ADS optimization design of GPS RF front-end circuit with auto gain control

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Abstract. A GPS RF front-end receiving circuit is designed in accordance with the superheterodyne. The stage of the mixer is three and the signal of hybrid frequency is optimized through multiple filters to suppress the image signal. The ADS is used to establish the simulation platform for the RF front-end receiving circuit based on the L1 wave band. The pre-LNA is used to reduce system noise while the auto gain control element is used to achieve a large dynamic range of the RF receiver front-end. The parameters of the RF front-end including sensitivity, noise figure, IP3 and other indicators were simulated by the software simulation tools. The results indicate that this circuit could successfully implement the down-conversion and reception of radio frequency signal and meet the requirements of the design.

1. Introduction

GPS (Global Positioning System) is a new generation of satellite positioning system developed by US Army in the 1970s. It is based on 24 satellites and can provide global, real-time and all-weather navigation service for the land, sea and air. The GPS receiver is the main tool for users to receive GPS signals. Its main task is to receive signals transmitted by GPS satellites and to obtain the necessary navigation and positioning information. Because the GPS satellite is in an elliptical orbit of 2020 kilometers, in order to reduce the cost and extend the life of the satellite, the signal power transmitted by the GPS satellite to the receiver is very weak. Moreover, after the atmospheric -ionosphere attenuation, building obstruction and other negative environmental factors, the average power of the signal which reaching the ground is only -160 dBw, which is about 1 billion times lower than the power of common TV antenna receivers. Such extremely weak signals require higher demands of the design of GPS receivers, especially in the sensitivity and dynamic range which need to be compatible with GPS signal characteristics [1].

The RF front-end is an important part of the receiver. The main function of it is to filter the GPS signal through the pre-filter and amplifier, then mix it with the sine wave signal generated by the local oscillator while the frequency of the original signal is converted into the intermediate frequency (IF) [2]. Finally, the modulo (A/D) converter converts the IF signal into a discrete time digital signal.

In this paper, the GPS RF front-end circuit is designed based on the superheterodyne circuit structure. The expected technical specifications are proposed in the second section of the paper. The third section analyzes the sensitivity, noise figure, dynamic range, cut-off point and other parameters of the RF front-end circuit. By comparing the relationship between the third-order intercept point and the noise figure of the system, the optimal combination is selected, which reduces the influence of the spurious signal generated by the dual tone jamming signal without increasing the noise figure of the receiver. The auto
gain control module (AGC) is arranged at the back end of the circuit, which solves the problem of large fluctuation of the instantaneous dynamic range of the RF front-end circuit, and provides an effective solution for realizing stable reception of large dynamic range of IF receivers with multiple RF links.

2. Overall design of GPS RF front-end

The superheterodyne structure is used in the main body of the system and the overall design block diagram is shown in Figure 1. Since the signal received by the receiver antenna includes other noise signal except the useful signal, the GPS signal and other noise signal should be filtered by the pre-filter to remove the out-of-band interference signal, then amplified by the pre-amplifier. The amplifier must have high gain and low noise, which is related to the noise figure of the entire system [3]. The output signal from the low noise amplifier is sent to the three-stage mixer, and the first stage mixer down-converts the GPS signal from L1 band to 175.42 MHz, then the other two mixers further down convert the signal to 35.42MHz and 4.309MHz. The local oscillator of three-stage mixer generates the oscillating signal of 1400MHz, 140MHz and 31.11MHz IF for the phase-locked loop. The reference clock of the phase-locked loop is local 10.23MHz IF which is consistent with the reference frequency of satellite clock.

The purpose of design for the RF front-end is to allow the signal to enter the subsequent processing circuitry successfully. Since the effective level of thermal noise and jamming noise should be a constant at the input of the Analog-to-Digital Converter (ADC), it is necessary to add a Self-Gain Control element (AGC) before the ADC [4]. When RF jam occurs, the AGC will quickly reduce the gain and maintain the input of the ADC at the initial active level, avoiding the effects of jamming signal on subsequent circuits.

![Figure 1. Overall design block diagram of the RF front-end system](image)

2.1. RF front-end circuit structure selection

There are three typical structures in the GPS RF front-end, which are zero intermediate frequency structure, low intermediate frequency structure and superheterodyne structure. The zero IF structure composed of few components and it has low power consumption with good image suppression, but the local oscillator signal will leak to the RF signal input which makes the output generate DC component, mixing the output signal and resulting in the jam to the circuit. The low IF structure down converts the signal to the lower IF instead of the baseband which make the DC offset be effectively controlled, but its ability of image supression is limited. The superheterodyne structure was proposed by E.H.Armstrong in 1918, which solves the problem that the original receiver generates weak signal and has poor stability, while the signal generated by this receiver has high selectivity and good frequency characteristics. The multi-level structure with the external high-Q value and higher order filters can suppress the image signal and jam of adjacent channels effectively [5].

