An Automatic DSP-based Classifier for Impairments on QAM Modulations

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Abstract- This paper presents an instrument for the automatic classification of the common impairments on Quadrature Amplitude Modulation (QAM) signals. The instrument is intended to help telecommunication service providers to guarantee Quality of Service (QoS) to their customers. Starting from an already developed method based on the processing of the constellation diagram image, the paper presents both significant improvements in the method and the realization of a prototype of impairment classifier, based on a multi-DSP hardware architecture. Experimental results of the validation phase of the realized instrument are presented, too.

I. Introduction

In the last years, the Quality of Service (QoS) is becoming a key factor in determining the market position of telecommunication service providers. The attention of companies is not only focused on reducing the costs for network installation and maintenance, but it is based also on providing the customers with a QoS consistently higher than the competitors' one. This leads to frequent investments in technological innovation for the continuous network monitoring, in order to quickly identify and remove the QoS drops. For this reason, it is necessary to check continuously the status of the managed network, by verifying the compliance to specified quality objectives and avoiding sudden quality drops, which can be perceived by the customers. This may be carried out by identifying quickly the QoS degradation causes and their locations on the network and executing a suitable preventive maintenance.

Currently, the network monitoring is performed by looking at the constellation diagram and evaluating some characteristic parameters of the digital modulation, such as the Modulation Error Rate (MER), Bit Error Rate (BER), Error Vector Magnitude (EVM). This analysis is performed by instruments that are generally remotely accessible and managed by professionals, able to act on the malfunction occurrences. The main disadvantage of this approach is the intervention of expert personnel, able to interpret the huge amount of data produced and to formulate a hypothesis about the fault causes.

Great importance has acquired the development of new techniques to detect the presence, type, and, therefore, the causes of the impairments on the network, before the customer can perceive the QoS decrease. In particular, classification methods are required to allow, at low cost, either the realization of new specialized measuring instruments or the implementation on the existing ones.

A method for the automatic classification of the impairments overlapped to the QAM transmission, based on image processing, has been presented in [1, 2]. The basic idea of the proposed classification method consists of extracting the information on the quality of the signal, looking at the image of its constellation diagram. Starting from [2], the method has been improved, by adding the Quadrature error and modifying the Phase jitter classification module, in order to obtain a better classification of such impairment. After verifying the potentiality of the method by means of a simulation analysis, a measurement instrument prototype has been implemented on a multi-DSP board. The probability of correct classification of the instrument has been evaluated during an experimental validation phase.

In the following sections, a description of the new image processing method will be presented. Then, the prototype will be described and the implementation of the method will be presented. Finally, in the last section, the results, obtained during the experimental validation phase, will be shown and discussed.

II. Improved method

The method presented in [2] has a modular architecture and is capable of identifying the following impairments: Amplitude imbalance, Phase offset, Phase jitter, Interference. The classification works as follows:

i. The images of two decision areas are selected from the constellation diagram. Each image has a resolution of 50 × 50 pixels with 256 values of the gray-scale.

ii. A filter is applied on the images in order to emphasize the distinctive features of each impairment.

iii. The filtered images are compared with some previously recorded reference images, one for each type and value of impairment that the method is able to detect and classify. The comparison is performed using an algorithm derived from the template matching technique [1]. In particular, the normalized mutual correlation function *R* between the examined image and the reference images is determined by:

$$R = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} t(i,j)\, f(i,j)}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}\left(t(i,j)\right)^2 \cdot \sum_{i=1}^{m}\sum_{j=1}^{n}\left(f(i,j)\right)^2}}, \quad (1)$$

where $t(i,j)$ is the luminance level of the pixel with coordinates (i,j) of the test image, $f(i,j)$ is the luminance level of the pixels (i,j) of the image that must be classified m and n are the image dimensions.

iv. The obtained correlation value is then compared with some experimentally evaluated detection thresholds. Such comparison allows avoiding wrong classifications, when no impairment is present.

