ECAI 2019 - International Conference – 11th Edition
Electronics, Computers and Artificial Intelligence
27 June -29 June, 2019, Pitesti, ROMÂNIA

Performance Analysis of Transmitter Identification Based on I/Q Imbalance Estimation

Özlem Alpergün
Department of Electrical and Electronics Engineering,
Ankara University, Ankara, Turkey
ozlem.alpergun@gmail.com

Selçuk Taşcıoğlu
Department of Electrical and Electronics Engineering,
Ankara University, Ankara, Turkey
selcuk.tascioglu@eng.ankara.edu.tr

Memduh Köse
Computer Sciences Research and Application Center, Kırşehir Ahi Evran University, Kırşehir, Turkey
memduh.kose@ahievran.edu.tr

Abstract—**Performance of a transmitter identification method based on I/Q imbalance estimation is analyzed for different modulation types in this work. This analysis is considered on the basis of the constellation structure of proper and improper modulation signals. The effect of impropriety of complex signals on the features obtained from I/Q imbalance is analyzed. Simulation results show that transmitters can be identified with a high accuracy for proper communication signals even at low SNR, whereas the identification performance degrades for improper communications signals, especially at low SNR.**

Keywords— I/Q imbalance, proper and improper communications signals, transmitter identification.

I. INTRODUCTION

Gain and phase imbalances resulting from I/Q modulator impairments degrade overall communication performance if not compensated properly. However, I/Q imbalances carry some unique characteristics for a specific transmitter, since they are caused by hardware imperfections in the elements of the modulator such as mixers and local oscillators. These unique characteristics can be exploited to identify the transmitters. This approach is a class of physical layer security schemes which are considered to be more robust than traditional wireless security methods [1]-[6]. It is hard to impersonate the physical layer characteristics of a transmitter, since it will not be possible for a malicious user to generate the legitimate characteristics perfectly due to its own characteristics embedded in the transmission signal.

I/Q imbalance estimation based transmitter identification methods have been widely used for various communication systems [3], [4], [7]-[11]. For example, IEEE 802.11 network interface cards were identified by using radiometric features consisting of phase and magnitude errors in I/Q modulation domain [7]. These features were employed to classify 130 network cards by using k-nearest neighbor and support vector machines algorithms with a high accuracy. In [3], radio boards using differential quadrature phase-shift keying for modulation were identified by using phase, magnitude and frequency characteristics in the modulation domain in addition to the offset in the oscillator frequency. Radio frequency transmitter impairments such as quadrature modulator imbalances, constellation origin offset, and carrier frequency offset obtained from transmitters were measured in [8]. It was shown that nine different USRP radios could be identified reliably by using these impairments even under fading channels. For the device authentication in an IoT network, I/Q imbalance features can be employed on a stand-alone basis or as a part of traditional security solution. It was shown by conceptual analysis that inherent I/Q imbalance features can be exploited for device authentication in asymmetric IoT networks [4]. The authors considered the device identification problem as a nonlinear multidimensional classification problem and an artificial neural network was employed to solve this problem. The classification problem may be solved by using convolutional neural networks trained with raw I/Q samples [10], [11].

Performance analysis of a transmitter identification method based on I/Q imbalance estimation is considered in this study. Background information including I/Q imbalance model and feature extraction method is provided in Section II. In Section III, the effect of impropriety of complex signals on the I/Q features is discussed. Simulation results are presented in Section IV, and Section V concludes the work.

II. BACKGROUND

A. I/Q Imbalance Model

I/Q modulators are widely used in modern wireless communication systems due to their advantages, such as providing bandwidth efficiency. However, due to imperfections in in-phase and quadrature branches, there are some distortions called I/Q imbalance which may seriously affect the performance of the communication system [12], [13]. In the literature, several methods have been developed to compensate I/Q imbalance effects, e.g. [14].

Block diagram of an I/Q modulator with imbalance is given in Fig. 1. In this figure, I/Q imbalance parameters, i.e. gain imbalance ε and phase imbalance θ, are shown in each branches. In this block diagram $z(t)$ may be encoded complex constellation symbols for a digital modulation or may be an analytic signal for analog single sideband (SSB) modulation and can be given in terms of in-phase and quadrature components as

$$z(t) = z_I(t) + jz_Q(t) \qquad (1)$$

RF signal $s_{RF}(t)$ is obtained by adding the multiplications of these components with the sinusoidal

