Fast BER Test for Digital RF Transceivers

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Abstract—The paper presents a fast bit-error-rate (BER) test suitable for digital receivers or transceivers. The test technique makes use of an elevated BER which can be achieved by geometrical translation of the signal constellation points on the IQ plane. As the elevated BER requires much less bits (or symbols) to be measured, significant savings in the test time can be anticipated. Also a maximum sensitivity to impairments in the noise factor is obtained in this way. To develop an effective elevated-BER test for a device in mass production a careful characterization procedure must be carried out, followed by a fine tuning procedure aimed at improving the test resolution and thereby the test coverage. The technique is supported by a simple statistical model and illustrated by a simulation example of a 4QAM receiver.

I. INTRODUCTION

In digital communications the concept of error rate measurements has been well established as a way to verify the quality of a transmission link. The transmitted signals usually tend to suffer from noise, reduction in power and other disturbances that result in erroneous bits in the receiver. This effect can be quantified by bit-error-rate (BER) which is measured as a ratio of the incorrect received bits to all bits sent. The BER measurements are useful to characterize various communication channels (wireless and wireline) and also to test hardware, in particular the digital receivers or transceivers. The existing standards define the respective test requirements in different variants. For example, radio receivers can be tested for BER in terms of sensitivity, interference, blocking or intermodulation [1]. The specified BER values tend to be small such as 1e-4…1e-8 (and even 1e-15 in case of SerDes devices) so the test signals capable of measuring BER are usually long bit sequences. As a rule of thumb an adequate test sequence should comprise at least (10...100)×BER bits [1,10]. Because of the test time the BER measurement can be expensive as a production test so in some cases it is replaced by the EVM test [2]. An alternative approach using spectral tests has been proposed as well, where BER was shown predictable by a statistical regression model [3]. Modified BER tests that aim at increasing fault detectability on chip and reducing the test time have also been proposed [5-7], where the means have been an elevated BER. The elevated BER was also shown competitive to the EVM test in terms of fault detectability (sensitivity) versus overhead [7].

In this paper the elevated BER technique is discussed in terms of the required test sequence length and the test coverage. The translation technique using the constellation signal model on the IQ plane is exploited [7]. In Section II the underlying concept aimed at the maximum test sensitivity is presented. In Section III a simple statistical model which relates the standard BER and the elevated BER is introduced and based on this the test yield is discussed. An example of a 4QAM system under test is provided in Section IV. It is shown that the test sequences providing high test coverage can be reduced by more than one order of magnitude compared to the standard BER test when some practical assumptions are made. Final conclusions are provided in the last section.

II. ELEVATED BER TEST

Several techniques have been proposed to elevate the BER in order to sensitize the BER test response and/or to reduce the test sequences, cutting thereby the test time. The recent approaches that consist in direct modification of signal constellations have proven superior to the techniques proposed earlier [5]. Here, we refer to the translation technique proposed in [7].

Consider a fragment of a signal constellation shown in Fig.1a. Assume it represents a baseband 4QAM signal in a receiver exposed to noise (scattered points). Also assume the possible IQ imbalance has been corrected [9]. The signal-to-noise ratio (SNR) is here relatively large so almost all the constellation points are apart from the decision boundaries of the 4QAM demodulator and the measured BER (SER) is close to zero. Observe that a bit/symbol error only occurs if constellation points cross over the boundaries, here, the IQ axes. Using a translation vector \( \mathbf{V} = [V_I, V_Q] \) we can shift the constellation points toward the decision boundaries only changing the signal power and not the noise component (Fig.1b). Received at a time \( t_k \) the 4QAM symbol \( x(k) = [x_I(k), x_Q(k)] \) is translated to:

\[
\hat{x}_I(k) = x_I(k) - V_I \times \text{sgn}(x_I(k)) \\
\hat{x}_Q(k) = x_Q(k) - V_Q \times \text{sgn}(x_Q(k))
\]

