An anti-image interference quadrature IF architecture for satellite receivers

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Abstract Since Global Navigation Satellite System (GNSS) signals span a wide range of frequency, wireless signals coming from other communication systems may be aliased and appear as image interference. In quadrature intermediate frequency (IF) receivers, image aliasing due to in-phase and quadrature (I/Q) channel mismatches is always a big problem. I/Q mismatches occur because of gain and phase imbalances between quadrature mixers and capacitor mismatches in analog-to-digital converters (ADC). As a result, the dynamic range and performance of a receiver are severely degraded. In this paper, several popular receiver architectures are summarized and the image aliasing problem is investigated in detail. Based on this analysis, a low-IF architecture is proposed for a single-chip solution and a novel and feasible anti-image algorithm is investigated. With this anti-image digital processing, the image reject ratio (IRR) can reach approximately above 50 dB, which relaxes image rejection specific in front-end circuit designs and allows cheap and highly flexible analog front-end solutions. Simulation and experimental data show that the anti-image algorithm can work effectively, robustly, and steadily.

1. Introduction

As GNSSs are developing rapidly, radio frequency (RF) signal congestion for the allotted spectrum becomes significant. Specifically, signals, such as B2 (Beidou), L5 (GPS), E5 (Galileo), L3 and L5 (Glonass) in 1154–1226 MHz (L-band); L2 (GPS), L2 (Glonass) in 1226–1260 MHz; B3 (GPS) and E6 (Galileo) in 1260–1300 MHz, occupy the relatively small bandwidth allocated for satellite navigation. As a result, image interference becomes a potential problem for satellite receivers. Digital receivers with quadrature IF architectures are becoming very popular for satellite signal reception. This kind of architecture has received a great deal of interest and becomes the main choice for use in single-chip digital receivers, but it is vulnerable to mismatches caused by any gain or phase imbalance between the I/Q paths in a system. As a result, an image is aliased into the signal passband. This problem must be solved, or else it will degrade the performance of a receiver. This paper...
investigates the image aliasing problem and a novel solution is developed. Besides, typical receiver architectures are also analyzed in view of the image aliasing issue.

2. Receiver architectures

In wireless receiver systems, a heterodyne architecture implies a high/low-IF or digital IF device architecture. A direct down conversion receiver down converts a received RF signal into a complex baseband signal directly; a heterodyne receiver, on the other hand, requires an IF stage to down convert the RF to an IF before demodulating the received analog signal to a complex baseband signal.

2.1. Heterodyne receiver architecture

A heterodyne architecture is utilized in most modern RF communication receivers. Fig. 1 shows an example of this design. LO1 and LO2 in Fig. 1 mean the first and second stage local oscillator. LNA refers to low noise amplifier and IR is short for image rejection. With a collection of discrete-component filters, this architecture is implemented with various active semiconductor device fabrication technologies such as gallium arsenide, silicon bipolar, and Complementary Metal-Oxide-Semiconductor (CMOS). In heterodyne receiver architectures, the sideband image caused by the I/Q phase and gain mismatch is located at twice the IF distance from the primary carrier, and therefore the quality of the desired signal is not significantly affected by I/Q imbalance. However, the sideband image should be eliminated by appropriate filtering (such as a low-pass filter or a bandpass filter) or otherwise suppressed sufficiently so that optimum receiver performance is maintained.

A heterodyne receiver asks for high-Q character of these discrete components which makes it difficult and even impractical to implement as an integrated solution at high frequencies; therefore this solution is not suitable for cost and area designing considerations.

2.2. Direct conversion receiver (homodyne)

Homodyne, zero-IF and direct conversion systems use the same basic topology: the local oscillator (LO) frequency is equal to the input carrier frequency in this type of receiver. Fig. 2 shows the basic design of a homodyne receiver architecture.

Direct down conversion architectures do not include an IF stage between the RF signal and the baseband. The RF input signal is received and then directly demodulated. This approach clearly implies that the RF input frequency and the LO frequency are the same.

Obviously, a direct conversion receiver is easy for higher levels of integration, but problems are associated with this architecture. The unintentionally transmitted LO signal may reflect off of nearby objects and be “re-received”, consequently self-mixing with the LO resulting in a time-varying direct current (DC) offset. Additionally, because the sideband image resulted from the I/Q phase and gain mismatch is located at the baseband frequency and overlaps with the desired carrier signal, an appropriate adaptive digital signal processing used to correct the image component must be considered.

