Deinterleaving method of complex staggered PRI radar signals based on EDW fusion

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Abstract: Most of the existing pulse deinterleaving algorithms cannot deal well with complex staggered pulse repetition interval (PRI) radar signals which have >10 stagger levels. To solve this problem, a deinterleaving method based on emitter description word (EDW) fusion is proposed here. The sub-PRIs of a complex staggered PRI signal are detected by applying histogram statistics with overlapped PRI bins, then a data fusion is carried out to distinguish between complex staggered PRI signals and jittered PRI signals according to their characteristics in the set of PRI values. Furthermore, a general deinterleaving framework for PRI agility complex signals including jittered PRI signals, complex staggered PRI signals, and sliding PRI signals is also presented. Finally, experiments with collected real data demonstrate that the authors’ proposed method is very effective in deinterleaving of complex staggered PRI signals.

1 Introduction

In the deinterleaving of radar signals, the more stagger levels a staggered pulse repetition interval (PRI) radar signal has, the harder it is to be deinterleaved. In this paper, complex staggered PRI radar signals refer to the \( N \) level staggered signals where \( N > 10 \). In fact, the complex staggered PRI signal is one kind of PRI agility radar signals, and other typical PRI agility radar signals include jittered PRI signals, sliding PRI signals, and so on.

When applying histogram-based methods including cumulative difference histogram (CDIH), sequential difference histogram (SDIH), and others [1–3] to deinterleave signals, pulse pairs of PRI agility signals may be distributed over a number of PRI bins in the histogram, making the height of these PRI bins too small to cross the detection threshold. In contrast, pulse pairs of regular signals with constant PRIs often concentrate in a PRI bin. As a result, conventional histogram-based deinterleaving methods using PRI bins with fixed width to detect PRIs do not do well in the deinterleaving of PRI agility signals. To solve this problem, Nishiguchi et al. [4] proposed the modified PRI transform algorithm using overlapped PRI bins to generate time difference of arrival (TDOA) histograms of jittered PRI signals.

We found the complex staggered PRI radar signal from a set of collected real data. The complex staggered PRI radar signal cannot be deinterleaved effectively by most of the existing pulse deinterleaving algorithms [1, 2, 5–7] of staggered PRI signals, and the reasons are analysed in details in Section 2.2. During the analysis of the real data, we found that the complex staggered PRI signals had similar histogram features to jittered PRI signals. This brought us the idea that using the deinterleaving method of jittered signals [4, 8] to detect sub-PRIs of complex staggered PRI signals, followed by an emitter description word (EDW) fusion to distinguish between complex staggered PRI signals and jittered PRI signals according to their inherent characteristics in the set of PRI values. Furthermore, on the basis of above work, a general deinterleaving framework for PRI agility complex signals including jittered PRI signals, complex staggered PRI signals and sliding PRI signals is presented. We also use collected real data to verify the validity of our proposed deinterleaving method.

The organisation of the paper is as follows: In Section 2, the background and related work of the deinterleaving of staggered PRI signals are discussed. In Section 3, the details of the proposed method and the framework are described. Section 4 gives the experimental results, and Section 5 draws a conclusion.

2 Deinterleaving of staggered PRI signals

2.1 Histogram features of complex staggered PRI signals

First, an analysis of the histogram characteristics of complex staggered PRI signals in the TDOA histogram is given, assuming that the PRI bin width is fixed. Fig. 1a is the TDOA histogram of a jittered PRI signal and \( p \) is the average PRI. As the PRI values are randomly selected in a certain range, its pulse pairs of a jittered signal are distributed in a number of separated PRI bins around the average PRI. Moreover, the larger the jitter width is, the more distributed the pulse pairs are in the histogram.

Fig. 1b is the TDOA histogram of a staggered PRI signal with \( n \) stagger levels, its pulse pairs are distributed in several bins and one bin is corresponding to a sub-PRI, respectively. As a complex staggered PRI signal has more stagger levels, its pulse pairs may be distributed in more PRI bins (usually bin number \( \geq 10 \)). Besides, the more stagger levels the complex staggered signal has, the more distributed its pulse pairs are in the histogram. This distribution feature of pulse pairs is very similar to the distribution feature of pulse pairs of jittered signals with a jitter width of about 15%.

