Research on VLBI Digital Baseband Converting Methods Combining the Efficient Uniform Channelization with the Orthogonal Mixing

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Abstract To meet the special requirement of full spectrum processing in deep space TT&C, a new efficient VLBI baseband converting method, which can realize the processing of certain bandwidth without distortion and dead zone, is proposed. The method combines the efficient uniform channelization with the orthogonal mixing. By ingenious channelization and altering the coefficient of the low-pass prototype filter, the processing of the input signal analyzing bandwidth without distortion and dead zone in certain bandwidth is realized. Then with the flexibility of the orthogonal mixing, wide-band and narrow-band single-sideband output schemes are designed. Furthermore, the center frequency of the output signal can be changed arbitrarily and the bandwidth can be selected by different filter cascades.

Keywords VLBI, DBBC

1 Introduction

VLBI is a new interferometric measurement technique developed in the late 1960s with ultra-high precision of angle measurement [1]. At first, it was used in radio astronomy, geodesy, and geophysics. VLBI observations can provide complementary information on the three-dimensional with velocity and distance, it promotes the VLBI technology application and development of measurement and control in deep space. Currently, the U.S. National Aeronautics and Space Administration, the European Space Agency, and the Japanese Space Agency have developed measurement systems based on ΔVLBI (differential VLBI), and take it as the main tool to support spacecraft navigation in deep space [2]. DBBC (Digital baseband converter), which is an important part in VLBI receiving systems to complete data acquisition, channel selection, and baseband conversion, and some other functions, are the basis for the subsequent signal processing. Currently, the American Deep Space Network is using WVSR (Wideband VLBI Science Receiver) and VSR (VLBI Science Receiver) to complete broadband VLBI observations and ΔDOR [3], with the function of full spectrum recording. It requires DBBC that the center frequency of the output signal can be changed arbitrarily and the bandwidth can be selected according to the requirements. Orthogonal mixing and efficient uniform channelization are the main two methods in DBBC. A new VLBI baseband conversion method is proposed for special requirements of full spectrum processing in deep space TT&C. The method combines the efficient uniform channelization with the orthogonal mixing, which can realize the processing of certain bandwidth without dead zone and distortion.

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2 Efficient Uniform Channelization without Dead Zone and Distortion in Certain Bandwidth

2.1 The Derivation of the Efficient Uniform Channelization Model

Figure 1 shows the multi-channel parallel processing model of the orthogonal mixing baseband conversion.

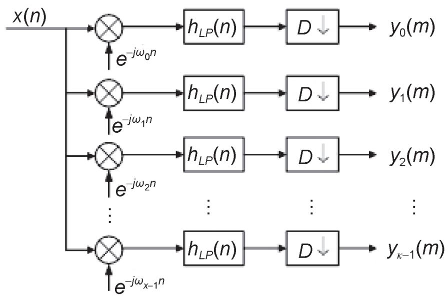

Fig. 1 Multi-channel parallel processing model of orthogonal mixing baseband conversion.

Achieving the multi-channel baseband conversion with this structure has the advantage of a flexible band selection. However, when the number of channels K is large, each channel requires an orthogonal mixer working at high speed. The hardware implementation pressure and resource consumption are large. Extraction is after the low-pass filter, so that a large number of data after conversion and low-pass filtering is not being used.

In order to reduce the front-end signal processing speed and to improve the overall operational efficiency, we can make the input signal uniform channelized filter over the entire frequency band, which can be analyzed when the following two conditions are met:

1. The bandwidth of each output channel is the same.
2. The difference between adjacent channel center frequency is (K is the number of channels). The output of the channel K is expressed as:

$$\begin{aligned} y_k(m) &= x(n)e^{-j\omega_k n} * h_{LP}(n)\,|_{n=m\mathrm{D}} \\ &= \sum_{i=0}^{\mathrm{N}-1} x(n-i)e^{-j\omega_k(n-i)}h_{LP}(i)\,|_{n=m\mathrm{D}} \\ &= \sum_{i=0}^{\mathrm{N}-1} x(m\mathrm{D}-i)e^{-j\omega_k(m\mathrm{D}-i)}h_{LP}(i) \end{aligned} \tag{1}$$

Equation (1) is a convolution, N is the number of filter coefficients.

