

Research Article

Feature Extraction for Evaluating the Complexity of Electromagnetic Environment Based on Adaptive Multiscale Morphological Gradient and Nonnegative Matrix Factorization

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In the current battlefield space, with the massive application of electromagnetic equipment, the electromagnetic environment in the battlefield space tends to be complex, which can lead to the electromagnetic equipment and personnel in the battlefield space receiving interference from the electromagnetic environment signal. To protect the safety of personnel and equipment quality, it is necessary to evaluate the complexity of the electromagnetic environment signal research, to use the corresponding measures. However, there is still little research related to the evaluation of the complexity of electromagnetic environmental signals. In this paper, a feature extraction method for electromagnetic environmental signals based on adaptive multiscale morphological gradient filtering and a nonnegative matrix factorization algorithm is proposed. First, the electromagnetic environment signal is filtered by AMMG, and then the filtered signal is processed by NMF for feature extraction. Finally, the complex electromagnetic environment signals after feature extraction are evaluated and classified by the SVM method. The results show that the evaluation results have good classification accuracy, and this paper provides an effective feature extraction method for the complexity of electromagnetic environment signals.

1. Introduction

With the development of science, a lot of electronic weapons are used in modern war, which will lead to a variety of electromagnetic signals on the whole battlefield space. These electromagnetic signals will build a complex and changeable electromagnetic environment. This will have a significant impact on the effectiveness of electronic weapon systems. Therefore, it is of great significance to study the complexity of the battlefield electromagnetic environment [1–4].

To classify the electromagnetic environment into different complexity degrees, feature extraction of electromagnetic environment signals is a key step. And before feature extraction, the signal needs to be preprocessed to reduce its complexity.

The theory of mathematical morphology is a very representative nonlinear signal processing and analysis

technology that has developed rapidly in recent years. Mathematical morphology is based on random sets and integral geometry. According to the shape characteristics of the processing object, it uses specific structural elements to carry out morphological transformation to achieve the purpose of signal processing. This method only depends on the local shape characteristics of the signal to be processed, decomposes a complex signal into parts with physical meaning by mathematical morphological transformation, strips it from the background, and maintains the main shape features of the signal, which is more effective than traditional linear filtering [5, 6]. As a nonlinear analysis method, mathematical morphology is not only simple and fast but also has a clear physical meaning, so it is especially suitable for signal feature extraction [7]. The mathematical morphological filter has been widely used in the fields of digital image processing [8] and mechanical systems [9–11]. At the

same time, it has also been fully used in medical signal processing [12]. In recent years, mathematical morphological filters have also been used in magnetotelluric signal processing. The authors in [13] used the mathematical morphology filtering (MMF) method to reconstruct effective low-frequency signals and protect. The authors in [14] constructed a combined generalized morphological filter and suppressed the noise from the measured magnetotelluric signals. The authors in [15] proposed a noise suppression scheme based on mathematical morphology top-hat transformation to denoise the magnetotelluric time-domain signal. The authors in [16] presented a combined filtering method, which combines empirical mode decomposition and mathematical morphological filtering, to filter the time-domain signals of magnetotelluric signals in mining areas. The authors in [17] proposed a magnetotelluric noise suppression method based on the combination of mathematical morphological filtering and wavelet threshold filtering.

However, there are few applications in electromagnetic environmental signal analysis. Therefore, a method called adaptive multiscale morphological gradient transform (AMMG) is presented in this paper, and this method is used to process electromagnetic environment signals to suppress noise effectively and enhance useful components at the same time.

To evaluate electromagnetic environments of different complexities, various features such as spatial coverage, spectral occupancy, temporal occupancy, and energy domain average power density spectra have been developed [18–21]. The authors in [22] used Analytic Hierarchy Process (AHP) to evaluate the complexity of the electromagnetic environment, which refined the evaluation index and gave specific evaluation criteria. However, the AHP method is subject to human influence and is not robust. The authors in [23] analyzed the complex electromagnetic environment and subsequently extracted the corresponding evaluation indexes and sent them into the PNN for analysis and evaluation, which achieved better evaluation results. However, the PNN structure is complicated, the model is not easy to build, and the program requires a large storage space during operation. The authors in [24] proposed a new fractal dimension evaluation method based on morphological coverage to evaluate the complexity of the electromagnetic environment.

The nonnegative matrix factorization (NMF) algorithm is a matrix decomposition method under the constraint that all elements in the matrix are nonnegative numbers. The psychological and physiological basis of nonnegative matrix decomposition is that the perception of the whole is composed of the perception of the parts that make up the whole, which is also consistent with the intuitive understanding that the whole is made up of parts [25–30]. The nonnegative matrix decomposition algorithm is easy to implement; the negative value will not appear in the decomposition result and has the advantages of interpret and clear physical meaning, as well as less storage space, which has made many scientists and researchers pay high attention to this. Now, the NMF algorithm has been widely used to deal with

multidimensional data in various fields, such as signal processing, biomedical engineering, pattern recognition, computer vision, and image engineering. Therefore, we apply nonnegative matrix factorization to the feature extraction of electromagnetic environment signals.

As a result, in this paper, we propose adaptive multiscale morphological gradient filtering to process the electromagnetic environmental signal in order to suppress noise on the premise of effectively retaining the signal components that reflect the characteristics of the electromagnetic environment. On this basis, the nonnegative matrix decomposition (NMF) technique is used to compress the signal and compute the characteristic parameter set for electromagnetic environment signal classification. The electromagnetic environment signals simulated under four levels of complexity are used to validate the signal processing and characteristic parameter calculation method proposed in this paper. The results show that the feature extraction algorithms based on AMMG and NMF have good classification accuracy and provide an effective method for assessing the complexity of electromagnetic environments.

The paper is organized as follows. Section 2 introduces the mathematical morphology filtering method, nonnegative matrix decomposition method, and support vector machine classification method used in this paper. In Section 3, the electromagnetic environment information is simulated, and the signal is tested using the method described in Section 2. Section 4 describes and comments on the experiments. Section 5 discusses the proposed method. Finally, the paper is concluded in Section 6.

2. Mathematical Morphology Filtering

2.1. Basic Morphological Filter. The most basic morphological filters can be constructed by using the four basic operators of mathematical morphology, namely, morphological corrosion filter, morphological expansion filter, morphological open filter, and morphological closed filter [31].

