Application and improvement of wavelet packet de-noising in satellite transponder

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Abstract: The satellite transponder is a widely used module in satellite missions, and the most concerned issue is to reduce the noise of the transferred signal. Otherwise, the telemetry signal will be polluted by the noise contained in the transferred signal, and the additional power will be consumed. Therefore, a method based on wavelet packet de-noising (WPD) is introduced. Compared with other techniques, there are two features making WPD more suitable to be applied to satellite transponders: one is the capability to deal with time-varying signals without any priori information of the input signals; the other is the capability to reduce the noise in band, even if the noise overlaps with signals in the frequency domain, which provides a great de-noising performance especially for wideband signals. Besides, an oscillation detector and an averaging filter are added to decrease the partial oscillation caused by the thresholding process of WPD. Simulation results show that the proposed algorithm can reduce more noises and make less distortions of the signals than other techniques. In addition, up to 12 dB additional power consumption can be reduced at –10 dB signal-to-noise ratio (SNR).

Keywords: wavelet packet de-noising (WPD), satellite transponder, power consumption reduction, real-time de-noising.

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1. Introduction

In satellite missions such as the satellite communication system [1], the satellite video transfer system [2], the two way satellite time and frequency transfer (TWSTFT) system [3] and the satellite coherent ranging system (SCRS) [4], the transponder is an important module which allows the signal to be transmitted from an earth station to another through the satellite. When the signal passes through the transponder, it is important to reduce the noise for two reasons. On one hand, it prevents the telemetry signals generated by the satellite from being polluted by the noise contained in the transferred signal. On the other hand, the noise will increase the power consumption because the noise is amplified and transmitted as well.

There are many methods to reduce the noise, such as finite impulse response (FIR) filtering, fast Fourier transform (FFT) based de-noising, Kalman filtering, averaging filtering, median filtering and wavelet packet de-noising (WPD). Among these methods, FIR filtering is widely used in satellite transponders for its linear phase characteristic, stability and simple structure [5]. If the approximate frequency band of the input signal is known in advance, it is easy to design an FIR filter to reduce the noise out of band. Besides, in some missions such as the SCRS, it requires that the group delays of different side-tone signals are identical which can be met by the FIR filter for its linear phase characteristic. However, the de-noising performance decays for wideband signals, as the FIR filtering can only reduce the noise out of band.

FFT based de-noising is an alternative way to reduce noise [6]. It transforms the signal into frequency domain and selects a suitable threshold to deal with the coefficients. All the coefficients below the threshold are set to zero. This method can be used only when all frequency coefficients of the signal are much larger than the coefficients of noise. Otherwise, it will cause distortions. Moreover, the de-noising performance is limited for wideband signals because only few coefficients are set to zero.

Kalman filtering is a modern method of de-noising, which has a great performance [7]. However, it is complicated and much priori information of the input signal needs to be informed in advance to set up the state-transition matrix, the measurement matrix and some other functions. If the priori information is insufficient or inaccurate, it will cost much time for the convergence process. Moreover, if the characteristic of the input signal changes, it will also cost some time for the convergence process.

Averaging filtering is a kind of time-domain filtering. It replaces the current value with the mean value of its neighboring values. Thus, it can reduce high frequency noise,
but some details of the signal will be eliminated as well, leading to distortions.

Median filtering is also a kind of time-domain filtering. Different from averaging filtering, it replaces the current value with the median value of some neighboring values. Its low-pass characteristic will also cause some details loss.

WPD is a modern de-noising method based on wavelet packet transform, developed from wavelet de-noising which was proposed by Donoho and Johnstone [8–10]. It has been widely used in image de-noising [11,12], speech signal de-noising [13–16] and sensing signal de-noising [17–19]. There is also application potential in satellite communication systems and satellite navigation systems [20,21]. The principle of WPD is that the energy of signals is concentrated in a limited number of coefficients in the wavelet packet domain, while the energy of noise is distributed in the entire wavelet packet domain. Therefore, after the wavelet packet decomposition, the wavelet packet coefficients of signals are larger than the coefficients of noise, leading to the separation of the signals and the noise [11]. Then a threshold is set for all coefficients. The coefficients below the threshold is set to zero, so the noise can be reduced effectively. Compared with other techniques, WPD can reduce noise in band, and avoid signal detail loss. However, partial oscillation caused by the nonlinear process of thresholding is a major disadvantage.