The image that presents the greatest correlation value will determine the class of impairment, if such value exceeds the corresponding threshold. Otherwise, the method gives as result the absence of impairments.

The classifier presented in [2] has been improved by making the following changes:

i. The Phase jitter pdf has been changed from uniform to Gaussian, in order to fit better the actual impairment characteristics.

ii. A new impairment, the Quadrature error, introduced in ETSI Technical Report ETR 290 [3], has been taken into account, by adding a module able to classify it.

iii. The filters of all modules have been modified, in order to adjust the method to the introduction of the Quadrature error and the modification of the Phase jitter distribution.

iv. The thresholds, used for the classification, have been adjusted to work with the improved method.

In addition, the number of the reference images has been increased, in order to improve the resolution of the classifier. In fact, for the amplitude imbalance, 12 images have been taken into account, 4 for each component (I-Q) and other 4 for the impairment on both components. Instead, 5 images for each other impairments have been taken. In Table 1, the ranges, in which the classification can be performed and the impairment values of the reference images are shown.

The block scheme of the improved method is shown in Fig.1.

Table 1. Classification range and reference images value.

Impairment	***Range***	***Impairment values of reference images***				
Amplitude imbalance [%Vfs]	2 – 5	2	3	4	5	-
Gaussian phase jitter [rad]	0.025 – 0.050	0.025	0.030	0.035	0.040	0.050
Interference [dB]	29 – 23	29	27	26	25	23
Phase offset [rad]	0.025 – 0.080	0.025	0.035	0.045	0.060	0.075
Quadrature error [rad]	0.025 – 0.080	0.025	0.035	0.045	0.060	0.075

A. Gaussian phase jitter

The fluctuations in phase and frequency of the oscillators used to modulate the digital signal, often, determine a sampling uncertainty in the receiver and, for this reason, the local oscillator makes a wrong phase lock on the modulated signal, introducing a random phase displacement. These fluctuations can be generated from various independent causes, which contribute to create the Phase jitter. Therefore, for the central limit theorem, the impairment is better modeled with a Gaussian random variable. To diversify as much as possible the Phase jitter reference image, this last is built by combining decision areas taken at the corners of the constellation, as it is reported in [1]. This image highlights the elongated shape of the symbol distribution.

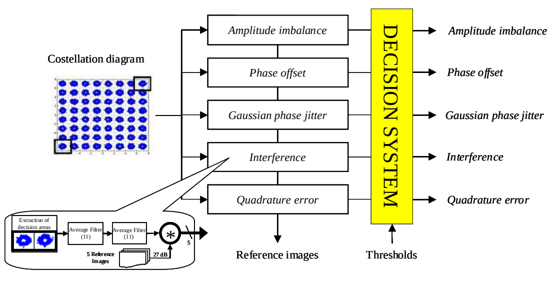

Fig. 1. Block diagram of the new classifier.

Because of the new Phase jitter model, the filter used in the Phase jitter module in [1] is not more effective. In fact, in the new version, the median filter is not applicable, because it "cuts" the tails of the Gaussian distribution. It was necessary to define the appropriate filter, in order to make the symbol spots smoother, reducing the noise effect. The types of filters, used to enhance the characteristics of this impairment, have been already presented in the literature [4]-[6], and a good solution has been found by means of a high-pass filter that emphasizes the contours of the distribution.

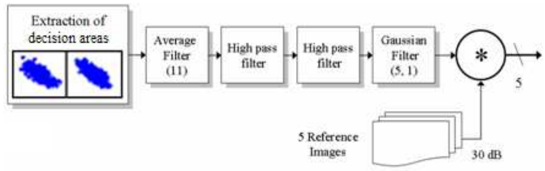

Fig. 2. Block scheme of the Gaussian phase jitter module. For each filter, the order is indicated between round brackets. The number of the reference images is also reported together with the SNR value used to generate them.

