Effect of Modulation Parameters on Radiometric Fingerprinting

Shouyun Deng, Zhitao Huang, Guodong Yang, Xueqiong Li, and Gangson Ding
College of Electronic Science and Engineering, National University of Defense Technology, Changsha, China
Email: dengshouyun@nudt.edu.cn, taldcn@yahoo.com.cn, {smartyangguodong, beryl_li}@163.com, 240553632@qq.com

Abstract—**In the same way that a biological fingerprint operates, radiometric fingerprinting can be used to designate the unique transmitter of a given signal to improve the security and privacy of wireless communication, using only external feature measurements to match with the feature library. Fingerprinting reflects the unintentional modulation of radio, and it contains rich non-ideal characteristics of internal components within emitter. Our previous research work on finding out effective fingerprintings to establish the unique identity of a transmitter. However, in practical use we find that the change of intentional modulation parameters will affect the working status of internal components, to further affect radiometric fingerprinting. This paper uses information dimension and box dimension of fractal dimension theory to extract the signals fingerprinting to identify three different radios. A signal acquisition system is designed to capture the signals to analyze the effect of modulation parameters on the fingerprinting, where signals are generated under three different modulation modes, signal bandwidths and transmission frequencies. The experimental results show that, firstly, the distribution of radio's fractal dimension feature is different under different modulation modes, secondly, signal bandwidth has little influence on the feature, thirdly, the change of transmission frequency will result in a great degree of drift on the feature.**

Index Terms—**radiometric fingerprinting, modulation parameters, fractal, box dimension, information dimension**

I. Introduction

Radiometric fingerprinting identification is called specific emitter identification, and it refers to the technology that uses the fingerprint contained in the radio transmitter to identify the unique radio device. Just like we each have unique fingerprints, even if transmitters producted by same manufacturers have same modes and production batches, there still are a few differences between them. These differences hidden in the transmission signal are known as fingerprinting of the individual transmitter, which play a special role in the security space. In the field of information security, the traditional security depends on the digital secret key or MAC address authentication. However, these security methods based on digital identifiers are limited due to the fact that keys or MAC addresses can be decrypted and replayed easily [1]. Individual transmitter identification based on radiometric fingerprinting uses the identification information that cannot be copied to detect intrusion effectively. So, the radiometric fingerprinting provides a very effective way to solve the communication and network security threats [2], and it can be also used for monitoring to management spectrum resources accurately.

Radiometric fingerprinting is a popular area of research in recent decades [3]-[6]. Jingwen Zhang *et al.* proposed three SEI algorithms based on the Hilbert spectrum [7]. Guangquan Huang *et al.* put forward a novel SEI method based on nonlinear dynamical characteristics [2]. Saeed Ur Rehman *et al.* studied the effect of the receiver SNR on the overall RF fingerprinting classification [8]. Previous research shows that the key to effective emitter identification system is to extract an robust and stable features from the given signals, and a good feature can achieve a good recognition result.

With the improvement of electronic process and the application of software radio technology, all kinds of communication equipments have a variety of working models and signal systems, and users can set up working parameters of the communication system according to the communication requirement and the actual environment. Radiometric fingerprinting is generated by the physical characteristics inside devices and the interactions between circuit componets, and it is usually shown as nonlinear, non-stationary, non-Gaussian characters and so on, which is the reflection of unintentional modulation of radio. But when the communication system is working, the change of intentional modulation parameters will affect the working status of internal components, to further affect radiometric fingerprinting, and research reports on this point are also few. So, this paper uses information dimension and box dimension of fractal dimension theory as the signals fingerprinting. We design a signal acquisition system to collect signals under three different modulation modes, signal bandwidths and transmission frequencies, and analyse the effect of modulation parameters on radiometric fingerprinting.

II. Feature Extraction

A. Fractal Dimension Theory

Due to the differences inside the device, different communication emmiters often contain a wealth of non-

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linear, non-stationary characteristics in the form of signal. Fractal dimension was firstly introduced by B. B. Mandelbrot in 1975. Fractal dimension is an important numerical characteristic of fractal that contains geometry information of curves and images [9]. Fractal dimension is an important measurement tool to analyze fractal signal, and it can describe the geometric scale change and complexity of the signal very well. So the fractal dimension is widely used in the research of fingerprint feature analysis of communication radiation source. In the practical application, the box dimension and information dimension are usually used for the analysis of communication emmiter fingerprint.