As WPD has some particular advantages, we propose our satellite transponder de-noising algorithm based on WPD with averaging filtering.

The remainder of this paper is structured as follows. The typical structure of a satellite transponder is introduced in Section 2. Section 3 concentrates on the algorithm, including the basic WPD, the selection of threshold and threshold function, the elimination of partial oscillations, the time consumption evaluation and the workflow. Section 4 shows the simulation results compared with other de-noising techniques, both on the de-noising performance, the distortion performance and the power reduction performance. Finally, Section 5 concludes this paper.

2. Structure of satellite transponder

Fig. 1 shows the typical structure of a satellite transponder and the signal characteristics of all nodes. At first, the received signal as in Fig. 1(a) is mixed with the local oscillator signal to move the signal to the baseband, like Fig. 1(b). Then, some amplifiers are used to amplify the signal, and the noise is amplified as well, as in Fig. 1(c). After amplified, the signal passes through a filter to reduce the noise out of band, shown in Fig. 1(d). Then, demodulation is carried out to get the transferred signal (see Fig. 1(e)). The de-noised signal (see Fig. 1(f)) is modulated on the downlink carrier together with the telemetry signal as in Fig. 1(g). After the modulation, a series of amplifiers are adopted to amplify the signal, as in Fig. 1(h), and an up-converter is adopted to move the signal to the radio frequency (RF) band, as in Fig. 1(i). In order to reduce the noise out of band and the mirror signal caused by frequency mixing, an RF band-pass filter is adopted, as in Fig. 1(j). The last level is a power amplifier (PA), which makes the signal strong enough to be sent back to the earth station, as in Fig. 1(k).

\[
P_{\text{noise}} = -174 \text{ dBm/Hz} + 63 \text{ dBHz} + 135 \text{ dB} = 24 \text{ dBm}
\] (1)

From Fig. 1 and above introduction, two issues come up. First, the telemetry signal will be polluted by the noise contained in the transferred signal, leading to the increase of the bit error rate (BER). Moreover, this problem cannot be solved by increasing the signal power because the noise power will also increase and the signal-to-noise ratio (SNR) remains the same. Second, the noise is amplified several times and transmitted together with the signals, which will cost additional power, especially for the PA module. The satellite transponder developed by Microsatellite Research Center of Zhejiang University is discussed as an example. The total gain of this transponder is from 70 dB to 135 dB. Assuming that the bandwidth is 2 MHz (63 dBHz) and noise level is –174 dBm/Hz, the output power of the noise will be up to 24 dBm (251 mW), calculated by (1). With the PA efficiency of 20%, the additional power consumption caused by noise is 1.255 W. It is unacceptable as the total power consumption of the transponder is only 3.5 W. It means that if no de-noising method is adopted, 35.9% additional power will be consumed.
In (1), $P_{\text{noise}}$ is the power of output noise.

Therefore, we have to find a method to avoid the additional power consumption caused by the noise and to prevent the telemetry signal being polluted by the noise in satellite transponders. These requirements lead to the application of WPD in satellite transponders.

3. Algorithm and improvement

3.1 WPD algorithm

Assume that the signal is

$$f(k) = s(k) + \sigma \times n(k)$$

(2)

where $f(k)$ is the input signal, $s(k)$ is the original signal, $\sigma$ is the noise level and $n(k)$ is a uniform white noise.

Fig. 2 shows the de-noising process and the signal features. It can be divided into four steps.

Step 1 The input signal is decomposed to $L$ levels with a certain kind of wavelet function. In Fig. 2, it is decomposed in three levels.

Step 2 Select a group of optimal wavelet packet basis based on the entropy of every node in the decomposed tree.

