Boosting the Accuracy of Analog Test Coverage Computation through Statistical Tolerance Analysis*

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Abstract

Increasing numbers of analog components in today's systems necessitate system level test composition methods that utilize on-chip capabilities rather than solely relying on costly DFT approaches. We outline a tolerance analysis methodology for test signal propagation to be utilized in hierarchical test generation for analog circuits. A detailed justification of this proposed novel tolerance analysis methodology is undertaken by comparing our results with detailed SPICE Monte-Carlo simulation data on several combinations of analog modules. The results of our experiments confirm the high accuracy and efficiency of the proposed tolerance analysis methodology.

1 Introduction

Increasing levels of integration for mixed-signal circuits result in a need for hierarchical test generation where tests are generated by focusing on modules separately and applied at the system level by propagating the required signals to the primary pinouts. Whereas signal propagation can be achieved easily through external access to each module in the system, such an approach is particularly unpalatable in the case of analog circuits due to performance penalties.

As there is no storage for dynamic analog signals, functional signal paths which can be utilized for propagating test signals with no overhead exist in all mixed-signal systems. Utilization of high level models provides an efficient approach for such signal propagation, particularly for early design stages where the test plan and detailed design information are not frozen. Even though detailed transistor-level models can provide a more accurate behavior for the complete input spectrum, simple high level models, when the signals are confined within a given operating range, are highly accurate [1]. Therefore, use of high level models for test propagation provides the required computational efficiency for large circuits while ensuring accuracy.

In the analog domain, the basic source of information loss is parameter tolerances. Due to variations of parameters from their nominal values, a faulty response may be masked or a fault-free response may be classified as faulty at the primary output. In order to determine the test coverage, the composite tolerance of parameters that are utilized in signal propagation needs to be computed accurately. Inaccuracy in tolerance analysis results in over or underestimation of test coverages, thus resulting in poor test quality. The importance of computational efficiency is even more pronounced in tolerance analysis as several paths may need to be analyzed for a circuit. Most previous analog test generation approaches either resort to computationally expensive methods such as Monte-Carlo analysis, or methods that provide low accuracy and little information about the actual distribution, such as min-max analysis.

This paper presents an accurate tolerance analysis and signal propagation methodology for mixed-signal circuits. The proposed tolerance analysis utilizes mathematical probability computations rather than simulation-based techniques to ensure computational efficiency. High level behavioral models that are utilized for both analyses are complemented with expected non-ideal behavior such as noise and harmonic response which are propagated through the signal path together with test signals. As the methodology utilizes a library-based approach with high level models, it can be applied at early design stages even though the circuit specifications may not be robust at that point. The low computational complexity allows for repetitive application of the methodology at several design iteration phases to ensure that testability problems can be identified and targeted before the design is complete.

The next section provides an overview of research activities in the analog test area. Section 3 presents signal propagation basics and Section 4 discusses tolerance analysis. The results of the proposed approach are compared with Monte-Carlo SPICE simulations and associated results are presented in Section 5. Conclusions are discussed in Section 6.

2 Previous Work

The need for hierarchical test generation stems from the computational complexity of the test generation problem and the complexity of modern VLSI designs. The digital domain has encountered these complexity problems and several hierarchical test generation schemes have been proposed, such as [2, 3, 4]. In [2], the goal is to identify transparent channels in the modules, through which test vectors and output responses of other modules can be propagated. In [3], the goal is to propagate pre-computed test stimuli and output responses of

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a module by utilizing only transparency and inverse modes of other modules. In [4], system level constraints are identified on modules before module-level test generation is conducted.

Automation of analog test generation and tolerance analysis is still in the early research phase. The continuous feature of the analog domain further complicates modeling and detecting faults and failures [5]. Worst case tolerance analysis or sensitivity analysis has been popular in computing test coverages in the analog domain [6, 7, 8]. However, as illustrated in [9, 10], such worst case analysis includes low-probability corner cases and thus highly overestimates the tolerance windows.

