

A DIGITAL SIGNAL PROCESSING METHOD FOR THE DETECTION AND EVALUATION OF I/Q IMPAIRMENTS IN RF DIGITAL TRANSMITTERS

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Abstract – Troubleshooting of radiofrequency (RF) digital transmitters is here dealt with. Specifically, a new digital signal-processing method is developed, which is capable of both detecting and evaluating the most recurrent impairments in the I and Q paths of the transmitter. Only the acquisition either of intermediate frequency (IF) or RF output signal is needed, thus avoiding any difficulty connected with the inaccessibility of baseband and/or IF section in a fully assembled transmitter. Moreover, the method has the required features of automation and effectiveness, granted by the use of RLS-based algorithms and proved by the results obtained in many experiments on actual IF and RF output signals.

Even though the experiments presented in the paper refer to W-CDMA (Wideband Code Division Multiple Access) technology, the method shows itself suitable to troubleshoot any digital transmitter implementing quadrature amplitude modulation (QAM).

1. INTRODUCTION

Development and diffusion of digital communication technologies are driving towards fast productive processes, capable of balancing the growing demand. At the same time, the request of high quality services and the severe constraints imposed by international regulations justify the need of suitable troubleshooting methodologies during production, installation and maintenance stages of the main components and apparatuses (transmitter, receiver, channel infrastructure) of any communication system [1],[2].

With special regard to digital transmitters, their troubleshooting often proves a difficult and time-consuming task [3],[4]. Due to the high degree of integration among the single parts of a digital transmitter (indispensable to achieve compactness and miniaturization), many sections cannot be accessed; only its IF and/or RF output is, in fact, usually available for measurements.

The basic scheme of current digital transmitters always includes a QAM modulator; both real and imaginary part of the complex symbols coming from the symbol encoder (where packets of bits are translated into symbols, according to the chosen I/Q constellation) are separately sent into the I and Q paths of the baseband stage of the modulator. In this section impairments can occur, due to the different behaviour exhibited by the I and Q paths. I/Q impairments

in the baseband stages reflect into anomalies of the transmitted signal: the polar diagram of the transmitted signal reveals translation and/or distortion with respect to the nominal signal to be transmitted. As an intolerable consequence, the correct decision limits of the receiver reduce (the receiver is designed according to decision regions drawn for an assigned I/Q constellation), thus worsening the performance of the whole communication system.

The most common I/Q impairments are: gain imbalance (the I and Q components of the transmitted signal are differently amplified, after baseband lowpass filtering); nonzero offset voltages, introduced by analogue amplifiers; quadrature phase error affecting the carriers used for I/Q modulation.

Several techniques have been proposed to state whether or not I/Q impairments affect the transmitter and, in some cases, to evaluate their amount.

A major manufacturer suggests checking EVM (Error Vector Magnitude), constellation and polar diagrams to discover imbalances [5]. Such a kind of strategy, however:

- is not automated;
- does not provide accurate estimations of impairment amount (it returns only qualitative results);
- does not give the possibility, in the presence of simultaneous impairments, of establishing which one is present and which not.

In the literature many authors deal with the problem of I/Q impairments, even though they focus only on their compensation in order to enhance the receiver performance; no attention is given to the estimation of their amount. Above all, by neglecting the problem of offset voltages, they often simplify the compensation procedure in a linear problem to be solved by means of well-known equalization techniques [6]-[8] or algebraic methods based on the approximation of small phase angle errors [9].

The method proposed in the paper, instead:

- i) provides accurate estimations of I/Q impairment amount;
- ii) is fully automated;
- iii) evaluates also the offset voltages affecting the I and Q components;
- iv) does not need to access the baseband and IF sections of the transmitter.

According to the measurement procedure described in

the following section, the acquired signal (IF or RF output) is converted to the baseband, and then used to recover the transmitted information; this is used to generate a reference signal (without impairments) with which the received (baseband) signal is compared to evaluate the imbalances. I/Q impairments are then evaluated by applying RLS (Recursive Least Squares) based algorithms [10] to couples made up of samples of the transmitted signal and of the reference signal, both at baseband.