Step 3 Deal the wavelet packet coefficient $w_{j,k}$ with a threshold and a threshold function. Then get the de-noised coefficient $\hat{w}_{j,k}$.

Step 4 Reconstruct the signal from $\hat{w}_{j,k}$ by the inverse wavelet packet transform.

3.2 Threshold and threshold function

As the WPD algorithm has been discussed several times [11 – 14, 22], we do not cover every aspect of it. Instead, only threshold and threshold function are discussed in this paper, as the performance of WPD mostly depends on them. For the threshold, if it is too aggressive, some parts of signals will be eliminated, leading to distortions. However, if it is too conservative, the de-noising performance will be limited. The threshold function decides how to deal the coefficients with the threshold, so it is also important in WPD. Besides, the requirements of different application areas vary from each other, so the threshold and the threshold function should be selected according to calculation resources, distortion tolerance, de-noising requirement and working SNR in different applications. This is why they are discussed in our satellite transponder application.

In [11 – 13], several thresholds, such as sqtwolog, minimaxi, rigrsure, heursure, mean value and median value, are introduced.

For rigrsure and heursure, the process of risk calculation is complicated, calculation complexity is too high for the limited computing resources in the satellite transponder, so they cannot be adopted. The mean value method and the median value method do not take the SNR into consideration so they can only be used in the high SNR situation. The remaining methods as sqtwolog and minimaxi are compared in Fig. 3 when SNR is $-6$ dB. From Fig. 3, it is obvious that the sqtwolog threshold has a better de-noising performance, but it is too aggressive, causing more distortion. The minimaxi threshold is more conservative which leaves more noise and less distortion.

Define the mean square error (MSE):

$$\text{MSE}(\hat{s}) = \frac{1}{N} \sum_{k=1}^{N} (\hat{s}(k) - s(k))^2$$

(3)
where \(\hat{s}(k)\) is the de-noised signal. MSE is a comprehensive reflection of the de-noising performance and the distortion. The values of distortions and MSEs are compared in Table 1. It shows that the distortion of sqtwolog is much worse than that of minimaxi while the MSE of sqtwolog is just a little better than that of minimaxi. As the distortion and the MSE are both important for satellite transponders, the minimaxi threshold is adopted to keep them in balance. The function of the minimaxi threshold is

\[
\lambda_2 = \begin{cases} 
\sigma \times (0.393 \, 6 + 0.182 \, 9 \times \log_2 n), & n \geq 32 \\
0, & n < 32
\end{cases} 
\]  

where \(\sigma\) stands for the standard deviation of the noise, and \(n\) is the number of input signal points.

### Table 1 Comparison between minimaxi and sqtwolog

<table>
<thead>
<tr>
<th>Method</th>
<th>Minimaxi</th>
<th>Sqtwolog</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 kHz distortion/dB</td>
<td>2.548</td>
<td>8.276</td>
</tr>
<tr>
<td>100 kHz distortion/dB</td>
<td>0.700</td>
<td>3.236</td>
</tr>
<tr>
<td>200 kHz distortion/dB</td>
<td>1.284</td>
<td>4.606</td>
</tr>
<tr>
<td>MSE</td>
<td>0.501</td>
<td>0.385</td>
</tr>
</tbody>
</table>

After the selection of the threshold, threshold functions are discussed. In [14], threshold functions are summarized as follows.

**Hard threshold function** is

\[
\hat{\omega}_{j,k} = \begin{cases} 
\omega_{j,k} , & |\omega_{j,k}| \geq \lambda \\
0 , & |\omega_{j,k}| < \lambda
\end{cases}
\]  

**Soft threshold function** is

\[
\hat{\omega}_{j,k} = \begin{cases} 
\text{sgn}(\omega_{j,k})(|\omega_{j,k}| - \lambda) , & |\omega_{j,k}| \geq \lambda \\
0 , & |\omega_{j,k}| < \lambda
\end{cases}
\]

