Boosting SER Test for RF Transceivers by Simple DSP Technique

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Abstract

The paper presents a new technique of symbol error rate test (SER) for RF transceivers. A simple DSP algorithm implemented at the receiver baseband is introduced in terms of constellation correction, which is usually used to compensate for IQ imbalance. The test is oriented at detection of impairments in gain and noise figure in a transceiver frontend. The proposed approach is shown to enhance the sensitivity of a traditional SER test to the limits of its counterpart, the error vector magnitude (EVM) test. Its advantage over EVM is in simple implementation, lower DSP overhead and the ability of achieving a larger dynamic range of the test response. Also the test time is saved compared to a traditional SER test. The technique is validated by a simulation model of a Wi-Fi transceiver implemented in Matlab™.

1. Introduction

Due to complexity of today VLSI ICs, production test is becoming increasingly expensive. Its contribution to the total production cost is significant and in case of mixed signal/RF chips it can even exceed the direct manufacturing expenses [1]. For this reason chip manufacturers are ever more interested to develop better test strategies in order to cut the costs while maintaining the required test performance. Besides looking for cheaper and faster test instrumentation, recently, the design for test (DfT) and built-in self-test (BiST) have attracted much attention also in the analog/RF domain. Chip reconfiguration, sharing of on-chip resources, and the on-chip test circuitry reflect the key directions in DfT/BiST for mixed-signal/RF chips. On the software side those techniques are accompanied by optimal stimuli generation and response analysis, usually facilitated by DSP techniques implemented on chip (BiST) or off chip, i.e. with testers [2-7].

In this paper we address the symbol error rate test (SER) useful for digital RF transceivers (or receivers). The required test setup is a loopback made of a transmitter and a receiver, where both of them or one is subject to test. In the latter case a RF tester can play a role of a receiver or transmitter, respectively. The paper gives attention to the sensitivity of SER response to possible impairments in gain or noise figure (NF) of the involved RF blocks. We propose a simple technique boosting the SER test so it can achieve the relative sensitivity as good as its counterpart, the error vector magnitude test (EVM), while saving the required DSP overhead. Moreover, by tuning the SER test out from that optimum a much larger dynamic range of the SER response can be achieved, which is an advantage over the EVM test. The algorithm is developed in terms of the correction of signal constellations that is typically used in case of IQ imbalance.

The paper is arranged as follows. In Section 2 we present the previous work and briefly summarize the results obtained for fault sensitive SER and EVM test techniques. Based on this a new approach to SER test is developed in Section 3. It makes use of a simple DSP algorithm at receiver baseband (BB) that precedes demodulation. A simulation model and the results validating this technique are presented in Section 4. The advantage of implementing the bypassing technique on a chip [12] is demonstrated as well. Conclusions are provided in the last section.

2. Previous work

Symbol Error Rate (SER) and Error Vector Magnitude (EVM) tests are common techniques of verifying the performance of digital RF receivers and transmitters [9]. While for transmitters mainly the EVM test is used, for receivers and transceivers both EVM and SER are common. Specifically, SER test requires the loopback technique to be employed so that the sent digital signal can be compared with the demodulated response in a receiver. The loopback setup can be implemented for any pair of a receiver (Rx) and a compatible transmitter (Tx). Both Tx and Rx can be under the test such as often used for one-chip CDMA transceivers. Alternatively, if only Rx is under test an external test instrumentation (RF tester) can serve as a Tx or vice versa.

To avoid a long test time for standard SER test, recently, an alternative approach using AC tests has been

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proposed. The SER values have been shown predictable from statistical regression models that map the AC- to SER (BER) response [8]. In another time saving technique the SER is elevated by modifying phase relations between the transmitted symbols [13].

