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PRI modulation recognition and sequence search under small sample prerequisite

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Abstract: Pulse repetition interval (PRI) modulation recognition and pulse sequence search are significant for effective electronic support measures. In modern electromagnetic environments, different types of inter-pulse slide radars are highly confusing. There are few available training samples in practical situations, which leads to a low recognition accuracy and poor search effect of the pulse sequence. In this paper, an approach based on bi-directional long short-term memory (BiLSTM) networks and the temporal correlation algorithm for PRI modulation recognition and sequence search under the small sample prerequisite is proposed. The simulation results demonstrate that the proposed algorithm can recognize unilinear, bilinear, sawtooth, and sinusoidal PRI modulation types with 91.43% accuracy and complete the pulse sequence search with 30% missing pulses and 50% spurious pulses under the small sample prerequisite.

Keywords: inter-pulse slide, pulse repetition interval (PRI) modulation type, bi-directional long short-term memory (BiLSTM) network, sequence search.

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1. Introduction

In increasingly complex electronic reconnaissance [1], the signal environment of electronic warfare is becoming denser, and radar types are becoming more diverse [2], which makes radar signal deinterleaving a challenging task [3]. Radar signal deinterleaving is a significant means in electronic support measurement. Clustering technologies are used to dilute the pulse stream into different electromagnetic space through the angle of arrival (AOA), carrier frequency (CF), and pulse width (PW) [4,5]. Then, the radar pulses are extracted by the time of arrival (TOA) [6,7].

Radar pulse repetition interval (PRI) modulation recognition and pulse sequence search are crucial for effective radar signal deinterleaving system operation [8,9]. The traditional PRI modulation recognition algorithm utilizes PRI histogram statistics to recognize simple modulations [10]. In recent years, with the deepening of research, researchers have analyzed the features of different PRI modulation modes and then used their features in combination with corresponding methods to recognize PRI modulation. Gencol et al. used wavelet transform features combined with the support vector machine (SVM) classifier to recognize PRI modulation modes [11]. Some researchers used PRI sequence features such as peak value, intension of monotone, energy of sequence [12], or transient variation features [13] for recognition. Ahmed et al. chose five-dimensional features in a sequential hierarchy for PRI modulation recognition [14], and also Kauppi et al. classified received pulse trains hierarchically [15]. Ducdzyk et al. used pulse descriptor word graphical representation for recognition [16]. With the trend of artificial intelligence, more researchers have applied it to PRI modulation type recognition, such as decision trees [17,18], convolutional neural networks (CNNs) [19] and recurrent neural networks (RNNs) [20,21]. Due to the particularity of radar signals, the labeled samples are seriously insufficient. In the statistical sense, when the sample size exceeds a certain value, the samples have certain statistical characteristics, which can be called large sample. The value is usually within 100. There is much research on the recognition of PRI modulations under the condition of large samples. However, litter considered recognition under the small sample prerequisite.

The traditional pulse search is based on PRI and designed tolerance to search pulses in electromagnetic space, which positively searches fixed and staggered radar signals. Xi et al. proposed the dynamic sequence search, which can effectively search jittered radar signals in 10%

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[22]. However, there is little literature on the sequence search for slide radars.

With the steady advancement of radar jamming technology [23] and the diversification of radar functions [24], inter-pulse slide radar signals have become a bottleneck hindering radar signal deinterleaving technology owing to its complex PRI modulation modes [25]. Compared with fixed and staggered modulations, the slide PRI modulation is complex and confusing [26]. As a very effective technique against jammers [27], it is difficult to search and extract its pulse sequences by electronic support measures, which cannot further reduce the complexity of electromagnetic environments and severely impact subsequent reconnaissance tasks. Moreover, in practical application scenarios, a small number of available samples influence the network training effect [28]. In this paper, we propose an approach using bi-directional long short-term memory (BiLSTM) [29] networks to recognize four types of slide signals with small samples and select different timing analysis modes to search radar pulse sequences according to the results. The simulation results demonstrate that the proposed algorithm can effectively recognize and search for inter-pulse slide radar signals in complex environments.

