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Optimization of GNSS Signals Acquisition Algorithm Complexity Using Comb Decimation Filter

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***Abstract*—GNSS system is one of the most widely used *wireless* systems. A GNSS receiver must lock on satellite signals effectively and quickly. The fastest known algorithm to solve this problem is based on the Fast Fourier Transform(FFT) and the Invert Fast Fourier Transform(IFFF). This paper proposed a novel architecture to implement GNSS signal acquisition system on digital IC or FPGA. Former researchers tended to use FIR filter to compensate for the CIC filter. By adding the CIC filter only, the proposed system aims to reduce the overall calculation complexity by reducing the FFT size. By simplifying the calculation of GNSS acquisition, the memory usage efficiency will be highly improved. Additionally, there will be a significant reduction in GNSS system power consumption.**

General Terms : GNSS, IFFT, FFT, Acquisition, Decimation, CIC filter.

Keywords: Microwave and millimeter wave devices, circuits, and hardware

I. INTRODUCTION

The Global Navigation Satellite System(GNSS) is one of the most pervasive wireless technologies. GNSS receivers have been widely applied in civilian technologies, scientific research as well as military. And acquisition is a vital technique of the receiver's baseband signal processing. Synchronizing with the satellite signal, however, is a costly process that requires tens of millions to billions of digital multiplications. A large fraction of power is consumed by the synchronization process (30% to 75% depending on the required accuracy), so the new design is expected to conduct a significant reduction in GNSS system power consumption.

CIC filter is widely used in the digital signal processing field because of its low complexity, but the filter exhibits high pass-band droop, so FIR filter is used to compensate the droop, but FIR is two complex and has canceled out the benefit of CIC[2], compensation filter using the least square criterion is also used to compensate the droop[18], but for the GNSS signal has high SNR, the compensation can be deleted in the practical GNSS acquisition process, and the accurate frequency estimator can be done in the tracking loop process or use more accurate FFT[1-5,17].

This paper proposes a practical implement GNSS acquisition circuit, in which the CIC decimation filter, FFT, and IFFT are used. It gives a practical implementation to simplify the algorithm and can be implemented on digital IC or FPGA. The paper is organized as follows: Section II presents the GNSS baseband processor model and explains the mathematical model, Section III provides details on the decimation algorithms and FFT/IFFT re-usage algorithm. And finally, in section IV, the decimation simulation result and the complexity improvement are analyzed.

II.GNSS BASEBAND PROCESSOR MODEL

Currently, mainstream commercial GNSS receivers generally employ the IF sampling front end and use the bandpass resampling strategy to downsample the IF[2]. A typical IF based GNSS receiver contains the radio frequency (RF), the intermediate frequency (IF), and the base band processor, as described in Figure 1. The system incorporates an intermediate frequency (IF) that is lower than the carrier frequency and higher than the baseband frequency. The use of an IF reduces the number of components that must be compatible with high frequencies, and simplify the design of bandpass filters before the ADC, because the reduced center frequency results in a lower Q-factor requirement. Besides, an IF-based system allows for more robust implementation of quadrature demodulation.

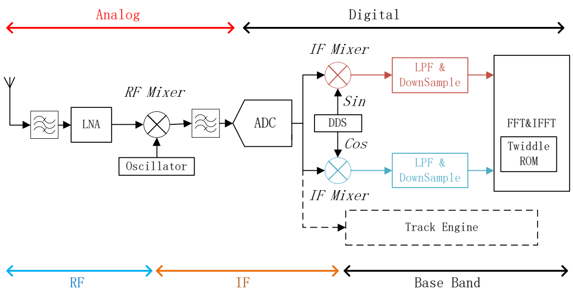

Figure 1 GNSS Receiver Architecture

At a high level, GNSS synchronization works as follows: each satellite is assigned a CDMA code. For each satellite, the

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receiver needs to align the corresponding CDMA code with the received signal. The process is complicated because GNSS signals are very weak (about 20 dB below the noise level)[1]. To find the right alignment of each satellite, a GNSS receiver conducts a search process. It computes the correlation of the CDMA code with the received signal for all possible shifts of the code concerning the signal. The correct shift is the one that maximizes the correlation. Long coherent integration time and more incoherent integration steps are efficient ways to improve the acquisition performance for weak GPS signals[1,2,3,4].