SER and EVM tests have been also discussed in terms of defects and faults which degrade the chip performance. Those faults are basically impairments in gain and noise figure (NF) of the involved RF blocks (amplifiers, mixers, filters). It has been shown that to achieve a high sensitivity of the SER- or EVM test response a very low signal power should be applied at the Rx input [5,7]. In case of SER test using additionally a low signal-to-noise ratio (SNR) has been proven crucial. The reasoning behind those strategies is as follows. For a given modulation scheme (e.g. QPSK, QAM) the EVM as a quantity, is closely related to SNR. If the reference constellation points are same as the mean measured for the scattered points (due to noise) then EVM squared equals 1/SNR. Hence, a low power of signal guarantees that an increase in noise (considered a fault) entails a significant change of EVM. The average distance between the scattered constellation points and the reference becomes significant compared to the distance between the reference and the origin. In a similar way, also impairments in gain or IQ imbalance will be pronounced.

On the other hand, SER as a quantity to be measured requires the constellation points be close to the decision boundaries of a demodulator. A straightforward way to make SER well measurable and sensitive to impairments in gain or NF is to use very low power and low SNR, e.g. by adding large noise at Tx baseband. In this way the reference points are located close to the origin and some of the constellation points tend to cross over the decision boundaries (Fig.1). Upon extra noise added by the involved blocks more points cross over. Also more points cross over if the gain path decreases since any noise added (after the block with degraded gain) becomes more powerful.

A variant of this technique makes use of a low frequency interferer introduced in place of noise [7]. A comparison between SER- and EVM test implemented as described above revealed the EVM test to be superior in terms of sensitivity and resolution. Apparently, upon a fault the EVM response reflects variations of all constellation points while SER only of those, which cross over the decision boundaries. On the other hand, SER seems to be attractive since it requires less computation than EVM.

Even though impairments in gain can be measured directly, the EVM and SER test display an advantage over it. In terms of production tolerances the possible impairments tend to be obscured and one can quantify this effect by the detectability thresholds (smallest measurable fault). It has been shown that in a typical case, when impairments in Rx gain (actually in LNA) are accompanied by impairments in NF the detectability threshold for the direct gain measurement is larger than for EVM or SER [6].

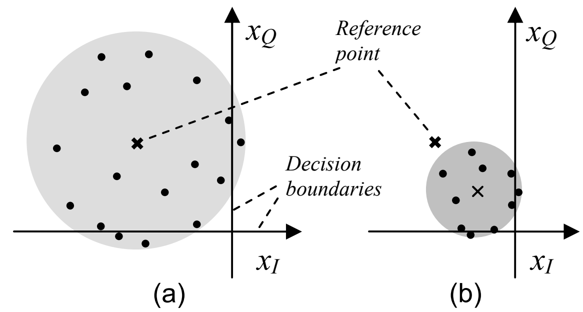


Figure 1. Constellation points of noisy QPSK signal, (a) fault free RF path, (b) RF path with reduced gain

3. Enhanced SER test

In the context of the previous section consider a fragment of a signal constellation shown in Fig.2a. Assume it represents a baseband fault-free response in a QPSK receiver (a possible IQ imbalance is neglected here for brevity). Since the SNR is much smaller than shown in Fig.1, all the constellation points are apart from the decision boundaries so in practice the measured SER is zero. Next, define a vector $V = [V_I, V_Q]$, where both coordinates are positive real numbers. Using V we can shift the constellation points towards the decision boundaries without scaling. Received at a time t_k the QPSK symbol $x(k) = [x_I(k), x_Q(k)]$ is translated to:

$$\begin{aligned} \hat{x}_I(k) &= x_I(k) - V_I \times \operatorname{sgn}(x_I(k)) \\ \hat{x}_Q(k) &= x_Q(k) - V_Q \times \operatorname{sgn}(x_Q(k)) \end{aligned} \quad (1)$$

where the sgn(·) function secures the desired direction of translation. The choice of vector V can result in any value of SER measured after the translation is performed. In particular, if V is chosen so that the mean constellation points are brought to the origin, then for the evenly distributed noise the SER can be estimated by inspection as 0.75. A vector V larger than this will result in larger values of SER, up to 1 when all the received symbols are in error.