2. Material

2.1 Four slide radar PRI modulations

The inter-pulse slide radar changes the PRI value by a specific law in a certain range to avoid electronic countermeasure reconnaissance and anti-blind speed, which are favored over the conventional radars.

Compared with the other PRI modulations, such as fixed, staggered, and jittered PRI modulations, the slide PRI variation pattern is the most complex, varying the PRI value in some combinations of single or multiple slide intervals within a slide period. Typical slide radar PRI modulations are unilinear, bilinear, sawtooth, and sinusoidal.

Unilinear PRI: Unilinear PRI is the most fundamental type of inter-pulse slide radar, whose PRI varies at a single slip interval from the initial PRI value during the slide period. The mathematical model is defined as

$$\mathrm{PRI}_{i+1}-\mathrm{PRI}_i=c \tag{1}$$

where PRI_i is the ith PRI value. The PRI first-order difference is a fixed constant c within the same slide period.

Bilinear PRI: Bilinear PRI is a variant of unilinear PRI. Setting different initial PRI values for odd and even pulse points within the slip period can achieve a strong interference effect and significantly improve the deinterleaving difficulty of electronic countermeasures. The mathematical model is defined as

$$\mathrm{PRI}_{i+1}-\mathrm{PRI}_i=c_1, \tag{2}$$

$$\mathrm{PRI}_{i+2}-\mathrm{PRI}_i=c_2, \tag{3}$$

where PRI_i is the ith PRI value. In the same period, the first-order difference c_1 and second-order difference c_2 of the PRI are fixed constants. When $c_2/c_1=2$, unilinear PRI can be seen as a particular bilinear PRI.

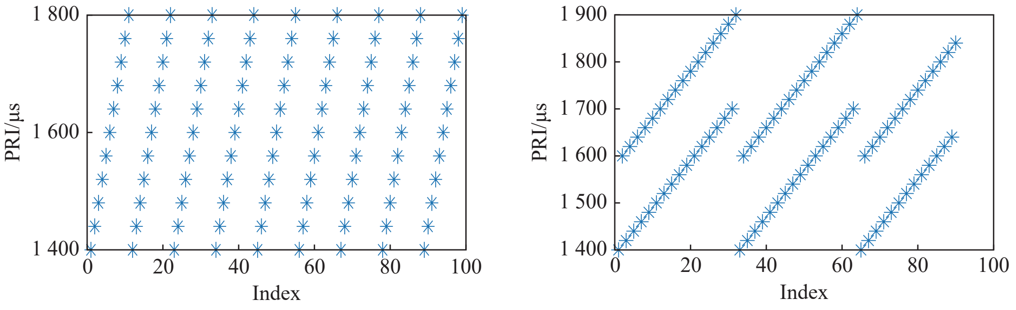
Sawtooth PRI: Sawtooth PRI is a variant of bilinear PRI. In the slide period, the initial PRI values of odd and even pulse points are different, but both PRIs slide in a sawtooth pattern. The absolute values of its PRI first-order and second-order differences are fixed constants.

Sinusoidal PRI: Sinusoidal PRI is a nonlinear slide PRI, and there is no constant slide interval, the PRI at each pulse pair follows the sinusoidal law. The mathematical model is defined as

$$\mathrm{PRI}_i=\mathrm{PRI}_0+\frac{A}{2}\cdot\sin\left(\frac{2\pi i}{B}\right) \tag{4}$$