2.3. Wide-band IF with double conversion receiver

Wide-band IF with double conversion is another good choice for integration. As shown in Fig. 3, with a single-frequency local oscillator, all the potential channels and frequencies are translated from RF to IF. Compared with heterodyne receivers, this approach also implements the frequency translation in multiple steps. However, the difference is that for wide-band receivers, all of the receive channels are translated by the first local oscillator frequency, maintaining a large bandwidth signal at IF. The channel separation can be realized at baseband.
Two potential advantages can be offered by the wide-band IF architecture. Firstly, the local oscillators operate at different frequencies as the incoming RF carrier. Consequently, the LO retransmission problem which plagues a direct conversion system and results in a time-varying DC offset is eliminated. Considering the same frequency between the second local oscillator and the IF desired carrier in the wide-band IF system, a relatively constant DC offset is produced at baseband by self-mixing, but it may be cancelled using one of the proposed methods described in Refs. 10, 11, for example a high pass filter.

Another advantage is image-rejection ability. For the two frequency translations occur in cascade, the implementation of the image-reject function can be achieved using a six-mixer configuration. This image-rejection mixer shares a similarity to the Weaver technique 12 which can be best understood using a frequency domain interpretation for a real value input signal as indicated by Fig. 4. $F_{LO1Q}$ and $F_{LO1I}$ in Fig. 4 represent for the first stage local oscillator frequency of quadrature and in-phase channels, while $F_{LO2Q}$ and $F_{LO2I}$ represent for the second stage local oscillator frequency of quadrature and in-phase channels. By properly adding four baseband channels in pairs, the desired band can be made constructively for both I/Q channels while the image frequencies being cancelled. The outputs of both I/Q channels contain two frequency components, labeled as 1 and 4 in Fig. 4. Notice that component 4 is the conjugate of 1 for the quadrature output channel, and as a result, the quadrature and in-phase channels always remain orthogonal. Meanwhile, for the reason that 2 and 3 is opposite, they can be cancelled by the combination. And $j$ in Fig. 4 is for conjugate denoting imaginary part.

As with conventional image-rejection mixer systems, 13–16 the magnitude of the image attenuation in the wide-band IF architecture is a function of the phase mismatch between the inphase and quadrature phases of the first and second local oscillators and the gain difference between the I/Q signal paths. The IRR as a function of the mismatch is given by Ref. 5.

$$\text{IRR} = 10 \cdot \lg \left[ \frac{1 + (1 + \Delta A)^2 + \Delta A \cos(\phi_{1i} + \phi_{2i})}{1 + (1 + \Delta A)^2 - \Delta A \cos(\phi_{1i} - \phi_{2i})} \right]$$

where $\phi_{1i}$ and $\phi_{2i}$ represent the deviations between I/Q local oscillators in the first and second LOs, respectively. $\Delta A$ is the aggregate gain error between the I/Q signal paths. A plot of Eq. (1) is given in Fig. 5, in which $\Delta A = 0.04$ ($A$ is normalized to 1). Using this approach, most applications can reach 35 dB of image-rejection at best, in which the phase error of the local oscillator can be no greater than $2^\circ$ and the gain error between any two of the four signal paths must be less than 3.6%. 9

2.5. Proposed low-IF architecture

The proposed low-IF architecture is similar to the wide-band IF architecture except the analog-to-digital converter’s place and the anti-image engine block as indicated in Fig. 6. All the potential channels and frequencies are translated to IF using a mixer with a single-frequency local oscillator.
appropriate filtering, the channels are all converted to digital signals by the ADC. A digital down converter (DDC) converts the channel selected from IF to baseband and completes the task of channel selection. Selection is completed in the digital domain which gives the architecture flexibilities. Because the down conversion is completed in a complex (I/Q) mode, the signal and image can be selected after combination by the “I+jQ signal select” block (I is for the real part and Q is for the imaginary part). The signal and image are then fed into the anti-image engine block. Here, several parameters must be adjusted smartly so that the image can be stripped off above 60 dB. The proposed architecture looks much like the Weaver architecture, except that the second stage of mixers is done in the digital domain. The overall image-reject ability gives a great margin to integrated circuit fabricating specifications thus saving cost and enhancing performance especially for a low-cost receiver.

3. Complex LMS anti-image engine

The complex down-conversion is completed by multiplying the desired RF signal with a complex LO carrier, as indicated in Fig. 7. $F_{LO2}$ means the second stage frequency. Sig is short for signal and Img for image. In practice, this is implemented by using two real mixers with cosine and sine LO carriers from a complex LO carrier to simulate the multiplication. The signal becomes complex after being down-converted and is represented by two real signals. Only the desired RF signal is down-converted to IF in case that the two real mixers are ideally matched. However, due to the gain and phase mismatches along the data paths, the unwanted image component will appear at the IF, attenuated by a factor $\delta$, which also represents the level of mismatch. This is defined as the “image rejection ratio” or “image leakage factor”. The desired signal and image vectors are known as $I+jQ$ and $-jQ$, respectively. The definitions of the signal and image vectors are interchangeable.