(1)

where \( V_I, V_Q > 0 \) and the \( \text{sgn}(\cdot) \) function secures the desired direction of the translation. The choice of vector \( \mathbf{V} \) length can result in any value of BER measured after the translation is
performed. In particular, if \([V_I, V_Q]\) are chosen so that the mean constellation points are brought to the origin, then for the evenly distributed noise the symbol error rate (SER) can be estimated by inspection as 0.75 which for 4QAM corresponds to BER=0.75/2. A vector \(V\) larger than this will result in larger values of SER, up to 1 when all the received symbols are in error. The elevated BER (SER) can be measured with much shorter test sequences compared to the standard test (#bits ~ BER \(-1\)). Observe that upon the translation the SNR can be changed from \(SNR_0\) to an arbitrary value \(SNR\)

\[
SNR = SNR_0 \left(1 - \frac{|V|}{|x_0|}\right)^2
\]  

(2)

where \(|x_0|^2\) is the signal power and the coordinates of \(V\) are assumed \(V_I = V_Q = |V|/\sqrt{2}\). The above concept can be reinforced by using a probabilistic model of the 4QAM demodulator [8]:

\[
p_e = \text{erfc} \left( \frac{SNR \times R_s}{B} \right) - \frac{1}{4} \text{erfc}^2 \left( \frac{SNR \times R_s}{B} \right)
\]  

(3)

where \(p_e\) denotes the probability of symbol error (SER) while \(R_s\) and \(B\) stand for bit rate and the system bandwidth, respectively. Figure 2 illustrates how \(p_e\) can be elevated by the translation represented here by a factor \(\beta = \left(1 - |V|/|x_0|\right)^2\). Apparently, for \(SNR > 10\text{dB}\), \(p_e\) can be raised even by several orders of magnitude. Based on this model one can also identify the optimum translation vector for a given signal. In this case the objective is to achieve maximum sensitivity \(dp_e/dSNR\) (or \(dp_e/dF\) where \(F\) is the receiver noise factor) that is equivalent to achieving the best detectability of impairments in the respective specs. The optimum can be found for the reduced \(SNR^* = SNR_0 \times \beta^* \approx 1.35\) as shown in Fig.3 for various power levels at the receiver input. Around the maximum \(dp_e/dF\) is rather flat so in practice the test sensitivity does not suffer much from imprecise tuning for optimum.

The elevated BER measurements can be run with test sequences of reduced-length that support fast test. From the above discussion one could expect the reduction factor to be the ratio between the elevated- and the standard BER. Also the optimum \(SNR^*\) seems to be the best choice. The problem appears more complicated, when statistical properties of the devices under test are accounted for. This issue is discussed in the following section.

**III. STATISTICAL MODEL OF BER TEST**

The measured BER (or SER) is a random variable. Even for a specified value of \(SNR\) the BER can take on different values subject to the probability distribution. Assuming the normal distribution and a confidence level of \(\alpha\) the corresponding confidence interval can be estimated:

\[
\mu_{BER} - k\sigma_{BER} \leq BER \leq \mu_{BER} + k\sigma_{BER}
\]

(4)
where \( \mu_{\text{BER}} \) is the mean value and \( \sigma_{\text{BER}} \) denotes the standard deviation. \( k \) follows \( \alpha \) for the normal distribution, e.g. for \( \alpha = 0.99 \) \( k \approx 2.58 \). The mean value \( \mu_{\text{BER}} \) and the standard deviation \( \sigma_{\text{BER}} \) can be calculated from a production sample as \( \overline{\text{BER}} \) and \( s_{\text{BER}} \), respectively. Here, we assume the sample is only composed of fault-free devices which, in fact, do not differ in SNR substantially. The formula (4) applies both to the standard- and elevated BER measurements. \( \overline{\text{BER}} \) and \( s_{\text{BER}} \) are random variables as well. Specifically, the corresponding sampled variance \( s^2_{\text{BER}} \) is subject to chi-squared distribution. The confidence interval of (1-\( \epsilon \)) for the true variance \( \sigma^2_{\text{BER}} \) is given by:

\[
(n-1)\frac{k^2_{\epsilon/2}}{K^2_{\epsilon/2}} \leq \sigma^2_{\text{BER}} \leq \frac{(n-1)k^2_{1-\epsilon/2}}{K^2_{1-\epsilon/2}}
\]