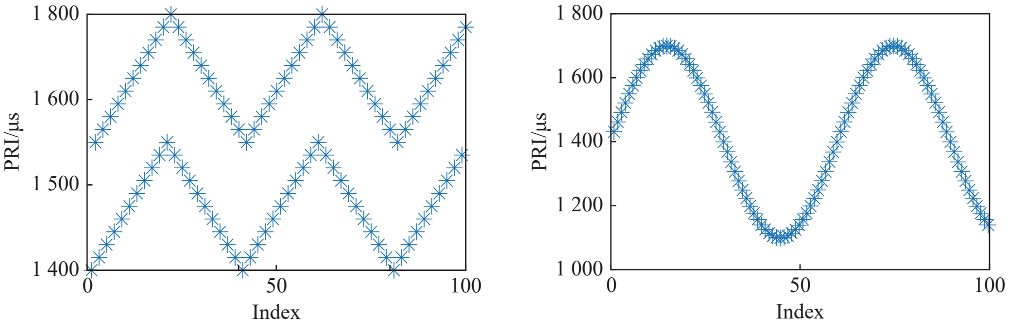
where PRI_0 is the slide center, A is the PRI range, and B is the number of pulses in one slide period.

The PRI sequences of four slide PRI modulations under the ideal condition are shown in Fig. 1.



(a) Unilinear slide radar

(b) Bilinear slide radar



(c) Sawtooth slide radar (d) Sinusoidal slide radar

Fig. 1 Four slide PRI modulations

2.2 Problem formulation

The modern electromagnetic environment is more complex and problematic compared to the last century with the following characteristics:

Missing pulses: Owing to the advancement of the low probability of interception technology and the increase in pulse density, missing pulses are inevitable, leading to difficulties in recognition and search.

Spurious pulses: More than one radar can be found in a sophisticated electromagnetic space. When analyzing a specific radar, other radar pulses and noise will inevitably be mixed into spurious pulses.

A wide range of slide variations: With the steady advancement of radar technology, the slide radar's PRI variation range expands to 50% while the slide period becomes longer. Traditional methods may be insufficient for a wide range of slide variations.

We simulate a complex electromagnetic environment, including multiple complex problems, as shown in Fig. 2. The rectangles are the received radar pulses; solid rectangles are the detected pulses and dotted rectangles are missing pulses. The black rectangles are the target radar pulses, which have 16 different intervals in a slide period. The other color rectangles are the spurious pulses. The width of the rectangle is the PW.

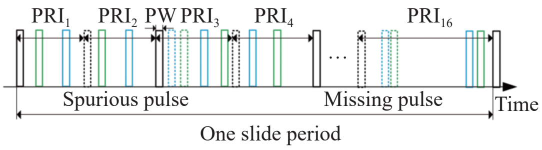


Fig. 2 Complex electromagnetic environment

3. PRI modulation recognition and sequence search algorithm

3.1 PRI modulation recognition based on BiLSTM

3.1.1 BiLSTM network

BiLSTM network is an improvement of long short-term memory (LSTM) network [30], which belongs to a type of RNNs. LSTM solves the difficulties of gradient explosion and disappearance during the training process of RNNs. With the long and short term memory functions, LSTM can acquire knowledge quickly by a small sample. Moreover, it does not limit the length of the input data, which is more suitable for temporal data in practical situations.

The BiLSTM network consists of a forward LSTM and a backward LSTM. The LSTM network can only encode the data from the front to the back, resulting in serious confusion in recognizing each slide PRI modulation. LSTM networks add gates to RNNs to realize selective memory and solve the distance learning problem. The first is the forget gate, whose input is the current layer input and the previous layer output. It decides whether to forget information in the cells. Next is the input gate, where the sigmoid layer decides which information is to be updated. The tanh layer creates a candidate vector for the output gate. Finally, the output gate determines the final output of the information. The detailed procedures are

$$\boldsymbol{f}_t = \sigma(\boldsymbol{W}_f[\boldsymbol{h}_{t-1}, \boldsymbol{x}_t] + \boldsymbol{b}_f), \tag{5}$$

$$\boldsymbol{i}_t = \sigma(\boldsymbol{W}_i[\boldsymbol{h}_{t-1}, \boldsymbol{x}_t] + \boldsymbol{b}_i), \tag{6}$$

$$\tilde{\boldsymbol{c}}_t = \tanh(\boldsymbol{W}_c[\boldsymbol{h}_{t-1}, \boldsymbol{x}_t] + \boldsymbol{b}_c), \tag{7}$$