3.1. Previous anti-imaging receiver development

Both phase and gain mismatches between I/Q paths contribute to image energy. To achieve high image rejection, several anti-image techniques have been proposed. One method is analog calibration techniques using variable gain and phase (delay) cells. Another method is to inject a test tone, and then the gain and phase errors of the Sig and Img are evaluated by an I/Q imbalance estimation algorithm and compensated

![Fig. 5](image1.png) Image rejection as a function of LO phase mismatch.

![Fig. 6](image2.png) Proposed receiver system with a digital anti-image engine.

![Fig. 7](image3.png) Complex down-conversion with image leakage.
digitally at last. However, the problem is that all these offline calibration techniques tend to be not accurate enough for all signal conditions. As a result, online without training signal is desirable if all signal conditions are considered. Several digital image rejection techniques have also been suggested recently. Some low-IF receivers choose a digital compensation algorithm of interference cancellation or blind signal separation, but the performance is strongly dependent on the accuracy of the parameter estimation. A symmetric signal separation by decorrelation can also be used to correct the I/Q mismatch and it is basically a complex adaptive filtering algorithm applied symmetrically to both the Sig and Img paths. Although the decorrelation algorithm is generalized in concept, it does not appear in GNSS receiver designers’ consideration yet. Even the complex adaptive filtering algorithm can be used in general GNSS receivers, the traditional multi-tap decorrelation process will not converge correctly for multi-frequency GNSS receivers, because there are two or more different frequency channels existing simultaneously. In this paper’s work, the same decorrelation algorithm is modified for one complex tap only.

3.2. Complex least mean square (LMS) anti-image concept

The foundation of digital image rejection mainly lies on the assumption that there is no correlation between the signal and the image. Fig. 8 shows a simplified block diagram of the LMS anti-image algorithm. The image component is separated by the standard LMS algorithm from the signal. \( \delta \) and \( \delta' \) in Fig. 8 mean the actual leakage factor from Img into Sig and the estimated factor respectively, and * means conjugate. After the estimated complex Img, \( \delta' \times \text{Img} \) is subtracted from the complex Sig which contains the Img, and the Img component in the Sig becomes \( (\delta - \delta') \times \text{Img} \). The polarity of \( (\delta - \delta') \) can be calculated by filtering the correlation result of \( (\delta - \delta') \times \text{Img} \) and the complex conjugate of the Img. Then the value of \( \delta' \) can be adjusted with this polarity until the complex Img disappears from the desired Sig. Fig. 8 shows the basic idea of the anti-image process. LPF means low pass filter. One of the signal loops represents the adaptive cancellation of the image leakage into the signal, and the other loop is for the signal leakage into the image.

3.3. Architecture for digital anti-image

The proposed anti-image receiver architecture is further detailed in Fig. 9. \( \omega_k \) in Fig. 9 means carrier frequency. Firstly, signals are down converted by an I/Q mixer, and then the complex baseband I/Q signals are filtered and converted to digital signals by an ADC. The LMS error of the Img component leaking into the Sig is detected by \( w_i(k) \), which are adaptive filters. Similarly, the Sig leaking into the Img is detected by correlating the signal leakage with the conjugate of the Sig. These two adaptive filters will not be exactly conjugate if the two leakage paths have different gains. In most cases, the leakage is symmetric. For this paper, considering the two signal channels existing at the same time, the adaptive filter is optimized to one tap only, ensuring correct and steady convergence ability. Note that the DC component will accumulate and make an LMS error. Here, we assume that two signals \( y_i(k), y_2(k) \) can be written as

\[
y_i(k) = s_i(k) + h_i(k) \otimes s_j(k) (i = 1, 2; j = 2, 1)
\]

where \( s_i(k) \) and \( s_2(k) \) represent the uncorrelated Sig, \( h_i(k) \) is for transferring function. Both \( y_1(k) \) and \( y_2(k) \) have \( s_1(k) \) and \( s_2(k) \) components. “\( \otimes \)” means convolution. The signal leakage problem can be modeled by Eq. (2). “\( k \)” means value at “\( k \)”

Fig. 8  Complex LMS anti-image concept.

![Complex LMS anti-image concept.](image)

![Fig. 9  Proposed anti-image architecture.](image)
shown in Fig. 10. $F_{RF}$ means RF frequency. Part $A$ generates the normal signal source. The image signal is imported in part $B$, which works in the analog domain. $\delta$ and $\theta$ refers to gain and phase mismatch respectively. In part $C$ of Fig. 10, the complex incoming Sig of part $B$ is further down converted by a local DDC, and there are four channels after the DDC operation behind the combiner block. $w$ in part $B$ and part $C$ refers to local frequency used in down conversion. Then the anti-image engine works on the four channels and separates Img from desired Sig and the results are shown in part $D$.

