

## A MEASUREMENT INSTRUMENT FOR FAULT DIAGNOSIS IN QAM-BASED TELECOMMUNICATIONS

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**Abstract** – A method for diagnosing faults in communication systems based on QAM (Quadrature Amplitude Modulation) modulation scheme is proposed. The most relevant faults affecting this modulation have been observed and modelled. Such faults, individually and combined, are classified and estimated by analysing the statistical moments of the received symbols. Simulation and experimental results of characterisation and validation highlight the practical effectiveness of the proposed method.

**Keywords:** Fault diagnosis, telecommunication, testing, QAM.

### 1. INTRODUCTION

Quadrature Amplitude Modulation (QAM) is an attractive method for transmitting two data streams in channels where the transmitter power can be used to increase the data rate without affecting the signal bandwidth [1]. Such a modulation scheme is now used in the European Digital Video Broadcasting (DVB) system and the DOCSIS cable modem transmission over Hybrid Fibre Coaxial (HFC) channels.

The required quality level needs for a reliable In-Service Monitoring (ISM) system capable of detecting and removing fault effects as soon as possible [2]. Moreover, a fault diagnosis based on the identification of the disturbances could be useful both in identifying the fault in the QAM transmission, and in verifying the design of communication devices, such as modulators, upconverters, and so on. At to date, instruments for QAM signalling diagnosis are based on the BER (Bit Error Rate) monitoring or on a visual analysis of the constellation diagram. However, some drawbacks arise: (i) by a BER monitor, only the fault effect on the signal can be detected, without providing any additional information about the causes; moreover, a large time slot has to be observed to provide a good estimate of the signal quality loss; (ii) by the visual analysis of the constellation diagram, the fault type has to be diagnosed by a human operator.

This kind of analysis is now performed through the EVM (Error Vector Magnitude), that gives a measure of the difference between the actual and ideal position of the received symbol on the constellation diagram [3].

Some techniques for classifying automatically the main faults on QAM modulation via the constellation diagram were proposed. The approach followed in [4] is based on a Wavelet Network (WN). This method provides very good results on simulated and actual signals.

Another method classifies the faults through an image-processing approach [5]. The constellation diagram is digitised, then the obtained image is compared with some fault models, by using a correlation method, and a similarity score is provided.

However, both the WN- and the image processing-based methods can recognize and eventually measure only the dominating fault, and can not recognize the simultaneous presence of several faults.

In this paper, a diagnostics method, based on analytical estimation of the statistical moments of the received symbol distribution, is proposed for QAM-modulation. This method is capable of recognising several faults simultaneously present, and, moreover, estimating the contributes related to each of them. In particular, in Section 2, main faults affecting QAM communication are analysed and an analytical model of the actual signal is proposed. In Section 3, the proposed method for classifying the faults is described. Finally, in Section 4 the first results obtained by applying the method on simulated and actual QAM signals are reported.

### 2. MAIN FAULTS AFFECTING THE QAM MODULATION

The usually effects of the main faults on the QAM transmission are derived by the constellation diagram [5]. In the example of Fig. 1, the classical 16-QAM modulated signals in an AWGN (Additive White Gaussian Noise) environment are considered. In presence of AWGN only, the received symbols are distributed around their ideal positions. When a fault affects the signal, the spots produced by the symbols have different shapes and positions. In particular, four typical faults can be considered:

- *Amplitude Unbalance*: it is produced by different actual gains for the in-phase (I) and quadrature (Q) paths in the transmitter and in the receiver; it leads to symmetrically distributed shifts of the symbol (Fig. 1a).