$$\boldsymbol{c}_t = \boldsymbol{f}_t \odot \boldsymbol{c}_{t-1} + \boldsymbol{i}_t \odot \tilde{\boldsymbol{c}}_t, \tag{8}$$

$$\boldsymbol{o}_t = \sigma(\boldsymbol{W}_o[\boldsymbol{h}_{t-1}, \boldsymbol{x}_t] + \boldsymbol{b}_o), \tag{9}$$

$$\boldsymbol{h}_t = \boldsymbol{o}_t \odot \tanh(\boldsymbol{c}_t), \tag{10}$$

where $\boldsymbol{f}_t$, $\boldsymbol{i}_t$, and $\boldsymbol{o}_t$ are the outputs of the forget gate, the input gate, and the output gate, respectively. $\sigma(\cdot)$ is the signoid activation function. Other parameters include cell state $\boldsymbol{c}_t$, candidate vector $\tilde{\boldsymbol{c}}_t$, connection matrix $\boldsymbol{W}$, bias $\boldsymbol{b}$, current layer input $\boldsymbol{x}_t$, the current layer output $\boldsymbol{h}_t$, and pointwise product $\odot$. The four subscripts $\boldsymbol{f}$, $\boldsymbol{i}$, $\boldsymbol{c}$ and $\boldsymbol{o}$ mean four states respectively, namely, the forget gate, the input gate, the current memory unit and the output gate. The LSTM cell structure is shown in Fig. 3.

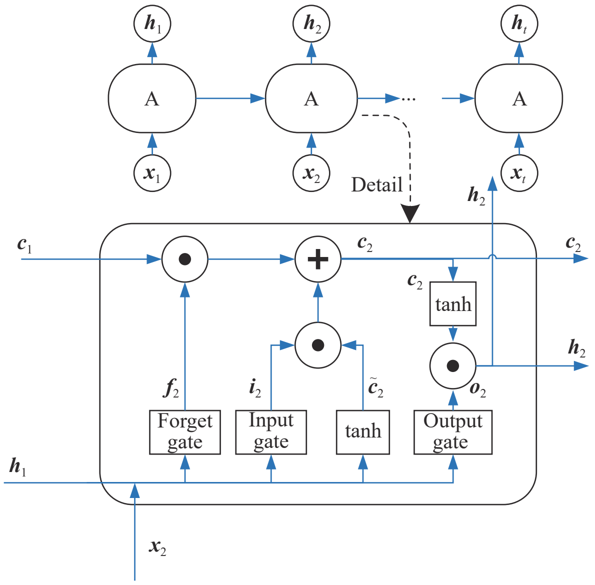


Fig. 3 LSTM cell structure

3.1.2 Preprocessing

When the features of several radars are quite similar, PRI deinterleaving can be a superior solution in such cases. Reliable PRI values are obtained by the PRI transformation method, and a coarse search is performed in the possible slide range. The obtained pulse sequence is preprocessed and utilized as the input to the BiLSTM network. The coarse search results are preprocessed to enhance the BiLSTM network generalization performance. The preprocessing steps are as follows:

Step 1 The histogram statistics of the first-order difference of the pulse sequences after coarse searches are performed. Remove the pulse points with too low frequency in the histogram for preliminary denoising.

Step 2 The average PRI value of the coarse search pulse sequence is set to 1. The whole PRI values are reduced in the same proportion to retain the PRI variation features of the slide PRI and improve the generalization performance for different PRI signals.

Step 3 Calculate the first-order, second-order, and third-order differences of the coarse search sequence to generate three-dimensional features, which provide a comprehensive PRI variation trend for the BiLSTM network to recognize under small sample prerequisite.

3.1.3 Training the BiLSTM network

In this paper, we use 204 sets of three-dimensional sequence data as the network input, containing coarse search pulse sequence data for four slide signals at 0%, 10%, 20%, and 30% missing pulses and different spurious pulse ratios. Under the small sample prerequisite, a dropout layer is applied to prevent the network training from overfitting. The number of hidden units is an important parameter that affects the performance of network recognition. When the number of hidden units is too small, it will be easier to overfit. Conversely, when the number of hidden units is too large, it becomes difficult to fit. After the experiments to select the optimal parameters, the number of hidden units is chosen to be 100. The batch size is 51, the training period is 5 000 times, and the learning rate is 0.001.