Although these basic morphological filters can extract the contour information of the signal, the effects are different. The impact of morphological filtering not only depends on the use of morphological operations but also has a close relationship with the use of structural elements. Only the primitives that match the size and shape of the structural elements can be retained. The selection of structural elements is flexible and changeable, including the type, length (the definition domain of structural elements), and height (the amplitude of structural elements). According to the shape characteristics of the processed signal, a variety of different structural elements can be selected, such as straight line, regular triangle, square, sines, and so on.

However, in grayscale morphological signal processing, because it is impossible to predict the gray value of the function (or signal) to be processed, it is often difficult to determine the gray value of structural elements when selecting or constructing structural elements. The gray value of the structural element is too small for the signal to be processed with a large gray value, and the gray value of the

structural element does not play an obvious role in the expansion and corrosion operation. If the gray value of the structural element is too large, the result of the expansion and corrosion operation is more determined by the gray value of the structural element, and the signal to be processed with a smaller gray value will be “submerged” in the structural element, so the processing effect of feature extraction cannot be achieved [32].

As a result, a common method is to set the gray value of the structure element to zero, that is, the flat structure element. Because it does not change the gray value of the processed signal, this flat structural element can extract the shape features of the signal to be processed more intuitively and accurately than the nonzero structural element, which is also consistent with the simplest starting point of the morphological method.

Support that $f(n)$ and $g(n)$ are discrete functions defined on $F = \{0, 1, 2, \dots, N-1\}$ and $G = \{0, 1, 2, \dots, M-1\}$ and $N \gg M$. $f(n)$ is the input signal and $g(n)$ is the structural element. The morphological operation of $f(n)$ concerning $g(m)$ is as follows:

$$\begin{aligned} (f \oplus g)(n) &= \max\{f(n-m) + g(m), m \in G\}, \\ (f \ominus g)(x) &= \min\{f(n+m) - g(m), m \in G\}, \\ (f \circ g)(n) &= (f \ominus g \oplus g)(n), \\ (f \bullet g)(n) &= (f \oplus g \ominus g)(n). \end{aligned} \quad (1)$$

In the formula, “ \oplus ” is the symbol of morphological dilation operation; “ \ominus ” is the symbol of morphological erosion operation; “ \circ ” is the morphological closed operation symbol; and “ \bullet ” is the morphological open operation symbol.

Therefore, a common method is to set the gray value of the structure element to zero, that is, the flat structure element. In fact, because it avoids the modification of the gray value of the processed signal, this flat structural element can extract the shape features of the signal to be processed more intuitively and accurately than the non-zero structural element, which is also in line with the simplest starting point of the morphological method.

2.2. Morphological Gradient Filter. Although the basic morphological filter can extract the pulse information of the signal, it can only extract the negative pulse or positive pulse information of the signal, respectively. In practical application, it is sometimes difficult to obtain a priori knowledge of the positive and negative impact of the actual signal. And more generally, the signal has both positive and negative shocks. At this time, it is necessary to use the combination of erode, dilate, open, and close operations to construct the morphological gradient operator to extract the positive and negative pulses in the signal at the same time [33].

Support that $f(n)$ and $g(n)$ are discrete functions defined on $F = \{0, 1, 2, \dots, N-1\}$ and $G = \{0, 1, 2, \dots, M-1\}$ and $N \gg M$. $f(n)$ is the input signal, and $g(n)$ is the structural element. Morphological gradient (MG) is the difference of signal $f(n)$ after dilate and erode of a structural element $g(n)$

or close and open operation. In this paper, it is defined as morphological expansion-corrosion gradient MG_{DE} and morphological open-closed gradient MG_{CO} ; the expression is

$$\begin{aligned} MG_{DE}(f)(n) &= f \oplus g(n) - f \ominus g(n), \quad n = 0, 1, 2, \dots, N-1, \\ MG_{CO}(f)(n) &= f \bullet g(n) - f \circ g(n), \quad n = 0, 1, 2, \dots, N-1. \end{aligned} \quad (2)$$

In the formula, “ \oplus ” is the symbol of morphological dilation operation; “ \ominus ” is the symbol of morphological erosion operation; “ \bullet ” is the morphological closed operation symbol; “ \circ ” is the morphological open operation symbol.

In image processing, MG is often used to detect edges in images. If the gradient value at a point is large, it means that the light and shade of the image at that point change rapidly, so that edges may pass through. In one-dimensional signal processing, the morphological gradient operator can be used to detect the transient information added to the steady-state signal. It considers both positive and negative pulses, so it is a powerful tool to highlight the pulse information, so it can effectively detect the position of the pulse and better retain the shape of the pulse.

2.3. Adaptive Multiscale Morphological Gradient.

Although the morphological gradient operation can enhance the signal to a certain extent, due to the use of single-scale structural elements to process the signal, although it can retain more signal details on a small scale, it will be affected by noise at the same time. Although the noise can be greatly suppressed on a large scale, the signal details will also be blurred, so there are some deficiencies in the use of single-scale morphological transformation to extract the impact features of the signal.

At the same time, the objective world has multiscale characteristics, and all things can become meaningful entities only on a specific scale. Analysis of the signal at only one fixed scale does not reveal the inherent multiscale nature of the signal itself, which limits the accuracy of the results [34].

Morphological corrosion, morphological expansion, morphological opening, morphological closing, morphological expansion-corrosion gradient, and morphological opening-closing gradient are the six operators of morphological filtering operations [35]. Based on the analysis of six basic morphological filter operators, the adaptive multiscale morphological gradient transform (AMMG) is applied to EME signals.

First, multiscale structure elements are used to perform morphological gradient transformation on the signal. In this paper, we use the morphological expansion-corrosion gradient, the scale is set to $S = \{S_1, S_2, \dots, S_K\}$, and a series of processed signals can be obtained:

$$\begin{aligned} f g_k(n) &= f \oplus S_k g(n) - f \ominus S_k g(n) \quad k = 1, 2, \dots, \\ K n &= 0, 1, 2, \dots, N-1. \end{aligned} \quad (3)$$

Then, the final gradient signal is obtained by multiscale synthesis algorithm:

$$fg(n) = \sum_{k=1}^K w_k \cdot fg_k(n). \quad (4)$$

w_k is the weight of each scale signal, which can be calculated by the following formula:

$$w_k = \frac{S_k}{\sum_{k=1}^K S_k}, \quad k = 1, 2, \dots, K. \quad (5)$$

The main idea of adaptive multiscale morphological gradient transformation is to use structural elements of different sizes to extract signal impact features. Small-sized structural elements have weak noise-removing capabilities but can retain good signal details. Large-sized structural elements have strong noise-removing capabilities but will blur signal boundaries. As a result, combining various signals of different scales can extract more ideal impact features.