According to the number of channels K, let us make the low-pass prototype filter polyphase decomposed. Suppose (L is an integer), then:

$$y_k(m) = \sum_{p=0}^{K-1}\sum_{i=0}^{L-1} x(mD-iK-p)e^{-j\omega_k(mD-iK-p)} \cdot h_{LP}(iK+p) \tag{2}$$

Suppose $x_p(m) = x(m\mathrm{D}-p)$, $h_p(m) = h_{LP}(m\mathrm{K}+p)$, and $F = K/D$ then:

$$\begin{aligned} y_k(m) &= \sum_{p=0}^{\mathrm{K}-1}[\sum_{i=0}^{\mathrm{L}-1} x_p(m-i\mathrm{F})e^{-j\omega_k(m-i\mathrm{F})\mathrm{D}}h_p(i)]e^{j\omega_k p} \\ &= \sum_{p=0}^{\mathrm{K}-1}[\sum_{l=0}^{(\mathrm{L}-1)\mathrm{F}} x_p(m-l)e^{-j\omega_k(m-l)\mathrm{D}}h_p(\frac{l}{\mathrm{F}})]e^{j\omega_k p} \end{aligned} \tag{3}$$

Let $h'_p(l) = h_p(\frac{l}{\mathrm{F}})$, that $h'_p(l)$ is F times the intervening sequence of $h_p(l)$, then:

$$y_k(m) = \sum_{p=0}^{\mathrm{K}-1}\left\{[x_p(m)e^{-j\omega_k m\mathrm{D}}] * h'{}_p(m)\right\}e^{j\omega_k p} \tag{4}$$

In practical applications, depending on the channel division, we can get all kinds of high-channel structure by taking ω_k into Equation (4).

2.2 Real Signal Uniform Channelization Without Dead Zone

The different channel division decided a different channelized efficient structure. The literature [4] shows that the low-pass prototype filter cannot be ideal (rectangular factor of 1). So, there will be a dead zone in the conventional method of channel division. In order to achieve real signal processing without dead zone, using the symmetry of its positive and negative spectrum, the center frequency of each channel is divided into the following:

$$\omega_k = -\frac{2\pi}{\mathrm{D}}k + \frac{\pi}{2\mathrm{D}} \qquad k = 0,1,2,\ldots,\mathrm{D}-1 \tag{5}$$

In Equation (5), the multiple of the decimation D is equal the number of channels K. In order to ensure the spectrum of each channel signal after extraction does not overlap, we design the low-pass prototype filter as the magnitude response in Figure 2.

Usually, in order to realize easily, set the passband equal to transition (shape factor of 2). Based on the above channel division mode and low-pass prototype filter design, we can get the real signal uniform channelization without dead zone in Figure 3.

Since the input signal is a real signal, the signal spectrum in Figure 3 frequency axis in the positive

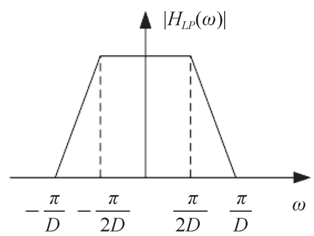

Fig. 2 Magnitude response of low-pass prototype filter.

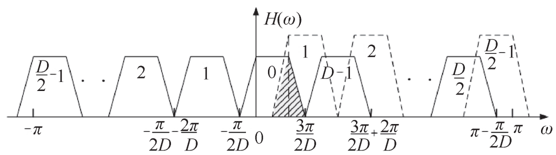

Fig. 3 Real signal uniform channelization without dead zone.

"$0 \sim \pi$" and negative "$-\pi \sim 0$" are the mirror each other. Positive frequency spectrum in dotted line is the mirror spectrum of the axis of the negative frequency axis. The output signal from channel 1 to channel "$D/2-1$" is the mirror spectrum of the real input signal. By clever channelization, using the mirroring features of real signal spectrum, the receiving of the whole channel without dead zone is realized.

2.3 Uniform Channelization without Dead Zone and Distortion in Certain Bandwidth

In Figure 3 by clever channelization, the receiving of the whole channel without dead zone is realized. However, it cannot realize receiving without distortion in certain bandwidth. When the signal is located in the triangle shaded area as shown in Figure 3, because of the transition zone adjacent to the channel, it will cause the attenuation of the amplitude of the received signal, thereby causing signal distortion.

To solve this problem, we improve the amplitude-frequency characteristics of the low-pass prototype filter. We expand the low-pass prototype filter pass bandwidth, make the two equivalent adjacent channel passband overlapping ranges greater than or equal to the VLBI maximum output signal bandwidth, improved uniform channelization without dead zone is shown in Figure 4.