In summary, although the superheterodyne structure has the circuit of the complicated structure, but it will not have the problem of DC offset, and the ability of image supression is good. This structure can obtain accurate selectivity and higher sensitivity by selecting the appropriate filter. Combining the advantages and disadvantages of the three receivers, the stability and reliability of the superheterodyne structure are significantly better than the other two. Therefore, the RF front-end of the receiver adopts a superheterodyne structure.
2.2. RF front-end AGC circuit design

In order to make sure the RF front-end have large dynamic range and ensure linear amplification of the receiving signal, the input signal level should be maintained in the appropriate range so that the receiver will not work properly since the input signal is too weak, nor does it jam due to the saturated input signal [6]. Adding an auto controllable gain element (AGC) to the multi-RF receiving link and adjusting the gain parameters of the AGC device can ensure the secondary gain of the system without affecting the total gain of the tuner module.

The composition of the AGC circuit is shown in the figure 2. It is composed of controllable gain circuits, level detected circuits, filters, comparators, and control signal generators. When the signal is input, the level detected circuit detects the level value of the output signal, and then the filter controls the output level to follow the change of the input level, the level U4 which is output from the filter is compared with the reference level through the comparators. By comparison, the error signal U5 is output. The function of the control signal generator is to convert the error signal U5 into the signal required by the variable gain circuit. This transformation is usually an amplification of the amplitude or a transformation of the polarity. The function of the controllable gain circuit is to change the gain with the change of the control voltage. When the gain of the circuit changes, the signal will not lead to the linear or nonlinear distortion. It also has a large dynamic gain range, which will directly affect the gain of the AGC system. The performance of the controllable gain circuit has a large impact on the technical specifications of the entire AGC system.

![Figure 2. Controlled gain element (AGC) circuit composition](image)

2.3. Project design and main indicators

The main technical indicators of the GPS receiver RF front-end circuit include sensitivity, system coefficient, working frequency band, intermediate frequency output power, IF output frequency, dynamic range. The choice of RF front-end is critical to the overall receiver performance and will directly impact subsequent signal processing. The main indicators of the RF front-end circuit of the receiver are shown in Table 1:

| Indicators                      | Numerical value |
|---------------------------------|-----------------|
| Working frequency               | 1500~1600 MHz   |
| Sensitivity                     | $>-133$ dBm     |
| Noise Figure                    | 6.5 dB          |
| Dynamic Range                   | 130 dB          |
| Spurious free dynamic range     | 100 dB          |
| IF output frequency             | 4.309 MHz       |
| IF output power                 | 0 dBm           |
3. Rf front-end system behavior level simulation and analysis

According to the overall design block diagram, the simulation block diagram of the system built with the ADS software is shown in Figure 3.

3.1. Band Selective Simulation

The band-selective simulation of the receiver is shown in Figures 4 and 5. As shown in Figure 4, the receiver gains 39.53dB at the center frequency of the filter. There is approximately 57 dB of attenuation at 230 MHZ off center frequency. As is shown in Figure 5, the fluctuation in the RF front-end band of the receiver is less than 0.3 dB and it proves that the circuit has good stability.

3.2. System Link Budget Simulation

The system budget gain of the receiver is simulated in the AC analysis. The input signal power is set to -130 dBm. As is shown in Figure 6, the overall gain of the system in the various modules of the circuit is revealed. The total gain of the system is 130dB. The output IF signal is processed by the receiving AGC component while the power is about 0dBm, which means the system has good stability.
3.3. System noise figure simulation

The noise figure is a physical quantity used to measure the noise characteristics of a linear circuit or system. Through this measure the noise performance of different circuits are compared. In a consumable two-port network, the noise figure is defined as the ratio of the signal-to-noise ratio at the input to the signal-to-noise ratio at the output[7], which is interpreted in the following equation:

$$N_F = \frac{P_{si}/P_{ni}}{P_{so}/P_{no}}$$

Or expressed in dB as:

$$\left( N_F \right)_{dB} = 10\log_{10}\left(\frac{P_{si}/P_{ni}}{P_{so}/P_{no}}\right)$$

For systems where multiple two-port networks are cascaded, the total noise figure of the system can be expressed as:

$$F_{cas} = F_1 + \frac{F_2-1}{G_{A1}} + \frac{F_3-1}{G_{A1}G_{A2}} + \ldots + \frac{F_n-1}{G_{A1}G_{A2}\ldots G_{An-1}}$$

Where the parameter $P_{si}/P_{ni}$ and $P_{so}/P_{no}$ in equation (2) represent the signal-to-noise ratio at the input and output respectively. Parameter $F_n$ is the noise figure of the nth level and $G_{An}$ is the gain of the nth level. It can be judged that the first-stage gain and noise figure of the system have a great influence on the noise figure of the whole system, because the noise figure of the latter stage is reduced by the gain of the previous stage. Therefore, the key to reduce the total noise figure is to reduce the noise of the first stage or increase the gain of the first stage. In this system, the preamplifiers are low noise amplifiers to reduce the overall noise figure. The simulation results of the noise figure are shown in Figure 6. Figure 6 shows that System noise figure fluctuates between 6.5 dB and 7 dB with input power, When the input power reaches the GPS signal power (-130dBm), the noise figure is 6.5 dB.