1) Box dimension

Box dimension is one of the intuitive fractal analysis approaches, which can be used to measure the degree of irregularity of signal and reflect the geometric scale of signal [10].

Let us denote a metric space by (x,d), where F is compact spaces no empty on X dominating. The variable ε is a non-negative real number, and $B(x,\varepsilon)$ represents a closed sphere centered at x, with a radius of ε. A is a nonempty set in X . $N(A,\varepsilon)$ denotes the minimum number of closed ball covering for each positive ε, and it can be described by the following equation:

$$N(A,\varepsilon)=\left\{M \middle| A\subset\bigcup_{i=1}^{M}B(x_i,\varepsilon)\right\} \tag{1}$$

f is defined as a continuous function on a closed set T, and A is a set defined on R^2. Then the box dimension of function f can be calculated as follow:

$$D_B(f)=\lim_{\varepsilon\to 0}\left\{sup\frac{\ln N(A,\varepsilon')}{\ln(1/\varepsilon')}:\varepsilon'\in(0,\varepsilon]\right\} \tag{2}$$

2) Information dimension

By the definition of box dimension we can see that the box dimension can reflect the geometric scale of signals, but box dimension cannot measure the inhomogeneity of fractal in spatial structure [11], which is just the spatial distribution density of fractal sets on the scale. So the information dimension was proposed.

$$P_j=\frac{N(X)_j}{N(X\bigcap U_j)}, j=1,2,...,N \tag{3}$$

where X is a set defined on R^n, and $\{U_j\}(j=1,2,...,N)$ is a finite δ-covering of X. The probability of elements of the set X falled on the collection U_j is P_j. $N(X)_j$ and $N(X\bigcap U_j)$ denote the number of elements respectively.

Let information entropy $E_I=-\sum_{j=1}^{N}P_j\ln P_j$ denote configurational entropy of X, then the information dimension of X can be defined as:

$$D_I=-\lim_{\delta\to 0}\frac{E_I}{\ln\delta} \tag{4}$$

B. Calculation of Fractal Dimension Feature

Based on the above analysis, we extract the envelope of the radio communication signal, and then calculate box dimensions and information dimensions of the envelope time series as a radio signal fingerprint feature. The feature can be calculated by following these steps:

(a) Capture the time slot from the radio communication signal as the signal sample $\{\mathrm{x}(i)\}(i=1,2,...,N)$ for the feature extraction, where N is the signal length,

(b) Calculate the envelope sequence $\{\xi(i)\}(i=1,2,...,N)$ from the signal sample $\{\mathrm{x}(i)\}$,

(c) Put the signal envelope sequence $\{\xi(i)\}$ in the unit square box, where the minimum distance of horizontal coordinate is $\delta=1/N$, then define function $N(\delta)$ as:

$$N(\delta)=N+\left\{\sum_{\mathrm{i}=1}^{N-1}\max(x(i),x(i+1))\delta-\sum_{\mathrm{i}=1}^{N-1}\min(x(i),x(i+1))\delta\right\}/\delta^2 \tag{5}$$

so the box dimension $D_B(\delta)$ can be calculated by the formula:

$$D_B(\delta)=-\frac{\ln(N(\delta))}{\ln(\delta)} \tag{6}$$

(d) The signal envelope sequence is reconstructed according to the following formula:

$$\xi_0(i)=\xi(\mathrm{i}+1)\text{-}\xi(\mathrm{i}),i=1,2,...,N\text{-}1 \tag{7}$$

Then we can get a new sequence $\{\xi_0(i)\}(i=1,2,...,N\text{-}1)$,

(e) Use the reconstructed signal sequence to calculate the information dimension. Let $P(i)=\frac{|\xi_0(i)|}{E}$ represent the probability distribution function, where $E=\sum_{i=1}^{N-1}|\xi_0(i)|$. Finally, the information dimension $D_I(\delta)$ can be carried out by the formula:

$$D_I(\delta)=-\sum_{i=1}^{N-1}P_i(\delta)\ln P_i(\delta) \tag{8}$$

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Experimental Structure and Signal Acquisiton