3.2 Sequence search based on temporal correlation

Based on slide PRI modulation recognition results, different temporal correlation patterns are selected to process the coarse search pulse sequence, extract the slide interval, determine the slide period. The radar's PRI variation law is analyzed to achieve an accurate pulse sequence search.

3.2.1 Slide interval

The slide interval is the fundamental feature of the linear inter-pulse slide signal, obtained by the order difference in the coarse search pulse sequence with the statistical histogram results.

Since the sinusoidal PRI is nonlinear, it is impossible to accumulate a specific histogram frequency by performing the order difference on the pulse sequence within the same observation time. Therefore, it is infeasible to obtain the slide interval of the sinusoidal PRI.

3.2.2 Slide period

The slide period is a critical feature of all slide signals, and the selection of slide periods occupies a powerful position in the search for pulse sequences. An incorrect slide period will cause the search algorithm to gradually deviate from the intended range of the search, resulting in a low search success rate.

The steps to determine the slide period are as follows:

Step 1 The coarse search pulse sequence is processed by a first-order difference operation, and the result with the highest frequency is selected as the search target according to the statistical histogram.

Step 2 Find all positions where the search target occurs in the first-order difference results of Step 1 and acquire the TOA information corresponding to the search positions.

Step 3 Store the first-order difference results of all TOAs searched in Step 2.

Step 4 Because of the characteristics of bilinear, sawtooth, and sinusoidal slide signals, the equivalent PRI pulse point may occur twice in the same slide period.

Therefore, the N results of the first-order difference in Step 3 and the $N(N-1)/2$ results of the first-order difference results from two together must contain the slide period.

Step 5 A total of $N+N(N-1)/2$ results in Step 4 are eliminated from the repetitive values, sorted in ascending order, and the search is started at the initial point of the pulses. If multiple pulses can be searched continuously for this slide period beginning with this pulse, the result is selected as the final slide period.

3.2.3 PRI variation pattern

For linear slide radar signals, if the central PRI value, the slide interval, and the slide period are known, then the entire PRI variation pattern can be analyzed according to each slide PRI's characteristics. The bilinear and sawtooth slide radar must first determine the initial PRI value of pulses owing to the complicated pattern.

Bilinear PRI initial value:

$$\mathrm{PRI}_{\mathrm{initial}} = (\mathrm{PRI}_0 - s_1 - (P/2-1)\cdot s_2)/2 \tag{11}$$

and sawtooth PRI initial value:

$$\mathrm{PRI}_{\mathrm{initial}} = (\mathrm{PRI}_0 - s_1 - (P/4)\cdot s_2)/2 \tag{12}$$

where $\mathrm{PRI}_{\mathrm{initial}}$ is the PRI initial value; PRI_0 is the center PRI; s_1, s_2 are the primary and secondary slide intervals, respectively; P is the slide period.

For sinusoidal slide radar signals, which are nonlinear, it is difficult to accurately analyze the PRI variation law of sinusoidal PRI. However, the PRI slide range can be roughly estimated by combining the absolute minimum value resulting in the first-order difference with the sine formula. Since there is no cliff-like change in the sinusoidal PRI, the incorrect PRI slide range result has less influence on the search.

3.3 Slide PRI recognition and sequence search overall process

Combining PRI modulation recognition based on the BiLSTM network with the sequence search based on temporal correlation can effectively break through the bottleneck of electronic reconnaissance in complex environments. The diagram of the slide PRI modulation recognition and search system is shown in Fig. 4.