3.4. Sensitivity

The sensitivity of the receiver refers to the lowest input signal level that the receiver can detect at a certain signal-to-noise ratio. Since the GPS signal is attenuated by the unfavorable environmental factors, the actual strength of reaching the ground is only -130 dBm, therefore, high sensitivity is critical to the receiver. The receiver sensitivity calculation formula is:

$$S = -174 \text{ dBm} + 10\log(BW) + NF + \frac{E_b}{N_0}$$

Where the BW(1KHz) is the receiver bandwidth, and the noise figure NF is about 6.5dB according to Figure 7.SNR is set to 5 dB, the system sensitivity is 132.5dBm as shown in the equation (5), which is corresponding to the system design indicators.

$$S = -174 \text{ dBm} + 10\log(BW) + NF + \frac{E_b}{N_0}$$

Figure 7. System noise figure simulation
3.5. Optimization design of the third-order intercept point optimization design

When two strong interfering signals of a certain frequency are input to the receiver, the two signals will be mixed due to the zero-linear action of the active device, and a spurious signal is generated, which is called the intermodulation product. When the intermodulation products fall within the passband, an interference signal is formed to produce nonlinear distortion.

In general, the second-order and third-order intermodulation distortions have great influence. The product of the second-order intermodulation can be generally filtered by the RF front-end preselector which is composed of a band-pass filter. The third-order intermodulation can be reduced by narrowing the filter bandwidth, but the relative bandwidth of the preselector used in the RF front-end is 20% and it is difficult to achieve such narrow bandwidth of the preselector[8]. In the GPS receiver, due to the high signal density, when two strong interfering signals fall into the passband at the same time, the probability of generating corresponding spurious products in the tuning band of the receiver is very high, which will lead the system to distorted. The third-order intercept point is usually used as an important indicator to measure the linearity and distortion of the system. Therefore, it is necessary to test the third-order intermodulation distortion characteristics of the system and determine the third-order truncation point of the system, so as to optimize and improve the actual design of the receiver.

3.5.1. Test of the third-order intermodulation distortion characteristic

Two equal-amplitude two-tone signals at the frequency of 1575.42 MHz and 1227.6 MHz are input in the RF front end of the receiver, which is corresponding to the two bands of the GPS signal. In Fig. 8, the power unit are logarithm. The curves a and b are the fundamental component and the cubic component of the Fourier frequency response of the weakly nonlinear system respectively, and the linear portions of the two curves are extended, the intersection is the third-order intercept (16.754 dB) of the system's equal-amplitude two-tone signal intermodulation input.

![Figure 8. Third-order intermodulation distortion characteristic test](image)

3.5.2. Relationship between third-order intercept point and system noise figure

The higher the third-order intercept point, the influence of the spurious response generated by the inter-band strong signal intermodulation is less. However, as the intersection point increases, the noise figure of the system will also increase according to the simulation results. The relationship between the third-order intercept point and the system noise figure is obtained by adjusting the gain and noise figure of the low-noise amplifier in the band. As is shown in Figure 9, the noise figure is 6.5dB while the third-order truncation point of the system is about 16.5 dB, which is consistent with the simulation results. In the simulation process, after selecting the appropriate noise figure, it is necessary to determine whether the third-order intercept point is suitable for the range that the system can withstand. In the actual design of the receiver, a compromise is usually adopted to balance the noise figure of the receiver with the third-order intercept point. In that way the whole system has both a low noise figure and good anti-interference ability.
Figure 9. The relationship between the third-order intercept point and the system noise figure

3.6. Dynamic range and 1dB compression point
When the power of the signal drops 1dB from the ideal state, this point is called 1dB compression point (P1dB), which is a parameter of the output power. The higher the compression point, the higher the output power. The simulation result is shown in Figure 10. As is shown in the figure, the P1dB of the system is about 1.215 dBm.

The dynamic range (DR) of the receiver is the definition of a magnitude range that the receiver can detect the GPS signal but not cause the distortion of the input signal [9]. The relationship between the dynamic range and the 1dB compression points is determined by:

\[ DR = P_{1dB} - S \]

where S is the sensitivity in section 3.4, with this equation, the dynamic range of the system is calculated as 133.715 dBm, which meets with the design specifications.

Figure 10. RF front-end circuit 1dB compression point simulation

4. Conclusion
The optimization design of GPS RF Front-end Circuit with Auto Gain Control is reported. The following conclusions are drawn:

1) Since the power of GPS signal propagating to the ground is very weak, the specific characteristics of the GPS signal must be considered when designing the GPS receiver, especially its RF front-end circuit. Moreover, the appropriate circuit topology should be selected to make it have higher sensitivity and good stability;

2) The superheterodyne structure has strong suppression for image signal and adjacent channel interference. The simulation results show that the circuit has good linearity, high sensitivity, large dynamic range, and strong capability for dealing with the useful signal in the situation of large interference.
3) According to the actual simulation results, when designing the third-order intermodulation distortion of the RF front-end circuit, the receiver noise figure should be taken into consideration. The parameters of the circuit should be adjusted according to the simulation results of the third-order intermodulation distortion characteristics. The optimal combination will avoid the receiver to bring a large noise figure due to the reduction of intermodulation products, which deserves attention when designing this type of circuit.

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