2. PROPOSED METHOD

To deal with the problem of I/Q impairments in the baseband and IF-modulation stages of the digital transmitter, it is necessary to determine an analytical model of the signal affected by impairments.

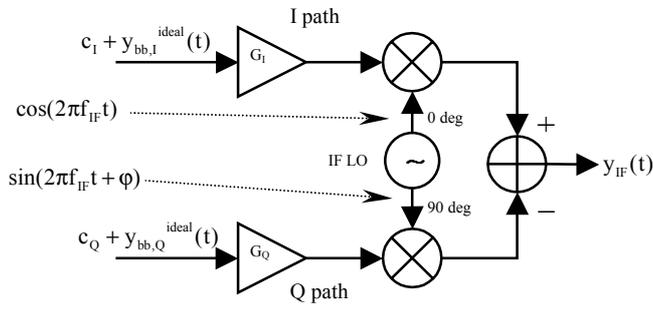


Fig. 1. Sources of I/Q impairments in a digital transmitter.

Both in Fig. 1 and in the following, c_I and c_Q are the absolute values of the offset voltages introduced by the amplifiers, respectively on the I and Q paths of the modulator; g is the gain on the Q path, related to the gain on the I path ($g = G_Q/G_I$); φ is the difference between the initial phase of the carrier on the Q path and the initial phase of the carrier on the I path; $y_{bb}^{ideal}(t)$ refers to the baseband, not impaired signal (i.e. the baseband signal provided by an ideal transmitter); $y_{IF}(t)$ is the IF impaired signal. The expression of $y_{IF}(t)$ as a function of both the baseband, not impaired signal and the amounts of the impairments is (Fig. 1):

$$y_{IF}(t) = (c_I + y_{bb,I}^{ideal}(t)) \cdot \cos(2\pi f_{IF} t) + -g \cdot (c_Q + y_{bb,Q}^{ideal}(t)) \cdot \sin(2\pi f_{IF} t + \varphi) \quad (1)$$

This signal is equivalent to a baseband version given by

$$y_{bb} = (c_I + y_{bb,I}^{ideal}) + j \cdot (c_Q + y_{bb,Q}^{ideal}) \cdot g \cdot e^{j\varphi} \quad (2)$$

which is the baseband, impaired signal provided by the real, imperfect modulator.

Equation (2) can be written, in matrix form, as:

$$\begin{bmatrix} y_{bb,I} \\ y_{bb,Q} \end{bmatrix} = \begin{bmatrix} 1 & -g \cdot \sin \varphi \\ 0 & g \cdot \cos \varphi \end{bmatrix} \cdot \left(\begin{bmatrix} y_{bb,I}^{ideal} \\ y_{bb,Q}^{ideal} \end{bmatrix} + \begin{bmatrix} c_I \\ c_Q \end{bmatrix} \right) \quad (3)$$

Through the introduction of the matrix \underline{V} , defined as

$$\underline{V} = \begin{bmatrix} 1 & -g \cdot \sin \varphi \\ 0 & g \cdot \cos \varphi \end{bmatrix} \quad (4)$$

the relation (3) becomes:

$$\begin{bmatrix} y_{bb,I} \\ y_{bb,Q} \end{bmatrix} = \underline{V} \cdot \left(\begin{bmatrix} y_{bb,I}^{ideal} \\ y_{bb,Q}^{ideal} \end{bmatrix} + \begin{bmatrix} c_I \\ c_Q \end{bmatrix} \right) \quad (5)$$

Equation (5) shows that I/Q impairments in the actual transmitter can be revealed by comparing its baseband signal to a reference one, characterized by the same sequence of bits and generated by an ideal transmitter. A measurement system is so suggested (Fig. 2), equipped with:

- a receiver, capable of down-converting the transmitted signal to the baseband and recovering the binary information;
- an ideal transmitter, mandated to the generation of the baseband reference signal according to the digital modulation of interest.