Several experimental sampling and simulation methods, such as Monte-Carlo analysis [10] and Taguchi's method [11], exist to estimate the tolerance windows of an output function more accurately. Whereas Monte-Carlo analysis is widely used due to its simplicity, the number of samples for simulation greatly affects the accuracy of the computation. Taguchi's method constitutes a deterministic approach to statistical sampling that accurately computes the distribution of a response function by simulating 3^n combinations of element values. Whereas Taguchi's method serves as a good comparison point due to its high accuracy, the high number of required samples precludes its practical application to today's circuits.

In most of the aforementioned approaches, circuits are studied at resistor-transistor level and most approaches rely on a detailed circuit simulator, such as SPICE. While such test generation approaches can be utilized at the basic block level, as the complexity of systems increases, their computational complexity precludes the utilization of these detailed approaches. Justification of the generated basic block tests at the system level has not as of yet received attention commensurate to its increasing importance in the analog domain.

3 Test Propagation using High Level Models

The fundamental concepts of test propagation in the analog domain have been introduced in [12, 1]. A set of signal attributes have been identified to ensure conservation of test related information during propagation. The basic signal attributes, amplitude, frequency, and phase, are needed to compute the circuit parameters. Attributes related to noise and harmonic behavior are needed to ensure that the propagated test signals are not corrupted by these unwanted signal components.

In the analog domain, signal propagation is further complicated due to parameter tolerances that result in information loss and non-linear behavior that complicates modeling. A test propagation methodology needs to address these challenges in order to provide accurate computation of targeted parameters and test coverage.

3.1 High Level Modeling

Even though analog circuits exhibit highly non-linear behavior, within a given operating range, the input-output behavior can be expressed with simple linear relations. The operating range where these linear relations hold can be limited by a number of attributes, such as frequency, amplitude, and number of tones. For highly non-linear components, such as mixers, the amplitude range can be fairly small. This limitation is also valid during the normal mode of operation. In order to ensure accuracy of test propagation, the proposed method further limits the amplitude range to 1dB below the 1dB compression point (P_{1dB}) for highly non-linear elements. Figure 1 shows the input-output voltage transfer curve and the operating range both for test propagation and for normal functional mode for a mixer.

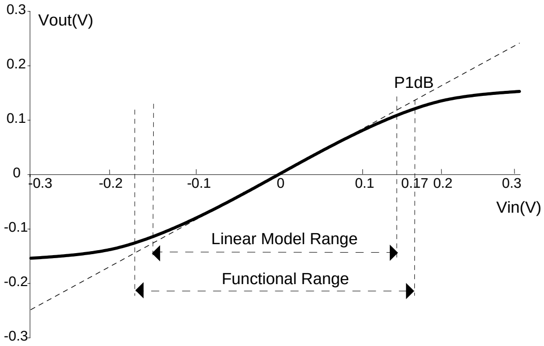


Figure 1. Input-output transfer curve for a mixer

Outside the operating range, there exists a transition range where the circuit behavior is unpredictable and highly dependent on process variations. Finally, in the stop-band region, the circuit response is below the noise level and is assumed to be zero.

In the test environment, the attributes and the complexity of input signals can be totally controlled. One can take advantage of the simplicity of behavioral models by limiting the attributes of test signals to the operating range of modules. Even though the behavior can still be approximated in the transition regions, the high dependency of circuit behavior on process variations results in high levels of information loss, and thus in poor fault coverage. Thus, propagation within the transition region should be avoided to ensure high test quality. The majority of analog tests can be conducted within the operating range of basic blocks in the propagation path. However, if a required test signal falls within the transition range of a basic block, a DFT technique becomes necessary.

Even at their most complex forms, input-output relations remain approximations of the real behavior. Each circuit generates a certain amount of noise and harmonic components due to the interaction between signal tones. Noise behavior and expected non-ideal components in the signals need to be incorporated into the analysis to ensure correctness of computed test coverages. The proposed tolerance analysis and test propagation methodology employs a library-based approach where the library includes simplified input-output relations and the corresponding operating range for amplitude and frequency, and expected non-ideal behavior in terms of noise and non-linear components.

