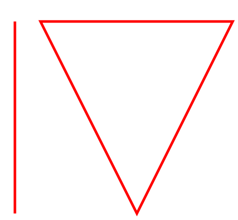
Figure 2.2: Basic block diagram of GPS Receiver [7]

The next section will discuss the receiver components one by one.

2.2 GPS Receiver Components

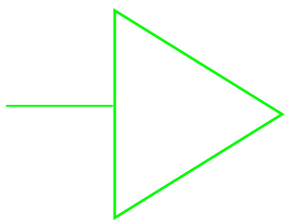
2.2.1 Antenna

The symbol for the antenna is



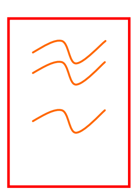
The antenna is the first part of the receiver. It receives the signal coming from the satellite. The design is working at 1.57GHZ, so it detects the signal coming at this frequency from the satellite. It is actually a narrow band device of the receiver. Its sensitivity is very important, meaning that it should be highly sensitive because the signal coming from the satellite is at about 20,000 KM, as the satellite is at MEO distance so there will be a huge path loss as the signal that arrives at the receiver will be very weak.[7]

2.2.2 Low Noise Amplifier (LNA)
The symbol for LNA is.



The low noise amplifier is the component of the receiver which is placed earliest in the receiver. The reason for it being put at the earliest stage is that it amplifies the signal. As the signal is coming from far away it is very weak as it reaches at the antenna of the receiver. So if the signal is weak at the initial stage of the receiver then it will affect the whole performance of the receiver. Thus the LNA amplifies the signal and then it goes to the other components of the receiver. There is another problem with these components which is that they have their own internal noise as well, so if the signal strength is low at the initial stage of the receiver, then noise may overcome the actual signal which can be a problem for us as well so for that reason we shall have to put the LNA at the earlier stages of the receiver [6]. As the focus will be on the LNA of the receiver so the detailed study of LNA will be discussed later on.

2.2.3 Filters
The symbol for the filter is.

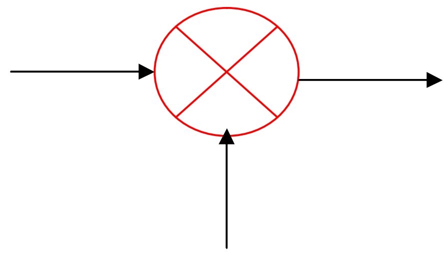


The word filters is used instead of filter because we use this component more then once and it can have different types. We use the one based on requirement.
Filters can have the following three types:

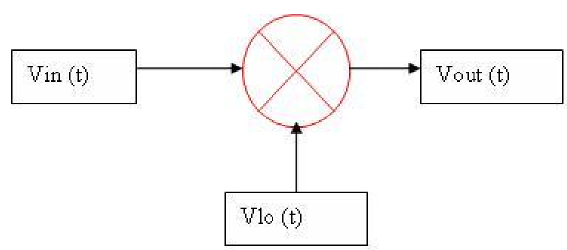
i) Low pass filter
ii) Band pass filter.
iii) High pass filter.

Which particular type of filter we are going to use depends upon the requirement, e.g. a low pass filter will only pass low frequencies and will filter out all other frequencies. A high pass filter will pass high frequencies and will reject all others. Whereas a band pass filter will pass a band of frequencies and will filter out the frequencies below and above that [7].

2.2.4 Mixers



The mixer is another important receiver component. The mixer is used for frequency conversion of the information and can be used at different places in the receiver chain. Its function is actually multiplication. The Mixer multiplies the input signal and the local oscillator signal. Multiplication in the time domain becomes a convolution in the frequency domain. Information in the input signal can be up converted which is called sum or it can be down converted which is called difference. The ratio of output signal power (Intermediate frequency) to the input signal power gives us the conversion gain [6][7].



Vout (t) = Vin (t).Vlo (t) [7].

2.2.5 Oscillator
Oscillators are sine wave or square wave generators. An oscillator provides a signal at a particular frequency. It consists of an amplifier and a feed back circuit. The frequency of the Oscillator can be tuned by varying the feed back circuit.
An ideal Oscillator provides a single sine wave. It may consist of thermal noise and phase noise etc.
These are some of the important components of the Superhetrodyne receiver. There are of course other components which include the DSP part of the

receiver as well but we are not going to discuss them here.

2.2.6 IF Filter

We use an IF Filter at this stage (IF stage) to filter the incoming signal and to remove those unwanted harmonics which are generated by the mixer. It is difficult to remove the unwanted harmonics because they lie very close to the wanted signal. Thus their performance is critical.

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2.3 GPS Receiver Link Budget

Before you design any communication system you need to know the receiver requirements in terms of its sensitivity, selectivity, link margin, gain, path losses and noise figure. So the calculation of these values is called the link budget. Below are the specifications for the link budget for this particular application:

The total received power is given by the following equation:

Prx = Ptx + Gtx +G rx +FSL +Ap

Where,

Prx = is received power.