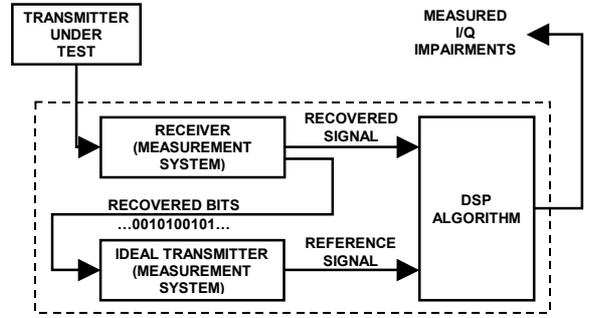


Fig. 2. Main blocks of the suggested measurement system.

Equation (5) shows that, if I/Q offset voltages were absent, the matrix \underline{V} could be obtained by inverting the linear relation

$$\begin{bmatrix} y_{bb,I} \\ y_{bb,Q} \end{bmatrix} = \underline{V} \cdot \begin{bmatrix} y_{bb,I}^{ideal} \\ y_{bb,Q}^{ideal} \end{bmatrix} \quad (6)$$

which is obtained from (5) when $c_I = c_Q = 0$. An estimate of the matrix $\underline{U} = \underline{V}^{-1}$ can be computed through the application of RLS algorithms to a sequence of couples of samples provided by the measurement system in Fig.2; each couple includes one sample both of the recovered signal and the reference signal. At each step, a new couple of samples is processed by the algorithm, which provides the minimum mean square error solution on the basis of current and previous acquired samples. In this context the desired signal is y_{bb}^{ideal} and the received signal is y_{bb} (for more details, see appendix A).

Nevertheless, when I/Q offset voltages are supposed to affect the transmitter, the RLS algorithm is not able to provide a proper solution because relation (5) is no longer linear, thus making its inversion unfeasible. The easiest way to proceed is to assign trial values to c_Q and c_I . This way, relation (5) becomes linear and the opportunity of estimating g and φ is given. At each recursive step of the algorithm,

new trial values are evaluated on the basis of the old values of c_Q and c_I , according to

$$c_I^{new} = y_{bb,I} - y_{bb,I}^{ideal} + g \cdot \sin\varphi \cdot (c_Q^{old} + y_{bb,Q}^{ideal})$$

and

$$c_Q^{new} = \frac{y_{bb,Q}}{g \cdot \cos\varphi} - y_{bb,Q}^{ideal},$$

and used in (5) in order to get more accurate solutions; it's worth noting that both expressions (7) are obtained resolving (5) with respect to c_I and c_Q .

Fig. 3 shows the basic steps of the proposed algorithm; N represents the length of the acquired record.

3. METHOD VALIDATION

The performance of the method has been assessed referring to W-CDMA modulation scheme, which characterizes the European proposal of a 3G mobile communication system (UMTS).

3.1. Preliminary considerations

To achieve an exhaustive characterization, a transmitter with adjustable and known I/Q impairments is needed. Because commercial transmitters do not satisfy this requirement, a suitable solution has been suggested, which makes use of electronic instrumentation designed for baseband, IF, and RF applications.

3.2. Adopted instruments

The following instruments have been adopted for the validation tests:

- baseband and IF generator: Sony-Tektronix AWG 2020™;
- RF generator: Hewlett-Packard ESG 4431B™;
- spectrum analyzer: Hewlett-Packard 8594E™;
- data acquisition system: LeCroy LC574/A™.

A workstation has also been used both for instrumentation control and numerical generation of the signal samples to be downloaded into the internal memory of the baseband and IF generator. The workstation is equipped with an Intel Celeron® CPU at 733 MHz.

The ideal, baseband transmitter and the receiver have, instead, been implemented via software. With regard to the former, 3GPP W-CDMA specifications [11] have been referred to; as for the latter, a common QAM receiver has been added to the descrambling and despreading blocks (more details are given in appendix B).