**Improved threshold function 1** is

\[
\hat{\omega}_{j,k} = \begin{cases} 
\omega_{j,k} \cdot \exp\left(\frac{-\lambda}{|\omega_{j,k}| - \lambda}\right) , & |\omega_{j,k}| \geq \lambda \\
0 , & |\omega_{j,k}| < \lambda
\end{cases}
\]

**Improved threshold function 2** is

\[
\hat{\omega}_{j,k} = \begin{cases} 
(1 - \mu)\omega_{j,k} + \mu \cdot \text{sgn}(\omega_{j,k})(|\omega_{j,k}| - \lambda) , & |\omega_{j,k}| \geq \lambda \\
0 , & |\omega_{j,k}| < \lambda
\end{cases}
\]

where \(\mu\) is defined as follows:

\[
\mu = \frac{\lambda}{|\omega_{j,k}| \cdot \exp\left(1 + \frac{|\omega_{j,k}| - \lambda}{|\omega_{j,k}| + \lambda}\right)}
\]

**Improved threshold function 3** is

\[
\hat{\omega}_{j,k} = \begin{cases} 
\text{sgn}(\omega_{j,k})\sqrt{|\omega_{j,k}|^2 - \lambda^2} , & |\omega_{j,k}| \geq \lambda \\
0 , & |\omega_{j,k}| < \lambda
\end{cases}
\]

**Improved threshold function 4** is

\[
\hat{\omega}_{j,k} = \begin{cases} 
\text{sgn}(\omega_{j,k})\left(\frac{|\omega_{j,k}| - \lambda}{\exp\left(|\omega_{j,k}|/\lambda - 1\right)}\right) , & |\omega_{j,k}| \geq \lambda \\
0 , & |\omega_{j,k}| < \lambda
\end{cases}
\]

In all the threshold functions, \(\lambda\) is the threshold, \(\text{sgn}(\cdot)\) is the sign function, \(\hat{\omega}_{j,k}\) is the coefficient and \(\hat{\omega}_{j,k}\) is the result coefficient.

Fig. 4 shows the behaviors of threshold functions with threshold \(\lambda = 10\). As the coefficients larger than the threshold are kept unchanged in hard threshold function, the distortion caused by de-noising is the smallest among all the threshold functions. This assumption is supported by the simulation results shown in Table 2. The input signal in this simulation is a multi-tone signal with frequencies of 16 kHz, 100 kHz and 200 kHz, and the SNR is 0 dB. It shows that the hard threshold function makes the least distortion at all frequencies. Moreover, since de-noising is a nonlinear process, the distortions of 16 kHz, 100 kHz and 200 kHz are at different levels, which makes the distortions more unacceptable in satellite transponders. Therefore, the hard threshold function is selected.

### Table 2 Distortion value of different functions

<table>
<thead>
<tr>
<th>Function name</th>
<th>16 kHz</th>
<th>100 kHz</th>
<th>200 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard</td>
<td>0.441</td>
<td>0.449</td>
<td>0.402</td>
</tr>
<tr>
<td>Soft</td>
<td>3.825</td>
<td>2.529</td>
<td>2.750</td>
</tr>
<tr>
<td>Improved 1</td>
<td>4.615</td>
<td>2.838</td>
<td>3.127</td>
</tr>
<tr>
<td>Improved 2</td>
<td>4.001</td>
<td>0.697</td>
<td>0.665</td>
</tr>
<tr>
<td>Improved 3</td>
<td>1.001</td>
<td>0.709</td>
<td>0.683</td>
</tr>
<tr>
<td>Improved 4</td>
<td>0.987</td>
<td>0.635</td>
<td>0.565</td>
</tr>
</tbody>
</table>

Besides, the hard threshold function is the simplest one among all functions. Every coefficient should be dealt with the threshold function, so a little difference in the complexity of functions will cause a big difference in computing resources and time consumption. The computing time and resources are limited in satellite transponders, which is the other reason why the hard threshold function is selected.
3.3 Eliminate partial oscillation

In Fig. 4, it is shown that the hard threshold function is the only one which is discontinuous at $\lambda$. This drawback leads to more partial oscillations in time-domain, as shown in Fig. 5.

