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Procedia Computer Science 107 (2017) 472 – 477

Procedia Computer Science

International Congress of Information and Communication Technology (ICICT 2017)

Radio Frequency Fingerprint Extraction of Radio Emitter Based on I/Q Imbalance

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Abstract

Specific emitter identification use external signal feature called radio frequency fingerprint to identify the different radio transmitter, which does not rely on information content. A radio frequency fingerprint feature extraction approach based on I/Q imbalance of quadrature modulation signal is proposed. A I/Q modulator model is utilized to investigate the sources of radio frequency fingerprint and the effect on signal. A fingerprint features extraction based on signal space is proposed, but the SNR (Signal to Noise Ratio) need to be estimated before. Simulation results demonstrate that the method have superior performance than previous bispectrum-based, Hibert-Huang transform-based approaches.

Keywords: specific emitter identification; I/Q imbalance; signal space; autocorrelation matrix

1. Introduction

Radio frequency fingerprint can provides a novel technology for emitter identification using the external signal feature rather than the information content. With the transmission information encryption, the approach of emitter identification relied on information content is invalid. So, specific emitter identification has good application prospect in intrusion detection [1].

Radio transmitter individual identification developed from radar emitter identification. The difference between radio transmitters is subtle, and some basic functional features such as radio frequency, transmission rate, and modulation pattern cannot distinguish different radio transmitters[2].

Transforming signals to other domains and extracting fingerprint feature provides a new perspective. Bertoncini et al utilized Wavelet-Transform and image process to extract radio frequency fingerprint[3]. The time-frequency feature that can establish the relationship between time and frequency of signal can represent more subtle characteristics [4,5].

Peer-review under responsibility of the scientific committee of the 7th International Congress of Information and Communication Technology
doi:10.1016/j.procs.2017.03.092

The time-frequency feature obtained by Hilbert-Huang transform constructed thirteen features of four types to classify different kinds of wireless emitters[5]. Integral bispectrum of signals that can represent higher-order moment feature is used to identify radio emitters[6].

These methods above all maybe used to extracted transmitters feature, and have good identification performance; however, there are several shortcomings. Such as, the transform maybe affected by random data, which the transform will change with the change of transmit data. Then hardware imperfections were researched deeply. The I/Q imbalance characteristic of I/Q modulator is researched and radio frequency fingerprint feature is extracted in this paper. The simulation demonstrate that the application can identify the different radio emitters.

Radio frequency fingerprint feature extraction based on I/Q imbalance is studied in this paper. Section 2 details the I/Q imbalance model of I/Q quadrature modulation and demonstrates the I/Q imbalance feature mechanism. In Section 3, the method based on signal space to extract features is explained. Simulation experiment is made and results are discussed in Sections 4, and finally we drew the conclusion.

2. I/Q imbalance model

Because of the hardware imperfections and the influence of environment, there will be I/Q imbalance in the I/Q quadrature modulator. The I/Q orthogonal imbalance shows that the difference of phase of carriers does not equal to 90^0. The I/Q gain imbalance shows that the gain of carriers is different. Fig.1 shows the I/Q modulator with I/Q imbalance.

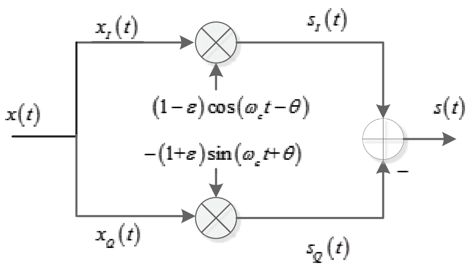

Fig. 1. I/Q modulator with I/Q imbalance

As we can see in Fig.1, ε and θ are the parameter of I/Q gain imbalance and I/Q orthogonal imbalance respectively. $x(t)=x_I(t)+jx_Q(t)$, $x_I(t)$ is the in-phase component and $x_Q(t)$ is the quadrature component. The modulator maybe a digital QAM (Quadrature Amplitude Modulation) modulator, then $x_I(t)$ and $x_Q(t)$ is the baseband signals after shaping. The modulator also maybe an analog SSB (Single Side Band) modulator, and then $x_I(t)$ is an analog signal, and $x_Q(t)$ is the Hilbert transform of $x_I(t)$. The output signal is

$$s(t)=\frac{1}{2}m(t)(1+\varepsilon)\cos(2\pi f_c t+\theta)-\frac{1}{2}\hat{m}(t)(1+\varepsilon)\sin(2\pi f_c t-\theta) \quad (1)$$

Unfolding the trigonometric function, we obtain

$$s(t)=s_I(t)\cos(2\pi f_c t)-s_Q(t)\sin(2\pi f_c t) \quad (2)$$

where

$$s_I(t)=x_I(t)(1+\varepsilon)\cos(\theta)+x_Q(t)(1-\varepsilon)\sin(\theta) \quad (3)$$

$$s_Q(t)=x_I(t)(1+\varepsilon)\sin(\theta)+x_Q(t)(1-\varepsilon)\cos(\theta) \quad (4)$$