3.3. IF experiments

For this tests, the IF output of the transmitter has been supposed to be available. In particular:

- i) a suitable algorithm has been designed to numerically generate the samples of the IF-modulated signal according to the scheme in Fig. 4 and compliant to the aforementioned specifications;
- ii) calibrated I/Q impairments have been introduced on the digital sequence of samples;

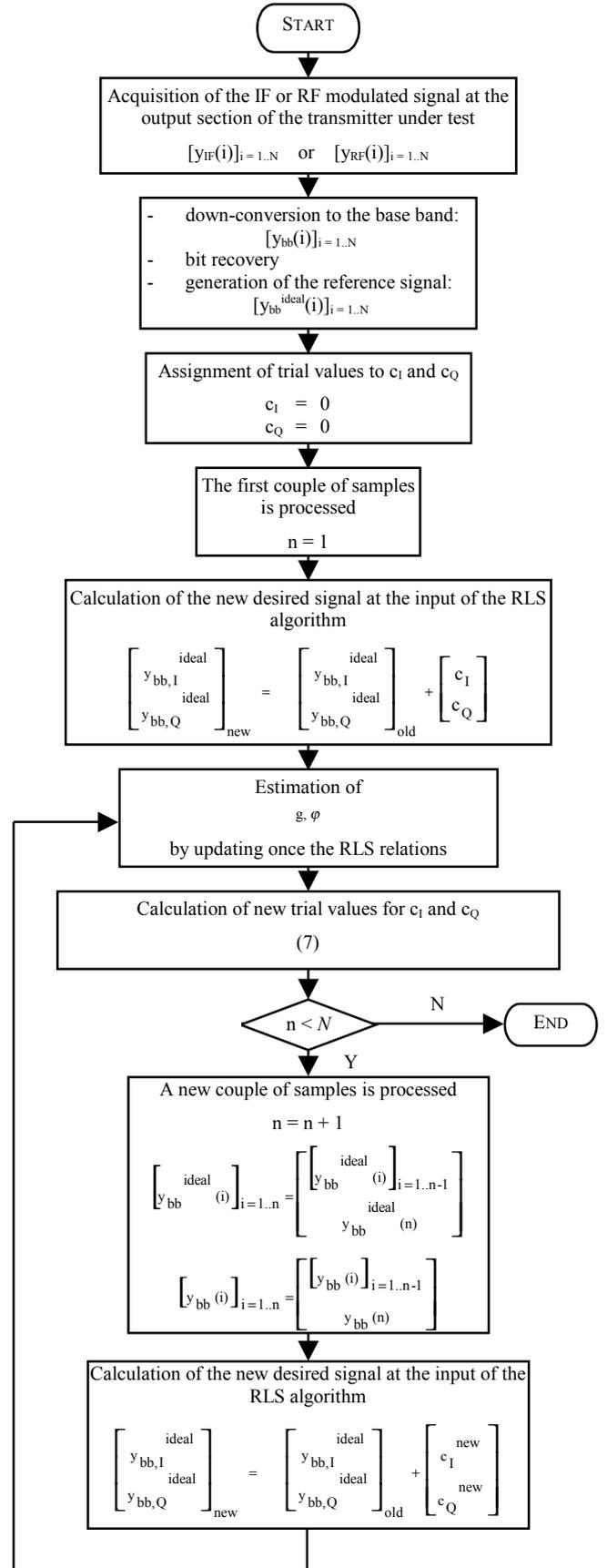


Fig. 3. Flow diagram of the proposed measurement algorithm.

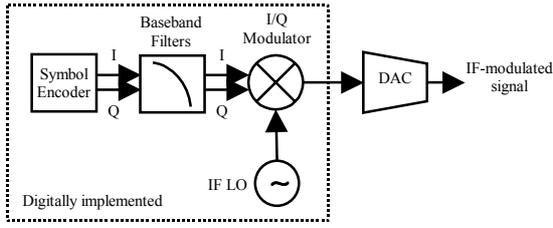


Fig. 4. Transmitter with digital IF modulation.