3. Feature Extraction of Nonnegative Matrix Factorization

Nonnegative Matrix Factorization (NMF) is matrix decomposition method. By this method, we can decompose a matrix of a larger dimension into two matrices of a smaller dimension such as

$$\mathbf{V}_{i \times j} = \mathbf{W}_{i \times r} \mathbf{H}_{r \times j}. \quad (6)$$

In this formula, W is called the base matrix, H is called the coefficient matrix, V is called the original matrix, and i and r represent the height and width of the matrix W , r and j represent the height and width of matrix H . After obtaining W and H , the coefficient matrix H can be used to replace the original matrix V . The extracted feature of each sample is each column vector of H . The rank r of the factorization is often selected to follow the rule of $(i + j)r < ij$, and by this way, the compression or dimensionality reduction can be achieved.

For obtaining W and H , a multiplicative update rule is given as follows:

$$\begin{aligned} \mathbf{W}_{ia} &= \mathbf{W}_{ia} \sum_{j=1}^m \frac{\mathbf{V}_{ij}}{(\mathbf{WH})_{ij}} \mathbf{H}_{aj}, \\ \mathbf{W}_{ia} &= \frac{\mathbf{W}_{ia}}{\sum_{i=1}^m \mathbf{W}_{ia}}, \\ \mathbf{H}_{aj} &= \mathbf{H}_{aj} \sum_{i=1}^n \mathbf{W}_{ia} \frac{\mathbf{V}_{ij}}{(\mathbf{WH})_{ij}}. \end{aligned} \quad (7)$$

After obtaining W , input the test data S_{test} and get the features data H_{test} through

$$\mathbf{H}_{\text{test}} = \mathbf{W}^+ \mathbf{S}_{\text{test}}. \quad (8)$$

W^+ is the pseudo inverse matrix of W . The extracted feature of each sample is each column vector of H_{test} .

4. Results

4.1. EME Simulation

4.1.1. Main Signal Simulation. The main signal includes radar signal, communication signal, and jamming signal [36].

In this simulation, the communication signal is composed of four kinds of digital modulation signals, which are amplitude keying (ASK), phase shift keying (PSK), frequency shift keying (FSK), and quadratic amplitude modulation (QAM). In this part, 17 modulation modes and 20 different frequencies are used to simulate signals, as shown in Table 1. By this way, we acquire $20 * 17 = 340$ communication signals and simulate signals at random occurrence time and random amplitude for building the complicated electromagnetic environment. The 2ASK signal and 4ASK signal are shown in Figure 1.

The radar signal is composed of six kinds of digital modulation signals, which include continuous wave (CW), Linear Frequency Modulation (LFM), Nonlinear Frequency Modulated (NLFM), 8PSK, and 8FSK. In this part, 20 different frequencies, 8 PW, and PRI, 6 modulation types are used to simulate signals, as shown in Table 2. In this way, we acquire $20 * 8 * 6 = 960$ radar signals and simulate signals at random occurrence time and random amplitude for building the electromagnetic environment signals. The CW signal and LFM signal are shown in Figure 2.

The jamming signal is composed of 4 kinds of digital modulation signals, which include radio frequency noise (NRF), amplitude modulation noise (NAM), frequency modulation noise (NFM), and phase modulation noise (NPM). In this part, 20 different frequencies and 4 modulation types are used to simulate signals, as shown in Table 3. In this way, we acquire $20 * 4 = 80$ jamming signals and simulate signals at random occurrence time and at random amplitude for building the complicated electromagnetic environment. The NRF signal and NAM signal are shown in Figure 3.

4.1.2. EME Signal Construction. The EME signal is composed of the signals constructed above. There are four categories of electromagnetic radiation signals, including simple, mildly complex, moderately complex, and heavily complex. We used 100, 316, 735, and 1380 kinds of main signals to construct four electromagnetic environment signals of different complexities, as shown in Table 4.

The random occurrence time and amplitude of the simulated EME signal are shown in Figure 4. The time-domain waveform and spectrum of simple, slightly complex, moderately complex, and severely complex electromagnetic environmental signals are arranged from top to bottom.

TABLE 1: Simulation parameters for commutation signal.

Frequency (MHz)	Modulation type
50 100 150 200 250	2ASK 4ASK 8ASK 16ASK
300 350 400 450 500	2PSK 4PSK 8PSK 16PSK
550 600 650 700 750	2FSK 4FSK 8FSK 16FSK
800 850 900 950 1000	8QAM 16QAM 32QAM 64QAM 128QAM

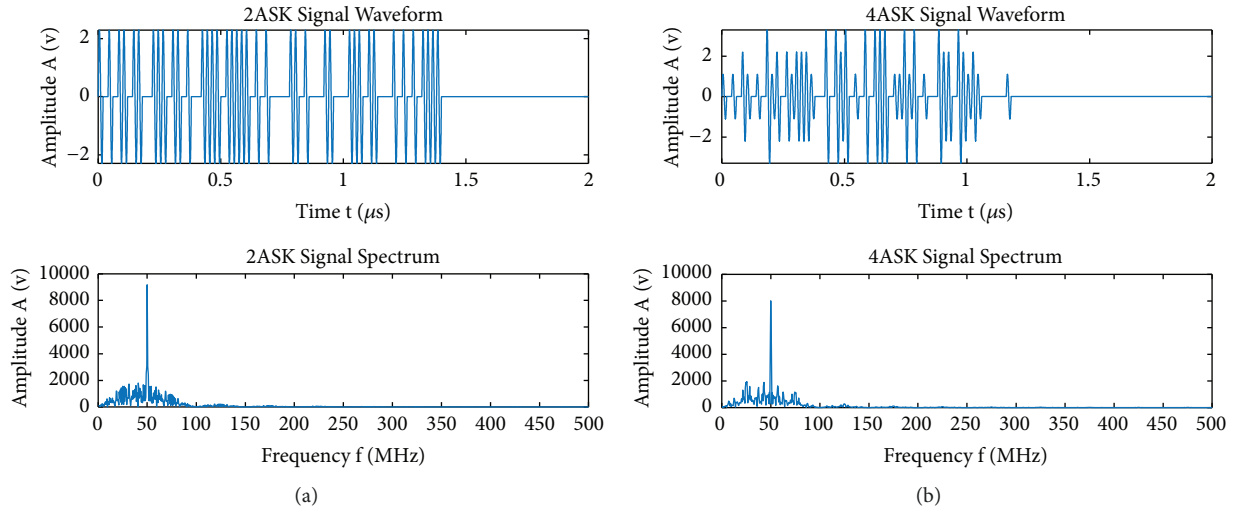


FIGURE 1: Simulation for (a) 2ASK signal and (b) 4ASK signal.