$s_B(t)=s_I(t)+js_Q(t)$ is the equivalent lowpass complex signal of $s(t)$, and we can obtain

$$s_B(t)=\alpha x(t)+\beta x^*(t) \tag{5}$$

where

$$\begin{cases}\alpha=\cos\theta+j\varepsilon\sin\theta\\ \beta=\varepsilon\cos\theta+j\sin\theta\end{cases} \tag{6}$$

Fig.2 shows the influence of I/Q imbalance, where we simulate the QPSK (Quadrature Phase Shift Keying). As we can see, I/Q imbalance make the constellations whirl and extension.

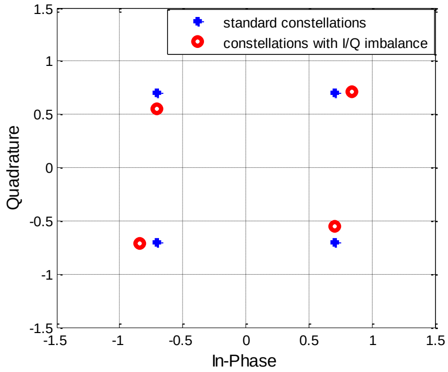

Fig. 2.The influence of I/Q imbalance

3. Feature extraction

Brik presented an approach called PARADIS to extract fingerprint feature by the way of comparing standard constellations with constellations with I/Q imbalance, which is valid only for digital modulation[7]. A novel approach based on signal space not only for digital modulation but also analog modulation is proposed in this paper.

Polluted by white Gaussian noise, the received signal is

$$r(t)=\alpha x(t)+\beta x^*(t)+v(t) \tag{7}$$

Combining (7) and the complex conjugate of received signal $r^*(t)=\beta^* x(t)+\alpha x^*(t)+v^*(t)$, we can obtain

$$\mathbf{Y}(t)=\begin{bmatrix} r(t)\\ r^*(t)\end{bmatrix}=\begin{bmatrix}\alpha & \beta\\ \beta^* & \alpha^*\end{bmatrix}\begin{bmatrix} x(t)\\ x^*(t)\end{bmatrix}+\begin{bmatrix} r(t)\\ r^*(t)\end{bmatrix}=\mathbf{AX}(t)+\mathbf{V}(t) \tag{8}$$

The input signal is proper[8,9], which $E\left[x^2(t)\right]=E\left[x_I^2(t)+2jx_I(t)x_Q(t)-x_Q^2(t)\right]=0$ is satisfied, and then $x^*(t)$ is proper too. The autocorrelation matrix of $\mathbf{X}(t)$ can be expressed by[8,9]

$$R_X=E\left[\mathbf{X}(t)\mathbf{X}(t)^H\right]=E\begin{bmatrix} x(t)x^*(t) & x(t)x(t)\\ x^*(t)x^*(t) & x^*(t)x(t)\end{bmatrix}=\sigma_X^2\mathbf{I} \tag{9}$$

where $\sigma_x^2=E\left[\left|x(t)\right|^2\right]$ is the power of $x(t)$, and we can obtain

$$\begin{aligned} R_Y &= E\left[\mathbf{Y}(t)\mathbf{Y}(t)^H\right] = E\left[\mathbf{AX}(t)\mathbf{X}(t)^H\mathbf{A}^H\right] + E\left[\mathbf{V}(t)\mathbf{V}(t)^H\right] \\ &= \sigma_X^2 \begin{bmatrix} \alpha\alpha^* + \beta\beta^* & 2\alpha\beta \\ (2\alpha\beta)^* & \alpha\alpha^* + \beta\beta^* \end{bmatrix} + \sigma_v^2 I \\ &= \begin{bmatrix} \sigma_s^2 + \sigma_v^2 & 2\alpha\beta\sigma_x^2 \\ (2\alpha\beta)^*\sigma_x^2 & \sigma_s^2 + \sigma_v^2 \end{bmatrix} \end{aligned} \tag{10}$$

$\sigma_s^2 = \left(\alpha\alpha^* + \beta\beta^*\right)\sigma_x^2$ and σ_v^2 are the power of $s_B(t)$ and noise respectively. With(10), we can construct

$$\frac{2\alpha\beta\sigma_x^2}{\sigma_s^2 + \sigma_v^2} = \frac{2\alpha\beta\dfrac{\sigma_x^2}{\sigma_s^2}}{1 + \dfrac{\sigma_v^2}{\sigma_s^2}} = \frac{2\alpha\beta\dfrac{1}{\left(\alpha\alpha^* + \beta\beta^*\right)}}{1 + \dfrac{1}{SNR}} \tag{11}$$

where $SNR = \dfrac{\sigma_s^2}{\sigma_v^2}$ is the SNR. The traditional least square algorithm based on eigenvalue decomposition is used to estimate SNR[10], and $\dfrac{2\alpha\beta}{\left(\alpha\alpha^* + \beta\beta^*\right)}$ is obtained. $\theta = \left[\operatorname{Re}\left(\dfrac{2\alpha\beta}{\left(\alpha\alpha^* + \beta\beta^*\right)}\right), \operatorname{Im}\left(\dfrac{2\alpha\beta}{\left(\alpha\alpha^* + \beta\beta^*\right)}\right)\right]$ is constructed as the radio frequency fingerprint feature.