These oscillations may cause many problems in satellite transponders, such as bit error for data transmission, loss of lock for phase lock loop (PLL), and fake information for images. Thus, it is important to reduce them in satellite transponders. To reduce these oscillations, we have two choices: one is to select other threshold functions instead, at the cost of more distortions and more computing resources; the other is to detect and eliminate these oscillations after the de-noising process. Since we do not want to compromise on the distortions, the latter one is selected.

At first, we need to detect the oscillations as follows:

(i) Divide the de-noised signal into several time intervals.

(ii) Calculate the number of peaks in each time interval.

(iii) Compare the number of peaks in an interval with the average value of its eight neighboring intervals. If it has three more peaks, the oscillation is confirmed.

As the signals through satellite transponders are modulated and band-limited, the number of peaks will not change rapidly among neighboring intervals. However, if the oscillation occurs, the number of peaks in an interval will increase rapidly, as shown in Fig. 6. Thus, the above process can detect the oscillations effectively. Once the oscillation is detected, we need to find a method to eliminate it. The averaging filter is a good choice for its low-pass characteristic. Only the intervals that the oscillation occurs are dealt with the averaging filter, to avoid the detail loss of signals in other intervals.

After the process, the signal shown in Fig. 5 is converted to the signal shown in Fig. 7, with the oscillation decreased.

3.4 Time consumption evaluation

Since the transponder is a real-time system and WPD is a frame-based system, the signal should be buffered at the length $n$ and then be dealt with WPD. The de-noising performance increases with $n$ increasing. However, the requirement of real-time means that $n$ cannot increase unlimitedly.

The time delay of WPD includes three parts: buffering, processing and unbuffering. Assuming that the sample frequency is $f_s$, the buffering delay is $n/f_s$. The processing delay is determined by the complexity of the algorithm and the ability of processor. If the field programmable gate array (FPGA) is adopted to carry on parallel processes with high speed, the processing delay is quite small and can be ignored. Different from buffering, the unbuffering is to convert the signal from frame-based to time-based with only one clock delay, so the delay is also small and can be ignored. As a result, $n$ is determined by the sample frequency $f_s$ and the total delay tolerance $t_d$ as follows:

$$n \leq f_s t_d.$$  \hspace{1cm} (12)

In this paper, the signal length $n$ is set to $2^{13}$, and the sample frequency is 10 MHz. Therefore, the corresponding time delay is 0.82 ms.

3.5 Workflow of algorithm

The workflow is introduced as shown in Fig. 8 based on the above discussions.
Step 1 At first, buffer the signal to length $n$;
Step 2 Decompose the signal with optimal basis and calculate the threshold with estimated noise power in parallel, to get the coefficients and threshold at the same time;
Step 3 Deal the coefficients with minimaxi threshold and hard threshold function;
Step 4 Reconstruct the signal by inverse wavelet packet transformation;
Step 5 Divide the reconstructed signal into several time intervals;
Step 6 Calculate the number of peaks in every interval;
Step 7 For all intervals, detect whether the oscillation occurs;
Step 8 If the oscillation occurs, deal the interval with an averaging filter to eliminate the oscillation;
Step 9 After all the intervals has been processed, repeat the Step 6 – Step 8, until there is no new oscillation detected.
Step 10 Unbuffer the frame-based signal to time series.

Fig. 8 Workflow of the proposed algorithm

4. Simulation results

Two kinds of signals are adopted in simulation, shown in Fig. 9. Fig. 9(a) is a multi-tone signal, with frequencies of 16 kHz, 100 kHz and 200 kHz, representing for narrowband signals. Fig. 9(b) is a phase modulation (PM) signal, with carrier frequency of 500 kHz and modulation depth of 400 rad, representing for wideband signals.

To explain the performance of the proposed method, we compare it with an averaging filter, a median filter, a FIR filter and the original WPD. The comparison is on the MSE performance and the power reduction performance.