The traditional approach involves the received signal with the CDMA code of each satellite in the time domain. The correct alignment corresponds to the one that maximizes this convolution. This approach has a certain computational complexity. But it is not appropriate to be used in real-time applications. On the other hand, frequency-domain estimators based on FFT have the advantage of high computation speed and can easily be realized in hardware [17]. The low-cost GNSS modules use this way, but more high-end GNSS receivers or SDR-based GNSS receivers [2] lock on the satellite using frequency domain computation. The frequency domain computation based on the principle that the circular cross-correlation sequence between the two finite-length sequences with length N and with periodic repetition, which can be computed as the complex conjugate of the FFT translation [3,4]. FFT is a computation-efficient algorithm for computing a Discrete Fourier Transform(DFT). The algorithm multiplies the FFTs of the received and the FFT of the locally generated signal, which concludes to IFFT to be the resulting signal. The output of the IFFT spikes at the shift that correctly synchronizes the code with the satellite signal.[4]. By this method, the computational complexity decreases to $O(n\log(n))$.

Although, GNSS signal can use SFT to compute the IFF, and can achieve 1.5x-4x speed up. It does not practical for digital IC or FPGA design because IFFT and FFT structures are similar in hardware. Thus, the FFT module can be reused as IFFT, but the SFT cannot be reused.

Most importantly, a re-sampling strategy is proposed. In this way, the IF ADC data can be processed at a minimal data speed without losing the information. The front IF ADC usually runs at high speed to get better. Most of them are above 16Msps, which can help the GNSS track loop to get better performance [9]. The larger the bandwidth of the RF band, the better ADC could be used, additionally, the fewer errors the pseudo-range and phrase measure could get [9]. But in the signal acquisition stage, only coarse estimations of the code delay and carrier frequency shift need to be provided. More specifically, only the GPS C/A or BEIDOU B1I need to be processed, which has a code rate of 1.023Mbps. And it has two 2.046MHz lobes below and up the center frequency. So the ADC data can be decimated, as described in the bandpass sampling theory [2]. If a digital I(in-phase) and Q(quadrature-phase) mixer are used to move the ADC data to baseband, the ADC data rate can be decimated to 4.092MHz, which is the minimum data rate without losing the key information, as much as half of the data rate needed by bandpass sampling. Although the up and down 2.046MHz lobe will be aliased at low frequency, it can be split by I/Q separate processing easily [13]. By this operation, the FFT/IFFT size can decrease to the minimum requirement. For instance, the FFT/IFFT size turns to 4096 to calculate one millisecond ADC data's FFT, which is affordable for digital IC or FPGA. One millisecond is the repeat cycle of GPS C/A or Beidou B1I code.

III. Details on digital decimation algorithms and FFT/IFFT reuse algorithm

A. *Decimation processing*

The decimation operation is the key to reduce the acquisition algorithm complexity. A typical baseband ADC data has a 38.192MHz sample rate and 9.548Mhz IF. The oversampling strategy has been adopted to get the data, so these data can be down-sampled to the minimal requirement sample rate. Before the decimation, an I/Q channel 'IF mixer', as shown in Figure 1, is used to turn the IF frequency signal to zero frequency signal, then a low-frequency pass filter, as shown in Fig.4, is added to filter out the GPS C/A or BEIDOU B1I baseband signal, which included the Doppler drift. The low-frequency pass filter can avoid the signal alias caused by decimation [5]. A typical baseband system is taken as an example, and the decimation operation shows in Figure 1.

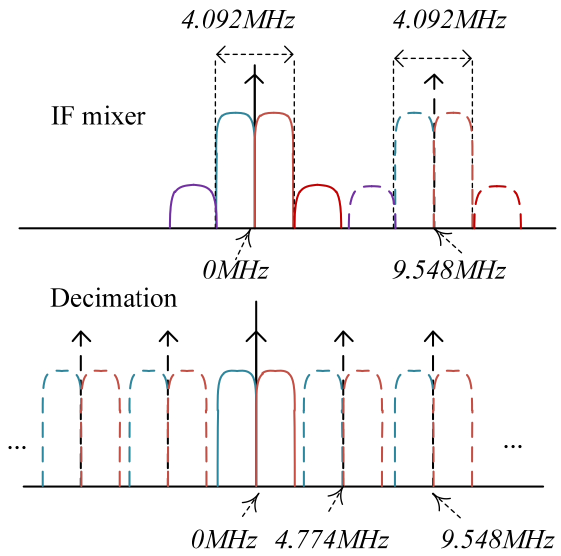

Figure 2 the effect of IF mixer and decimation

A low pass filter is needed to filter the mirrors caused by decimation. Combined with an interpolator or decimator, cascaded integrator–comb (CIC) is an optimized class of Finite Impulse Response (FIR) filter. CIC has low computation complexity and usually uses fixpoint adders for it only has delayed and added units. A typical CIC filter structure is as Figure 3[15], and the Comb and Integrator stage can exchange as needed.