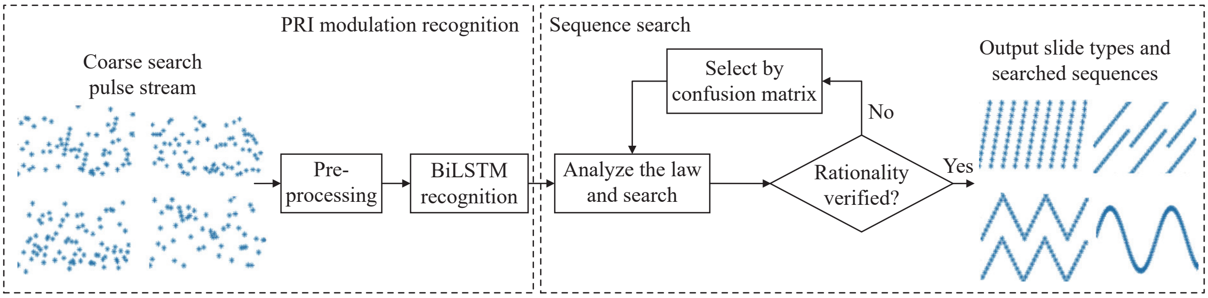


Fig. 4 Slide PRI recognition and search system diagram

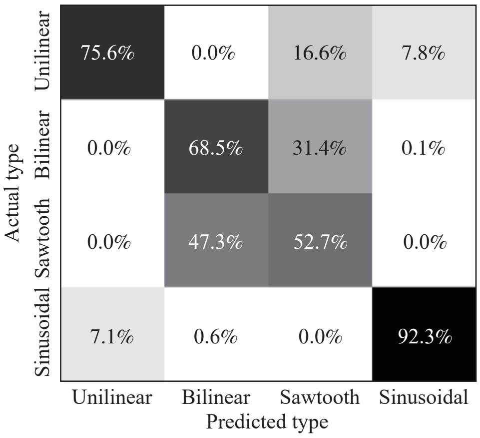
Firstly, based on the PRI value and the approximate variation range provided by the front-end signal deinterleaving algorithm, a coarse search is performed in the electromagnetic environment. Furthermore, the coarse search pulse sequence results are preprocessed and utilized as the BiLSTM network input. Secondly, according to the recognition results, different temporal correlation patterns are selected to obtain the slide interval, determine the slide period, and analyze the PRI variation pattern to search the pulse sequence effectively. Suppose that the number of pulses searched is too small compared to the number of coarse search pulses. In that case, it implies that the PRI modulation recognition fails, so that the modulation with higher confusion is selected and analyzed again to search pulses. Eventually, it is achieved to correctly recognize the PRI modulation and accurately search the relevant pulse sequences in complex electromagnetic environments to alleviate the subsequent reconnaissance obstacles.

4. Simulation results

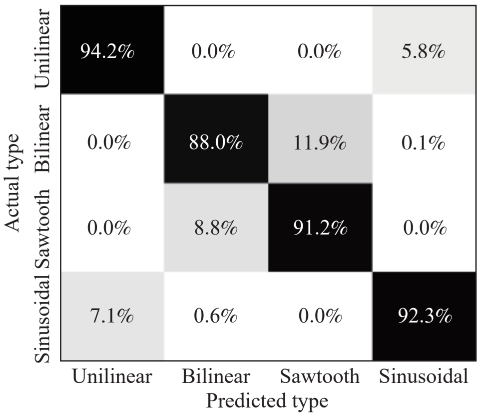
4.1 Contribution of sequence search verification

The simulation is performed in a complex environment containing four slide radars with four different modulations with identical parameters except for PRI. The slide PRI range is set to vary randomly between 30% and 50% of the central PRI value. The missing pulse rate is 30%, and the percentage of spurious pulses is 50%. The recognition results are verified with the temporal correlation and re-recognized according to the confusion matrix to validate the proposed algorithm. A total of 1 000 Monte Carlo experiments are conducted for each of the four slide radars to recognize this PRI modulation and analyze the proposed algorithm's recognition performance in complex environments. Only the BiLSTM network is used for another 4 000 tests in the same complex environment as the previous one to verify the sequence search verification contribution proposed in this paper.