The processing of these images is very complex, because noise and Phase jitter, in this case, have the same statistical distribution and, thus, a simple linear filtering reduces both the noise and Phase jitter. The proposed solution uses different filters for the reference images and the test ones:

- for the reference images, the following cascade of filters is adopted: *average_filter (11th order), high_pass_filter, high_pass_filter, gaussian_filter (5th order and unitary variance), average_filter.*
- for the test image, the following cascade of filters is adopted, as shown in Fig. 2: *average_filter (11th order), high_pass_filter, high_pass_filter, gaussian filter (5th order and unitary variance).*

The *high_pass_filter* is not too much aggressive, because it is used to outline the spot distribution in the decision area. The kernel of the filter is shown in (2), while the image filtering results are depicted in Fig.3, using the HSV (Hue, Saturation, Value) colormap.

$$\begin{bmatrix} 2 & 2 & 2 \\ 2 & 0 & 2 \\ 2 & 2 & 2 \end{bmatrix} \qquad (2)$$

Contrarily to test images, reference images are filtered with an additional average filter, to obtain a high correlation value, even if test images present a low SNR.

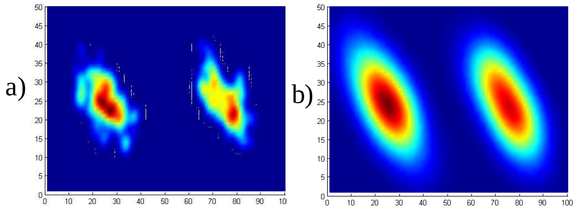
Fig. 3. Typical jitter impairment images processed with the old filtering approach (a) and the new filtering approach (b).

B. Quadrature error module

The Quadrature error is an impairment characterized by a horizontal spot displacement. To distinguish it from the other impairments, it is possible to look at the symbol position distribution. A median filter is used to clean the image from any isolated pixel and to round the symbol spots. Then, two average filters like that used for the Phase jitter module, are able to make the reference images similar with the test images that have a low SNR. In the proposed module (Fig.4), the examined decision areas are positioned at the top corners of the constellation.

C. New filters

The new Phase jitter model leads inevitably to adjust the filtering schemes of the other modules. The image processed with the new filters, in fact, creates a harmful interference with those of other modules, lowering the correct classification probability. Therefore, also the Gaussian phase jitter reference images, constructed with the same decision areas of the method [2], require different filters as shown in Fig. 2.

The Amplitude imbalance moves with different gains the symbols along the I and Q directions. This leads to symmetrically distributed shifts of the actually received symbols from their ideal positions. Using a third order median filter, it is possible to clean the image, highlighting the position of the spots, while a fifth order Gaussian filter, with null average and unitary variance, allows making the image more homogeneous. Respect to the previous method [2], the new proposed Amplitude imbalance module includes different filters (Fig. 5a), while the decision areas and the number of considered reference images remain unchanged.

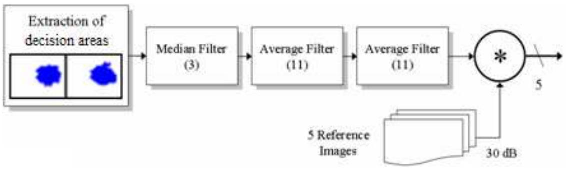

Fig. 4. Block scheme of the Quadrature error module. The filter order is reported between parentheses. The number of the reference images is specified together with the SNR value used to generate them.

The Interference is recognizable from the constellation diagram because the symbols are spread over a circumference, giving the characteristic ring shape. Any linear filter gives, as a result of convolution, a greater image extension. It was decided, therefore, to enhance the ring shape, using two average filters with eleventh order. The new module for Interference (Fig.5b) uses the same decision areas and executes the same filters proposed in [2].