As an alternative approach one can consider a phase shift rather than the amplitude shift [13]. In such a case the phase of each symbol must be calculated and next increased by a predefined angle. Finally, the new IQ coordinates must be retrieved, rendering the overall computer overhead much larger as compared to (1).

To understand the advantage the translation technique, consider a drop in gain (fault) in the loopback path or additionally more noise added by any of the involved

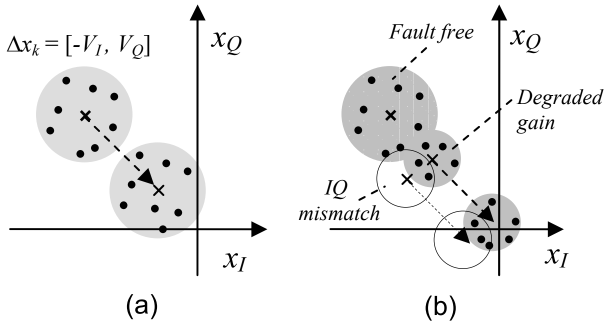


Figure 2. Translation of constellation points (a) for fault free RF path, (b) for degraded gain in RF path.

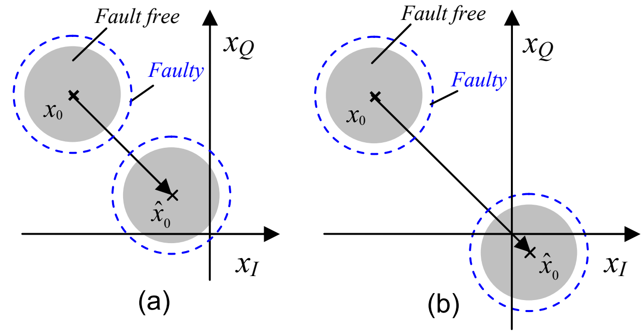


Figure 3. Two variants of translation of constellation points (a) for $|V| < |x_0|$, (b) for $|V| > |x_0|$

blocks. Upon the fault, the constellation points $x(k)$ scale down towards the origin and next, they are amplitude shifted. Compared to the fault-free case a number of them cross over the decision boundaries so the corresponding increase in SER can be large (Fig. 2b). In extreme cases a large drop in gain can bring the constellation points close to the origin, and the fixed, translation vector V can move all of them across the boundaries.

If a fault or parameter tolerances entail IQ imbalance in the RF path, the constellation scales down unevenly. Still the translation can provide very good detection by SER as shown by solid-line circles in Fig.2b. Apparently, a proper choice of V seems to be crucial for the test to be effective.

In a broader perspective, one can combine this technique with the IQ imbalance correction [11]. We assume the correction provides new constellation points while the scattering remains unchanged. Based on the SNR value (known from the model) and its relation to SER, the vector V can be estimated. A possible strategy is as follows. Assume the baseband signal of the fault-free RF path (and no IQ imbalance) has a power $S_0 = |x_0|^2$ and the corresponding $SNR = SNR_0$. The maximum sensitivity of SER response to impairments in NF of the path appears usually for a lower value of SNR. Using the translation (1) SNR can be reduced to the optimum value SNR_{opt}:

$$SNR_0 = \frac{S_0}{N_{FF}} = \frac{|x_0|^2}{N_{FF}} \qquad\qquad (2)$$
$$SNR_{opt} = \frac{S_{opt}}{N_{FF}} = \frac{|x_0 - V|^2}{N_{FF}}$$

where N_{FF} stands for the noise power of the fault-free test path. Assuming x_0 and V to be co-linear :

$$|V| = |x_0|\left(1 \pm \sqrt{SNR_{opt}/SNR_0}\right) \qquad (3)$$

with equal coordinates $V_I = V_Q = |V|/\sqrt{2}$. The two possible solutions are shown in Fig. 3 where the shaded circles represent scattered constellation points of the fault-free path. If the RF path is faulty (degraded is NF) and the possible IQ imbalance has been corrected the corresponding scattered constellation can be thought as the larger dashed-line circles. For the translation shown in Fig. 3a the fault would raise the measured number of errors compared to the fault-free path, while in case shown in Fig. 3b the number of errors would drop.