(5)

where \( n \) is the sample size. To limit the upper bound for \( \sigma_{\text{BER}} \) one should choose a large enough sample size. For example, with confidence (1-\( \epsilon \)) = 0.95 and \( n = 10 \) the ratio \( \sqrt{(n-1)/K^2_{1-\epsilon/2}} \) is 1.83 while for \( n = 30 \) and \( n = 100 \) it drops to 1.34 and 1.16, respectively. Apparently, shrinking the bounds requires a relatively large sample size to characterize the device before test. But the test time of the actual volume test is not affected in this way.

On the other hand, the standard deviation of the mean \( \overline{\text{BER}} \) can be calculated as \( \sigma_{\text{BER}} / \sqrt{n} \) so its impact on the confidence interval (4) is less meaningful provided \( n \) is large enough (e.g. \( n \geq 100 \)).

Using the same sample of devices we can carry out the elevated-BER test and identify the corresponding confidence interval:

\[
\mu^*_\text{BER} - k\sigma^*_\text{BER} \leq \text{BER}^* \leq \mu^*_\text{BER} + k\sigma^*_\text{BER}
\]

(6)

In order to introduce the elevated BER test the device, which is subject to test, has to be characterized by the conditions (4) and (6). The problem is in choosing the elevated BER value and also the test sequence length. As the employed translation technique acts as a nonlinear operator the problem goes beyond the standard BER estimates [10]. In a broader perspective, the specification space (4) defined for the standard BER is mapped into the measurement space (6) and the pass/fail decision is taken with respect to (6), where in fact, only the upper bound is of interest.

The following reasoning can be carried out. If a device passed the standard test it should pass the elevated BER test as well. By transposition we infer that if a device failed the elevated BER test then it would fail the standard test. Unfortunately, due to the limited confidence levels the above thesis tends to be confined and in practice “false rejects” are not unusual, i.e. a good device can fail the elevated BER test. On the other hand, the test “escapes” support the thesis, i.e. a faulty device can pass the elevated BER test while it would not pass the std. BER test.

Both types of misclassification mainly apply to the devices with BER close to the decision boundaries, i.e. the upper bounds in (4) and (6). To limit this effect the decisive test (here, the elevated BER) should achieve enough resolution. So far the maximum sensitivity of BER response has been the objective as discussed in the previous section. From the practical case study one can also infer that in order to reduce the effect of misclassification and to improve the test coverage also the relative sensitivity \( \frac{d\text{BER}}{d\text{SNR}} \) should be taken into account. The respective plot is shown in Fig. 4 and it corresponds to \( \frac{d\text{BER}}{d\text{F}} \) shown in Fig. 3. Apparently, the relative sensitivity is rising with SNR that helps to improve the test resolution so a tradeoff exists between the effectiveness of test and the test time. Obviously, larger values of SNR make BER lower which in turn claims longer test sequences. This problem is illustrated by an example in the next section.

IV. TEST EXAMPLE

Consider a 4QAM transceiver chip under production BER test using the loopback mode. Suppose, the production lot has been characterized by a sample of \( n = 100 \) fault-free devices. The sample chips feature BER with mean equal \( \overline{\text{BER}} = 18e-5 \) and sample standard deviation \( s_{\text{BER}} = 3.2e-5 \) obtained for test patterns of 1e5 symbols. These data have been achieved using a simulation model implemented in Simulink®. The corresponding mean SNR = 12.7 (11dB).