- iii) the D/A conversion has been obtained by downloading the generated samples into the volatile memory of the baseband and IF generator (Fig. 5);
- iv) the IF-modulated waveform has been digitized by the data acquisition system, and has been sent to the receiver, which has converted it to the base band (Fig. 5).

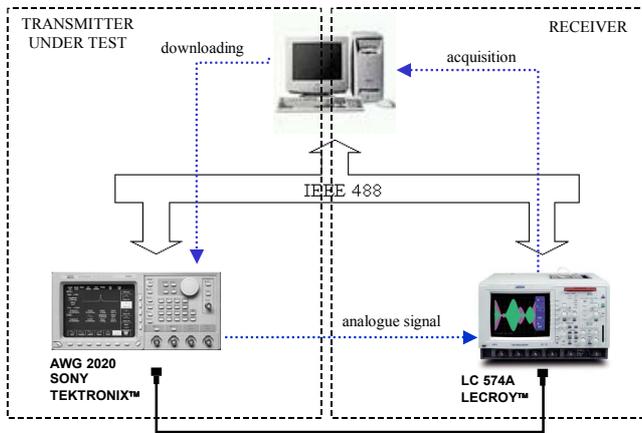


Fig. 5. Measurement set-up for IF experiments.

Different amounts of the I/Q impairments and different sets of experiments are considered. In particular, each set includes about one hundred tests carried out with the same amounts of the impairments. It is worth underlining that these amounts are required to be within the range of correct operability of the receiver (the receiver must be in condition of correctly demodulate the transmitted bits).

For each kind of impairment, the estimates obtained from each set of experiments have allowed the evaluation of:

- the percentage relative difference (Δ %) between their mean value and the amount originally imposed to the impairment;
- the experimental standard deviation (σ %), expressed in percentage relative terms.

Some results are given in Fig.6; similar outcomes have been obtained in any other experiment.

From the analysis of all the results some considerations can be drawn.

- For each impairment:
 - the value both of Δ % and σ % (i) increases upon the increasing of the amount of the other impairments, and (ii) decreases upon the increase of the amount of the impairment itself;
 - the lower the amount of the impairment, the poorer the accuracy in its detection; that proves the

existence of a sensibility limit of the proposed method.

- Difference and experimental standard deviation, both expressed in percentage relative terms, fall within the lower and upper limits summarized in Tab.1.

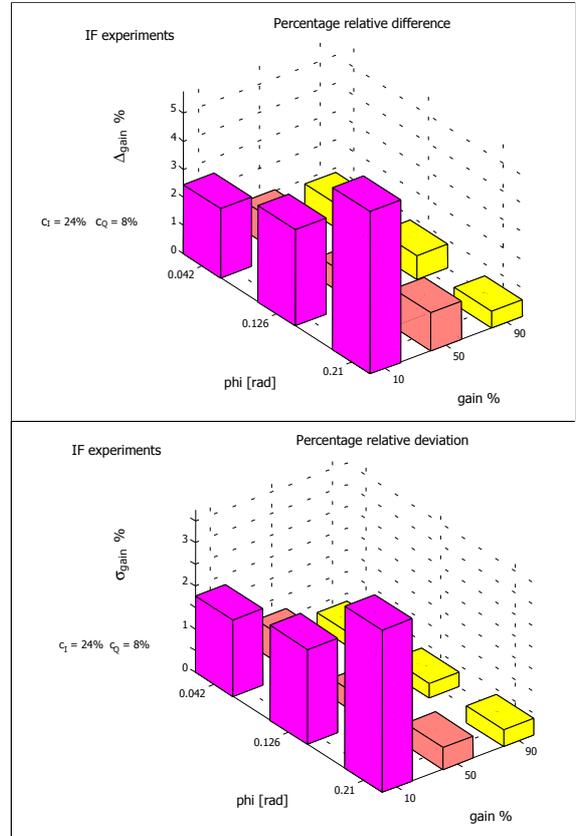


Fig. 6. IF tests – gain impairment estimate with $c_I = 24\%$, $c_Q = 8\%$ (related to the peak value of the baseband signals).