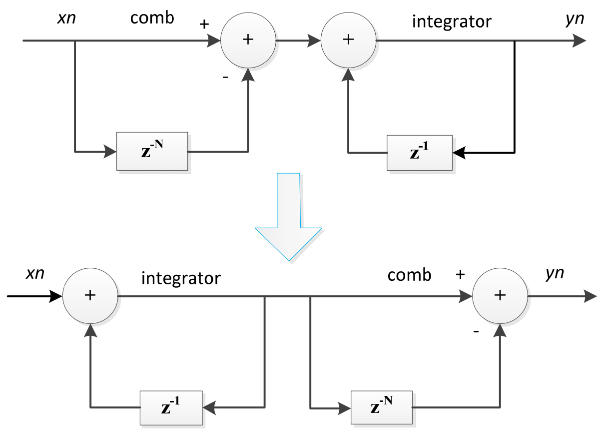

Figure 3 CIC Filter

The 4-order CIC low pass filter is designed in Matlab with a decimator factor of 8, which can convert the 38.192MHz sample rate to 4.774MHz. The frequency-domain response is shown in Figure 4. As Figure 4 shows, the CIC filter has some gain ripple in the passband. Former researchers tended to use the FIR filter to compensate for the CIC filter.

Based on the GNSS IF sample data of Kai et al [4], operating Acquisition Algorithm with Matlab GNSS, the gain ripple does not affect the acquisition process, as Figure 5 Acquisition result with CIC decimation filter shows, it works well without the FIR filter. The same result has been concluded after we used the SDR platform(Limesdr) to sample.

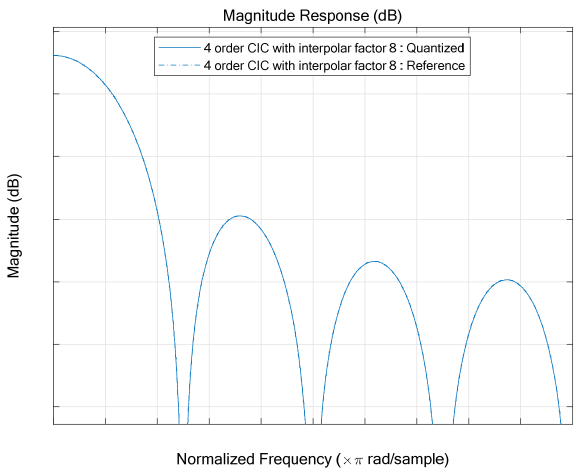

Figure 4 Alias low-pass filter frequency domain response

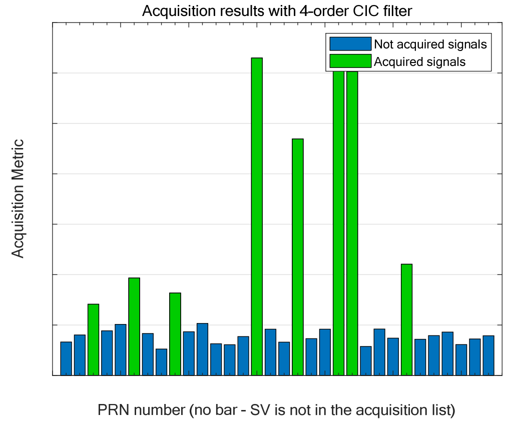

Figure 5 Acquisition result with 4-order CIC filter

After the decimator, the data rate has been slow down, and the FFT size also decreased by the decimator factor, so the computation complexity decreases at the cost of adding a CIC low pass filter.