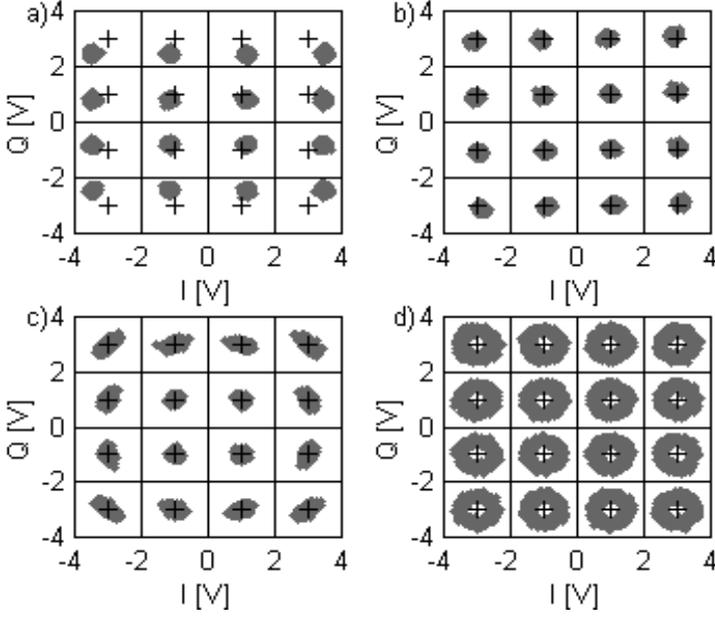


Fig. 1. Main faults affecting the QAM modulation: a) amplitude unbalance, b) phase offset, c) phase jitter, and d) interference.

- *Phase Offset*: a deterministic error on the carrier phase estimation gives rise to a rotation of the entire constellation diagram as a whole (Fig. 1b).
- *Phase Jitter*: random variations in the carrier phase estimate produces a random rotation of the diagram (Fig. 1c).
- *Interference*: a spurious tone overlapped to the signal in the receiver bandwidth causes a typical ring shape of the spot (Fig 1d).

In the following, each disturbance is modelled separately by observing its effect on the constellation diagram. The amplitude unbalance is defined as:

$$Unb = \frac{\min(I_n, Q_n)}{\max(I_n, Q_n)} \cdot 100\% , \quad (1)$$

where  $I_n$  and  $Q_n$  are the amplitudes respectively of the in-phase and quadrature component.

It can be modelled by introducing two different gains  $g_1$  and  $g_2$ , respectively, on the paths I and Q.

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} g_1 & 0 \\ 0 & g_2 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}, \quad (2)$$

where  $\mathbf{x} = (x_1 \ x_2)^T$  and  $\mathbf{y} = (y_1 \ y_2)^T$  are the transmitted and the received symbol, respectively. The phase offset is a deterministic phase error, modelled as a rotation by an angle  $\theta_{off}$  of the ideal point around the centre of the constellation:

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{off} & -\sin \theta_{off} \\ \sin \theta_{off} & \cos \theta_{off} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \quad (3)$$

The phase jitter is a random phase error. Also this disturbance can be modelled as a rotation  $\theta$  of the constellation diagram, but the angle  $\theta$  is a random variable with a known distribution. In this work,  $\theta$  is modelled to have a gaussian distribution with zero mean and variance  $\sigma_j^2$ :

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_j & -\sin \theta_j \\ \sin \theta_j & \cos \theta_j \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}, \quad (4)$$

with  $\theta_j \sim N(0, \sigma_j^2)$ .

The interference is produced by a spurious tone and gives rise to a displacement of the symbol on the constellation diagram. It can be modelled by a vector of amplitude equal to the amplitude  $A$  of the spurious tone, and phase  $\varphi$  depending on the difference between the frequency of this tone and the carrier frequency and the sampling instant. If the sample number is large enough, the phase of this vector can be assumed to have a uniform distribution between 0 and  $2\pi$ . The resulting model is:

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} A \cos \varphi \\ A \sin \varphi \end{pmatrix} \quad (5)$$

with  $\varphi \sim U(0, 2\pi)$ .

The signal, affected simultaneously by all the above disturbances in an AWGN environment, can be modelled as:

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = K \begin{pmatrix} \alpha & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & \beta \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} A \cos \varphi \\ A \sin \varphi \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \quad (6)$$

where:

- $\theta \sim N(\theta_{off}, \sigma_j^2)$ , having a mean value equal to the value of the phase offset  $\theta_{off}$  and a variance  $\sigma_j^2$  equal to the variance of the jitter, takes into account the effects due to both the phase disturbances;
- $A$  and  $\varphi$  are the phase and the amplitude, respectively, of the displacement vector caused by an interfering tone eventually overlapped to the signal;
- The matrices containing the parameters  $\alpha$  and  $\beta$  take into account the different gains on the I and Q paths in the receiver and the transmitter, respectively;
- $K$  is a gain; and
- $n_1$  and  $n_2$  are the I and Q components respectively of the white noise.

### 3. THE PROPOSED METHOD

An algorithm for the estimation of unknown parameters in the model (6), by analysing the statistical moments of the received symbols, has been developed. The method of moments is widely known as a simple method for constructing consistent estimators [6]. As an example, it is used in electromagnetic field modelling [7-9] or in image processing [10].

The method works as shown in Fig.2. First, the received symbols are distributed in the decision cells of the constellation diagram.