There are also differences of histogram characteristics between complex staggered PRI signals and jittered PRI signals. The height of PRI bins of a jittered PRI signal in the histogram is uneven due to the randomly selected PRI values, while the height of a complex staggered PRI signal is more or less even.

2.2 Deinterleaving methods of staggered PRI signals

There are two major kinds of methods to deinterleave staggered PRI signals now. The process of these two kinds of methods is shown in Fig. 2.

(i) Framework-period deinterleaving method [1, 2, 5, 6]. In this kind of method, the framework-period that is the sum of all sub-periods of a staggered PRI signal is detected first. Then, a sequence search is done repeatedly according to the framework-period until all the sub-PRIs are found out. The threshold \( T_0 \) used to detect staggered PRI signals in this kind of method is shown in expression (1), where \( N \) is the number of stagger level. \( T_0 \) is the threshold used to detect constant PRI signals as shown in expression (2), where \( t \) is the entire observation time, \( \alpha \) is a tunable parameter, and \( r \) is a PRI value corresponding to some bin’s centre in a histogram.
Sub-period deinterleaving method [7]. In the sub-period deinterleaving method, sub-PRIs of a staggered PRI signal are detected directly. The threshold $T_c$ for detection of sub-PRIs is shown in expression (3), where $m$ is the number of stagger level. After all the sub-PRIs are confirmed, the framework period can be calculated.

$$T_g = T_r \times N \quad (1)$$
$$T_r = \alpha \frac{T}{\tau} \quad (2)$$
$$T_c = \frac{T_r}{m} \quad (3)$$

However, neither of the above two kinds of methods does well in the deinterleaving of complex staggered PRI signals. The reasons are analysed as follows.

In order to meet the requirements of real-time signal deinterleaving, the computation complexity of the deinterleaving algorithm and the memory consumed by the algorithm need to be under control. Therefore, when using the framework-period deinterleaving method, the maximum framework period supported by the method cannot be set too large, usually not larger than 10,000 μs. Thus for a complex staggered PRI signal, if the sub-period is around 1000 μs and the stagger level is over 10, its framework-period has already exceeded the maximum value that can be set, leading to a large probability of deinterleaving failure.

On the other side, the sub-period deinterleaving method also has difficulties in deinterleaving complex staggered PRI signals, especially in the case that only a small number of pulses are intercepted. For example, if there are only 30–40 intercepted pulses, then only 2–3 pulses are intercepted in each sub-period. This leads to the problem that the PRI bins’ height is too small to cross the detection threshold, resulting in a deinterleaving failure or a recognition of only the sub-set of all the sub-PRIs.

Therefore, an effective deinterleaving method of complex staggered PRI signals is needed.

### 3 Deinterleaving of complex staggered PRI signals

#### 3.1 EDW fusion

The EDW fusion in this paper refers to the fusion of EDWs generated in multiple deinterleaving time intervals. Details are described as below.

In the actual design of passive radar, in order to make sure that the deinterleaving can operate in real-time and to make full use of computing resources, a deinterleaving time interval (e.g. a hundred
millisecond) is often set. In every deinterleaving time interval, all the intercepted pulses are deinterleaved to generate EDWs and the generated EDWs are called deinterleaving interval EDWs (hereinafter referred to as I-EDWs). Further, all the I-EDWs generated in multiple deinterleaving time intervals are fused according to some defined rules, and the goal is to merge I-EDWs coming from the same radar signal as much as possible. Finally, all the fused EDWs are associated with existing target EDWs to make an update of some target EDW or to initiate a new target EDW.

