AUTOMATIC MULTITONE ALTERNATE TEST GENERATON FOR RF CIRCUITS USING BEHAVIORAL MODELS

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Abstract[†]

In the past, it has been difficult to perform test generation for complex RF subsystems due to the cost of repeated system level simulation necessary for running a test generation algorithm. In this paper, a new test generation method for RF sub-systems driven by behavioral models is presented. The test generator produces an optimized multi-tone test stimulus (alternate test) from which the subsystem test specifications can be simultaneously computed. The test generation algorithm attempts to maximize the accuracy with which all the system test specifications can be determined from knowledge of the different ways in which perturbations of the behavioral model parameters affect the test specifications. Pass/fail test decisions are made using the specification values computed from the observed test response (single test). Simulation results using the proposed test approach show accurate tracking of multiple system specifications, such as gain and IIP3 for the receive channel of an RF transceiver, with an error within ±1 dB.

1. Introduction

In the domain of wireless communication systems, there is increased impetus among system manufacturers towards integrating the base-band, IF and RF functionalities into as fewer numbers of ICs as possible. Although, in general, this trend reduces system-size and improves system performance, the manufacturing test cost of these systems has been increasing as a proportion of the total manufacturing cost. This is due to the high cost of RF test instrumentation and the fact that many complex test specifications need to be determined during production test [7],[8],[9], [11].

The key problems with testing RF subsystems are the following:

- The cost of testing complex RF test specifications is high and at high frequencies, the costs increase further.
- Any viable automated test generation algorithm requires repeated simulation of the device under test. The cost of such repeated simulations is prohibitive for complex RF subsystems [14]

In this paper, a new test generation approach for RF subsystems is presented that handles the issue of high test-cost of RF subsystems in the following manner:

- *Alternate tests* [12][13] are used to test the RF subsystem. In the alternate testing approach, the test specifications of the circuit-under-test are not measured directly using conventional methods (such as circuitry and stimulus to measure common-mode-rejection-ratio (CMRR), for example). Instead, a specially crafted stimulus is applied to the circuit-under-test and the (conventional) test specification values are computed (predicted) from the observed test response. In general, all the test specifications can be computed from the response to a single applied test stimulus. In the presented work, a single alternate test consisting of an optimized multi-tone AC stimulus is used. This is in contrast to past alternate test method, which used test stimulus [16] unsuitable for RF test.
- All the RF subsystem test specifications are computed (predicted) from the response of the RF subsystem to the multi-tone AC stimulus. Hence, significant *test time savings* are obtained. At the same time, the quality of the alternate test is high form the viewpoint of fault coverage and yield coverage.

Note that in alternate test, the test limits can be set [12] so that a small number of marginal circuits are subjected to the conventional specification tests. In this way there is no loss in fault and yield coverage due to the use of the alternate test itself. The issue of high simulation cost of RF subsystems is addressed in the following manner:

- Behavioral models [3][14] are used to simulate the RF subsystem. By perturbing the behavioral model parameters, the correlation between the perturbation in the test response due to an applied multi-tone stimulus and the corresponding perturbation in the test specifications can be monitored. In this way, it is possible to determine

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how accurately all the test specifications are computed (predicted) from the observed test response.

- After the tests are generated, the quality of the tests can be determined by studying how, in the presence of process/circuit parameter variations, the test specifications of an RF subsystem as well as its response to the computed multi-tone AC test stimulus are affected. From this, the quality of the computed test (discussed later) can be determined. This is a one-time simulation study as opposed to the many simulations needed during test generation.

As will be shown in a case study, common test specification such as the system gain and the third order intercept (IIP3) specification for receive channel of a wireless transceiver, can be predicted using the proposed test methodology with an error below 1 dB.

The paper is organized as follows. Section 2 discusses the basic concepts of the proposed test generation methodology. Section 3 describes the test architecture. In Section 4, the behavioral modeling approach for system-level simulation is explained in detail. The test generation algorithm and final validation of the test is described in Section 5. Simulation results for an RF subsystem of a transceiver are presented in Section 6 with conclusions discussed in Section 7.