To study the effect of modulation parameters on fingerprinting, an experimental system shown in Fig. 1 is implemented. The test equipment comprises PCs, Anykey AKDS700 radios, a digital receiver, and an oscilloscope. Two radios are installed in two PCs respectively to form a transmitter and a receiver. Then, real time wireless communication is performed between the transmitting side and the receiving side. Users can set the communication parameters according to their needs and communication environment. Following this, a digital oscilloscope is utilized to collect the radio's RF signals. The experiment is carried out under three different modulation modes, signal bandwidths and transmission frequencies. We collect communication signals from three same model digital radios, and three radios are named ip2, ip3, and ip4 separately.

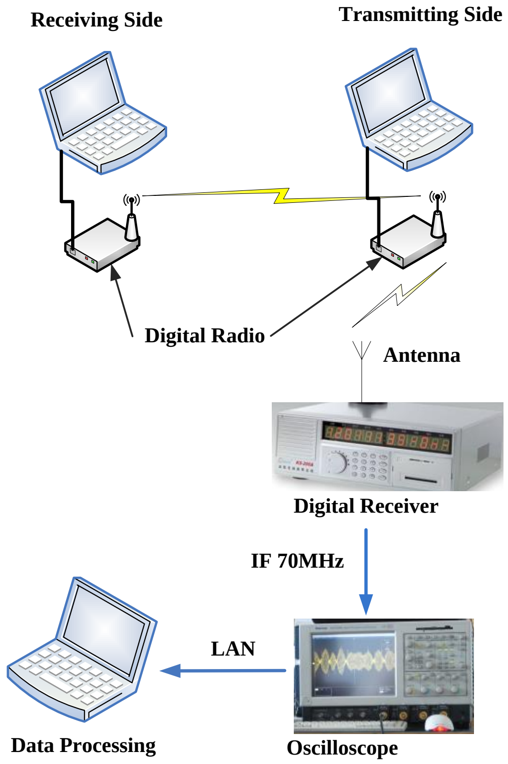


Figure 1. The scheme of experiment.

B. *Experimental Results*

In the experiment, one hundred sets of datas are collected for each radio, and each set of data is made up of multiple data slots. The time-domain waveform of signal is shown in Fig. 2, and the corresponding spectrogram is shown in Fig. 3.

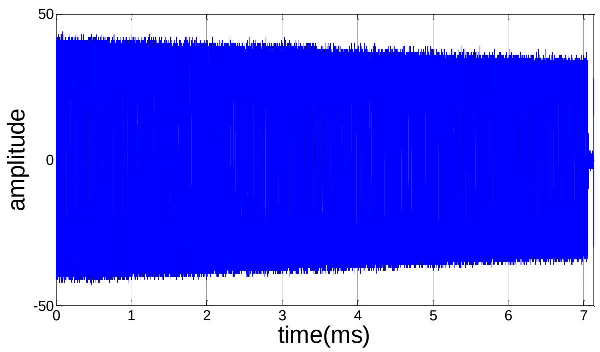


Figure 2. The time-domain waveform.