4 Tolerance Analysis

Due to the variations in the process parameters during the manufacturing of circuits, parameters of an analog circuit are allowed to vary within a given tolerance. Since it is not possible to determine the exact values of circuit parameters, one can only utilize the nominal values during signal propagation. However, the difference between the actual values and the nominal values of parameters that are utilized in propagation may lead to rejection of a fault-free circuit or acceptance of a faulty circuit. Such misclassification basically reflects as decrease in fault and yield coverages of the tests [12]. Thus, the rate of misclassifying the targeted parameters needs to be computed in order to assess fault and yield coverages. If the resulting test coverage is not adequate, a DFT methodology needs to be applied. Underestimation of test coverage leads to unnecessary design modifications, and thus is undesirable. On the other hand, if test coverage is overestimated, tests may miss more faulty components than predicted, resulting in poorer product quality. Accurate tolerance analysis ensures the required accuracy in computing test coverages.

In the analog domain, circuit parameters exhibit a gaussian-like probability distribution. Since these parameters are utilized in test propagation, the attributes of test signals will also exhibit a similar probability distribution. The deviation of the test signal attributes from the nominal determines the misclassification of the targeted parameter. Figure 2 illustrates how the distribution probability of parameters can be utilized to compute the misclassification rates.

In order to compute the mean and the standard deviation of signal distributions, the distributions of the parameters that are utilized in signal propagation need to be convolved. Simple addition of tolerances as suggested in min-max analysis results in an overestimation of the standard deviation, thus resulting in an overestimation of misclassification rates. Therefore, a more accurate tolerance analysis utilizes the distributions of parameters together with the relations that are utilized in signal propagation. Methods that rely on sampling and simulation, such as Monte-Carlo analysis, are time consuming and thus need to be avoided. In the proposed approach, distributions of signal attributes during propagation are computed through their mathematical expressions. As propagation focuses only on operating ranges, the response of circuits to the propagating signals can easily be expressed analytically.

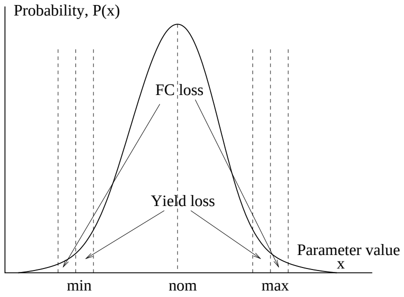


Figure 2. Probability distribution of a parameter

Using the high level models, the analytical expression of circuit response can be derived in terms of the input signals and circuit parameters. The mean and the standard deviation of the output signal can then be computed for any composite expression that involves the basic algebraic operations. Table 1 shows the computation of the distribution for these basic functions. If the analytical expression of the circuit response involves more complex operations, such as logarithms or exponents, a Taylor series expansion of these operations is utilized in order to derive the desired distributions.

Expression	Mean	Standard Deviation
$z = x + y$	$\mu_z = \mu_x + \mu_y$	$\sigma_z = \sqrt{\sigma_x^2 + \sigma_y^2}$
$z = xy$	$\mu_z = \mu_x \mu_y$	$\sigma_z = \sqrt{\sigma_x^2\sigma_y^2 + \mu_x^2\sigma_y^2 + \mu_y^2\sigma_x^2}$
$z = \frac{1}{x}$	$\mu_z = \frac{1}{\mu_x}$	$\sigma_z = \frac{\sigma_x}{\mu_x^2}$

Table 1. Computing composite distributions

4.1 Evaluation of the Computed Distributions

The computed signal distributions provide an estimate for the actual histogram of the signal attributes. In practice, since the actual parameter distributions are not perfect gaussians, there are a number of samples that fall outside the gaussian distribution. The notion of confidence level, denoting the percentage of samples that fall outside a given interval, has been widely utilized in statistical analyses [13, 14]. In the case of signal propagation, however, each sample that appears in the actual histogram but fails to appear in the approximated distribution model, and the distance of that sample from the nominal reduces test accuracy. As an example,