The Phase offset rotates the constellation by a certain angle. In this case, the noise has more influence on the correct classification, because few pixels more lead to a shift of some degrees. It has been preferred, therefore, to delineate the shape and pixel spot positions using a median filter. The action of this filter is to clean the image of any isolated pixel, highlighting the spot shape. An eleventh order median filter, in cascade, assumes the role of interpolating, so that the image becomes more compact and homogeneous. Compared with the module presented in [2], the proposed one (Fig.5c) includes different filters. The examined decision areas remain unchanged, while the number of the reference images is five, instead of four.

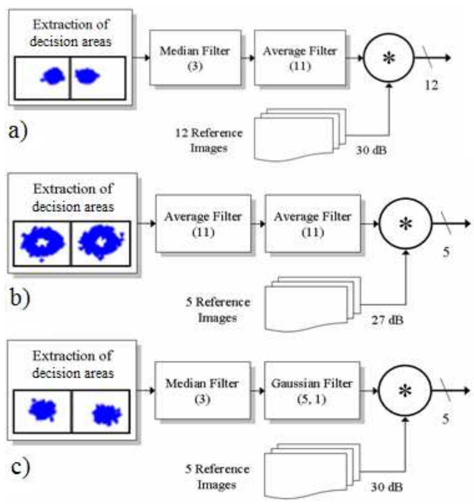

Fig. 5. The images show the different approaches to the impairments classification in several cases: a) Amplitude imbalance, b) Interference, and c) Phase offset.

The signals used for the construction of the reference images were generated with a SNR equal to 30 dB, in order to highlight their features. An exception is the interference signal that is generated by setting a SNR of 27 dB to emphasize the wider shape distribution.

The improved modules, respect to those presented in [2], are summarized in Fig.5. They highlight the decision areas used by each module for the construction of the tests images, the filters used for them and the number of the reference images used for each impairment. For the reference images, the value of the SNR is shown, too.

D. Classifier calibration

The changes to the classification method proposed in [1] required the revision of the thresholds for the impairment detection. It was necessary, therefore, a further experimental study, in order to identify the correlation values, able to discriminate the different impairments, as reported in [1]. The procedure was implemented and executed using the MATLAB 6.5 software. The results are presented in graphical form in Fig.6. Each diagram contains three lines: (i) the solid line (*) shows the evolution of the minimum correlation values between the test images and the reference images, for the same impairment; (ii) the dashed line (Δ) represents the maximum correlation between the test images and the reference images