The SNR_{opt} can be estimated using a mathematical model of the demodulator [10] or from simulations, which seems a more practical approach because of other side effects. For $|V| < |x_0|$ the mathematical model of a QPSK detector yields a value $SNR_{opt} = 1.5$ (1.76dB). As compared to the previous work, aimed at sensitizing SER test, here the optimum SNR can be achieved with no need of using very low signal power and very low SNR at Tx baseband. Both of them while useful have their drawbacks as well.

In the case of a one-chip transceiver, the attenuation possible to implement would be limited by isolation between the Tx output and Rx input. Specifically, it could be difficult to achieve isolation on chip better than 80 dB (for coupling and radiation). On the other hand, a very low SNR applied at BB (to compensate for insufficient attenuation) tends to limit the sensitivity of SER test. For explanation consider a receiver with noise factor F and $SNR = SNR_{in}$ at the input. From basic formulas we find SNR at the Rx output

$$SNR_{out} = \frac{SNR_{in}}{1 + \frac{SNR_{in}}{SNR_{ref}}(F-1)} \qquad (4)$$

where SNR_{ref} is a ratio of the signal- to reference noise power at the input. Apparently, for $SNR_{in} << SNR_{ref}$ the SNR_{out} is insensitive to impairments in F (NF). In other words, the fault is obscured by the noisy stimulus. On the other extreme, for the maximum possible to achieve $SNR_{in} = SNR_{ref}$, we find $SNR_{out} = SNR_{in}/F$. To summarize, achieving the optimum sensitivity of SER test with the previous approach (so that $SNR_{out} = SNR_{opt}$), was ultimately limited by the low sensitivity of SNR_{out} when SNR_{in} was low. Conversely, increasing SNR_{in} of the test signal to raise this sensitivity, set SNR at the demodulator

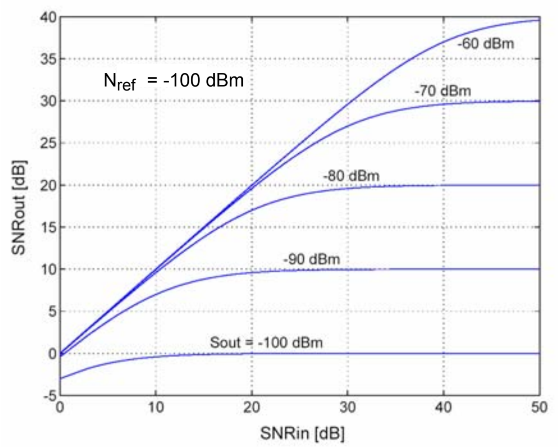


Figure 4. Noise performance of test attenuator.

input away from the optimum value.

As opposed to this, with the translation technique we can set SNR to the desired optimum value while keeping the test stimulus clean enough. There is however, a limitation to the SNR at the Rx input. For a large enough SNR at the Tx output, the SNR at the test attenuator (TA) output is S_{out}/N_{ref}. This can be verified by applying (4) to the TA and setting *F* equal TA's loss (i.e. 1/Gain). For example, a -80dBm signal at the TA output (Rx input) and reference noise of -100 dBm yield the SNR_{out} = 20 dB, while for a low SNR_{in} (< 10 dB) the $SNR_{out} \cong SNR_{in}$ (Fig.4). This observation is consistent with the simulation results addressed in the following section.

The presented translation technique can be adapted to other modulation schemes such as QAM, too. In this case identifying symbols with respect to the decision boundaries is more complicated than for QPSK but it is needed anyway, also for the EVM test.