TABLE 2: Simulation parameters for radar signal.

Frequency (MHz)	PW (us)	PRI (us)	Modulation type
250 440 750 1000	0.05	0.1	CW
1250 1500 1750 2000	0.2	0.25	LFM
2250 2500 2750 3000	0.3	0.35	NLFM1 (quadratic)
3250 3500 3750 4000	0.4	0.45	NLFM2 (logarithmic)
4250 4500 4750 4900			8PSK 8FSK

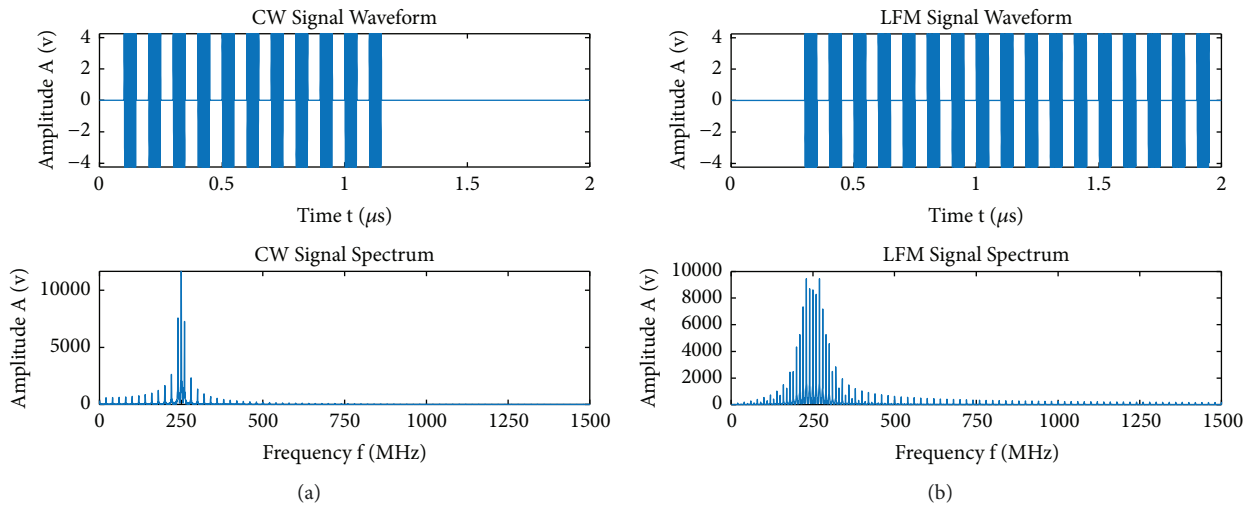


FIGURE 2: Simulation for (a) CW signal and (b) LFM signal.

TABLE 3: Simulation parameters for jamming signal.

Frequency (MHz)	Modulation type
200 440 660 880 1100	NRF
1320 1540 1760 1980 2200	NAM
2420 2640 2860 3080 3300	NFM
3520 3740 3960 4180 4400	NPM

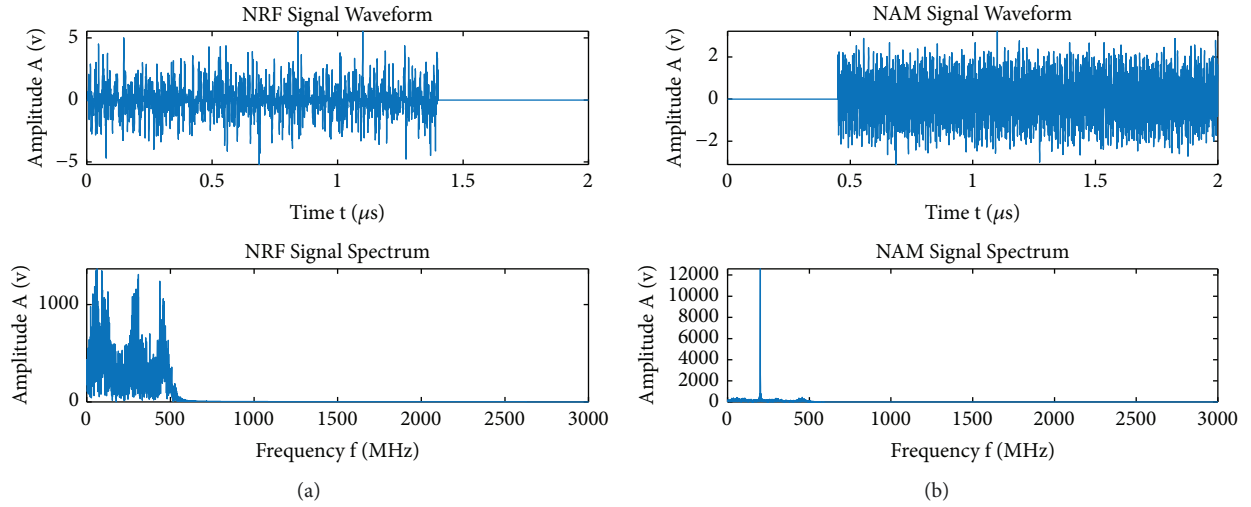


FIGURE 3: Simulation for (a) NRF signal and (b) NAM signal.

TABLE 4: Elements of EM signal with four complexity degrees.

Complexity degree		Simple	Mildly complex	Moderately complex	Heavily complex
Radar signal	Frequency	5	10	15	20
	PW (PRI)	2	5	6	8
	Modulation	4	4	6	6
Communication signal	Frequency	10	12	15	20
	Modulation	6	8	10	17
Jamming signal	Central frequency	0	10	15	20
	Jamming type	0	2	3	4
Amount of signal types		100	316	735	1380

4.2. Morphological Filtering. In this section, the mathematical morphology method is used to filter four kinds of electromagnetic environmental signals with varying complexity. Unit structure element g and maximum scale ε_{\max} are two key parameters in signal filtering based on mathematical morphology. In this paper, the flat structure element with length 3 is used as the unit structure element, that is, $g = \{0, 0, 0\}$. The advantage of selecting the flat structure element is that it can ensure that the estimation result is not affected by the amplitude range of the signal and reduce part of the amount of calculation; that is, the addition and subtraction operations can be omitted in the corrosion and expansion of the signal. There is no fixed method for the selection of scale, and too much scale will bring a large amount of calculation and affect the accuracy of estimation at the same time.