The true standard deviation calculated with (5) for the confidence level (1-\( \epsilon \)) = 0.99 is \( \sigma_{\text{BER}} = 3.2e^{-5} \times 1.21 = 3.87e-5 \) so that the BER for the production lot (devices with hard faults are discarded) would be \( \text{BER} = \overline{\text{BER}} \pm k\sigma_{\text{BER}} = 18e-5 \pm 2.58 \times 3.87e-5 \) (variation of the mean is neglected here). The BER upper bound calculated for the standard test is then 28e-5 with a confidence level of 0.99.
To characterize the test the same chip sample is subjected to the elevated test with a translation vector \( |V| = (2/3) \times |x| \) so \( SNR = SNR_0 \times (1/9) \approx 1.41 \) close to the optimum equal 1.35 is obtained. The corresponding BER\(^*\) for the reduced test sequence of 1e3 symbols is 0.110 \( \pm 21.2e^{-3} \) (the decision boundary is 0.1312). To verify this test another sample of 100 devices has been randomly generated but devices with hard faults were rejected as before in order to focus on the boundary decision problem (i.e. the test resolution). 62 of those devices passed the standard BER and the elevated BER test as good that means no false rejects were encountered. Among the remaining 38 faulty devices there were 15 which passed the elevated-BER test and are considered the test “escapes”.

To cope with this problem, the elevated BER test with the same vector \( V \) was characterized again using 10 times more symbols per sequence, i.e. 1e4 still 10 times less than needed for the std. BER test. The confidence interval shrunk to 9e-3 resulting in the decision boundary equal 0.123 as compared to 0.131 used before, but the test resolution only slightly was improved. As many as 13 “escapes” were encountered compared to 15 at the expense of 10 times longer test sequences.

Driven by the observation about the relative BER sensitivity (Fig.4), higher values of \( SNR_{out}^* \) were introduced to derive a more efficient elevated-BER test. For \( SNR_{out}^* \), equal (2.89, 4.16, 4.88) the corresponding BER confidence intervals were shrinking such as (±5.4e-3, ±2.8e-3, ±1.9e-3), respectively. The number of test “escapes” dropped while “false rejects” occurred instead but the total number of misclassified devices dropped to 8-9 for \( SNR_{out}^* = 4.88 \) resulting in the test coverage of 0.91, .. 0.92. This result was achieved with 1e4 symbols while with 1e3 symbols the test performance was much poorer.

In this way, most of the misclassified devices were found apart from the decision boundary and it was also possible to reduce the number of test symbols from 1e4 to 5e3, without degrading the fault coverage.

From the practical standpoint, if the chip has been designed with a reserve compared to formal specifications one can consider the standard BER upper bound (of 28e-5), derived from the test sample, not to be too strict. In this case defining a larger bound, such as 33e-5, ... 35e-5 and also slightly larger bound for the elevated BER (increased from 16e-3 to 18e-3) results in absorbing most of the misclassified devices. A careful inspection helped to define those new bounds and ultimately, the test coverage as high as 0.97,..0.98 was achieved in this case study.

V. CONCLUSIONS

In a production test of integrated circuits the test time is a critical issue. Savings which amount even for 10% are significant [1]. In this perspective a fast BER test has been proposed and investigated by a simulation model of a 4QAM receiver. Also different modulation schemes can be addressed in this way. This technique like the std. BER test can be used in several loopback variants; for a receiver driven by a “golden” transmitter, for a transmitter looped-back by a “golden” receiver or for a whole transceiver, especially when integrated on a chip. The advantage of BER test is in its simplicity, low computational overhead and a wide spectrum of applications so the improvement offered additionally by the elevated-BER test seems to be meaningful.

The proposed fast BER test makes use of the geometrical translation of the constellation points. This procedure should be performed in conjunction with correction of the IQ imbalance that is usually carried out in a receiver [9]. The translation elevates the BER so that less test symbols are required during the measurement and also the BER test sensitivity to SNR impairments is greatly improved. A reduction of the test sequence length by more than one order of magnitude at the test coverage of 0.97, .. 0.98 has been demonstrated for the confidence level 0.99 under practical assumptions. This result is promising but also reflects a tradeoff between the test performance and the test time. The elevated-BER test has a potential to be introduced as a fast production test provided the test decision boundaries and the test sequence lengths are carefully chosen during characterization of the production samples.

REFERENCES