978-1-7281-1624-2/19/$31.00 ©2019 IEEE

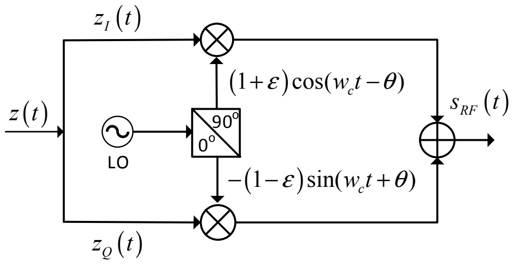

Fig. 1. Block diagram of I/Q modulator

carriers and is given by

$$s_{RF}(t) = z_I(t)(1+\varepsilon)\cos(w_c t-\theta) - z_Q(t)(1-\varepsilon)\sin(w_c t+\theta) \tag{2}$$

The complex valued baseband equivalent signal of $s_{RF}(t)$ can be given as [9], [13]

$$x(t) = \mu z(t) + \nu z^*(t) \tag{3}$$

where μ and ν are defined as

$$\mu = cos\theta - j\varepsilon sin\theta \\ \nu = \varepsilon cos\theta - jsin\theta \tag{4}$$

The equations (3), (4) give a model for the corresponding effect of I/Q imbalance, which occurs during RF signal generation process in I/Q modulator, on the baseband signal.

B. Feature Extraction

In order to quantify classification performance for the transmitter identification approach based on the I/Q imbalance estimates, feature extraction scheme proposed in [9] was employed in this work. The received signal corrupted by additive white Gaussian noise is modeled as

$$y(t) = x(t) + w(t) \tag{5}$$

Autocorrelation matrix of the combination of the received noisy signal and its complex conjugate of the form $Y(t) = \begin{bmatrix} y(t) \\ y^*(t) \end{bmatrix}$ can be given by

$$R_Y = E\left[Y(t)Y^H(t)\right] = E\begin{bmatrix} y(t)y^*(t) & y(t)y(t) \\ y^*(t)y^*(t) & y^*(t)y(t) \end{bmatrix} \tag{6}$$

Using the equality for proper signals $P_x = (\mu\mu^* + \nu\nu^*)P_z$, which will be derived in Section III, R_Y can expressed in the form [9]

$$R_Y = \begin{bmatrix} P_x + P_w & 2\mu\nu P_z \\ (2\mu\nu)^* P_z & P_x + P_w \end{bmatrix} \tag{7}$$

where P_w is the noise power, P_z and P_x denote power values of transmitted and noise-free received signals, respectively.

In [9], an I/Q imbalance feature was defined based on this autocorrelation matrix as follows. After calculating the autocorrelation matrix from the received noisy signal samples by using (6), the ratio

$$\frac{E\left[y(t)y(t)\right]}{E\left[y(t)y^*(t)\right]} = K \tag{8}$$

can be obtained. By using (7), this ratio can also be expressed as

$$K = \frac{2\mu\nu P_z}{P_x + P_w} = \frac{2\mu\nu\frac{P_z}{P_x}}{1+\frac{P_w}{P_x}} = \frac{\frac{2\mu\nu}{\mu\mu^* + \nu\nu^*}}{1+\frac{1}{SNR_{est}}} \tag{9}$$

The numerator of the last term of (9) was defined as the I/Q imbalance features of the form [9]

$$F = \left[Re\left(\frac{2\mu\nu}{\mu\mu^* + \nu\nu^*}\right), Im\left(\frac{2\mu\nu}{\mu\mu^* + \nu\nu^*}\right)\right] \tag{10}$$

These features are calculated by multiplying the complex constant K obtained from (8) with $1 + 1/SNR_{est}$. Since the noise free received signal $x(t)$ is not known, SNR value should be estimated. Note that these features consist of the parameters μ and ν which are related to gain imbalance and phase imbalance as defined in (4). This may be interpreted as the estimation of I/Q imbalance values indirectly, i.e. estimation of the combinations of I/Q parameters of the form given in (4) and (10).

The transmitter identification performance of the features defined in (10) was analyzed for SSB signals in [9]. We investigate the performance of transmitter identification based on these features for digital modulation signals in addition to SSB signals in this study. We also consider the effect of impropriety of communication signals on the classification performance of these features, the details of which are provided in the following section.