4.2.1. Basic Morphological Filtering. To intuitively demonstrate the role of different morphological filtering operators in pulse signal extraction, Figure 5 shows the

results and frequency spectrum of the simulation signal processing of a heavy complex electromagnetic environment using morphological dilate, morphological erode, morphological open, and morphological close, respectively. The structural elements are flat structural elements with a scale of 64. Each part of the blue line is the original noisy simulation signal, and the red line is the result of morphological processing.

4.2.2. Morphological Gradient Filtering. Based on basic morphological filtering, the morphological gradient is used to filter the signal. Figure 6 shows the results and frequency spectrum of the simulation signal processing of the heavy complex electromagnetic environment using morphological dilate-erode gradient and morphological close-open gradient. The structural elements are flat structural elements with a scale of 64. Each part of the blue line is the original noisy simulation signal, and the red line is the result of morphological processing.

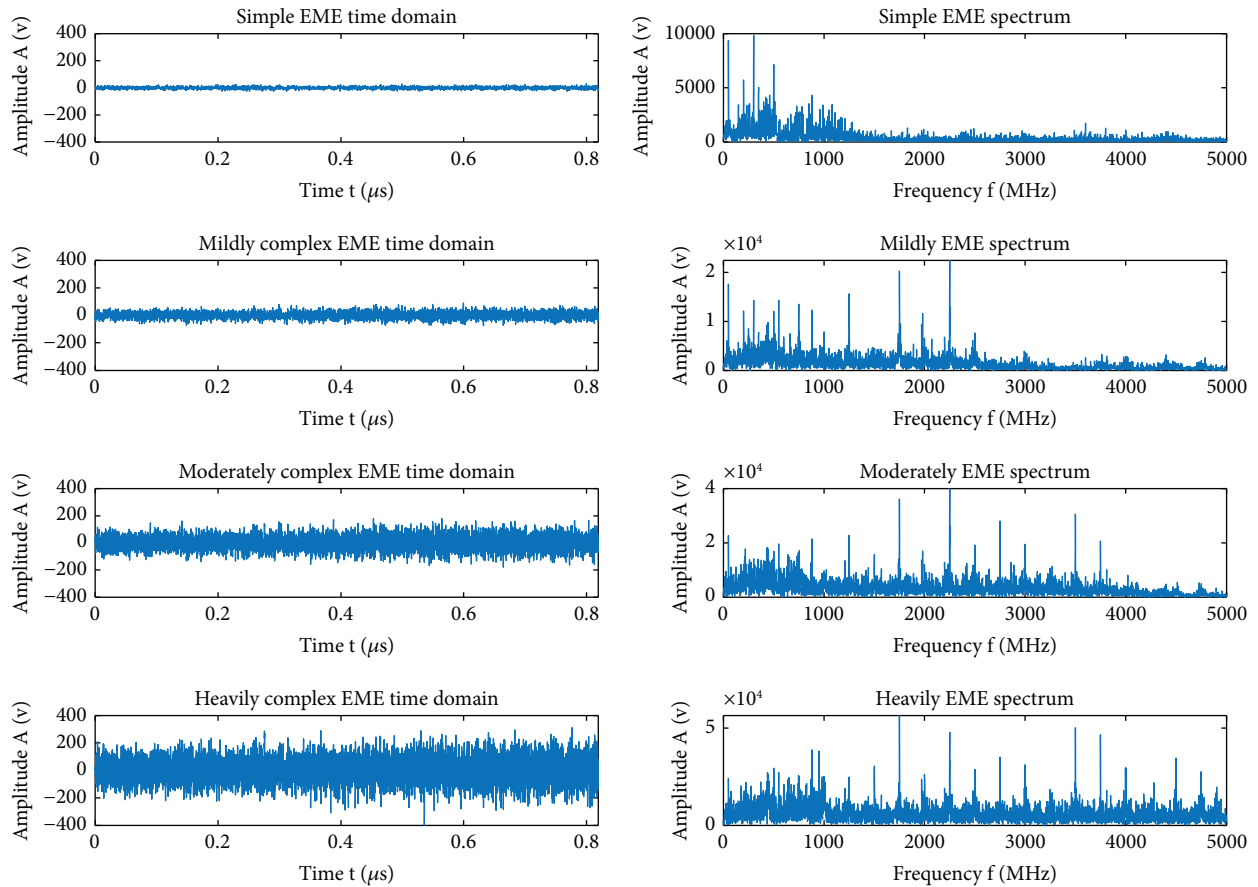


FIGURE 4: Simulation for EME signal.

As can be seen from Figures 5 and 6, the basic morphological filtering and morphological gradient filtering can filter the high-frequency components and retain the low-frequency classification but the filtered signal still has residual high-frequency components.

4.2.3. Adaptive Multiscale Morphological Gradient. The AMMG algorithm is used to process the analog signal, and the proportion of structural elements is selected as K . K ranges from 2 to 100 with a stride of 2. The results obtained by processing signals from heavily complex electromagnetic environments are shown in Figure 7.

The comparison between Figures 5–7 shows that AMMG can better extract the low-frequency signal components of the signal and filter the high-frequency components of the signal.

4.3. NMF Feature Extraction. After morphological filtering, 50 samples are selected for each complexity, and the time-domain signal is converted into a spectrum by the fast Fourier transform. These 200 samples are used to combine the matrix with a dimension of 400×200 . In each complexity, 25 samples are selected as training samples, so that the training sample set can be obtained, and other matrices can be used as test matrices. In this work, the rank r of the factorization ranges from 10 to 100 with a stride of 10.

Figures 8–10 show the feature matrix at $r = 20$, $r = 60$, and $r = 100$. Each row represents one complexity degree of EME. The results show that the feature vectors obtained by NMF have obvious similarities in the same complexity and have obvious differences in different complexities.

4.4. Classification. The data samples used are all from the feature matrix extracted by nonnegative matrix decomposition. After training the support vector machine with the training data, the test data are classified, and the classification accuracy is obtained. This process is repeated 50 times, and the average classification accuracy of support vector machines with different ranks is shown in Table 5.

The results show that the proposed feature extraction method has an effective effect on the complexity of electromagnetic environment classification. The accuracy of SVM classification reaches 90%. When the rank is 70, the performance of feature extraction classification is better than other ranks.