3.2 Deinterleaving method of complex staggered PRI radar signals based on EDW fusion

Section 2.1 has indicated that complex staggered PRI signals have similar histogram features to jittered signals. Therefore, the deinterleaving method of jittered signals can also be applied to detect sub-PRIs of complex staggered PRI signals, with a further modification. Recalling that the characteristics of the modified PRI transform method [4] are: (1) it applies the overlapped PRI bins, and the range of each bin is \( b_k = 2\varepsilon \times t_3 \) (\( t_3 \) is the PRI value of a bin centre, and \( \varepsilon \) is jitter width), (2) it introduces a phase factor to suppress sub-harmonics.

We find that when applying the modified PRI transform method [4] to deinterleave signals, the complex staggered PRI signals will be recognised as jitted signals temporarily in the deinterleaving time intervals, due to their similar histogram features to jittered signals. Thus, the key problem to successfully deinterleave complex staggered PRI signals is to distinguish between complex staggered signals and jittered signals, which can be solved by the comparison of sub-PRIs of generated I-EDWs.

A complex staggered PRI signal has its fixed sub-PRIs. Then, due to the limited intercepted pulses in a deinterleaving interval, not every generated I-EDW of a complex staggered PRI signal contains all the sub-PRIs. In other words, the sub-PRIs detected in one deinterleaving interval may be the sub-set of all sub-PRIs. If I-EDWs coming from the same complex staggered PRI signal are compared, there is a large probability that these I-EDWs may have some identical sub-PRIs. However, the probability that sub-PRIs of a jitted signal are identical is very low due to the randomly selection of PRI values. In this paper, two PRIs are considered to be identical if the difference of their values is below the defined threshold.

For comparison of two I-EDWs (denoted as \( E_i \) and \( E_j \)) coming from the same complex staggered PRI signal, if a sub-PRI \( p_n \) of \( E_i \) and a sub-PRI \( p_m \) of \( E_j \) are identical, the subsequent sub-PRIs \((p_{n+1}, p_{n+2}, \ldots) \) of \( E_i \) and the subsequent sub-PRIs \((p_{m+1}, p_{m+2}, \ldots) \) of \( E_j \) should also be identical, unless some sub-PRIs are not detected successfully. In other words, when comparing \( E_i \) with \( E_j \), the two I-EDWs can be determined to belong to the same complex staggered PRI signal if they have successive identical sub-PRIs.

The EDW fusion algorithm of complex staggered PRI signals is described as shown in Fig. 3.

3.3 Deinterleaving framework for PRI agility signals

In the above process, we find that all the PRI agility signals, including jittered signals, complex staggered signals and sliding signals, can be detected successfully by using the modified PRI transform method [4]. As they all have similar histogram features that their pulse pairs are distributed in a number of PRI bins in the TDOA histogram.

As a result, a general deinterleaving framework for PRI agility complex signals is proposed in Fig. 4. In the framework, regular signals with constant PRIs and level staggered PRI signals with \( m \leq 5 \) are first deinterleaved. Second, all the PRI agility complex signals are detected by using the modified PRI transform method [4] and recognised as jittered signal temporally, followed by the fusion of EDWs to distinguish among different PRI agility signals including jittered signals, complex staggered PRI signals and sliding signals according to their own characteristics in the set of PRI values. It should be noted that PRI agility signals with \( 5 < m < 10 \) are not included in the proposed deinterleaving framework. It is because such kind of staggered PRI signals are rarely be applied in real circumstances. Moreover, traditional histogram-based deinterleaving methods can deal with multiplePRI signals with \( 5 < m < 10 \), but with lower accuracy and more computation time. Finally, the frequency-hopping signals are deinterleaved. How to distinguish between a sliding signal and a jittered signal is not our focus in this paper. In fact, it is not difficult to recognise a sliding signal because of its linear feature of the variation of PRIs.

4 Experimental results

This section uses the real collected data to verify the validity of our proposed deinterleaving method of complex staggered PRI signals. The data are a set of pulses collected from a phased array radar on a foreign ship.