Then, for each cell, by approximating the relation for small phase angles, the expected value of  $y$  is calculated from the (6):

$$\begin{aligned} E\{y_1\} &= K\alpha x_1 - K\alpha\beta\theta_{off}x_2 \\ E\{y_2\} &= K\theta_{off}x_1 + K\beta x_2 \end{aligned} \quad (7)$$

where  $E\{ \}$  is the expected value operator.

By taking the sample mean of the I and Q components of the received symbols fallen within a decision area, for at least two areas, the unknown parameter  $\alpha$ ,  $\beta$ ,  $K$  and  $\theta_{off}$  in (7) can be estimated. These parameters represent the values of the amplitude unbalance and phase offset.

The phase jitter leads to a random rotation of the constellation diagram; therefore, in a signal corrupted by phase jitter, some dependency between the I and Q components can be found. This dependency can be determined by calculating the covariance between the two components of the received symbol:

$$Cov\{y_1, y_2\} = -K^2\alpha\beta x_1 x_2 \sigma_j^2 \quad (8)$$

Through the (8), the jitter variance  $\sigma_j^2$  can be estimated.

The amplitude of the interfering tone  $A$  can be revealed by computing the fourth-order moment of one component of the received symbol. In particular, by comparing it with the squared variance, the following relation can be found:

$$3\sigma_{y_1}^4 - m_{4y_1} = \frac{3}{8}A^4 \quad (9)$$

where  $m_{4y_1}$  is the fourth order moment calculated on  $y_1$ .

Finally, the contributes relative to Gaussian noise can be estimated by calculating the variance of the I and Q components of the received symbol, by using the relations:

$$\begin{aligned} \text{var}\{y_1\} &= (K\alpha\beta x_2)^2 \sigma_j^2 + \frac{A^2}{2} + \sigma_{n_1}^2 \\ \text{var}\{y_2\} &= (Kx_1)^2 \sigma_j^2 + \frac{A^2}{2} + \sigma_{n_2}^2 \end{aligned} \quad (10)$$

where  $\sigma_{n_1}^2$  and  $\sigma_{n_2}^2$  are the variances of the I and Q component of the Gaussian noise, respectively.

Once the unknown parameters of the model (6) were estimated, some thresholds can be set for classifying the

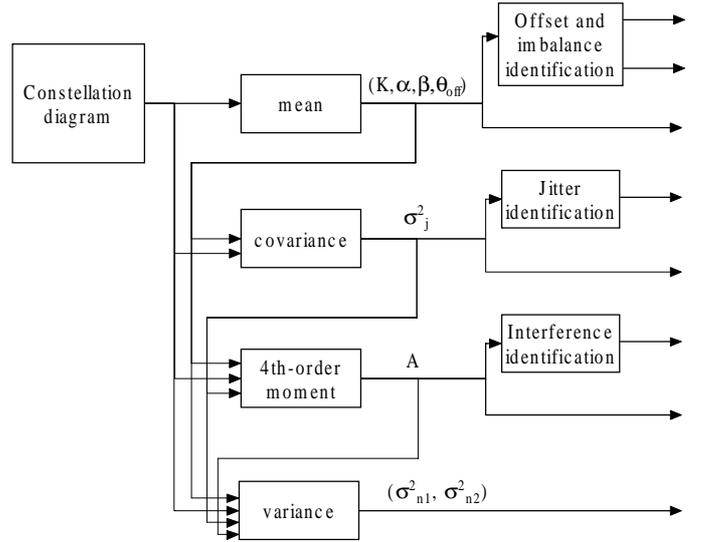


Fig. 2. Algorithm of the proposed method.

faults really present in the transmission. The presence of each kind of fault is detected when its threshold is exceeded.

### 4. SIMULATION AND EXPERIMENTAL RESULTS

The above method was implemented in MATLAB<sup>TM</sup>. The performance of the method were analyzed in simulation, in an AWGN environment, with different values of the signal-to-noise ratio (SNR) and different values of the disturbance amplitudes. Then, some tests have been carried out on actual signals, affected by the above disturbances.

#### Simulation results

The simulation was carried out on sets of 100 signals at varying the disturbance amplitude and the SNR. In Fig. 3 the results of the classification of the disturbances for a 64-QAM with one disturbance overlapped to the signal and with values of the SNR in the range [25 dB, 40 dB] are shown. The results of these simulations are provided in terms of correct classification percentages. They show how many times (over 100 signals) the algorithm identifies the presence of the considered disturbance and the absence of the others. As it is shown, all the disturbances are classified correctly in high percentage. In the cases of phase jitter and interference, poorer results for small values of the SNR and high values of the amplitude of the disturbance were obtained, when several points of the constellation diagram are out of the decision cells relative to its own ideal positions.