5. Discussion

This paper proposes a complex electromagnetic environmental signal feature extraction method based on adaptive multiscale morphological gradient filtering and nonnegative matrix factorization techniques. Among them, the adaptive multiscale morphological gradient filtering

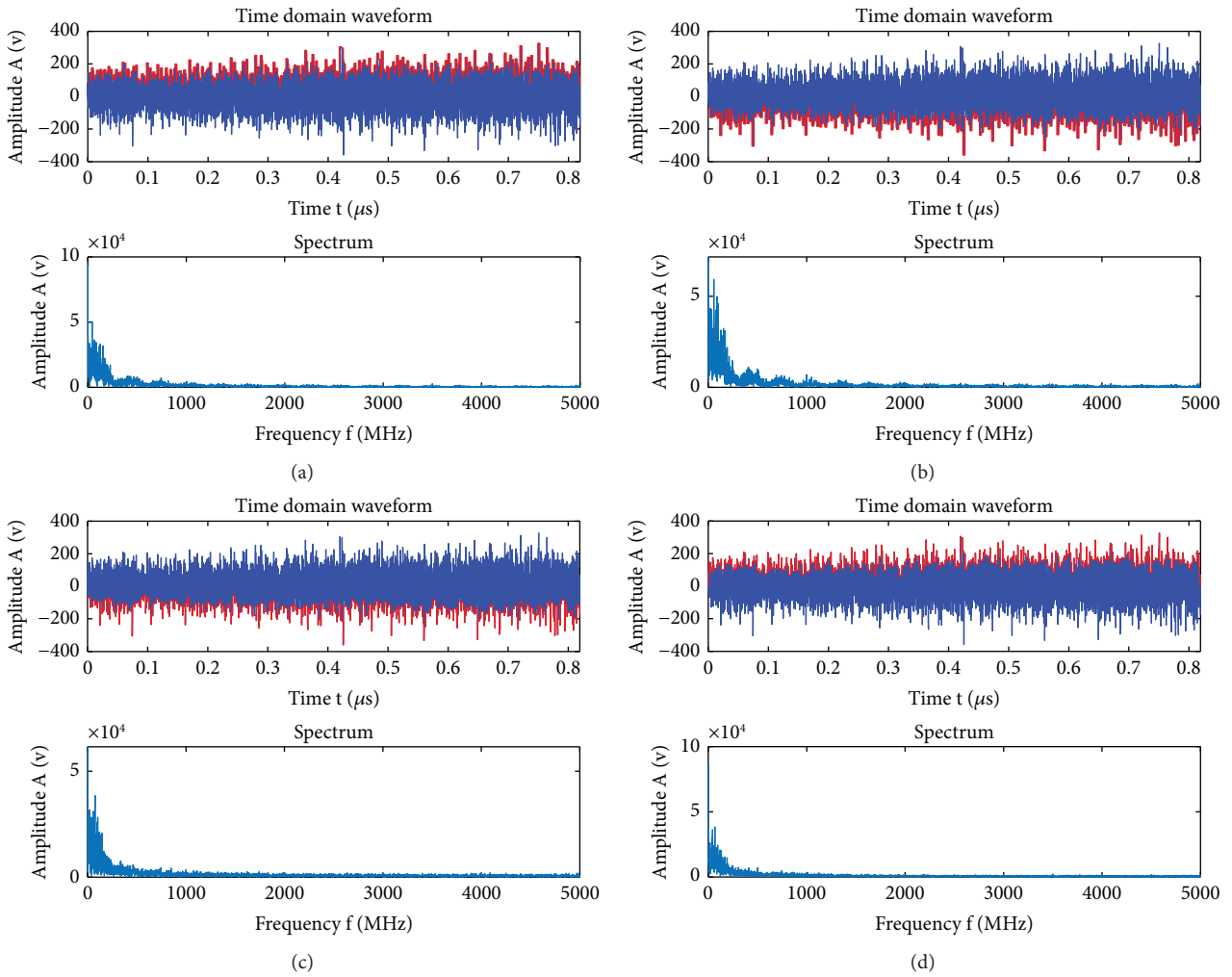


FIGURE 5: Basic morphological signals and spectrum of (a) dilate, (b) erode, (c) open, and (d) close.

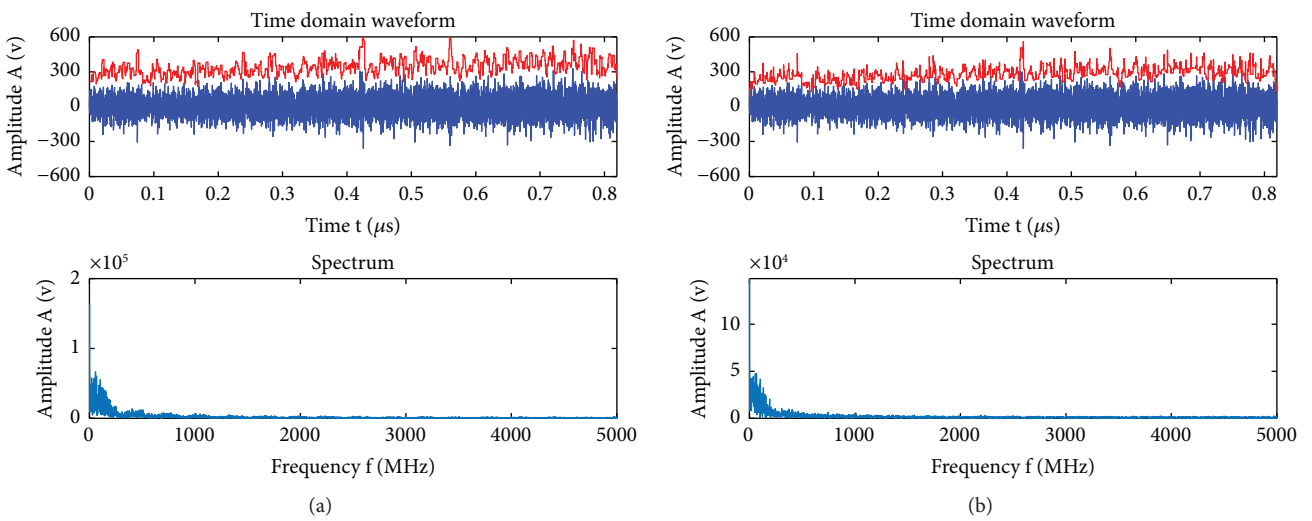


FIGURE 6: Morphological gradient signals and spectrum of (a) dilate-erode and (b) close-open.