2. Basic concepts

As shown in the literature [12][13], variation of any process or circuit parameter, such as width of a FET, value of a resistor, etc., in the process or circuit parameter space $\boldsymbol{P}$ affects the circuit specification $\boldsymbol{S}$ by a corresponding sensitivity factor. Let $\boldsymbol{M}$ be the space of measurements (amplitudes values of subsystem output spectrum, for example) made on the circuit under test. The variation in the parameters also affects the measurement data in the measurement space $\boldsymbol{M}$ of the circuit by a corresponding sensitivity factor. Figure 1 illustrates the effect of variation of one such parameter in $\boldsymbol{P}$ on the specification $\boldsymbol{S}$ and the corresponding variation of a particular measurement data in $\boldsymbol{M}$. Given the parameter space $\boldsymbol{P}$, for any point in $\boldsymbol{P}$, a mapping function (nonlinear) onto the specification space $\boldsymbol{S}$, $f{:}\boldsymbol{P}\rightarrow\boldsymbol{S}$, can be computed. Similarly, for the same point, another mapping function (nonlinear) onto the measurement space in $\boldsymbol{M}$, $f{:}\boldsymbol{P}\rightarrow\boldsymbol{M}$, can be computed. Therefore, for a region of acceptance in the circuit specification space, there exists a corresponding allowable "acceptable" region of variation of parameters in the parameter space. This in turn defines a region of acceptance of the measurement data in the space $\boldsymbol{M}$. A circuit can be declared faulty if the measurement data lies outside the acceptance region in $\boldsymbol{M}$.

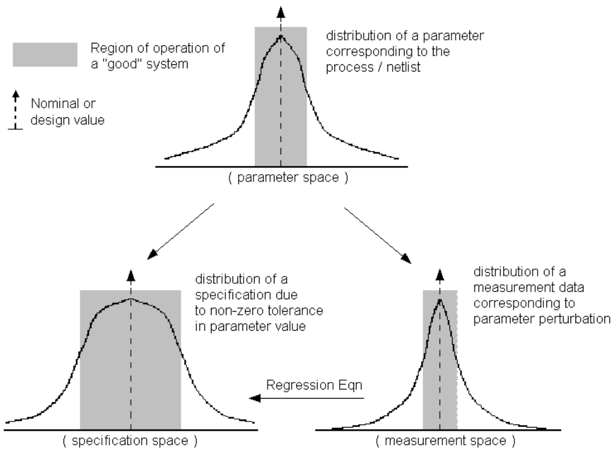

Figure 1. Variation in process or circuit parameter and its effect on specification and measurement.

Alternatively, as shown in [12][13], a mapping function $f{:}\boldsymbol{M}\rightarrow\boldsymbol{S}$ can be constructed for the circuit specifications $\boldsymbol{S}$ from all the measurements in the measurement space $\boldsymbol{M}$ using nonlinear statistical multivariate regression. Given the existence of the regression model for $\boldsymbol{S}$, an unknown specification of a system under test can be predicted from the measured data. In the proposed approach, Multivariate Adaptive Regression Splines (MARS) [5] are used to construct the regression models and estimate the test specifications of the subsystem from the frequency spectrum of the test response waveforms. The objective of the proposed test methodology is:

1. to find a simple test stimulus (i.e. the multi-tone sinusoid),
2. to predict circuit specifications accurately from alternate test response.

3. Test architecture and test approach

The test architecture relies on application of a multi-tone test stimulus designed to maximize the ability to predict the system-level specifications from the observed frequency spectrum of the test responses. In general, the stimulus can be generated externally using an RF source [6] (see Figure 2) or can be generated using the transmit RF subsystem. In this paper, we assume the simpler test scenario in which an external RF source is used. If the transmit RF subsystem is used, the kinds of test tones that can be used to test the RF receive subsystem are limited to the signals that can be produced at the output of the RF transmit path. The test generator described in this paper can accommodate such constraints with minor changes. Moreover, an approach similar to that for testing the RF receive subsystem described in the case study can be used to test the RF transmit path as well, thereby allowing comprehensive test of the complete system.