4. Simulation model

To validate the proposed approach a functional model of WLAN transceiver such as 802.11b std. has been implemented in Matlab™. The model is arranged as a direct conversion Tx and zero-IF Rx, and it operates as a QPSK coherent system. The test setup is enabled by the attenuator TA closing the loop between Tx and Rx frontend (Fig.5) The primary specifications for the transceiver components are given in Tab.1. Additionally, the LO phase noise is -125dBc/Hz at 20 MHz offset. Assuming 20 MHz band the reference noise for the model follows -174dBm/Hz +10log 20×10^6 = -101dBm. The NF parameters have been adjusted using the additive white gaussian noise sources (AWGN).

To limit the simulation time of the SER test we have applied a pseudo-random sequence of 1000 symbols, but for more confidence the simulations were repeated for

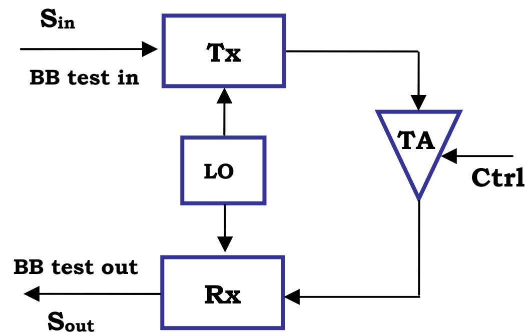


Figure 5. Loopback setup for transceiver RF frontend.

Table 1. Transceiver model specifications.

Block		NF [dB]	G [dB]
Rx	LNA	4	18
	Mixer	16	10
	LPF Filter	13	20
Tx	Mixer	15	10
	Filter/buffer	20	0

several different seeds of the AWGN sources, and the measured SER values were averaged, respectively. SNR_0 was estimated for the fault-free model for a given signal power controlled by TA. SNR_{opt} was found by direct measurements of the sensitivity, ΔSER/ΔSNR, by using an extra noise source at the demodulator input. In this case, the sensitivity function displayed a flat maximum for SNR_{opt} = 1.95… 2.05 (i.e. ≅ 3dB) which is larger than predicted by the math formulas (i.e. 1.5). The resultant $SER_0 \cong 0.16$, which in terms of the proposed translation technique, corresponds to $|V| < |x_0|$. For $|V| > |x_0|$ we found SNR_{opt} = 0.65 ... 0.70, which results in $SER_0 \cong 0.95$ (Fig.3). In this case however, the SER sensitivity to SNR was approx. 4 times smaller so the variant with $|V| > |x_0|$ was discarded.

Since the test is preceded by IQ correction the actual value of x_0 is available as well and the translation vector V can be found from (3). For QPSK modulated signal of SNR = 40dB at Tx BB, and power of -10dBm (5×10^{-3} V^2) at the Tx output, we measured $|x_0|^2 = 16\times10^{-6}$ V^2 and SNR_0 = 13.5 dB at the Rx output. The TA attenuation was 70dB. Hence, the translation vector needed for SNR_{opt} is $|V_I| = |V_Q| = 2.8\times10^{-3}$ V. The received baseband signal and the constellation are shown in Fig.6 and 7.

The test performance has been verified based on three faults located in the Rx mixer - F1, in LNA - F2, and in the output buffer of Tx - F3, each degrading both gain and NF by 3dB (ΔG = -3dB, ΔNF = 3dB).

The simulation results obtained for -80 dBm power at the Rx input are shown in Tab.2. For the fault-free TRx