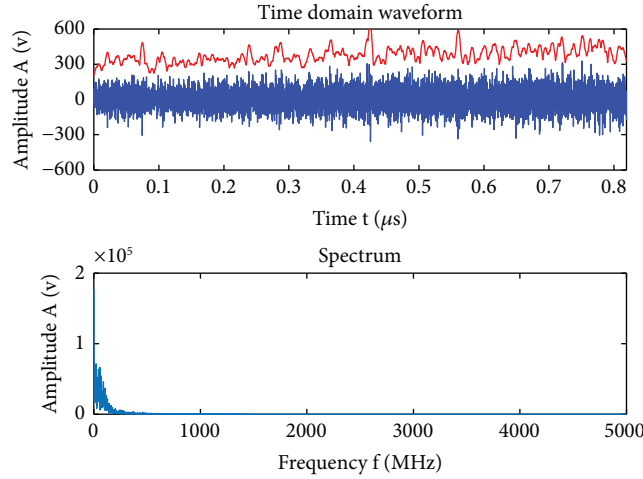


FIGURE 7: Adaptive multiscale morphological gradient (AMMG) signals and spectrum.

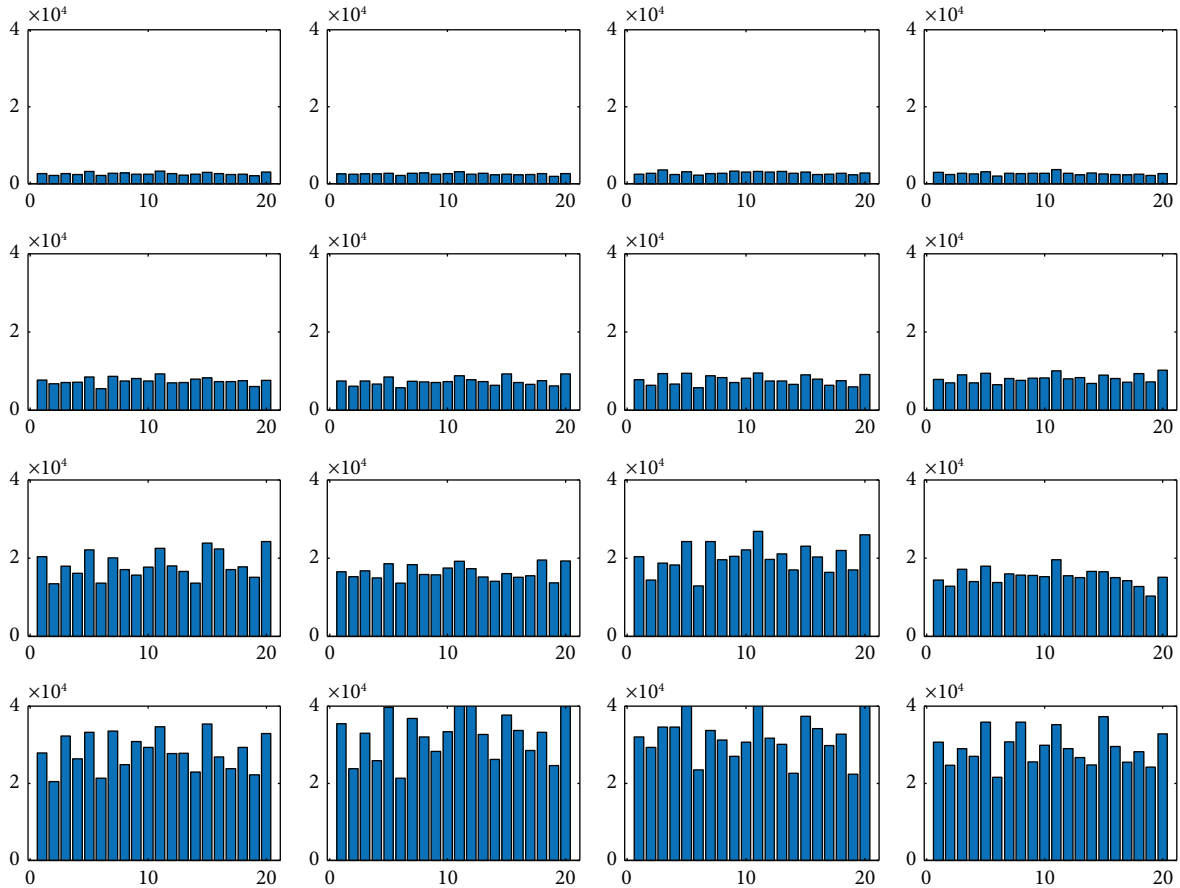


FIGURE 8: Feature matrix calculated by NMF at $r=20$.

method is derived based on mathematical morphological filtering and applies to the filtering of nonlinear signals. The method combines the advantages of retaining signal details at small scales and suppressing noise at large scales, which can effectively retain the impulse feature information in the signal and suppress the interference of noise and low-frequency

components. The nonnegative matrix decomposition technique reduces the dimensionality of the signal and adds the constraint of “nonnegative” to avoid generating meaningless negative numbers, which is interpretable. The resulting feature extraction method is also applicable to the analysis of other nonlinear signals, such as bearing fault signals.