In Fig. 4, some results of the classification with two disturbances simultaneously overlapped to the signal are shown. In these graphs, a column for each disturbance is reported. The height of each column shows how many times (over 100 signals) the algorithm identifies the corresponding disturbance. It is interesting to note how only two columns, corresponding to the disturbances actually present on the

signal, have high values when the others have very small values.

### Experimental results

The above proposed method has been verified by estimating the disturbances present on actual QAM signals. After estimation and classification, the actual signals are compared with the simulated signal obtained overlapping to the QAM transmission the identified disturbance with the estimated amplitudes. Two examples are shown in Fig.5. In Fig.5a the constellation of an actual signal is reported. This constellation has been identified to have a phase jitter of 1.03 deg and an interference tone of 0.49 V. In Fig.5b the constellation of the corresponding simulated signal is shown. In Fig.5c a signal with an I/Q unbalance of 97% is reported and in Fig.5d the corresponding simulated signal. As it can be seen, the two constellations are very

### 5. CONCLUSIONS

A method for diagnosing faults in QAM communications was proposed and experimentally verified. It is capable of recognizing several simultaneous faults and estimating the contribution of each of them.

The research work continues toward a complete characterization of the method, by evaluating the estimation uncertainty of the algorithm. The final aim is the algorithm implementation on an instrument hardware such as a DSP or an FPGA.

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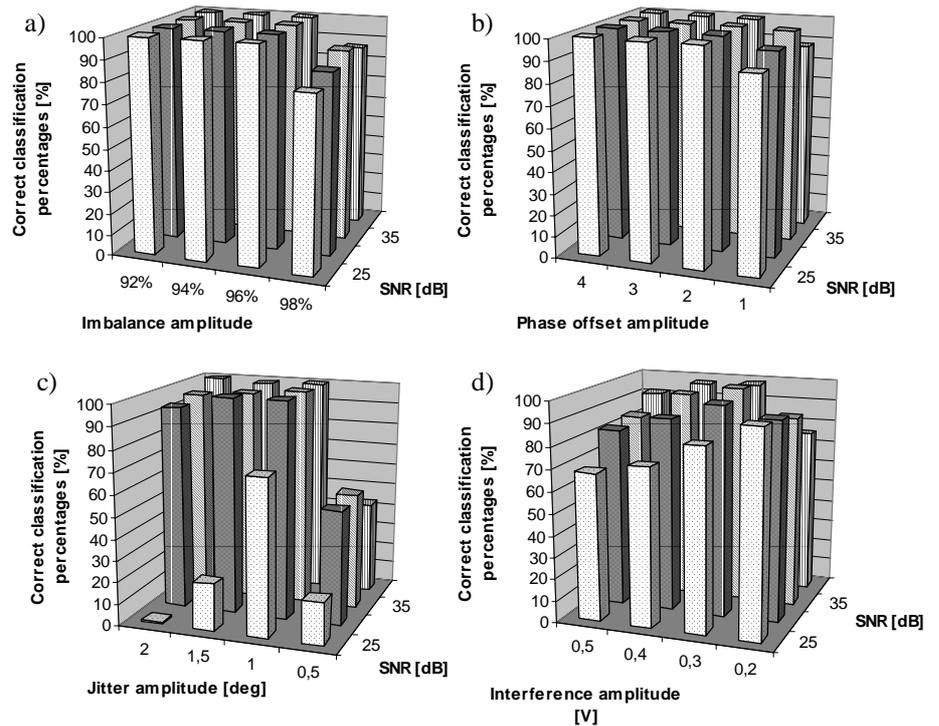


Fig. 3. Correct classification percentage with one disturbance: a) amplitude unbalance, b) phase offset, c) phase jitter, d) interference.