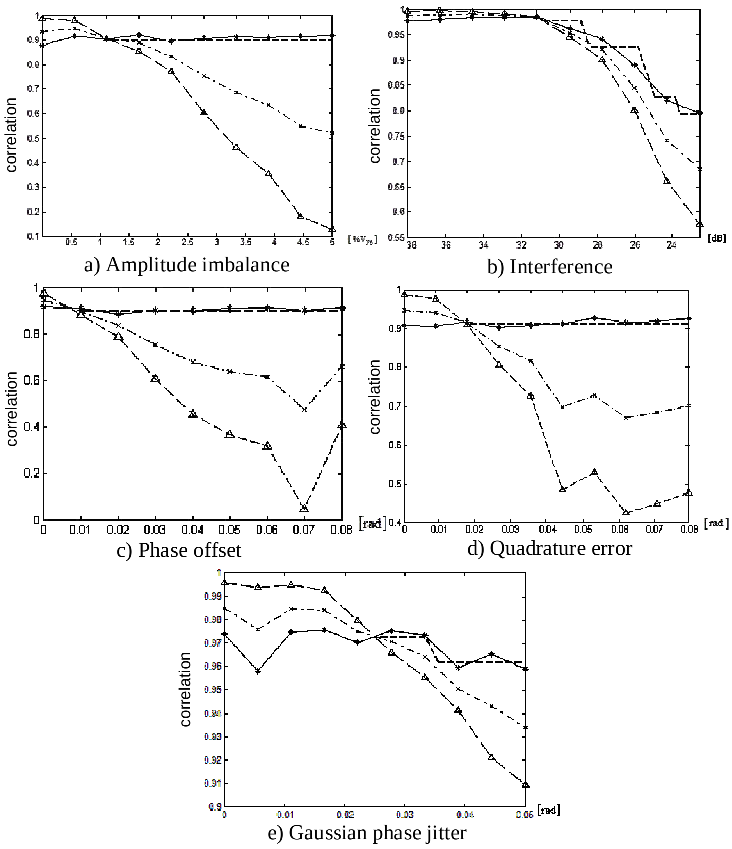

Fig. 6. The graphs depict the results of the calibration phase (continuous lines) and the estimated thresholds for classification (dashed line). The signals with Amplitude imbalance (a), Interference (b), Phase offset (c) and Quadrature error (d) have SNR equal to 24 dB while for the Gaussian phase jitter charts with SNR of 25 dB (e) are reported.

of the other impairments; (iii) the dashed-dot line (×) is obtained by interpolating the midpoints of each interval defined by the points on the solid line (*) and those on the dashed line (Δ) for each impairment value.

When the dashed line (Δ) is above the solid line (*), it is impossible to classify the impairment, because the noise makes the images too confused. The intersection point represents the lower bound for each classifiable impairment.

Moving to the right side of the intersection, the dashed line (Δ) falls below the solid line (*): the more distant they are, the greater is the probability of correct decision. It means that the impairment images under analysis are very different from those of the other impairments and, therefore, better distinguishable. The optimal condition would be to have the intersection between the curves close to zero and the three curves that open wide. To get closer to this ideal case, the action of digital filters is crucial. The best operating conditions were obtained with the filters presented in the previous section.

Using the graphs shown in Fig.6, it was possible to determine, for other impairments; (i) the classification lower bound, (ii) the amount of impairment used in the reference images, and (iii) the classification thresholds (dashed bold line). In fact, for each impairment, the decision threshold has been evaluated. For some impairments, like Amplitude imbalance, Phase offset, Quadrature error, the thresholds are constant. Instead, for the Gaussian phase jitter and the Interference, the thresholds have different values for different impairment value.

III. Realized instrument

The improved method, described in the previous section, has been implemented in an instrument prototype. The hardware architecture of the prototype is based on a Signatec PMP8A data processing board. It is a multi DSP board for parallel data processing [7], which presents a high processing power with a multitasking capability. The card consists of one Texas Instruments TMS320C6201 master DSP, called Program Execution Processor (PEP), and eight TMS320C6701 slave DSPs of the same manufacturer. The slave DSP task is to perform the assigned functions by PEP. Then, the process activity occurs in independently way on each slave DSP. When a DSP completes its task, the PEP will assign to it another one.

The software architecture is made of small tasks that can be executed simultaneously on several processors. In this way, it is possible to obtain a scalable solution that can be adjusted according to the available processing power. Moreover, it is possible to optimize the execution time by maximizing the parallelism between processors and minimizing the communication times among them.

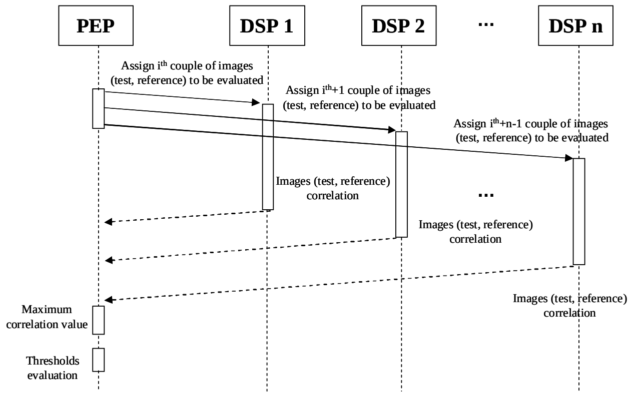

Fig.7. Sequence diagram of the program running on the multi-DSP processing board. The first step is to assign to each DSP, a couple of images (test, reference) to be evaluated. Then the PEP evaluates the maximum correlation value, thus finding the type of the impairment. Finally, it compares such value with the detection threshold.