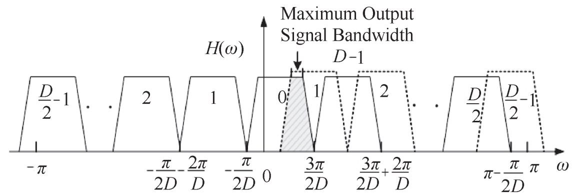

Fig. 4 Improved uniform channelization without dead zone.

Take the center frequency of each channel in formula (5) into formula (4),we can get the output of channel K:

$$y_k(m) = \sum_{p=0}^{D-1} \left\{ [x_p(m)e^{-j\frac{\pi}{2}m}] * h_p(m) \right\} e^{j\frac{\pi}{2D}p} e^{-j\frac{2\pi}{D}kp}$$
$$= \mathrm{DFT}[\left\{ [x_p(m)e^{-j\frac{\pi m}{2}}] * h_p(m) \right\} e^{j\frac{\pi p}{2D}}] \quad (6)$$

Among (6), $x_p(m) = x(m\mathrm{D}-p), h_p(m) = h_{LP}(m\mathrm{D}+p), p = 0,1,...,\mathrm{D}-1, x_p(m)$ is the multiphase delay component of the input signal. $h_p(m)$ is polyphase branch low-pass prototype filter. The signal processing block diagram is shown in Figure 5.

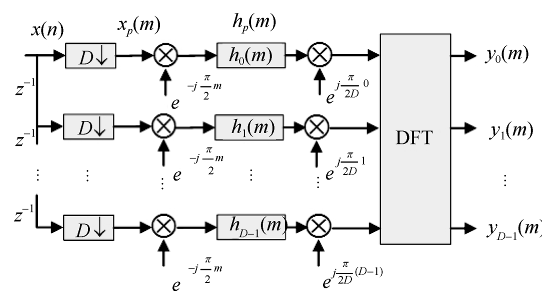

Fig. 5 Processing diagram of the improved uniform channelization without dead zone.

3 Wide-band and Narrow-band Single-sideband Output Schemes

The output signal after uniform channelization filter is lowering sampled baseband signal. The signal rate has been greatly reduced. So we can use the flexibility of orthogonal mixing. We can select the desired output signal from each uniform channel by changing the output frequency of the orthogonal local oscillator.

By loading different processing modes to achieve the bandwidth requirements of optional application.

Referring to the American Deep Space Network output bandwidth requirements for different observing modes [3], we design wide-band and narrow-band single-sideband output schemes.

3.1 The Design of Wide-band Single-sideband Output

In wide-band scheme, the bandwidth of the output real signal can be 16, 8, 4, 2, 1, or 0.5 MHz. Since the output bandwidth is a power of 2, the sampling rate of the input signal is usually a power of 2, we use half-band filter cascade to realize the wide-band output. The diagram of wide-band mode is shown in Figure 6.

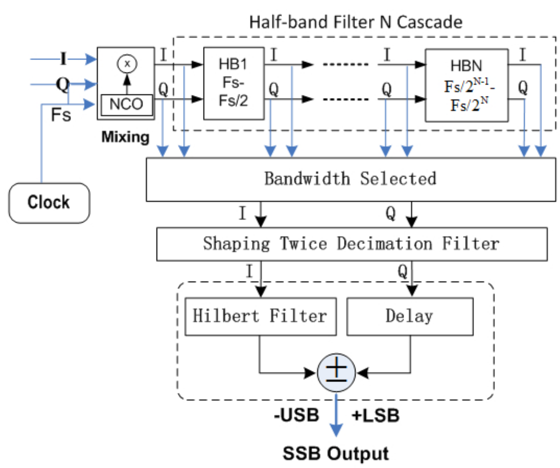

Fig. 6 Single channel diagram of wide-band mode.

3.2 The Design of Narrow-band Single-sideband Output

In narrow-band scheme, the bandwidth of the output real signal can be 200, 100, 50, 25, 16, 8, 4, 2, or 1 kHz. The literature [6] shows that, although the half-band filter passband ripple is small, if the high-power narrow-band signal decimation filtering, higher resource consumption but the filter order increase with the increase of filter progression. If the high-power narrow-band signal decimation filtering, the resource consumption is large. CIC, as an efficient filter, its stop-band attenuation and passband rolloff are only decided by the bandwidth scaling factor $b = \frac{B}{f_s/D}$, where B is the bandwidth and f_s/D is the sampling rate after decimation. The smaller b is, the greater is the CIC filter stopband attenuation of the aliasing signal bandwidth and the better the band flatness. So CIC filter is more suitable for narrow-band signal to filter and extract. The single channel diagram of narrow-band mode is shown in Figure 7.