Tab.1. Performance of the method in IF tests

| | Δ % | | σ % | |
|-----------|------------|------|------------|------|
| | min | max | min | max |
| g | 1.1% | 5% | 0.49% | 4% |
| φ | 0.095% | 6% | 0.69% | 5% |
| c_I | 0.062% | 2.2% | 0.30% | 2.5% |
| c_Q | 0.0050 % | 1.7% | 0.14% | 1.5% |

3.4. RF experiments

For these experiments it has been intended that only the RF section of the transmitter could be accessible, so a down-conversion to IF has been needed before sampling and digitizing at the receiver stage. In particular:

- i) a suitable algorithm (compliant to 3GPP specifications) has been designed to numerically generate the samples of the baseband signal according to the blocks contained in the dotted rectangle in Fig.7;
- ii) the D/A conversion has been obtained by downloading the generated samples into the volatile memory of the baseband and IF generator (Fig.8);
- iii) calibrated impairments have been introduced on the baseband analogue I/Q signals by directly unbalancing

gain and offset voltage of the two amplifiers of I and Q paths, and the initial phase difference of the carriers (these functionalities are available on the RF generator);

- iv) RF modulation and up-conversion have been achieved through the RF generator, featuring I/Q modulation capabilities (Figs.7,8);
- v) down-conversion to IF and acquisition of the analogue signal have been gained by means respectively of the spectrum analyzer and the data acquisition system (Fig.8).

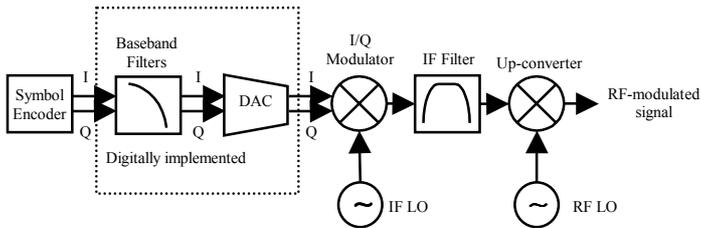


Fig. 7. Transmitter with analogue IF modulation.

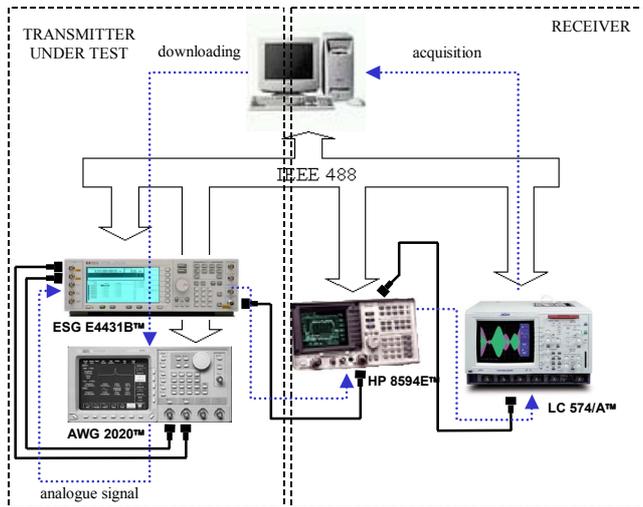


Fig. 8. Measurement set-up for RF tests.

Some results are given in Fig.9; similar outcomes have been obtained in any other experiment.

From the analysis of these results similar considerations to those exposed in the previous section (IF experiments) can be drawn. In particular, difference and experimental standard deviation, both expressed in percentage relative terms, fall within the lower and upper limits summarized in Tab.2.