In the 30% missing pulses and 50% spurious pulses environment, the confusion matrixes for recognizing the slide PRI modulations using the BiLSTM network only and the proposed algorithm are shown in Fig. 5. The confusion matrixes show that sawtooth PRI is most easily confused with bilinear PRI, while the sinusoidal PRI is recognized optimally. The PRI modulation recognition accuracy of the algorithm in this paper is significantly better than using only BiLSTM networks.



(a) BiLSTM



(b) Proposed algorithm

Fig. 5 Confusion matrix of algorithms with 30% missing pulses, 50% spurious pulses

4.2 Comparison of different models

We compare the recognition performance of different models under the small sample prerequisite, the same 204 sets of sample data are used for training. The PRI modulation recognition performance of different techniques is tested in the environment with six missing rates from 0% to 30% and 50% spurious pulses. Recognition techniques include the proposed algorithm, BiLSTM, CNNs [15], and the traditional SVMs. For each model, 1 000 Monte Carlo experiments are conducted at each missing rate for each modulation. The average recognition performance results for each model are shown in Fig. 6. We find that as the missing rate increases, the accuracy of the proposed algorithm decreases significantly slower than that of the BiLSTM network. Moreover, the accuracy is higher for the same case. CNNs and SVMs are not suitable for sequence recognition under the small sample prerequisite. In addition, their input sequence length is fixed, which is not suitable for practical environments.

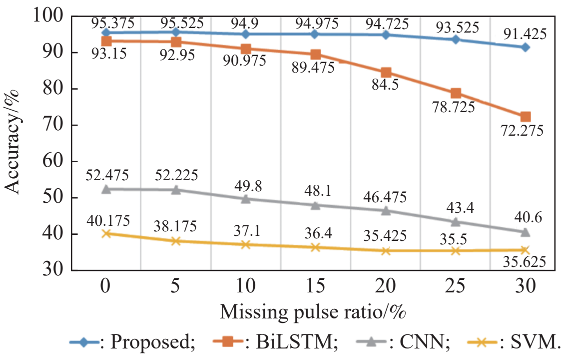


Fig. 6 Performance for various techniques with 50% spurious pulses and different missing pulses rates

4.3 Pulse search performance

Under the complex electromagnetic environment described in Subsection 4.1, the temporal correlation is performed based on the correct recognition results. The PRI variation law is analyzed for the search. The search results are compared with the original algorithm results. The results are shown in Table 1.

Table 1 Comparison of two algorithms' search results

PRI modulation	Missing pulse/%	Actual pulses count	Original algorithm				Proposed algorithm			
			Search pulses count	Relevant pulses count	Precision/ %	Recall/ %	Search pulses count	Relevant pulses count	Precision/ %	Recall/ %
Unilinear	30.37	697	798	481	60.28	69.01	709	697	98.31	100
Bilinear	31.06	637	814	431	52.94	67.66	645	637	98.76	100
Sawtooth	30.80	692	816	484	59.31	69.94	708	692	97.74	100
Sinusoidal	30.68	592	750	387	51.60	65.37	611	589	96.40	99.49

The expressions for precision and recall are given as

$$\text{Precision} = \frac{\text{Relevant pulses searched}}{\text{Total number of pulses searched}}, \quad (13)$$

$$\text{Recall} = \frac{\text{Relevant pulses searched}}{\text{All relevant pulses of the environment}}. \quad (14)$$

As shown in Table 1, for linear slide signals, the sequence search algorithm proposed in this paper can accurately analyze their PRI variation patterns in complex environments and search in electromagnetic space. For sinusoidal slide, the search effect is constrained by the slide range prediction and is slightly less efficient compared to linear slide signals. The precision and recall rates are substantially superior to those of the original algorithm.

5. Conclusions

In this paper, an approach based on BiLSTM networks and the temporal correlation algorithm for PRI modulation recognition and sequence search under the small sample prerequisite is proposed. Simulation results show the overall ratio of recognition is 91.43% with utmost 30% missing pulses and 50% spurious pulses under the small sample prerequisite. Besides, the algorithm can search and extract pulses to reduce the complexity of electromagnetic environments. Future research will be conducted to improve recognition and search performance at a high missing rate.

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