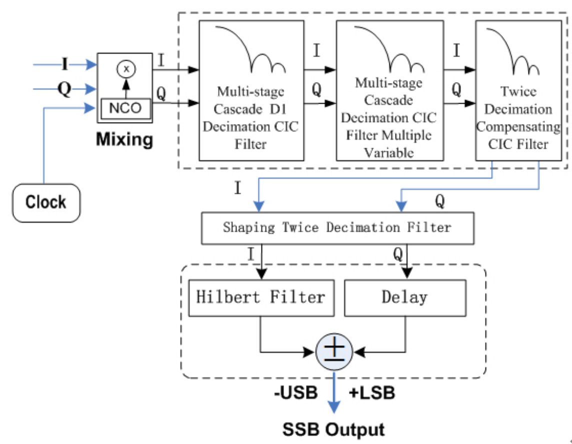

Fig. 7 Single channel diagram of narrow-band mode.

Because of the narrow-band output the signal bandwidth is narrow. So first reduce the signal rate by the high-powered CIC decimation filter, and then by changing the CIC decimation filter multiples to achieve the output signals with different bandwidths. As the CIC filter passband rolloff is large. Therefore, compensating for CIC compensation filter passband characteristic by the second stage of the CIC filter is needed, through the single sideband of the Hilbert transform to realize the SSB output.

4 VLBI Full Spectrum Digital Baseband Conversion Methods

Through the analysis above, the VLBI full spectrum digital baseband conversion method which the center frequency of output signal can be changed arbitrarily and the bandwidth can be selected is shown in Figure 8.

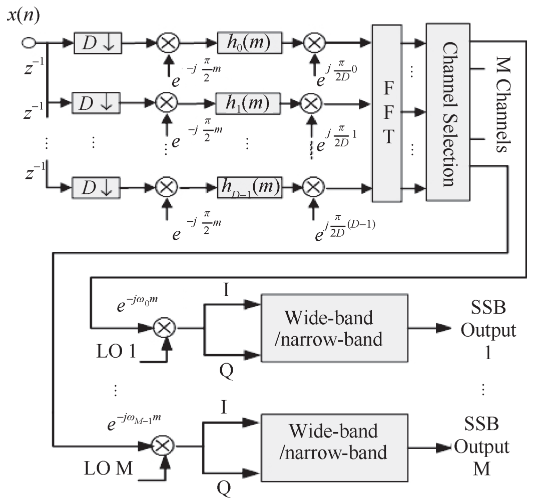

Fig. 8 Scheme of VLBI full spectrum digital baseband conversion.

First, the real input signal is done primary baseband conversion through efficient uniform channelized filtering, get down sampled complex baseband signal. Send the required signal into back-end orthogonal mixer unit by channel selection unit. In orthogonal mixer unit, we can realize the parallel multi-channel baseband signals output through multiple orthogonal mixer. In each orthogonal mixer unit, the frequency range of the desired output signal decides the oscillation frequency, the filter working methods, the output of the USB or LSB and so on. since the signal rate is low at this time, the realization difficulty and resource consumption of the multiple orthogonal mixer is small.

Compared with the orthogonal mixing method, this method has the advantage of low front-end signal processing pressure, high efficiency, and low consumption of resources. Compared with the efficient uniform channelization method, this method has the advantage that the center frequency of the output signal can be changed arbitrarily and the bandwidth can be selected.

5 Conclusions

A new VLBI baseband conversion method is proposed for special requirements of full spectrum processing in deep space TT&C. The method combines the efficient uniform channelization with the orthogonal mixing, which can realize the processing of certain bandwidth without dead zone and distortion. By clever channelization and change of low-pass prototype filter shape factor, the processing of input signal analyzing bandwidth without dead zone and distortion in certain bandwidth is realized. Using the flexibility of orthogonal mixing, wide-band and narrow-band single-sideband output schemes are designed. The center frequency of the output signal can be changed arbitrarily and the bandwidth can be selected by different filter cascades.

This VLBI baseband converting method has been used in CDBE (Chinese Digital Backend) developed by Equipment Academy. CDBE has played an important role in Chang'E-3 mission.

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