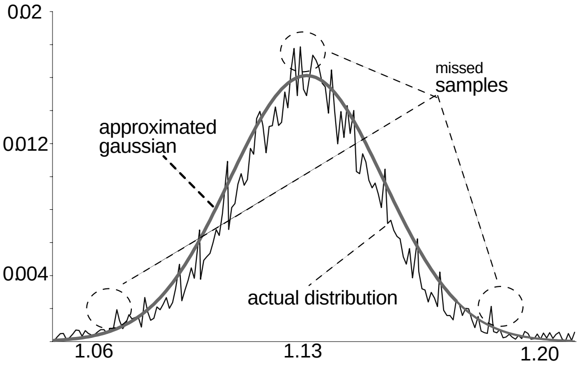
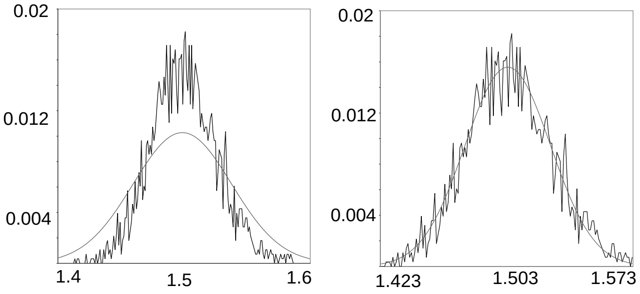


Figure 3. Mixer gain histogram and its gaussian approximation



a. Overestimated Gaussian b. Underestimated Gaussian

Figure 4. Gaussian approximations with 80% WCL

for the actual and approximated distributions in Figure 3, the missed samples around the median have almost no masking effect whereas the missed samples further away from the median mask high deviations, i.e., faults, in other parameters.

In the context of test propagation, a useful quality measure for a given distribution needs to include the distance of each sample from the nominal. A weighted confidence level is defined for this purpose:

$$WCL = 1 - \frac{\sum_{x_{min}}^{x_{max}} \frac{H(x)-P(x)+|H(x)-P(x)|}{2}(x-\mu)^2}{\sum_{x_{min}}^{x_{max}} H(x)(x-\mu)^2}$$

where $H(x)$ is the collected histogram, $P(x)$ is its approximated gaussian distribution curve, x_{max} and x_{min} are the maximum and minimum values that appear in the histogram, and μ is the median of the histogram. For all the samples that appear in the histogram and fail to appear in the approximated distribution, there is a confidence loss related to their distance from the mean.

Block-level parameter distributions generally can be approximated by gaussians with confidence levels of 90-95%. When high level techniques are utilized, some information loss is inevitable. This information loss results in a decrease in the weighted confidence level of the distribution of the propagated signal. A 1-2% drop in the confidence level is expected for each basic block that has been traversed. If a high number of basic blocks are cascaded on a propagation path, the overall weighted confidence level may drop significantly resulting in miscalculation of test coverages. As an example, Figure 4 shows two gaussian approximations of the gain distribution of a basic block with an 80% weighted confidence level. If this block is used to propagate signals to a target module, the test coverage is computed using the gaussian approximation of the gain distribution. However, the approximation in Figure 4a results in a 20% overestimation of fault coverage whereas the approximation in Figure 4b results in a 15% underestimation of fault coverage. As a result, if weighted confidence levels drop below a certain level, a DFT methodology, such as a test observation point needs to be applied. The overall weighted confidence level can be predicted through the number and the individual confidence levels of blocks in the path.