The collected data have 154 pulses totally, and a time span of 118.40 s. The intercept interval is around 3.58 s, and the number of pulses intercepted in each intercept interval is about 10–30. Fig. 5
shows the amplitude of the intercepted pulses by the time of arrival, and Figs. 6–8 show the amplitude and PRIs of the intercepted pulses in the 1st, 8th, and 9th intercept interval separately. It should be noted that the values of amplitude are added with 50 to be positive in order to facilitate analysis and display.

We implement our proposed deinterleaving method in the data processing module of one type passive radar, and the collected real data introduced above are used as the input of the method to carry
out the deinterleaving experiment. The detailed deinterleaving results are shown in Table 1, including the number of intercepted pulses, the average PRI, the sub-PRIs and the TOA of the generated I-EDWs in each deinterleaving interval. The frequency, pulse width and other parameters are not shown for reasons of confidentiality.

As we can see, the number and values of the sub-PRIs detected in each deinterleaving interval are different. In the first six intervals, the generated I-EDWs contain only sub-set of all the PRIs due to the limited intercepted pulses. Besides, the signal type is recognised as jittered type (type 5) temporally. By using our proposed EDW fusion algorithm to make a fusion of all the I-EDWs in seven deinterleaving intervals, they are confirmed to belong to the same complex staggered PRI signal. Finally, the successfully deinterleaved complex staggered PRI signal has 17 sub-PRIs, 732, 794, 960, 767, 918, 741, 833, 980, 776, 933, 750, 877, 724, 785, 939, 759, and 898.

5 Conclusion

The paper proposes a deinterleaving method of complex staggered PRI signals based on EDW fusion. The method applies histogram with overlapped PRI bins to detect sub-PRIs of complex staggered PRI signals, and then makes a fusion of I-EDWs to distinguish between complex staggered PRI signals and jittered PRI signals. Moreover, a general deinterleaving framework for PRI agility complex signals including jittered PRI signals, complex staggered PRI signals, and sliding PRI signals is presented. The proposed method has proven to be very effective in the deinterleaving of complex staggered PRI signals.

6 References

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Table 1 Deinterleaving results of a complex staggered PRI signal

| No. | PDW number | Average PRI | TOA | Radar type | Sub-PRI | Num | Sub-PRI value (μs) |
|-----|-------------|-------------|-----|------------|---------|-----|-------------------|
| 1   | 13          | 842.174     | 48,490.313421735 | 5 | 12 | 785.0, 939.0, 759.0, 898.0, 732.0, 794.0, 960.0, 767.0, 918.0, 741.0, 833.0, 980.0 |
| 2   | 13          | 842.175     | 48,493.897455796  | 5 | 12 | 785.0, 939.0, 759.0, 898.0, 732.0, 794.0, 960.0, 718.0, 741.0, 833.0, 980.0 |
| 3   | 13          | 842.175     | 48,562.050773267  | 5 | 12 | 785.0, 939.0, 759.0, 898.0, 732.0, 794.0, 960.0, 767.0, 918.0, 741.0, 833.0, 980.0 |
| 4   | 16          | 830.475     | 48,601.515298337  | 5 | 15 | 750.0, 877.0, 724.0, 785.0, 939.0, 759.0, 898.0, 732.0, 794.0, 960.0, 767.0, 918.0, 741.0, 833.0, 980.0 |
| 5   | 11          | 843.407     | 48,605.090898804  | 5 | 10 | 732.0, 794.0, 960.0, 767.0, 918.0, 741.0, 833.0, 980.0, 776.0, 933.0 |
| 6   | 13          | 824.508     | 48,605.100082896  | 5 | 12 | 877.0, 724.0, 785.0, 939.0, 759.0, 898.0, 732.0, 794.0, 960.0, 767.0, 918.0, 741.0 |
| 7   | 29          | 833.937     | 48,608.674932884  | 5 | 17 | 732.0, 794.0, 960.0, 767.0, 918.0, 741.0, 833.0, 980.0, 776.0, 933.0, 750.0, 877.0, 724.0, 785.0, 939.0, 759.0, 898.0 |