The response magnitude of part $D$ in the absence of the anti-image engine is shown in Fig. 11(a). The image aliasing can be clearly seen. This is an example with single-tone interference located inside the COMPASS signal band so that the signal and interference can be visually separated. In this case, conventional filtering would not be used because the interference signal is located inside the signal band. It can be seen that the single-tone interference is clearly cancelled in Fig. 11(b). Fig. 12(a) shows a more realistic scenario, with overlapped signal and image. Fig. 12(b) shows the mended output after applying the image-reject engine under wide-band interference. We can see that the image interference has corrupted the desired COMPASS signal and after the engine we get an almost clean desired signal. Fig. 13(a) and Fig. 13(b) also show the convergence lines in this case which show a rapid converging period. Fig. 14(a) shows the “eye” diagrams of the output before applying the image-reject engine. In Fig. 14(b), it can be seen that the proposed image-reject engine makes the eyes wide open and clear, which means the channel mismatch is well compensated and the signal to noise ratio (SNR) can reach to about 20 dB. Fig. 15 shows that the image part can be well rejected when there are even two strong signals existing, which can not be completed by traditional multi-tap decorrelation algorithms, and as a result, Fig. 15 demonstrates the superiority of the one-tap decorrelation algorithm adequately.

The fundamental function of satellite receivers is to measure the pseudorange, and the accuracy of pseudorange measurements being approached is determined by the variance of the tracking loop. Table 1 gives the simulation result when there is image interference. The GNSS signal chosen is COMPASS L1 and the SNR is 20 dB, while the image level added is showed in Table 1. It can be found that when the image is within about 56 dB, the tracking standard deviation is rather small, which means that the receiver can get a relatively precise pseudorange measurement result. The mismatch given in the front channel for Table 1 is 10% for magnitude and 1.6% for phase unbalance. Compared with phase imbalance of $1^\circ$–$2^\circ$ and amplitude imbalance of $1$–$2\%$ which can be reached by careful analog design,23 this is a very large unbalanced assumption parameter with enough unbalanced margin for a RF link. Simulation results show that for one-path image interference, the anti-image engine has a good performance of wiping off, for both one-tone and wideband-width image interference. The dynamics of the anti-image algorithm is determined by the step of the adaptive filter related to the filter coefficients. For rapid responses, the step should be adjusted bigger, but sacrificing convergence smoothness at the same time.

4. Test and conclusion

This section describes the experimental test platform of the architecture proposed in Section 2. The target application is a complex IF test platform. This implementation proves that

![Fig. 10 Dataflow of anti-image algorithm simulation.](image)

![Fig. 11 Single-tone image in baseband output spectrum.](image)
the anti-image quadrature IF architecture works well in a real electronic environment.

The experimental test platform includes a signal generator, a noise generator, and a Virtex5 XC5VFX70T evaluation board in which an anti-image quadrature IF architecture is implemented. The Virtex5 XC5VFX70T evaluation board embeds a power PC processor thus making it very powerful and flexible. A signal from the signal generator is modulated at L1 band and interference is located at 140 MHz upward from L1. The first down conversion described in Section 3.4 is implemented using an RF ASIC chip NUMAN D03 produced by Chinese academy of science, institute of automatic (CASIA). The image interference is added artificially and its energy is scaled large enough to make sure that the anti-image algorithm can be fully evaluated. The IF chosen is 16.02 MHz after the first down conversion and mismatch are imported. The second DDC down converts the modulated signal IF to zero and the anti-image engine is activated. Fig. 16 shows the comparison before and after implementing the anti-image engine under very wide-band interference image. The baseband data is captured using the “ChipScope” technology and then plotted using Matlab. It can be seen that the signal can be recovered even if the entire signal is submerged by image interference.

Image aliasing due to the I/Q channel mismatch is always a big concern in realizing quadrature IF receivers. The imbalance between I and Q channels exists along signal paths in subsystems such as the mixer and the modulator. The new quadrature IF receiver architecture proposed in this paper uses

**Fig. 12** Wide-band image in baseband output spectrum.

**Fig. 13** Mismatch convergence lines of anti-image engine.

**Fig. 14** Eye diagrams for baseband output signals.
a simple but effective algorithm to correct the mismatch. An experimental platform is implemented and results from simulations and real-time tests prove that the algorithm is feasible and stable. The anti-image IF architecture loosens the anti-image requirements for front-end circuit designs and gives more choices for single-chip integration receiver solutions.

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References

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