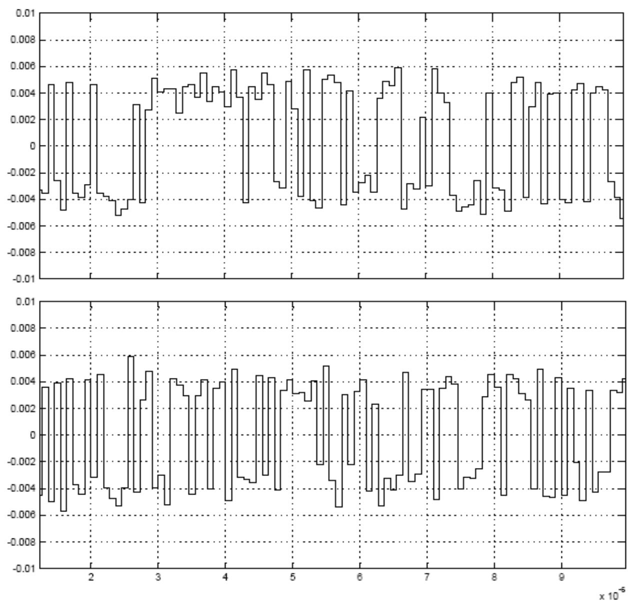


Figure 6. QPSK signal received at baseband with power $2{\times}16\text{e-}6$ V^2, SNR = 13.5 dB **and** f = 11$MS/sec.$

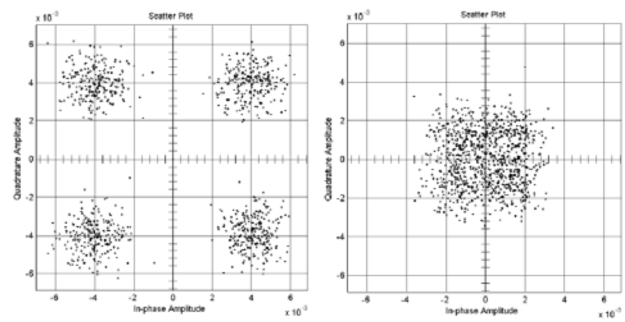
with the translation of constellations 159 (160) errors were measured for two different SNR's applied at Tx baseband (which is the optimum "bias point"). When the faults were injected (one by one) the number of errors increased up to 306 (for SNR = 40dB) and 216 (for SNR = 10dB) for F3 (fault in Tx buffer). F3 appears the most pronounced fault since it reduces the signal power before the noise of TA and Rx is imposed. Hence, the SNR at the Rx output suffers more than from F2 and F1. Those results can be compared with the EVM, or SNR also estimated (SNR = 1/EVM^2). When the relative sensitivity of the test responses is considered or the "dynamic range" (Max/Min), a comparison to SNR is more appropriate (fair) and from Tab.2 we can find SER- and SNR test to be equally effective in practice. However, more computations are required for SNR (or EVM) since the estimate for the signal noise is based on the formula:

$$\left|n\right|^2 = \sum_{k=1}^{N}\left(x_{Ik} - x_{I0}\right)^2 + \left(x_{Qk} - x_{Q0}\right)^2 \qquad (5)$$

In contrary, the proposed SER test only requires the translation $x_{Ik} \pm V_I$, $x_{Qk} \pm V_Q$, and the SER response is obtained by counting the symbols detected to be in error (not by algebraic addition of numbers).

On the other hand, when a noisy signal is used at Tx baseband (SNR=10dB) the test responses are much less pronounced. This effect is seen even better for larger power applied at the Rx input (-74 dBm) as shown in Tab.3. Apparently, this signal with SNR=10dB is only slightly affected by the faults.

Interestingly, the SER test can achieve a much larger dynamic range than EVM (SNR) if the translation vector is smaller than the optimal one. In this case, the sensitivity



(a) (b)

Figure 7. Constellations of QPSK signal (a) - shown in Fig.6, (b) – after translation with V = [2.8, 2.8]×e-3.

Table 2. Results for -80 dBm power at Rx input.

SNR @ Tx BB	SNR @ Rx inp	**Fault**	**@ Rx output**		
			SER	EVM	SNR [dB]
40 dB	19.9 dB	Fault free	0.159	0.211	13.5
		F1	0.199	0.230	12.7
		F2	0.277	0.282	11.0
	16.8 dB	**F3**	0.306	0.301	10.4
10 dB	9.5 dB	Fault free	0.160	0.381	8.4
		F1	0.173	0391	8.1
		F2	0.211	0.423	7.5
	9.1 dB	**F3**	0.216	0.436	7.2

Table 3. Results for -74 dBm power at Rx input.