Ptx = Transmitted power at the satellite, (assume Ptx=14dBw)

Gtx = Gain of the antenna of the satellite, (assume Gtx=13 dBw)

FSL is a free space loss= $[\lambda/4\pi R]^2$= -184 dBw.

λ is the wave length= 19cm.

R is satellite altitude=25000 km

Ap is a propagation losses because of rain, atmosphere. (Assume Ap = -2 dBw).

G rx is a GPS receiver antenna gain =0Dbw

So,

Prx =14 + 13 + 0 - 184 - 2

= - 159dBw

= - 127 dBm

Now we need to calculate the sensitivity of a receiver which is also known as minimum received power as following:

Pmin = Pn + NF+ C/N min

Where,

Pmin is a minimum received power

Pn is Noise power = 10 log K Ta B= - 133.97 dBw

K is Boltezman constant =1.38x 10^{-23} J/K

Ta is Antenna noise temperature= 290 k (assumption).

B is IF signal bandwidth=10 MGZ.

NF is the noise figure of the receiver =9 dBw (assumption).

C/N min is the minimum carrier to noise ratio at the detector input =10 dBw. (Assumption).

Pmin = -133.97+9+ 10

= - 114.97 dBw

= -84.97 dBm

Finally the dynamic range for the receiver should be measured. Typically it is between 40 dB and 80 dB [5].

Dynamic range = P1dB - Pmin

Where,

P1dB is the input 1dB compression point.

Pmin is the sensitivity of the receiver.

P1dB= 1dB output compression point –Gain +1

Where,

Gain = (GLNA +G RF filter) = 15-3=12dBw

P1dB=0 dB-(12) +1= -11 dBw

So,

Dynamic range = -11-(-84.97) = 73.97 dBw.

3 LNA Design and Introduction

Before going into the details of the LNA look at the basic block diagram again.

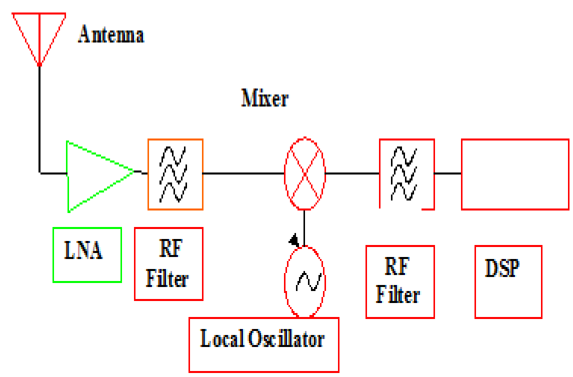

Figure 3.1: Receiver Block Diagram

Usually for a radio receiver front end the first stage element is a low noise amplifier (LNA). The LNA is very important for a high performance Radio frequency receiver. It plays a very important role to match the impedance as well. How to design a high performance LNA, depends upon the application, but there are different factors such as, Gain, stability, linearity, noise etc which determines its optimization. The design of the LNA has involved much effort during recent years to get the noise figure as low as possible and to get linearity to its highest possible limit. Our GPS receiver design is based on cascaded components. The noise performance of the given circuit is determined by the first few stages.

According to the formula for the calculation of the noise figure as follows:

$$F(Total) = F1 + \frac{F2-1}{G1} + \frac{Fn-1}{G1G(n-1)}$$

From the given equation it can be seen that noise factor of the first element clearly dominates the later stage elements provided that G >>1 which is of course in that case, so we design the first stage as low noise amplifier.

In this project LNA is at 1.57 MHz Typically GPS signal at receiver antenna are in the order of -150 dBm, while signal to noise ratio is around -20dB. This is very weak and it makes noise performance very poor as well. The bandwidth is between 2 to 20 MHz so the design will focus on noise performance of LNA, impedance matching linearity [3.1].

3.1 LNA Block Diagram

Below is the block diagram for LNA. It is a simple block diagram which gives the idea of how the circuit for LNA will look.

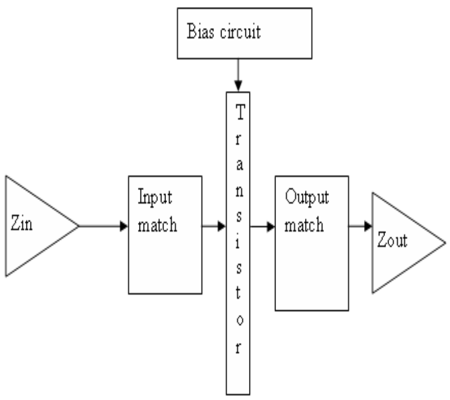

Figure 3.2: LNA Block Diagram

3.2 LNA Parameters

LNA has the following parameters.

i) Gain
ii) Noise Figure
iii) Unconditional stability
iv) Linearity
v) Input voltage

3.3.1 Gain

It is the ratio of output to input. For the LNA the value of gain is 15dB. It is not necessarily a fact that an LNA with maximum gain is very good. LNA is a nonlinear device and to make it linear there is a trade-off between gain and linearity. Because of the non linearity intermodulation products arise in LNA and as well in the receiver. So non linearity increases with gain, for that we choose an appropriate amount of gain depending upon the application to get the functionality appropriate.