Fig. 10(a) shows the MSE performances of the multi-tone signal. It can be seen that when the SNR is low, FIR performs best, because most noise is out of band for narrowband signals, which can be eliminated by FIR effectively. The performance of the improved WPD is close to FIR because it can also eliminate noise out of band effectively and the partial oscillations of the improved WPD can be decreased notably. The performance of the original WPD is worse than the improved WPD because the oscillations occur frequently when SNR is low. The performances of median filtering and averaging filtering are not so good as they can only eliminate noise at high frequencies.

When the SNR is high, the performance of FIR is degraded. The reason is as follows. The frequency response of FIR is not absolute flat in the passband, and narrower
passband leads to larger fluctuation, which will cause more distortions. For the multi-tone signal, the passband is very narrow, so the distortion becomes the major part of the MSE instead of noise, when SNR increases. As a result, the MSE is degraded. With the high SNR, the improved WPD performs best as the distortion is limited by selecting optimal threshold and threshold function. The MSE performance gap between improved WPD and original WPD is narrowed as the number of oscillations decreasing with SNR increasing.

For the wideband signal in Fig. 10(b), things are different. When the SNR is low, the improved WPD performs best, and the performance is similar to the result in Fig. 10(a). The reason is that the improved WPD can eliminate not only the noise out of band, but also the noise in band. Thus, the bandwidth of the signal will not affect the de-noising performance too much. The MSE performance gap between the improved WPD and the original WPD is still owing to the oscillations. For FIR, only the noise out of band can be eliminated, so compared with the narrowband signal, the performance is degraded for the wideband PM signal.

When the SNR is high, the MSEs of median filtering and averaging filtering are degraded much. The reason is that the wideband PM signal has some high frequency parts, which will be wiped out by median filtering and averaging filtering for their low-pass characteristics. Therefore, distortions occur and the MSEs are degraded. For FIR, the passband is relative wide so the frequency response is relative flat, resulting in very small distortions. The improved WPD still performs best, as it can keep high frequency details and avoid distortions concurrently.

Fig. 11 shows the power reduction performances of different methods. In the simulation, the power of signals is set to 24 dBm. The results show that the improved WPD can reduce most power for both the wideband signal and the narrowband signal. When the SNR is –10 dB, up to 12 dB power consumption can be reduced by the improved WPD. The main reason is that most power of noise is eliminated by the improved WPD, and even a small part of signals’ power is eliminated as well, especially at the low SNR. Besides, the averaging filter added in the improved WPD eliminates the power of oscillations.

However, some weak parts of signals will be eliminated by the improved WPD at the low SNR, leading to some
power loss, which can be seen in Fig. 11(b). This is a drawback of the improved WPD. Fortunately, the power loss is less than 1.5 dB and the MSE performance is not affected too much. Thus, this drawback can be tolerated for satellite transponders.

In Fig. 11(b), there is also power loss for averaging filtering and median filtering. It is because the high frequency parts of the signal that is eliminated by averaging filtering and median filtering for their low-pass characteristic.

In summary, the simulation results show that the improved WPD performs best on de-noising, distortion and power reduction, for both narrowband and wideband signals.

5. Conclusions In this paper, a de-noising method based on WPD is introduced and used to satellite transponders. An oscillation detector and an averaging filter has been added into the method, in order to decrease the oscillation caused by the WPD and some applicability adjustments are carried out to meet the specific requirements of satellite transponders.

With the proposed method used to satellite transponders, many benefits are achieved. As WPD can deal with all kinds of signals with a single system without any priori information, it improves the versatility of satellite transponders. The satellite transponders can transfer different signals without any changes if the proposed method is adopted. This is an important benefit brought by WPD. Besides, the capability of reducing the noise in band ensures the de-noising performance for wideband signals, so the power consumption is reduced and the telemetry signal is prevented from being polluted. Moreover, the oscillations caused by WPD can be eliminated by partial averaging filtering effectively, while most details of signals are kept, which improves the detail distortion performance further. These benefits make a great potential for the proposed method to be applied to satellite transponders.

References

Biographies

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