An analog multiplexer is used to isolate the test stimulus in test mode from the functional input of the circuit corresponding to its normal operational mode. For example (Figure 2), in order to test the specifications (e.g. gain, IIP3 for the RF subsystem) of the RF receive channel of a wireless transceiver system, the input from the duplexer is bypassed using the multiplexer in test mode and the test stimulus is applied from an RF signal generator. The amplitude spectrum of the test response waveform is used as the measurement space for subsequent prediction of the specifications [2]. For testing an RF receive channel transceiver, the measurements is made using a spectrum analyzer at the output of the down-converting mixer module (Figure 2).

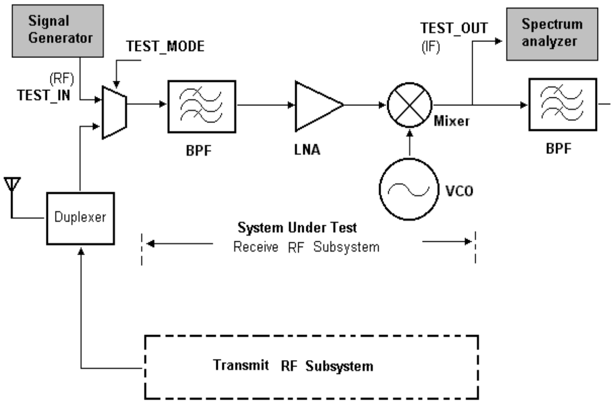

Figure 2. Test architecture for testing of the RF subsystem of receive channel of a transceiver.

The test stimulus consists of large-signal sinusoidal multi-tones (to expose the non-linearity of the sub-modules (e.g. LNA, Mixer etc.) of the RF subsystem under test). In the simplest case, the test stimulus consists of two-tone 'large signal' sinusoids, which, after being transformed through different cascaded blocks of the sub-system, exhibit the effects of linear small-signal gain as well as the non-linear effects of harmonics and inter-modulation. A test generation algorithm using subsystem-level simulation is used to determine the different parameters (e.g. amplitudes and frequencies) of the test stimulus tones. The subsystem simulations are performed using behavioral models as described in the following section.

4. System-level behavioral simulation for test generation

An iterative search algorithm is used to determine the optimum values of the parameters of the multi-tone test stimulus that gives the maximum specification prediction accuracy.

4.1. Objective of behavioral simulation

Behavioral level simulation of the system under test is performed during the test search process for the following reasons:

First, any iterative and deterministic test generation technique (in contrast to random or pseudo-random test technique) requires repeated simulation of the system under test. Although, the usage of transistor-level simulations for all the sub-modules yields high accuracy of simulation, the large simulation time makes the transistor-level system-simulation impractical [15]. The larger the size of the process and circuit parameter space (Figure 1), the more the number of iterations of the test generation algorithm is required by the search algorithm. Similarly, the higher the size of the search-variable space (e.g. the number of tones present in the test stimulus), the larger the number of simulations required for determining optimal combination of test stimulus parameters.

Second, the primary objective of test generation is to determine the optimal set of test stimuli (which is not a circuit design goal), rather than to verify the functionality of the design. Hence, the loss of accuracy in simulation data while using behavioral models does not hinder the search algorithm as long as the statistical trend in simulation data is maintained under parameter variations. Hence, the key assumption of the proposed test generation approach is: the variations in specification data and measurement data follow the same statistical trend under behavioral parameter perturbations as they would for transistor level parameter perturbations.

Therefore, in the proposed test generation methodology, a dual approach is taken (Figure 3).