III. The Effect of Impropriety of Signals

Contrary to the quadrature amplitude modulation (QAM) signals having a special symmetry in the signal constellation, some digital modulation techniques generate improper complex baseband signals such as binary phase shift keying (BPSK), pulse amplitude modulation (PAM), Gaussian minimum shift keying (GMSK), offset quaternary phase shift keying (OQPSK) [15], [16]. Since $E\left[z^2(t)\right] \neq 0$ for improper signals, the relation between P_x and P_z can be given as follows

$$\begin{aligned} P_x &= E\left[\left|\mu z(t) + \nu z^*(t)\right|^2\right] \\ &= E\left[\left(\mu z(t) + \nu z^*(t)\right)\left(\mu^* z^*(t) + \nu^* z(t)\right)\right] \\ &= \mu\mu^* E\left[z^*(t)z(t)\right] + \mu\nu^* E\left[z^2(t)\right] + \mu^*\nu E\left[z^{*2}(t)\right] \\ &\quad + \nu\nu^* E\left[z(t)z^*(t)\right] \\ &= \mu\mu^* P_z + \nu\nu^* P_z + \mu\nu^* E\left[z^2(t)\right] + \left(\mu\nu^* E\left[z^2(t)\right]\right)^* \\ &= \left(\mu\mu^* + \nu\nu^*\right)P_z + 2\,\mathrm{Re}\left\{\mu\nu^* E\left[z^2(t)\right]\right\} \end{aligned} \tag{11}$$

Due to the term $2\operatorname{Re}\left\{\mu\nu^{*}E\left[z^{2}(t)\right]\right\}$ in (11), (9) is not valid anymore, and therefore I/Q features will be distorted. This distortion will cause a degradation of transmitter identification performance. Quantitative evaluation of the distortion effect caused by impropriety of the signal on identification performance is carried out by simulations in Section IV. Note that $E\left[z^{2}(t)\right]=0$ for proper signals. In this case (11) reduces to $P_x=\left(\mu\mu^{*}+\nu\nu^{*}\right)P_z$ and (9) is valid as given in Section II.B.

IV. Simulation Results

The classification performance of the features based on I/Q imbalance was evaluated through Monte Carlo simulations. In simulations, transmission signals of length 1000 samples were generated for seven transmitters (Tx) having different gain and phase imbalance values. The gain imbalance and phase imbalance values given in the Table I were selected considering the practical values for these parameters [14], [17].

TABLE I. Gain and Phase Imbalance Values for Simulations

	Tx1	Tx2	Tx3	Tx4	Tx5	Tx6	Tx7
ε	0.10	0.25	0.23	0.15	0.18	0.20	0.11
θ	5.2	6.3	5.8	4.5	5.0	4.7	6.0

Simulations were performed by using Matlab and Communications Toolbox functions. Modulation signals $z(t)$ with following modulation types were generated: BPSK, QPSK, 8-QAM, 16 QAM and SSB. Investigation of transmitter identification performance based on I/Q imbalance features for these modulation schemes is important since they are employed in widely used wireless technologies, e.g. QPSK and QAM are used in IEEE 802.11 WiFi and IEEE 802.5.4 Zigbee standards. As explained in Section II.A, $z(t)$ is an analytic signal for analog SSB modulation and consists of encoded complex constellation symbols for digital modulation. For the generated signal $z(t)$, the complex valued baseband equivalent signals $x(t)$ were obtained with (3) and (4) for seven different transmitters by using the I/Q imbalance values given in Table I. For each transmitter, 200 different complex noise realizations were added to $x(t)$ in order to simulate the additive noise effect. Noise power was changed to obtain different SNR levels. The feature vectors based on I/Q imbalance estimates were extracted as explained in Section II.B. And lastly, features were classified by using a probabilistic neural network classifier. In classification, a quarter of 200 generated signals from each transmitter was employed for the training stage, and the remaining signals were used as a test set.

Visualization of the features obtained from I/Q imbalance estimates from 16-QAM signals is given in Fig. 2 and Fig. 3. As can be these figures, as the SNR decreases spread of features increases and the features lose their distinctiveness.