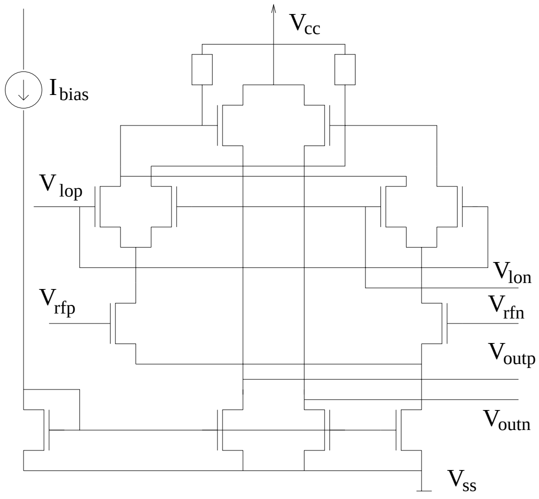


Figure 5. Transistor level mixer circuit

5 Experimental Set-up

In order to illustrate the efficacy of test signal propagation and tolerance analysis through high level models, we have compared the results of our methodology with the results obtained by a well-accepted circuit simulator, SPICE. As the experimental set-up, we have utilized three analog modules: a mixer, a low-pass filter, and an amplifier. Mixers exhibit the highest non-linear behavior among analog modules and their harmonic behavior can be quite complicated. In order to illustrate that even complex, highly non-linear components can be modeled with linear input-output relations within a given operating range as shown in Figure 1, we have included a mixer in our experimental set-up. The transistor level circuit of the mixer is shown in Figure 5 and the filter and the amplifier are shown in Figure 6.

First, the mixer and the filter are cascaded by terminating one of the differential outputs of the mixer with a load impedance equal to the input impedance of the filter. After obtaining the results for this two-module configuration, the amplifier is connected to the output of the filter and the tolerance analysis results are repeated. Since the amplifier is a fairly linear component, there is no reason to repeat the propagation analysis.

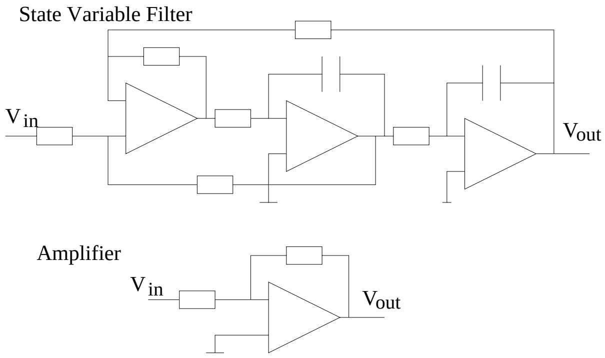


Figure 6. Amplifier and low-pass filter

In the first phase, the results of propagating the test signal attributes using high level models are compared with the results of SPICE simulations. A two-tone test signal within the operating range of the mixer and the filter is applied and transient analysis is conducted. During the analysis, the mixer's noise figure is incorporated as an independent source at the input. In both analyses, the noise generated by the filter is neglected as it is well below the noise level due to the mixer. The output pattern from the SPICE simulations is run through a Fast Fourier Transform (FFT) routine and the output frequency spectrum is determined as shown in Figure 7.

The same set of input signals is propagated through the two modules using high level models. Within the operating range, the mixer is a frequency shifter with a certain gain, and the filter is a gain element. Expected noise levels are computed using the mixer noise figure and the input noise level of -114dBm assuming a 1MHz noise bandwidth. The mixer has a harmonic bandwidth of 5 harmonics and the position of these harmonics is marked in the spectrum so as to avoid propagation of test signals that coincide with the harmonics. Figure 8 shows the output spectrum obtained through the proposed high level signal propagation methodology.

The high level analysis cannot estimate the power of the harmonics. However, in the context of test propagation, if a test signal coincides with a harmonic in the frequency spectrum, regardless of its power, the test signal will be degenerated. In order to avoid such cases, knowledge of the frequency information only for the harmonic components is sufficient. Therefore, the inability of determining the harmonic power through high level analysis is not a disadvantage as the important information, the frequency of the harmonics, is determined accurately. Through the proposed high level analysis, the output signal amplitude, frequency and the phase between the two tones is determined within 1% of SPICE simulation results.