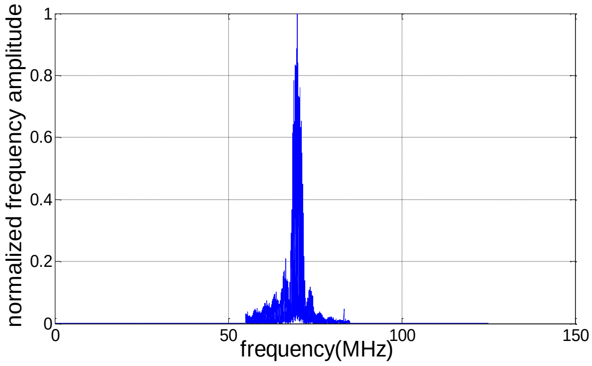
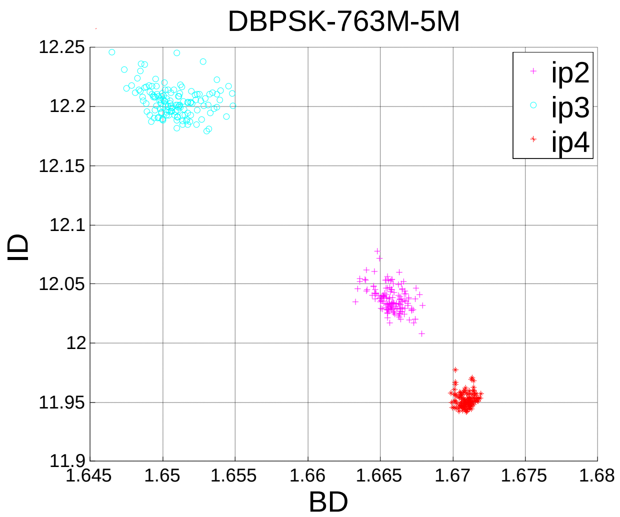


Figure 3. The spectrogram of signal.

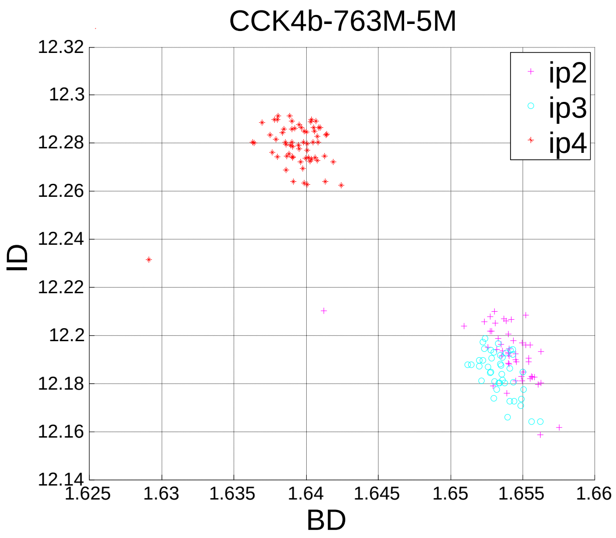
From the time-domain waveform we can see that duration of a complete data slot is approximately 7ms, and the spectrum reflects that the signal environment is relatively clean. We select the samples with high SNR for feature extraction, then we calculate the box dimension and information dimension of each sample from three radios under different situations:

1) Different modulation modes

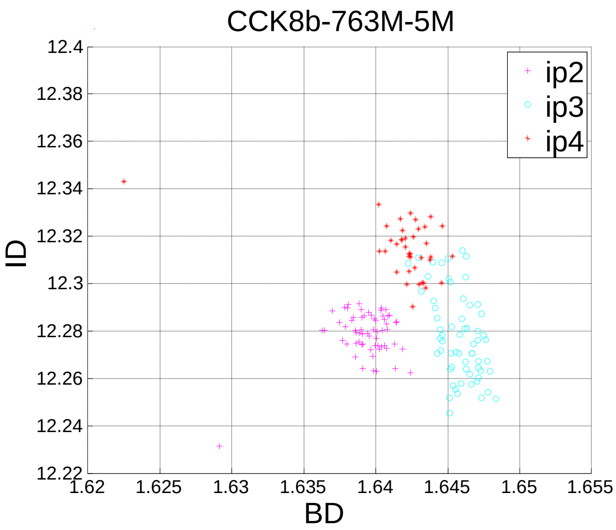
Fig. 4 shows that the distribution of box dimension and information dimension of each radio in the plane when the transmission frequency is 763MHz, signal bandwidth is 5MHz, and modulation modes are DBPSK, CCK4b and CCK8b. With Box Dimension (BD) on the horizontal and Information Dimension (ID) on the vertical, we can see that the distribution of radio's fractal dimension feature is different under different modulation modes. Fig. 4(a) shows that the feature can distinguish different radios easily for DBPSK. Fig. 4(b) shows that the box dimension and information dimension of radio ip2 and ip3 are partially overlapped for CCK4b. Fig. 4(c) shows that the feature distribution of the three radios for CCK8b is more divergent than that of the DBPSK modulation, and the distance between classes is smaller.