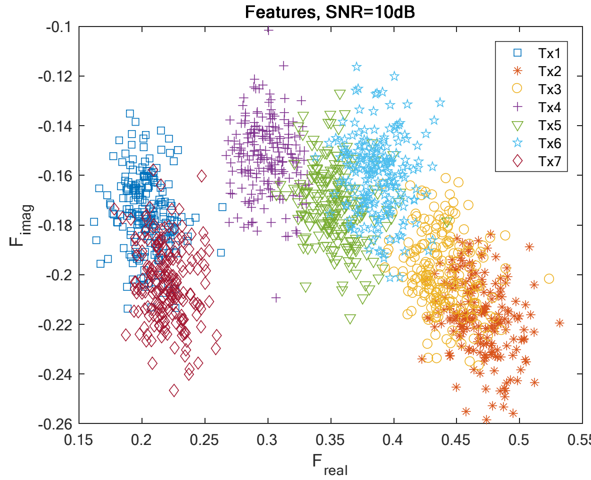

Fig. 2. I/Q features obtained from 16-QAM signals at 10 dB SNR

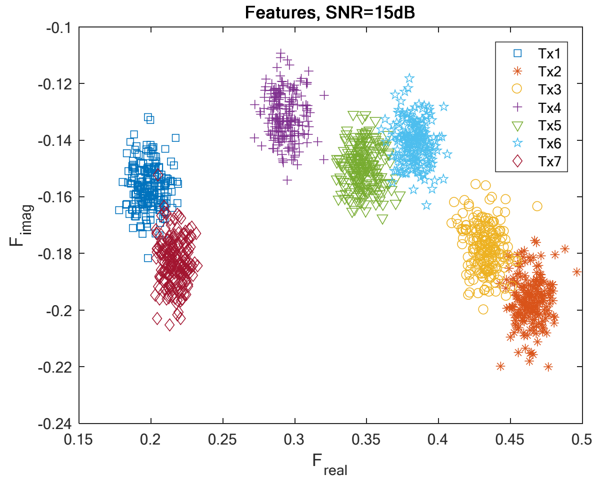

Fig. 3. I/Q features obtained from 16-QAM signals at 15 dB SNR

Classification performance results for different modulation types are given in Fig. 4. As can be seen from this figure, classification performance degrades as the SNR decreases for all modulation types. This figure also demonstrates that classification performance is higher for proper signals, i.e. QPSK, 8-QAM (circular), 16-QAM, and SSB, than for improper signals, i.e. BPSK and 8-QAM (rectangular). This result is valid for the SNR values in the interval [5, 20] dB. The performance degradation for BPSK is much higher than for 8-QAM (rectangular). This can be explained by the fact that degree of impropriety of BPSK is higher than that of 8-QAM (rectangular) [15], [16]. Note that circular 8-QAM produces proper complex baseband signals whereas rectangular 8-QAM produces improper complex baseband signals [15], [16].

The noise power is estimated by using the channel noise samples within a signal part when no signal is present. The duration of this signal part directly affects the performance of the SNR estimation which is used in (9). In order to measure this effect, two different signal duration values for noise power estimation, 10% and 1% of total signal duration, were tested in simulations. As expected, SNR estimation performance is low for the short signal duration value of 1%, which leads to degraded classification performance, especially at low SNR levels. This performance degradation can be seen when comparing the results in Fig. 4 and Fig. 5.

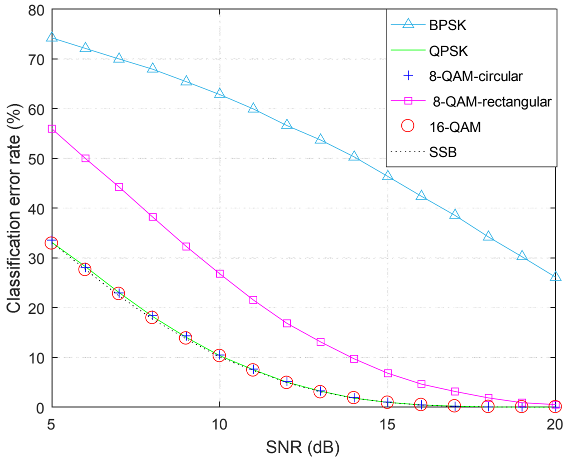

Fig. 4. Classification accuracy when SNR estimation error is low

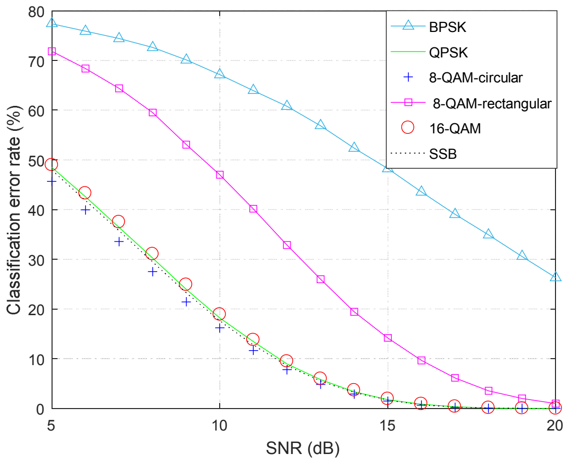

Fig. 5. Classification accuracy when SNR estimation error is high

These figures demonstrate that classification accuracy degrades about 10% for proper signals at 10 dB.