The proposed high level tolerance analysis is conducted on the signal amplitude using the high level model and the expressions given in Table 1. In order to compute the distribution of signal amplitude through SPICE simulations, a random sampling method, Monte-Carlo analysis, is conducted. A total of 10K simulations, with random sampling of circuit components with respect to a gaussian distribution, as shown in Table 2, are run in order to determine the mean and the standard deviation of the output signal. Matched transistors are sampled with respect to their matching tolerance in order to mimic the component variations in a real manufacturing environment.

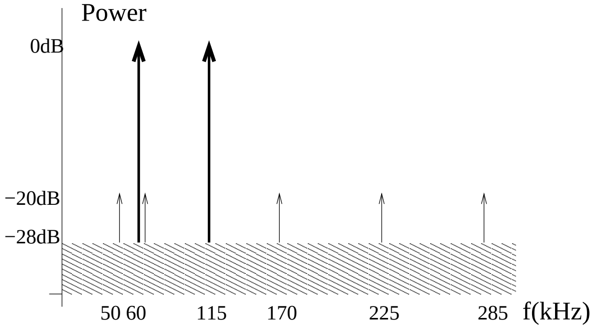


Figure 8. Output spectrum by the proposed approach

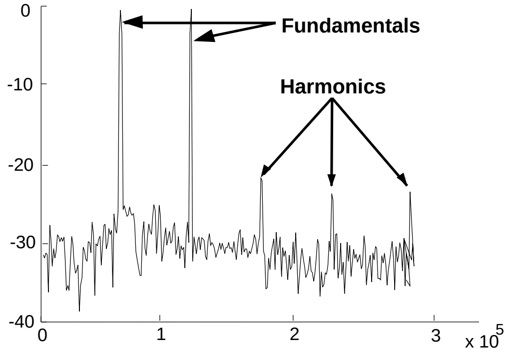


Figure 7. Output spectrum using SPICE simulations

Comp.	Abs. Tol.	Match. Tol.
R	6%	2%
C	6%	2%
W,L	5%	1%

Table 2. Absolute and matching tolerances

For the high level analysis, first, the distributions for the filter and mixer gain are obtained through simulations. Ideally, this data is already available through previous designs. These two blocks are designed anew for this experiment; therefore, the gain distributions need to be determined through simulations. The best-fit gaussian approximation is determined by utilizing a mean that is equal to the median and optimizing the weighted confidence level on the standard deviation. The distribution of the composite gain is then computed using the formulas given in Table 1. Figure 9 shows the computed gaussian curve and the histogram that is obtained through SPICE simulations.

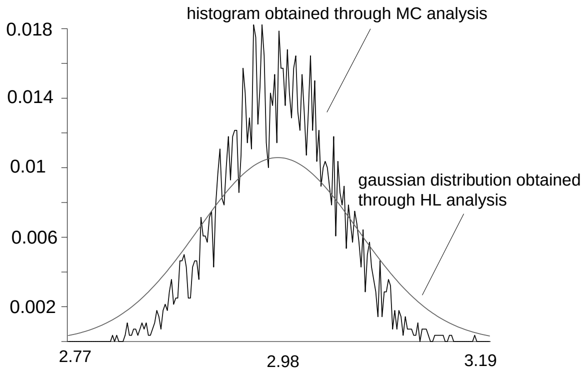


Figure 9. Distribution of the overall gain by MC and HL analyses

<table>
<tr><th colspan="7">Utilized Block Level Data</th></tr>
<tr><td>Module</td><td>Gain</td><td></td><td colspan="2">Std</td><td colspan="2">WCL</td></tr>
<tr><td>Filter</td><td>1.50</td><td></td><td colspan="2">0.05</td><td colspan="2">95%</td></tr>
<tr><td>Mixer</td><td>1.13</td><td></td><td colspan="2">0.022</td><td colspan="2">95%</td></tr>
<tr><th colspan="7">System Level Analysis</th></tr>
<tr><td></td><td>SPICE</td><td>HL</td><td>SPICE</td><td>HL</td><td>SPICE</td><td>HL</td></tr>
<tr><td>Total</td><td>1.72</td><td>1.70</td><td>0.060</td><td>0.064</td><td>95%</td><td>94%</td></tr>
<tr><td>Diff</td><td colspan="2">1.1%</td><td colspan="2">6%</td><td colspan="2">1%</td></tr>
</table>