(a) Modulation mode is DBPSK.



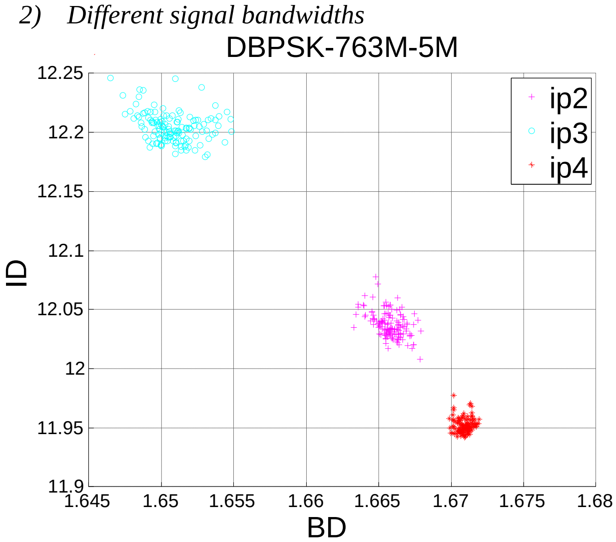
(b) Modulation mode is CCK4b.



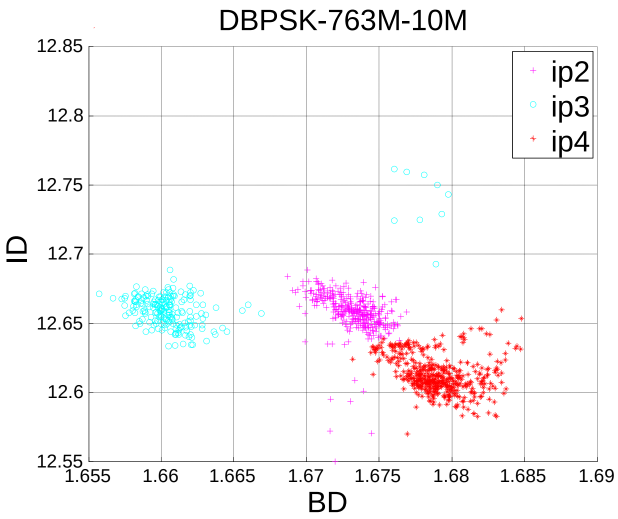
(c) Modulation mode is CCK8b.

Figure 4. The fractal dimension feature of radio signal under three different modulation modes.

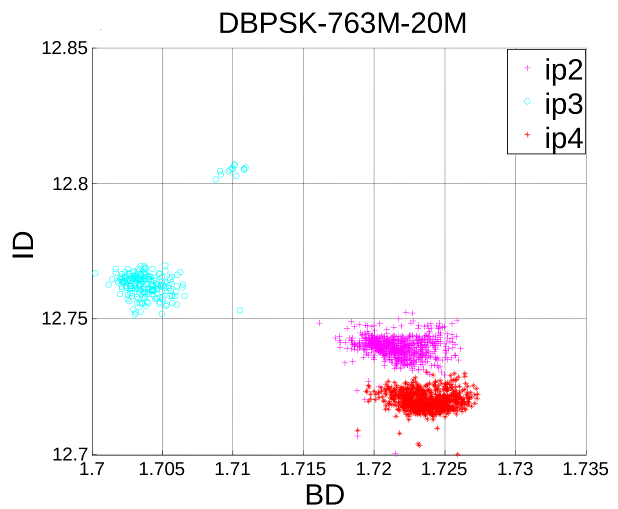
2) Different signal bandwidths



(a) Signal bandwidth is 5MHz.



(b) Signal bandwidth is 10MHz.