At the high SNR levels, SNR estimation performance does not affect the classification performance of the features. The reason for this is that feature values do not change significantly at high SNR even if the SNR estimation error is high. Note that the second term in the denominator of (9) goes to zero at high SNR.

V. Conclusion

It has been shown that the identification performance of the I/Q imbalance based features does not change as the modulation type changes for proper signals, whereas the performance changes with modulation type for improper signals. Future work will focus on developing a feature extraction method that can be used for both proper and improper communication signals.

References

[1] O. Ureten and N. Serinken, “Detection, characterisation and classification of radio transmitter turn-on transients,” in Multisensor Fusion, ed. A.K. Hyder et al., Dordrecht, Netherlands: Kluwer Academic Publishers, 2000, pp. 611-616.

[2] O. Ureten and N. Serinken, "Wireless security through RF fingerprinting," in Canadian Journal of Electrical and Computer Engineering, vol. 32, no. 1, pp. 27-33, Winter 2007.

[3] A. Candore, O. Kocabas and F. Koushanfar, “Robust stable radiometric fingerprinting for wireless devices,” 2009 IEEE International Workshop on Hardware-Oriented Security and Trust, Francisco, CA, 2009, pp. 43-49.

[4] B. Chatterjee, D. Das, S. Maity and S. Sen, “RF-PUF: Enhancing IoT Security Through Authentication of Wireless Nodes Using In-Situ Machine Learning,” in IEEE Internet of Things Journal, vol. 6, no. 1, pp. 388-398, Feb. 2019.

[5] S. Taşcıoğlu, M. Köse and Z. Telatar, "Effect of sampling rate on transient based RF fingerprinting," 2017 10th International Conference on Electrical and Electronics Engineering (ELECO), Bursa, 2017, pp. 1156-1160.

[6] M. Köse, S. Taşcıoğlu and Z. Telatar, "RF Fingerprinting of IoT Devices Based on Transient Energy Spectrum," in IEEE Access, vol. 7, pp. 18715-18726, 2019.

[7] V. Brik, S. Banerjee, M. Gruteser, S. Oh, “Wireless device identification with radiometric signatures”, Proc. 14th ACM Int. Conf. Mobile Comput. Netw. (MobiCom), pp. 116-127, 2008.

[8] M. Pospíšil, R. Marsalek and J. Pomenkova, “Wireless device authentication through transmitter imperfections - measurement and classification,” 2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), London, 2013, pp. 497-501.

[9] F. Zhuo, Y. Huang, and J. Chen, “Radio frequency Fingerprint extraction of radio emitter based on I/Q imbalance,” Procedia Comput. Sci., vol. 107, pp. 472-477, Jan. 2017.

[10] S. Riyaz, K. Sankhe, S. Ioannidis and K. Chowdhury, “Deep Learning Convolutional Neural Networks for Radio Identification,” in IEEE Communications Magazine, vol. 56, no. 9, pp. 146-152, Sept. 2018.

[11] L. J. Wong, W. C. Headley and A. J. Michaels, “Specific Emitter Identification Using Convolutional Neural Network-Based IQ Imbalance Estimators,” in IEEE Access, vol. 7, pp. 33544-33555, 2019.

[12] A. Schoonen, “IQ imbalance in OFDM Wireless LAN systems,” M.S. thesis, Eindhoven University of Technology, Eindhoven, Netherlands, 2006.

[13] A. Hakkarainen, “I/Q Imbalance in Multiantenna Systems: Modeling, Analysis and RF-Aware Digital Beamforming,” Ph.D. dissertation, Tampere University of Technology, Tampere, Finland, 2017.

[14] J. J. de Witt and G. van Rooyen, “A Blind I/Q Imbalance Compensation Technique for Direct-Conversion Digital Radio Transceivers,” in IEEE Transactions on Vehicular Technology, vol. 58, no. 4, pp. 2077-2082, May 2009.

[15] P. Schreier and L. Scharf, “Second-order analysis of improper complex random vectors and processes,” IEEE Trans. Signal Process., vol. 51, no. 3, pp. 714–725, Mar. 2003.

[16] T. Adalı, P. Schreier, and L. Scharf, “Complex-valued signal processing: The proper way to deal with impropriety,” IEEE Trans. Signal Process.,vol. 59, no. 11, pp. 5101–5125, Nov. 2011.

[17] J. Tubbax, B. Come, L. Van der Perre, L. Deneire, S. Donnay and M. Engels, “Compensation of IQ imbalance in OFDM systems,” IEEE International Conference on Communications, 2003. ICC '03., Anchorage, AK, 2003, pp. 3403-3407 vol.5.