Table 3. Comparison of the proposed approach with SPICE simulations

The weighted confidence level of the computed overall gain distribution is compared to the maximum achievable confidence level. In addition, the computed standard deviation of the overall gain is compared to the standard deviation obtained through system-level Monte-Carlo SPICE simulations. Table 3 summarizes the results. System level Monte-Carlo simulations take about 83 hours on an UltraSparc machine whereas the proposed high level analysis can be finished in just seconds. The use of high level analysis results in only a 1% decrease in the weighted confidence level, whereas the savings in terms of simulation time approach closely 100%.

As a further experiment, in order to illustrate the reason for limiting signal propagation to operating ranges, we have attempted to propagate a test signal that falls into the transition region of the filter. The behavior of the filter in this frequency region is approximated by the pass-band gain, cut-off frequency, and the skirt slope:

$$G = G_{pb} - s_{slope} * log(\frac{f_{signal}}{f_{cut-off}}) - 3dB$$

As shown in Table 4, the accuracy of this propagation is poor when compared to the first propagation.

There are several factors for the decreased accuracy when utilizing high level models outside the operating range. First, the circuit behavior involves an increased number of parameters, each of which contribute to the standard deviation. Since the standard deviation of the test signal attributes directly impacts test coverage, an increase in the standard deviation is undesirable. A second factor arises from the inability to express the circuit behavior accurately. The filter utilized in this simulation has two poles. Thus, the decrease in gain due to the second pole is not incorporated into the behavior since the test signal frequency falls before the second pole of the transfer function. Whereas one can include additional parameters to account for this change in gain, such an approach requires generation of library models for all possible architectures and thus is not feasible. Of course, propagation within the operating regions is not prone to these problems. These experimental data confirm that test propagation and tolerance analysis should be confined within the operating ranges of basic blocks in the propagation path.

<table>
<tr><th colspan="2">Gain</th><th colspan="2">Std</th></tr>
<tr><td>SPICE</td><td>HL Analysis</td><td>SPICE</td><td>HL Analysis</td></tr>
<tr><td>0.884</td><td>0.988</td><td>0.0283</td><td>0.0321</td></tr>
<tr><td colspan="2">11.7%</td><td colspan="2">9.5%</td></tr>
</table>

Table 4. Error in propagation outside operating ranges

<table>
<tr><th colspan="7">Utilized Block Level Data</th></tr>
<tr><td>Module</td><td>Gain</td><td></td><td colspan="2">Std</td><td colspan="2">WCL</td></tr>
<tr><td>Amp</td><td>10</td><td></td><td colspan="2">0.4</td><td colspan="2">95%</td></tr>
<tr><th colspan="7">System Level Analysis</th></tr>
<tr><td></td><td>SPICE</td><td>HL</td><td>SPICE</td><td>HL</td><td>SPICE</td><td>HL</td></tr>
<tr><td>Total</td><td>17.2</td><td>17.0</td><td>0.89</td><td>0.94</td><td>95%</td><td>94%</td></tr>
<tr><td>Diff</td><td colspan="2">1.1%</td><td colspan="2">6%</td><td colspan="2">1%</td></tr>
</table>

Table 5. Tolerance analysis results for the three-module configuration

In order to observe the amount of drop in the weighted confidence levels when an increased number of basic blocks are cascaded in a propagation path, we have conducted further experiments to collect additional data for the operating regions. In the new set-up, the amplifier is cascaded to the output of the filter to construct a three-module configuration. This three-module configuration approaches the limit of using SPICE for Monte-Carlo simulations as a single run of the complete system takes about 42 seconds and the overall time for Monte-Carlo simulations is 116 hours.