The implementation has been realized in C language, by dividing the computational load, such that the most part of the classification process can be executed in parallel. The developed algorithm can be summarized with the following steps (Fig.7): (i) the PEP assigns to each slave DSP the test image and a reference image, relative to a particular impairment value, (ii) the slave DSPs compute in parallel the correlation value between the images received, (iii) the PEP collects all the correlation values coming from all the DSPs and evaluates the maximum, (iv) finally, the PEP checks if the maximum value exceed the detection threshold for the found impairment.

IV. Experimental results

In a preliminary phase, the classifier has been experimentally validated with simulated signals. Several tests were carried out, in order to verify the ability of the instrument of identifying the impairments, in presence of different

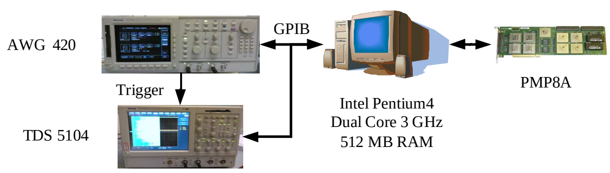

Fig.8. Test setup used during the experimental validation.

values of the SNR and the impairment amount. The main elements, taken into consideration, are the correlation thresholds, the operating range and the percentage of correct classification. Subsequently, further tests have been carried out on emulated signals. These signals have been obtained using the test setup shown in Fig.8. It is composed by the Tektronix AWG 420 signal generator [8] and the Tektronix TDS 5104 digital oscilloscope [9], both connected to a PC via IEEE 488 bus. The classifier test phase has been executed by choosing, inside the operating range of each impairment, 7 values, and for each one, 30 64-QAM signals have been generated with a fixed SNR. The test has been, then, repeated by varying the SNR value, in the range 24dB-30dB, with a step of 2dB. In Table 2 the comparison of the presented method respect that proposed in [2] is shown, giving good results, maintaining almost the correct classification percentages of the previous method [2]. In Table 3 the results of the classification of the impairments, whose modules have been added to the method, are reported, giving almost the 100 percent of correct classification, for all SNR values below 26 dB.

Table 2. Performances of the proposed method, expressed as percentages of correct classification, versus SNR values. For each SNR value, the left column reports the value obtained by the method proposed in [1], while the right column reports the results of the improved method.

Impairments	***SNR[dB]***							
	30		28		26		24	
Amplitude imbalance	100	100	100	100	100	100	100	98.5
Phase offset	100	100	100	100	97.5	100	94.7	97.1
Interference	100	100	100	100	100	98.5	100	97.6

Table 3. Results of the classification of the new impairment with the improved method, expressed in percentages of correct classification, versus SNR values.

Impairments	***SNR[dB]***			
	30	28	26	24
Gaussian Phase Jitter	100	100	100	78.3
Quadrature error	99.8	99.3	100	99.5
Only Gaussian noise	100	100	97.8	85.7

V. Conclusions

In this paper, a prototype of an automatic classifier for impairments overlapped on QAM signals, based on an image processing approach, has been presented. The classification method has been optimized, considering the Phase jitter as a Gaussian variable. It was, therefore, necessary to perform an experimental procedure for filtering selection, thresholds detection and correct working range determination. Starting from the improved method, an instrument prototype has been realized, which operates in parallel on a multi-DSP hardware. An experimental characterization of the classifier has been performed with simulated and emulated signals, with one impairment overlapped at time. Both on simulated and emulated signals the classifier gives high correct classification percentages in the established operational range. The developed prototype works with 64 QAM signals. If the modulation cardinality changes to 256 or 1024 the sizes of the decision areas change as well. However, the method works on images so it can still work with 256 or 1024 QAM by simply adjusting the image resolution according to the actual sizes of the decision areas.

Further work will be spent to improve the correct classification percentages, in particular, for the Gaussian phase jitter and to discriminate several impairments at the same time.

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