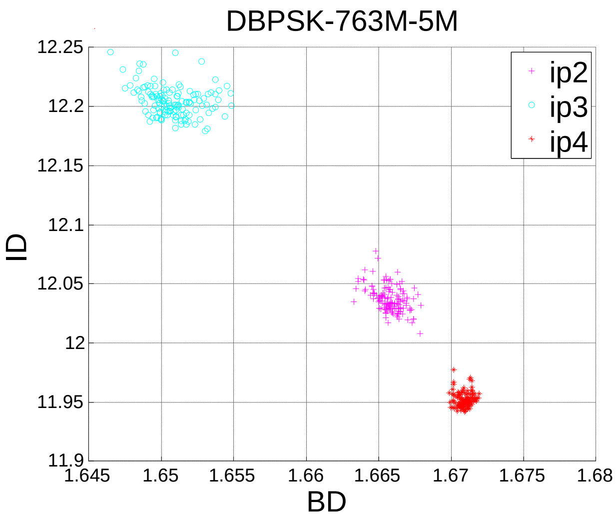
(c) Signal bandwidth is 20MHz.

Figure 5. The fractal dimension feature of radio signal under three different signal bandwidths.

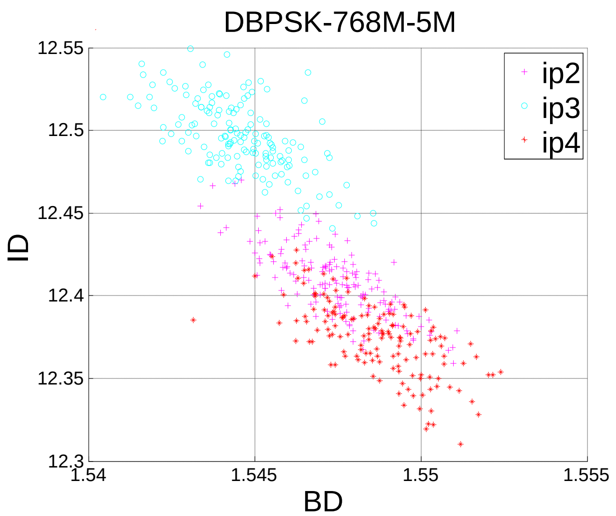
Fig. 5(a), (b) and (c) plot the distribution of box dimension and information dimension of radios in a plane when the signal bandwidths are 5MHz, 10MHz, and 20MHz. From Fig. 5 we can see that the fractal dimension features of three radios all have certain separability under the three signal bandwidths. But when the bandwidth is 10M or 20M, the relative positions of feature for three radios have changed compared with 5MHz.

3) Different transmission frequencies

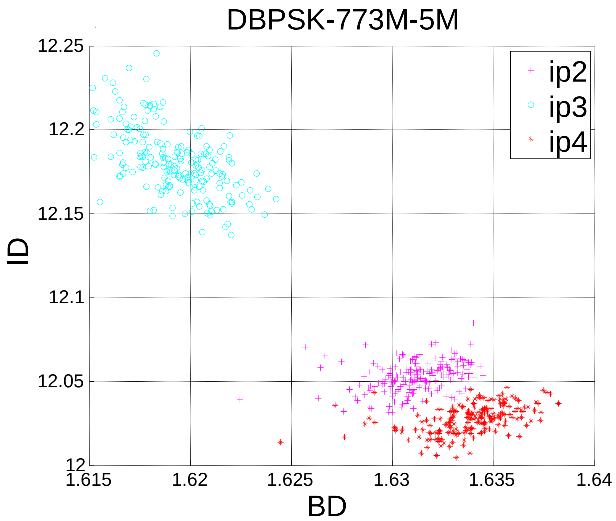
Fig. 6 shows that the distribution of fractal dimension feature of radios under three different transmission frequencies. As we can see from the Fig. 6(b), the divergence of eigenvalue becomes larger compared with Fig. 6(a), and the feature points of ip2 and ip4 have a small amount of mixing. Fig. 6(c) shows that the box dimension of ip4 radio decreases and the information dimension of ip4 radio increases. The distance between the classes of the feature points of the ip4 and ip2 in Fig. 6(c) decreases, but two radios can still be distinguished.



(a) Transmission frequency is 763MHz.



(b) Transmission frequency is 768MHz.



(c) Transmission frequency is 773MHz.

Figure 6. The fractal dimension feature of radio signal under three different transmission frequencies.