Table 5 shows the tolerance analysis results for the three-module configuration. When the proposed high level approach is utilized, there exists basically no drop in the weighted confidence level after connecting the amplifier. The high linearity of the filter and the accuracy of its model consequently is the reason for the high accuracy in predicting the signal distributions. Highly non-linear components in a path, as in the case of a mixer, can reduce the weighted confidence levels by 1-3%. Linear components, such as filters and amplifiers, on the other hand, do not cause an appreciable drop in the weighted confidence level. In most analog designs, the number of non-linear components cascaded in a path does not exceed 2-3 elements and the resulting drop in the weighted confidence level is acceptable. However, if the weighted confidence level for a path drops below a certain threshold, a testability modification may be necessary. Therefore, in the proposed methodology, the number of highly non-linear components is limited to 3, whereas there is no limit set for the relatively linear components. For paths that do not satisfy this condition, a test point is recommended to evenly distribute the confidence level loss.

Min-max analysis is a widely used alternative to our proposed approach. We have also computed the composite tolerance and the weighted confidence level of the min-max approach for the three-module configuration using the following relation:

$$G_T = G_M \cdot G_F \cdot G_A$$

$$\Delta G_T = \Delta G_M \cdot G_F \cdot G_A + \Delta G_F \cdot G_M \cdot G_A + \Delta G_A \cdot G_M \cdot G_F$$

The min-max analysis results in a tolerance window of 4.72, resulting in a 77% error when compared to the tolerance window from SPICE simulations at 2.67 whereas the error with the proposed approach is only 6%. The weighted confidence level of the min-max analysis is 55%. The insensitivity of the min-max analysis to the shape of the distribution is the reason for the low confidence level of this approach. Figure 10 shows all three analyses results, SPICE Monte-Carlo, the proposed high level approach, and the min-max analysis.

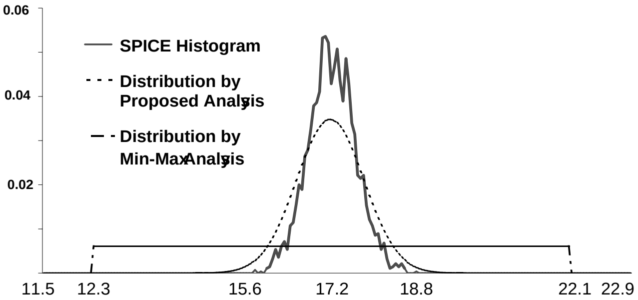


Figure 10. Comparison of the proposed approach with min-max analysis

6 Conclusion

In this paper, a high level test signal propagation and tolerance analysis methodology is presented. By limiting test signals that can propagate through the system to operating ranges of building blocks, one can utilize simple frequency domain input-output relations for even highly non-linear analog blocks. By taking advantage of this simplicity, highly efficient hierarchical test generation and test translation approaches can be developed.

In a hierarchical test approach for analog circuits, it is essential to estimate the tolerances at the circuit output so as to enable the computation of test coverages. In order to compute these distributions accurately, the proposed method utilizes mathematical analysis wherein the circuit function is expressed in terms of basic operations by utilizing the library models.

The proposed method is illustrated on a path that contains a mixer, a normally highly non-linear element, and a low-pass filter. The output spectrum is computed for a two-tone input using the proposed method and using a well-accepted transistor level simulator, SPICE. We show that within an operating range, the output spectrum of the combination can be predicted with high accuracy.

The proposed tolerance analysis is then utilized to compute the distribution of the output amplitude for a single-tone signal. In order to obtain this distribution with SPICE, a large set of Monte-Carlo simulations are conducted and the results of both analyses are compared. Experimental results also confirm that attempting test propagation and tolerance analysis outside the operating range results in poor fidelity. Since the majority of analog tests can be conducted within the operating range of basic blocks, test signals should be limited to these ranges to ensure accuracy of coverage computations.

These promising experimental results confirm the viability of high level signal propagation and accurate tolerance analysis that can be utilized in low-cost test development for mixed-signal systems.

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