4. Simulation

In order to confirm the validity of our method of features extraction based on signal space, simulation experiment is conducted. The process of specific emitter identification experiment is showed in Fig.3. The focus is the algorithm of feature extraction in this paper, and classifier is not studied, which Support Vector Machine is used[11].

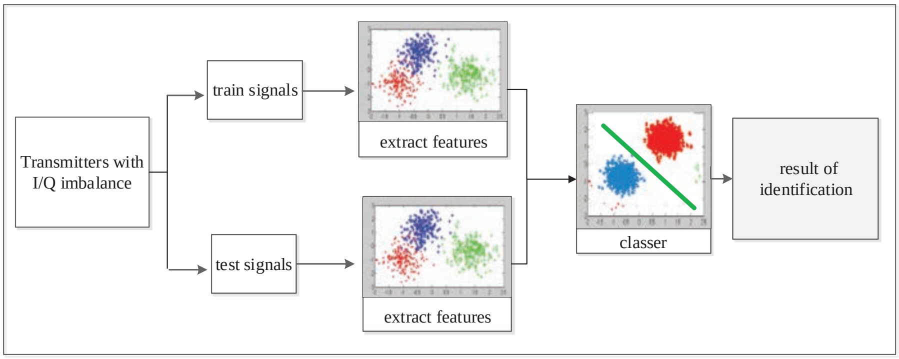

Fig. 3. SEI experiment process

Signals of five analog modulators with I/Q imbalance are simulated using computer, and the parameters is setup as Table 1. Each emitter generate 400 signals, half of the signals constructing the train set, while the test set being constructed by the rest half of the signals. The sampled points of a signal are a few, which only 1330 points. To investigate and compare the performance, the bispectrum based and Hibert-Huang transform based methods are adopted to extract signal features.

Fig.4 gives the view of the fingerprint features extracted with our method when the SNR is 15dB. As we can see, the features extracted with our method have the capability of classing the different radio emitters. Fig.6 shows the correct recognition curve with variation of SNR. Enough sampled points are required to obtain the correct bispectrum and time frequency energy distribution. Besides, the extracted features have no explicit physical significance and cannot demonstrate the difference of different radio transmitters. By comparison, our approach achieves the better performance.

Table 1. Parameters of I/Q imbalance

serial number	#1	#2	#3	#4	#5
ε_t	0.1	0.13	0.15	0.17	0.19
θ_t	3^0	3.3^0	3.6^0	3.9^0	4.2^0

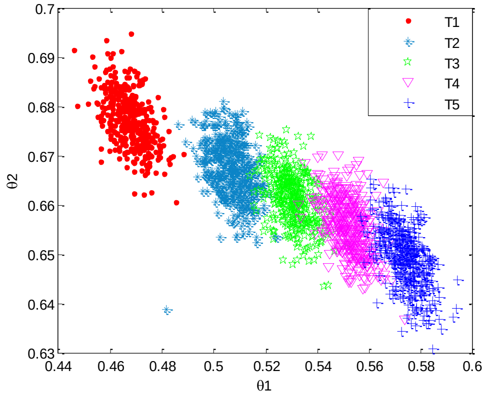

Fig. 4. Views of features when SNR=15dB

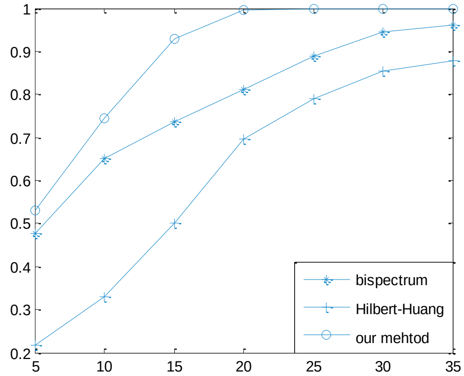

Fig.5. Accuracy of methods in the experiment

5. Conclusion

A feature extraction approach for specific emitter identification based on I/Q imbalance is proposed in this paper. A I/Q modulator model is used to investigate the sources of radio frequency fingerprint and a novel approach based on signal space is proposed. For the proposed method, demodulation is not needed, and is not only valid for digital modulation signal but also analog modulation signal. Compared with two existing approaches, our algorithm achieves the better identification performance.

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