B.FFT/IFFT Re-usage

Based on the following equation, the FFT of conjugated X(k) is the conjugated result of IFFT of x(n), so the FFT logic can be used to calculate IFFT by simple conjugate operations.

$$FFT\!: X(K) = \sum_{n=0}^{N-1} x\,(n) * e^{-i*2*pi*n*k/N} \quad for \quad k = 0 \ldots N-1$$

$$X^*(K) = \sum_{n=0}^{N-1} x^*\,(n) * e^{i*2*pi*n*k/N} \quad for \quad k = 0 \ldots N-1$$

$$IFFT\!: x(n) = 1/N * \sum_{n=0}^{N-1} X\,(k) * e^{i*2*pi*n*k/N} \quad for \quad n = 0 \ldots N-1$$

IV. Result and Improvement Analysis

A. Acquisition Result

The Matlab-based GNSS Software Defined Radio (SDR) is introduced in [4,9]. With a modified acquisition algorithm, adding the CIC decimation filter and using a logged IF data, which has 38.192Mhz sample rate and 9.548Mhz IF, the simulated acquisition result is shown in Figure 6 and Figure 5. It shows that the modified acquisition code works well. Figure 6 shows the original acquisition result in [9]. The acquisition result with 'decimation and CIC' showed in Table 1, Table 1 shows the difference between the two is less than 0.11, which is in the range of GNSS code loop's bandwidth.

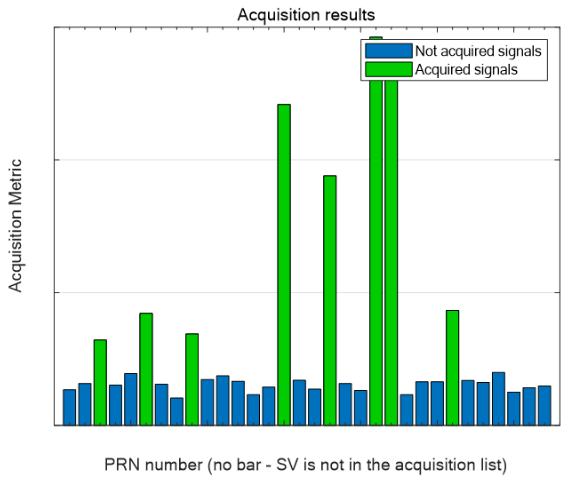

Figure 6 The original track result without CIC

TABLE I. CODE OFFSET WITH AND WITHOUT CIC

Sat No.	Original	Decimation	Difference
21	359.0357	358.9286	0.1071
22	168.4286	168.4286	0
15	972.8839	972.8571	0.0268
18	555.1071	555	0.1071
26	718.5804	718.5	0.0804
6	755.4107	755.3571	0.0536
9	125.7857	125.7857	0
3	916.3928	916.5	-0.1072

As described earlier, the GNSS signal has high SNR, although the CIC has high pass-band droop, it still works well without compensation, as shown in Figure 7.

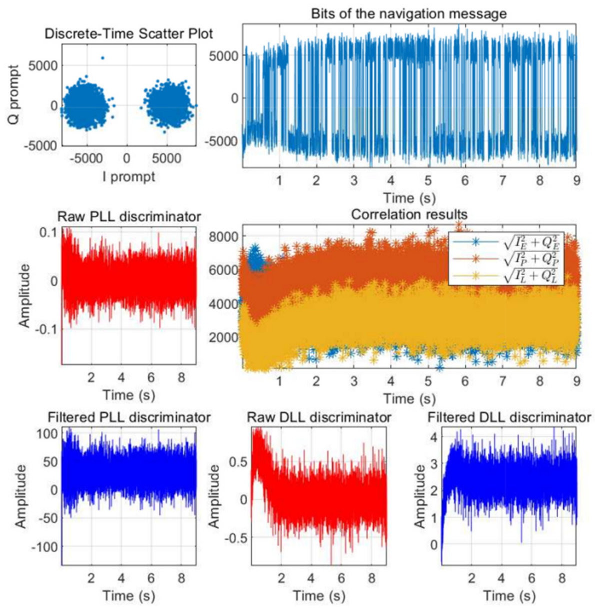

Figure 7 GNSS tracking result with the acquisition result using CIC

B. *Complexity Analysis*

If the decimation operation is used, the FFT/IFFT size can be decreased, at nearly no cost, for the CIC filter don't need multiplication operations. So, the computation complexity decreases by the decimation factor of the CIC filter. And the memory usage also decreased for the FFT/IFFT size's decrease. Even if the decimation factor is set to 2, the new system still would have some advantages from the perspectives of reducing algorithm complexity and memory usage efficiency.

V. CONCLUSION

CIC decimation filter can be widely used in the high IF structure GNSS receivers which is the mainstream architecture. And the CIC decimation filter can speed up the acquisition algorithm significantly. More importantly, the FFT/IFFT hardware can still be reused, the FFT/IFFT memory usage will also decrease to an affordable degree. The acquisition algorithms can be implemented in digital IC or FPGA practically.

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