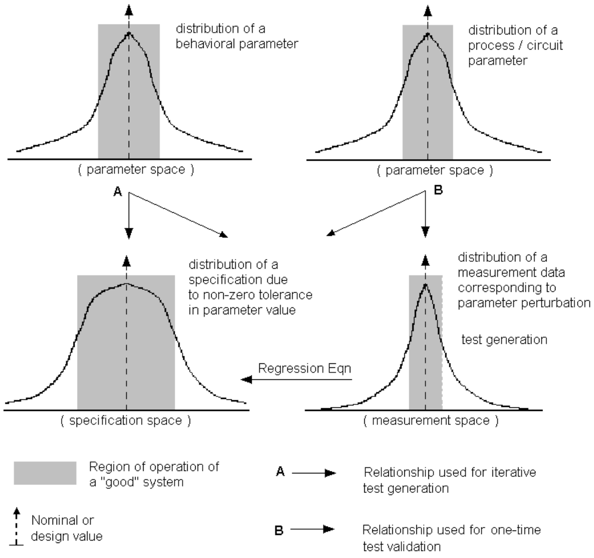

Figure 3. Test generation and test validation approach

First, the test stimulus parameters are determined using system-level behavioral simulations only. Second, the resulting tests are validated against transistor level simulations. The latter incurs a one-time transistor-level simulation cost (in contrast to repeated transistor-level simulations over different iterations of the algorithm) after the optimized test is computed by the test generation algorithm. The limitations due to the less accurate behavioral simulation of the test generation process are successfully overcome during test validation; the final regression models computed using transistor level simulation data can be used for accurate prediction of the subsystem-specifications.

Since, the measurement space is selected to be the amplitude spectrum (i.e. amplitude vs. frequency) of the test responses observed at the output of the RF subsystem under test, all the simulations for test generation can be performed in the frequency domain. The behavioral models used in the test generation procedure are described next.

4.2. Behavioral modeling of sub-modules

An RF subsystem in super-heterodyne narrowband wireless RF transceiver architecture contains amplifiers, filters, mixers, frequency synthesizers etc. operating in a certain range of frequency (Figure 5). The behavioral simulation engine is developed in MATLAB. The sub-modules of the RF subsystem are modeled as follows:

1. *Filter*: For test generation purposes, the band-pass filters of the RF sub-system (e.g. band-select filter) transfer functions are realized as linear transfer functions with different gains at different frequencies. The output of the filter is given by:

   $$[\ Y(f)\ ] = [\ H(f)\ ]\ .\ \mathrm{diag}(\ [\ X(f)\ ]\ ) \qquad (1)$$

   where, f is the frequency f and the operation. The different gain values corresponding to different frequencies are characterized by the center-frequency, filter-Q, and frequency roll-off. H, X, and Y are complex quantities representing amplitude and phase values together. The computation complexity for generating the mixer output spectrum is O(N), where N is the number of tones present in the input.

2. *Amplifier*: The amplifiers of the RF sub-system (e.g. LNA) are realized by implementing a non-linear transfer function of the type [1][2]

   $$y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) \qquad (2)$$

   where, α_0 = DC offset
   α_1 = small signal gain
   α_2, α_3 = non-linearity coefficients

   is used to realize the linear (gain) and non-linear (harmonics and inter-modulation terms) effects of the amplifier. For inputs with sufficiently low amplitude levels, as is the case for RF sub systems, the higher order terms (α_4, α_5 and so on) can be ignored as they have little effects compared to the lower order terms [1]. It is also assumed that the DC offset does not propagate across the cascade of sub-modules in narrowband RF subsystem; hence, $\alpha_0 = 0$. α_1 is characterized by the small-signal gain of the amplifier. α_3 is computed from –1dB compression point of the amplifier [1]. Hence, the small signal gain and –1dB compression point computed from the transistor level simulation of the amplifier characterizes the behavioral model of the non-linear transfer function.

Evidently, the time domain input-vs-output characteristic as in Eqn. (2) may not be used directly for frequency domain simulation. The output frequency spectrum (magnitude and phase) for any $x(t)$ expressed as sum of different tones can be computed as follows.

Given that Eqn. (2) is a polynomial in $x(t)$ of order 3, it can be shown that, for a 3-tone input, $x(t) = V_m \cos(2\pi f_m t+\phi_m) + V_n \cos(2\pi f_n t+\phi_n) + V_p \cos(2\pi f_p t+\phi_p)$, the harmonic terms of the spectrum will be generated at:

$f = 0, f_i, 2f_i$ and $3f_i$ frequencies, where $i \in \{m, n, p\}$.