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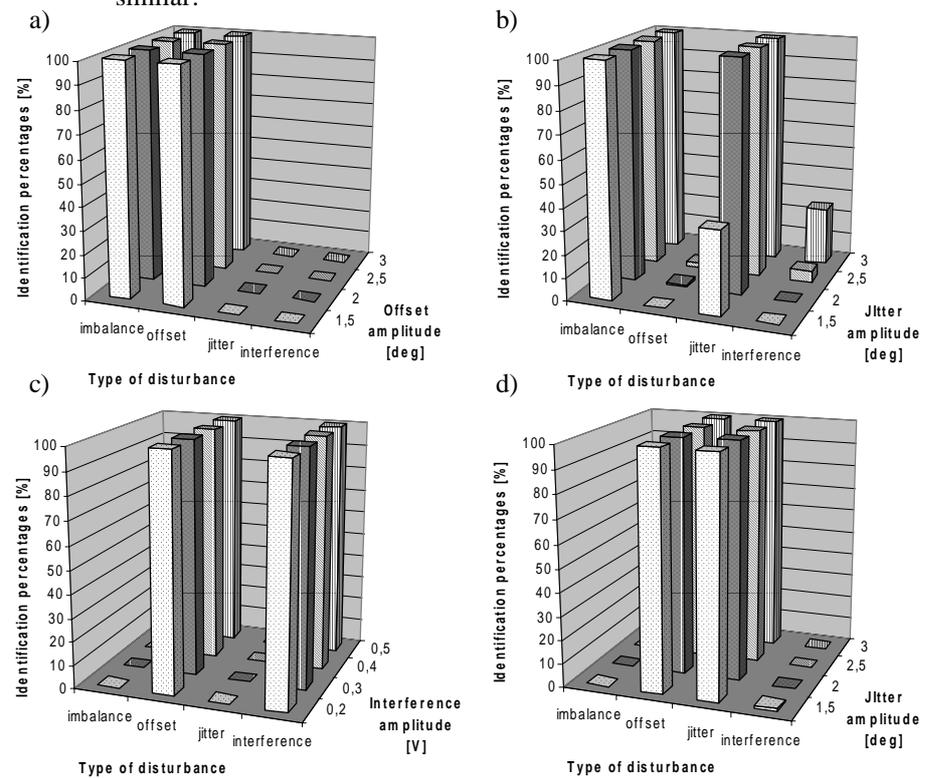


Fig. 4: Classification percentage with two disturbances simultaneously overlapped to the signal and SNR=32 dB: a) amplitude unbalance of 96% and b) phase offset of 96% and, c) phase offset of 2.5 deg and interference, d) phase offset of 2.5 deg and phase jitter.

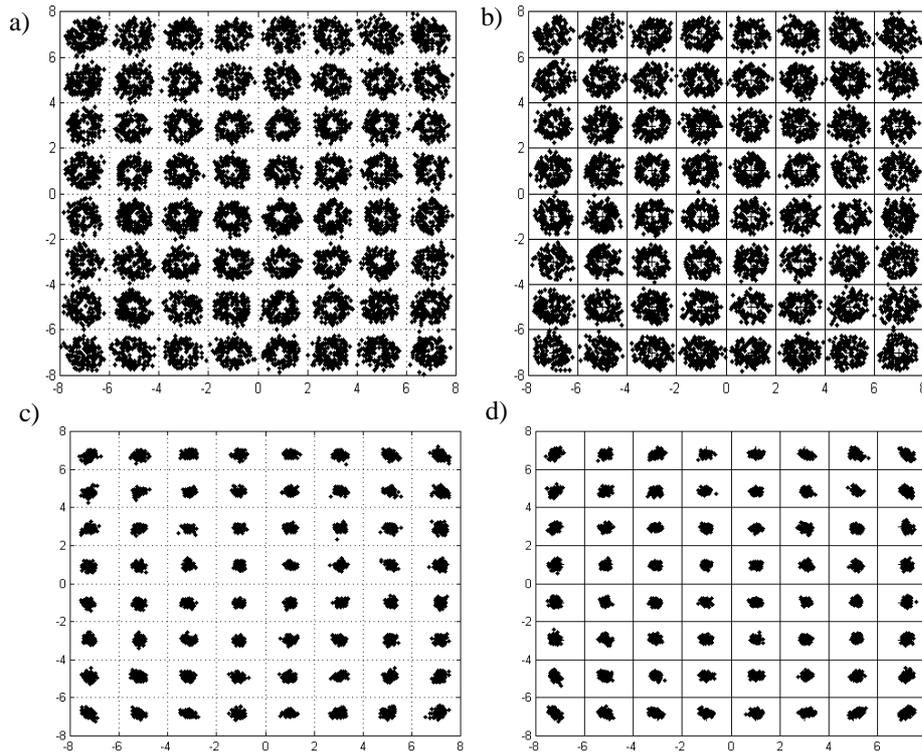


Fig. 5. Tests with actual signals: Two signals a) and c) and the simulated ones c) and d). The first has a phase jitter of 1.03 deg and an interference of 0.49 V. The second has an I/Q unbalance of 97%.

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