As can be seen from the above analysis, when the box dimension and information dimension are calculated as individual identification fingerprinting, the change in signal modulation mode will make the feature distribution of the radios different, and the features distribution of the radios may overlap with each other. Signal bandwidth have a little effect on radio's fractal dimension fingerprinting, and the feature distribution of radios change a little under different signal bandwidths. And the box dimension and information dimension are still valid for the individual identification of the three radios even the signal bandwidth is changed. The change of transmission frequency has such a great influence on the fractal dimension of the radios that it can cause the drift of the feature points and make divergence of eigenvalue for the radios become larger. This is because the frequency generator is a key source of non-ideal characteristic of radio equipment and that it is also the main generating mechanism of the fingerprinting. When the radio works in different transmission frequencies, frequency generator inside the radio will have different non-ideal characteristic. It also shows that the fractal dimension can well describe the nonlinear and non-stationary characteristics of the signal.

IV. Conclusions

Transmitter individual identification is a very challenging technology, and radiometric fingerprinting has a very complex generation mechanism [12]. This paper analyzed the effect of modulation parameters on radiometric fingerprinting. Box dimension and information dimension are extracted as fingerprinting feature of radios under different modulation parameters. Our experimental results show that the distribution of fractal dimension feature for radios is different under three modulation modes, the signal bandwidth has little influence on the fractal dimension of radio station, and the change of the transmission frequency can make the fractal dimension feature of radios drift.

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References

[1] A. Candore, O. Kocabas, and F. Koushanfar, "Robust stable radiometric fingerprinting for wireless devices," in *Proc. IEEE International Workshop on Hardware-Oriented Security and Trust*, July 2009, vol. 6, pp. 903-905.

[2] G. Huang, Y. Yuan, X. Wang, and Z. Huang, "Specific emitter identification based on nonlinear dynamical characteristics," *Canadian Journal of Electrical & Computer Engineering*, vol. 39, pp. 34-41, January 2016.

[3] K. I. Talbot, P. R. Duley, M. H. Hyatt, K. I. Talbot, P. R. Duley, and M. H. Hyatt, "Specific emitter identification and verification," *Technology Review*, 2003.

[4] K. J. Ellis and N. Serinken, "Characteristics of radio transmitter fingerprints," *Radio Science*, vol. 36, pp. 585-598, January 2001.

[5] O. Ureten and N. Serinken, "Wireless security through RF fingerprinting," *Canadian Journal of Electrical & Computer Engineering*, vol. 32, pp. 27-33, May 2007.

[6] V. Brik, S. Banerjee, M. Gruteser, and S. Oh, "Wireless device identification with radiometric signatures," in *Proc. ACM*

International Conference on Mobile Computing and Networking, 2008, pp. 116-127.

[7] J. Zhang, F. Wang, O. A. Dobre, and Z. Zhong, "Specific emitter identification via Hilbert–Huang transform in single-hop and relaying scenarios," *IEEE Transactions on Information Forensics & Security*, vol. 11, pp. 1192-1205, January 2016.

[8] S. U. Rehman, K. Sowerby, and C. Coghill, "Effect of receiver signal to noise ratio on the classification performance of RF fingerprinting," in *Proc. 15th Multitopic Conference (INMIC)*, 2012, pp. 143-148.

[9] J. Du, Z. Mu, Z. Xu, and Y. Tang, "Feature extraction in fingerprint of medicinal herbs via EMD and fractal technique," in *Proc. International Conference on Biomedical Engineering and Informatics*, Shanghai, China, 2011, pp. 1715-1719.

[10] L. S. Liebovitch and T. Toth, "A fast algorithm to determine fractal dimensions by box counting," *Physics Letters A*, vol. 141, pp. 386-390, September 1989.

[11] A. Langi, "Wavelet and fractal processing and compression of nonstationary signals," 1996.

[12] A. Candore, O. Kocabas, and F. Koushanfar, "Robust stable radiometric fingerprinting for wireless devices," in *Proc. IEEE International Workshop on Hardware-Oriented Security and Trust*, 2009, pp. 903-905.

Shouyun Deng received the BS degree from the School of Electronic and Information Engineering, Beijing Institute of Technology, Beijing, China, in 2015. He is currently pursuing the MS degree in the Electronic Science and Engineering College at the National University of Defense Technology. His research interests include signal processing, communications and hardware verification.