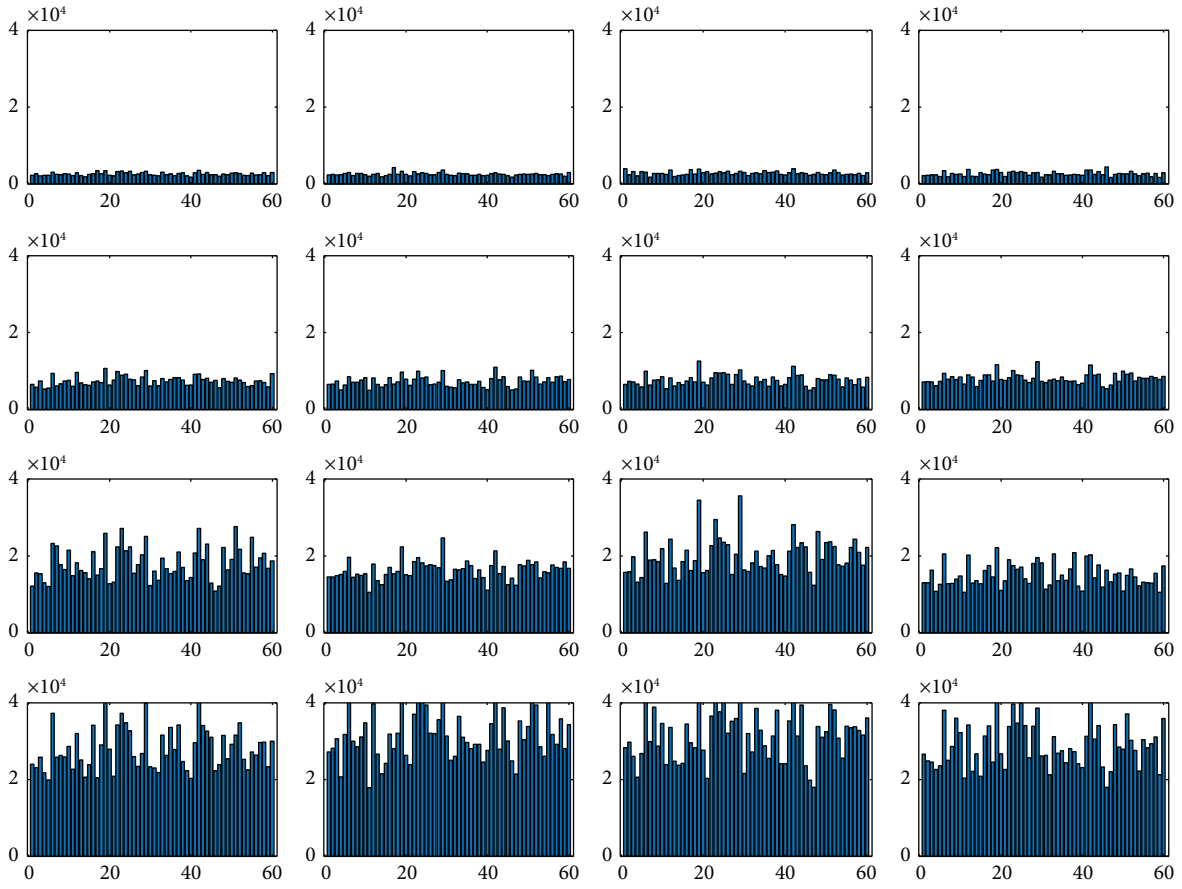
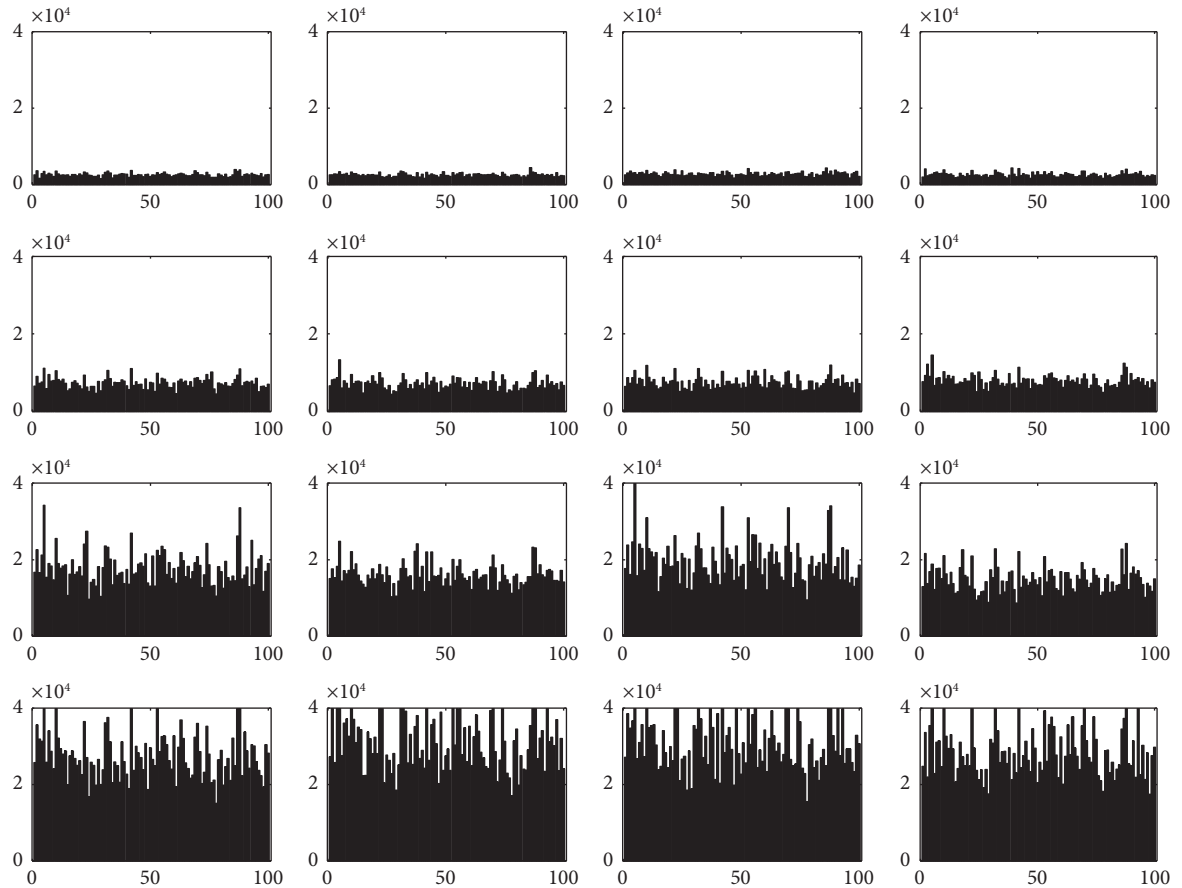
FIGURE 9: Feature matrix calculated by NMF at $r=60$.FIGURE 10: Feature matrix calculated by NMF at $r=100$.

TABLE 5: Classification accuracy.

r	10	20	30	40	50	60	70	80	90	100
Accuracy(%)	91.5	92.2	92.3	92.5	93.3	95.6	95.8	94.5	93.6	91.9

6. Conclusions

To address the typical nonlinear nature of electromagnetic environmental signals, the paper adopts mathematical morphology for signal processing and adaptive multiscale morphological gradient filtering for electromagnetic environmental signals to address the problem of one-sided signal processing structure due to the use of single-scale structural elements in morphological basic filtering and morphological gradient filtering. The results show that the adaptive multiscale morphological gradient operation can better filter the high frequencies of the signal, which is beneficial to the subsequent feature extraction of the electromagnetic environment signal.

Based on the adaptive multiscale morphological gradient for electromagnetic environmental signal processing, non-negative matrix factorization technology is used to extract characteristic parameters of the signal. The actual complexity classification results show that the proposed feature subset based on adaptive multiscale morphological gradient with nonnegative matrix decomposition has good classification accuracy.

In subsequent studies, mathematical morphology can be combined with methods such as wavelet decomposition and fractal dimensionality to extract features from several aspects of the complexity of the electromagnetic environmental signals. Mathematical morphology can also be combined with methods such as neural networks to evaluate and classify the complexity of electromagnetic environmental signals.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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