3.3.2 Noise Figure

The GPS receiver is a combination of cascaded components. The LNA is the one of the components. Noise figure is the ratio which determines the LNA noise power to total noise for the receiver. The weakest signal a receiver can detect indicates the sensitivity of the receiver. If the LNA has more noise, then the noise floor will be will be higher and will make the receiver less sensitive. In this specification the noise figure of LNA should be <= 1.6 dB.

3.3.3 Unconditional stability

Whether the circuit is unconditionally stable or not depends upon the value of K. K is the factor whose value is determined by the following formula

$$K = (1 + |Ds|^2 - |S11|^2 - |S22|^2) / 2 * |S21| * |S12|$$

If K > 1 then circuit is unconditionally stable.

3.3.4 Linearity

Linearity is very important parameter of LNA. LNA is a non linear device. The transfer function for linear device can be written as.

$$V_{out.} = C * V_{in.}$$

If $V_{in.}$ is a signal having only one frequency component, then there will be no intermediation product. But active circuits are never completely linear. We need to understand non linearity in the way that it can cause intermodulation products to arise which can distort the output. Too large an input signal can overdrive the device which will distort the output. The transfer function for non linearity can be written as

$$V_{out.} = C * V_{in.} + c_2 * Vin^2$$

It shows clearly that there is a frequency component which if not present in the input signal which will distort the output.

3.3.5 Input Voltage

The LNA will operate at around 3Volts. The input voltage coming from GPS receiver will be 12Volts. LNA has a voltage regulator that converts 12Volts to 3Volts.

The GPS LNA can be designed by different methods depending upon the application process. The design can be of using discrete elements or lumped elements. By using a discrete transistor we get low noise figures in amplifiers. These days the requirements are small circuits and should be available very quickly in the market so as to fulfil these requirements pHEMPT technology is used. Still discrete elements have the lowest noise figure but pHEMPT has a noise figure almost same discrete components but they have other advantages as well which are:

1) Circuit is unconditionally stable at which frequency range.
2) Internal feedback which makes impedance matching easier
3) Their linearity is consistently high and they have low noise as well.

3.4 Selective Active LNA Device

Selection of LNA device is the first and most important step in LNA design as known to us these are:
Gain = 15dB
f = 1.57 MHz
N.F <=1.0 dB
Current assumption = 15 mA
Input voltage = +3V
The rule for any electronic design is that if you want to make a circuit faster then you have to keep in mind two things

1) The smaller the circuit the faster it is.
2) The less components there are the faster it is, and also less power consumption.

This means that the size of the circuit should be kept small and if the number of components is less than it will count towards faster speed as well.
To minimize the NF of amplifier the input matching should be tuned in such a way that we get the optimized value of ' Γ '(reflection coefficient). As simulations are not to be done at this stage but we need to note the values of Input Output reflection coefficient and $\Gamma_{opt.}$

3.5 How to extract Maximum Gain

In the design where NF is not the important parameter, we can attempt to conjugate a match to get the maximum possible gain from the transistor. At the same time we can provide good values for S_{11} and $S_{22.}$ There are certain circuit topologies which can be considered, these will be described in the future work not at this stage.

3.6 Final approaches for LNA Design

The design of a LNA involves many issues addressed throughout the discussion. This is the problem with any RF circuit design. The technology chosen for the LNA device for this application is pHEMPT technology. The discrete elements have the lowest noise figure of all technologies, but they have other disadvantages as well, such as linearization and gain etc. by using pHEMPT we can improve gain and linearity over a frequency range. The design will be made using advance system design.

4. Conclusion and Future Work

The GPS receiver is now in increasing demand for civil purposes. Its cost is falling and it has become more user friendly. An initial study has been done for a Superhetrodyne GPS receiver front end. The market demand is increasing, so the objective is to introduce a low power, efficient user friendly and low cost receiver. We have discussed the architecture of the Superhetrodyne receiver and its functionality. The main focus of the project was on the Low noise amplifier of the receiver. We have discussed the LNA architecture, its design and the issues involving in its design. The LNA gain is 15dB and its noise figure should be below 1.6dB. Input voltage is kept small to LNA to avoid overdriving because LNA is a non linear device and also the most important part of the receiver. So we need to avoid any intermodulation produced by non linear devices including mixer. An enhancement mode pHEMPT technology will be used to design the LNA.

The design will be completed by using the software called advance system design. This is part of the future work. On the basis of the study done at this stage an LNA for a Superhetrodyne receiver will be designed. The results of the simulation should meet the LNA specifications mentioned above and in the end the whole simulation will be converted to a hardware circuit and will be ready to use.

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