Tab.2. Performance of the method in RF tests

| | Δ % | | σ % | |
|-----------|------------|-----|------------|-----|
| | min | max | min | max |
| g | 2.5% | 9% | 0.51% | 8% |
| φ | 5% | 10% | 1% | 9% |
| c_I | 0.56% | 5% | 1.0 % | 5% |
| c_Q | 0.50% | 4% | 0.84 % | 5% |

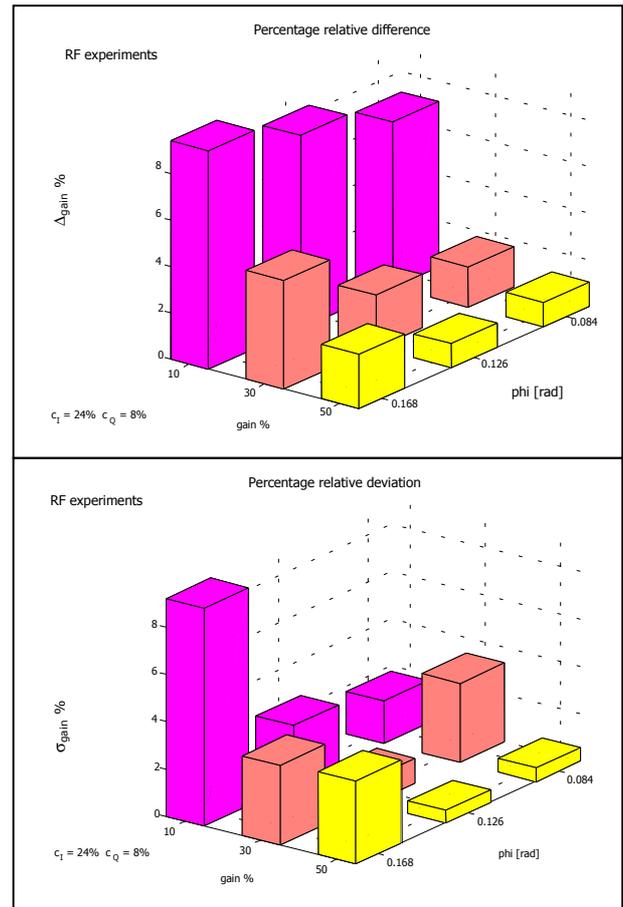


Fig. 9. RF tests – gain imbalance estimate with $c_I = 24\%$, $c_Q = 8\%$ (related to the peak value of the baseband signals).

4. CONCLUSIONS

The paper has presented a new digital signal-processing method for the automatic detection and evaluation of I/Q impairments, such as gain imbalance, nonzero offset voltages, and quadrature phase error, which generally affect both baseband and IF section of RF digital transmitters implementing QAM modulation. The method is based on RLS algorithms and needs only the acquisition of transmitter IF or RF output signal.

Some electronic instruments, designed for baseband, IF, and RF applications, have suitably been combined in order to emulate an actual transmitter on which calibrated impairments could be forced. The use of this transmitter has allowed the carrying out of a number of experiments aiming at an exhaustive metrological characterization of the method. The obtained results have confirmed method's efficacy and reliability; percentage relative differences, between estimated value of the impairment and imposed one, and experimental standard deviations always contained in few percents have been experienced.

Future research activity is mainly oriented to (i) compare the results provided by the method to those attainable through the measurement procedure suggested in [5], (ii) improve the efficiency of the method by enhancing the performance of the proposed receiver, and (iii) enlarge the set of impairments the method is capable of detecting and evaluating.

APPENDIX A – RLS ALGORITHM

RLS is a real time, recursive algorithm that, due to its capability of inverting a linear relation between the two sequences at its input, can be used to get the best estimation (in terms of minimum mean square error) of an unknown signal (said to be *desired*), exploiting its linear dependencies from available data (for example, the *received* signal in a communication system).