SNR @ Tx BB	SNR @ Rx inp	**Fault**	**@ Rx output**		
			SER	EVM	SNR [dB]
40 dB	25.9 dB	Fault free	0.160	0.106	19.5
		F1	0.199	0.115	18.8
		F2	0.280	0.141	17.0
	22.9 dB	**F3**	0.308	0.150	16.5
10 dB	9.84 dB	Fault free	0.158	0.334	9.5
		F1	0.163	0.337	9.4
		F2	0.170	0.346	9.2
	9.73 dB	**F3**	0.179	0.350	9.1

ΔSER/ΔSNR is lower, but the relative increments ΔSER/SER evoked by the faults are larger. The respective simulation results for SNR = 40 dB at Tx BB and-80 dBm power at the Rx input are shown in Tab.4. Specifically, using $|V_I| = |V_Q| = 2.4{\times}10^{-3}$ V we drive SER in the fault free RF path from the optimum 0.159 to 0.065, and the response to F3 is 0.178. For even smaller V the fault-free SER response of 0.015 is measured and the corresponding SER dynamic range is (0.100/0.015) ↔ 8.2 dB, while the dynamic range of SNR obtained from EVM measurements is still 3 dB. Also the increment equal 0.100-0.015 can be

Table 4. Simulation results for reduced sensitivity.

Fault	@ Rx output					
	SER				EVM	SNR [dB]
Fault free	0.159 optim	0.065	0.034	0.015	0.211	13.5
F1	0.199	0.086	0.050	0.028	0.230	12.7
F2	0.277	0.164	0.111	0.076	0.282	11.0
F3	0.306	0.178	0.136	0.100	0.301	10.4

Table 5. Simulation results for bypassed LNA.

SNR @ Tx BB	SNR @ Rx inp	Fault	@ Rx output		
			SER	EVM	SNR [dB]
40 dB	25.9 dB	Fault free	0.162	0.361	8.8
		F1	0.288	0.508	5.9
	22.9 dB	**F3**	0.288	0.510	5.9

well measured as compared to the maximum achieved increment of 0.306-0.159.

Those results are encouraging to be implemented in practice. However, a care must be taken in terms of the circuit tolerances. For example with a too small translation vector V the SER measurement can be unfeasible.

In the remaining of this section, we discuss an application of the proposed DSP technique to the loopback setup, where bypassing of LNA is adopted. The bypassing has been envisioned to provide better detectability for faults located in a mixer and in the other following blocks. Also some diagnosability can be achieved is this way. However, this approach requires a careful DfT implementation of LNA and the surrounding blocks as well [12]. The respective simulation results, for -74 dBm power at the Rx input, are given in Tab.5 (also obtained with the Matlab™ model). By comparison with Tab.3 we find that in favor of bypassing LNA the faulty mixer (F1) can respond in SER test like the LNA. As a consequence, the mixer and LNA can achieve the same detectability for impairments in the noise/gain specs.

5. Conclusions

In this paper we have presented a new approach to SER test for RF transceivers, which are suitable for the loopback test. The objective was to achieve maximum sensitivity of the SER response to impairments in NF and/or gain considered soft faults in the involved RF blocks. A simple DSP algorithm implemented at the receiver baseband has been proposed to raise SNR to the optimum value before demodulation. Since this value is by two orders of magnitude larger as compared to the standard SER test, a relatively low number of symbols can be used saving thereby the test time. The shortcomings of the previously reported techniques used for sensitization of SER are overcome.

The algorithm consists in a geometrical translation of the received constellation points. The transceiver model is used to capture the optimum translation vector, which can be scaled on-line, based on the IQ correction process preceding the actual test. The method can be adapted for different modulation schemes including multi-bit QAM.

By using a QPSK transceiver model the proposed SER test has been shown to achieve the same relative sensitivity as the modified EVM test where $1/EVM^2$ was measured for fair comparison. The required computation overhead for this SER test is lower than for EVM. Additionally, we have observed that reducing the SER sensitivity can provide much larger dynamic range of the test response, as compared to the EVM. This can be deemed another advantage of the proposed technique.

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