For our purposes (to get an estimate of matrix \underline{U} , (see Section 2), the desired signal corresponds to the reference one (y_{bb}^{ideal}), and the received signal is given by the transmitted one (y_{bb}). Their relationship, expressed in (6), can be written as:

$$\begin{bmatrix} y_{bb,I}^{ideal} \\ y_{bb,Q}^{ideal} \end{bmatrix} = \underline{U} \cdot \begin{bmatrix} y_{bb,I} \\ y_{bb,Q} \end{bmatrix} = \begin{bmatrix} \underline{w}_I^T \cdot \begin{bmatrix} y_{bb,I} \\ y_{bb,Q} \end{bmatrix} \\ \underline{w}_Q^T \cdot \begin{bmatrix} y_{bb,I} \\ y_{bb,Q} \end{bmatrix} \end{bmatrix}, \quad (8)$$

where the rows of matrix \underline{U} are put in evidence, thus giving the opportunity of deriving two linear relationships:

$$y_{bb,I}^{ideal} = \underline{w}_I^T \cdot \begin{bmatrix} y_{bb,I} \\ y_{bb,Q} \end{bmatrix} \quad (9)$$

and

$$y_{bb,Q}^{ideal} = \underline{w}_Q^T \cdot \begin{bmatrix} y_{bb,I} \\ y_{bb,Q} \end{bmatrix}.$$

Both relations in (9) can be inverted by using two proper RLS algorithms, thus leading to the estimates of \underline{w}_I and \underline{w}_Q , and consequently of matrix \underline{U} . RLS processing is done by recursively updating the following set of equations:

$$\begin{aligned} \underline{P}(0) &= \delta \cdot \underline{I} && \text{(initialization: } n = 0) \\ \vdots & \\ \mu(n) &= \underline{u}^T(n) \cdot \underline{P}(n-1) \cdot \underline{u}(n) \\ \underline{k}(n) &= \frac{\underline{P}(n-1) \cdot \mu(n)}{\lambda + \mu(n)} && (10) \\ \underline{P}(n) &= \frac{1}{\lambda} \cdot (\underline{I} - \underline{k}(n) \cdot \underline{u}(n)) \cdot \underline{P}(n-1) \\ \underline{w}(n) &= \underline{w}(n-1) + \underline{k}(n) \cdot (d(n) - \underline{w}^T(n-1) \cdot \underline{u}(n)) \end{aligned}$$

for $n = 1, \dots, N$, with:

$$\underline{u} = \begin{bmatrix} y_{bb,I} \\ y_{bb,Q} \end{bmatrix}$$

and

$$d = y_{bb,I}^{ideal} \quad \text{(if } \underline{w}_I \text{ is being estimated)}$$

$$d = y_{bb,Q}^{ideal} \quad \text{(if } \underline{w}_Q \text{ is being estimated)}$$

APPENDIX B – THE RECEIVER

According to the structure of the measurement system in Fig. 2, a receiver is needed to correctly recover the transmitted bits. Absence of any kind of synchronization between device under test and measurement instrument is to be overcome by a real, complete receiver capable of extracting the correct timing from the received RF or IF signal.

Fig. 10 shows the main blocks of the implemented receiver. More specifically, it:

- recovers the exact frequency and initial phase of the

carrier, in order to achieve coherent demodulation;

- produces an estimate of the impulsive response of the transmission baseband filter, which is used to build a matched filter allowing the maximization of the signal to noise ratio at the input of the detector;
- gets the necessary symbol timing;
- descrambles and despreads the recovered chips, in order to correctly demodulate the transmitted bits.

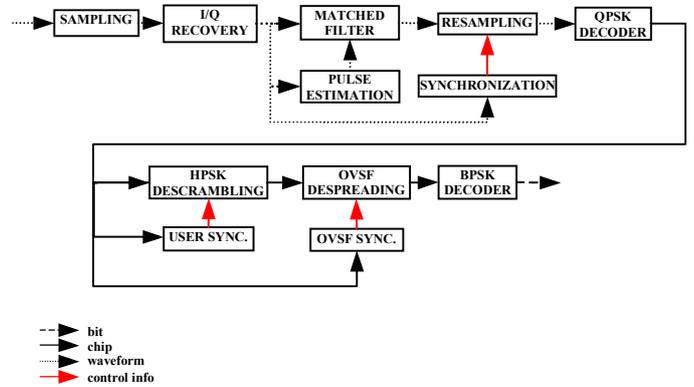


Fig. 10. The receiver.

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