The intermodulation product tones of the output spectrum will be generated at:

$f = f_i$ frequencies, where $i \in \{m, n, p\}$;

$f = |\ f_i \pm f_j\ |$ frequencies, where $i, j \in \{m, n, p\}$ and $(i-j)^2 > 0$; and,

$f = |\ \pm f_i \pm f_j \pm f_k\ |$ frequencies, where $i, j \in \{m, n, p\}$, and $(i-j)^2(i-k)^2 + (j-i)^2(j-k)^2 + (k-i)^2(k-j)^2 > 0$.

The corresponding amplitudes are computed using simple algebraic formulae as summarized in Table 1. In Table 1, the amplitude values V_i, etc are complex quantities representing magnitude and phase. For inputs having less than 3-tones, the remaining amplitude and frequencies in $\{m,n,p\}$ are set to zero and the same computation is carried out. For single-tone stimulus, for example, $V_n = V_p = 0$, will result in all the inter-modulation terms to be zeroes for different f's.

Table 1. Amplitude vs. frequency output for a non-linear transfer function

	f	**Output amplitudes**
harmonics	0	$0.5\ \alpha_2 V_i$
	f_i	$\alpha_1 A_i (1 + 0.75\ V_i^2)$
	$2f_i$	$0.5\ \alpha_2 V_i^2$
	$3f_i$	$0.75\ \alpha_3 V_i^3$
intermodulation	f_i	$0.75\ \alpha_3 V_i^3 (-1 + {}^{N}\Sigma_k (V_k^2/V_i^2))$
	$\lvert f_i \pm f_j \rvert$, $(i-j)^2>0$	$0.5\ \alpha_2 V_i V_j$
	$\lvert \pm f_i \pm f_j \pm f_k \rvert$, $(i-j)^2(i-k)^2 + (j-i)^2(j-k)^2 + (k-i)^2(k-j)^2 > 0$	$0.75\ \alpha_3 V_i V_j V_k$

For input having N-tones, $N > 3$; all possible distinct combinations of $\{m, n, p\}$ from N-tones are selected and the computation for the 3-tone case is carried out ${}^{N}C_3$ times. Hence, in general, the computation complexity is $O(N^3)$. Figure 4 shows a simplified flowchart for computing the output spectrum for the non-linear transfer function, as shown in Eqn. (2). Further, for a typical non-linear amplifier input vs. output transfer function curve, the transfer function exhibits odd symmetry, implying α_2, α_4, α_6 etc. = 0. Hence, α_2 is assumed to be zero.

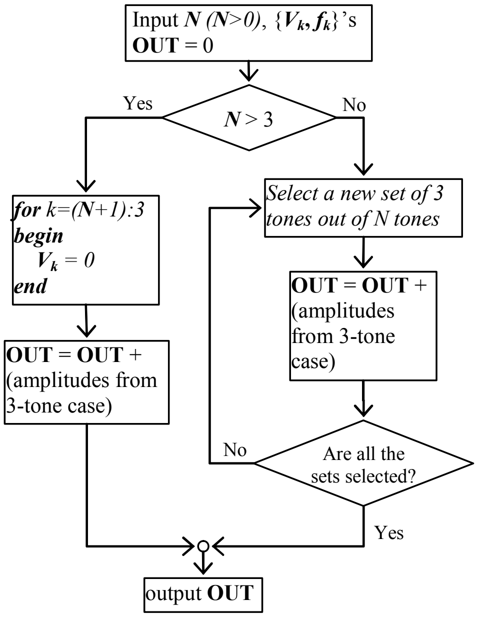

Figure 4. Computation of non-linear transfer function

3. *Mixer*: For test generation purposes, the mixer of the RF subsystem is modeled as a non-linear transfer function followed by an ideal multiplier. The non-linear transfer function is realized in the same manner as is done for the amplifier. The frequency mixing operation is realized by the multiplication operation.

$$y(t) = C \, . \, x_1(t) \, . \, x_2(t) \qquad (3)$$

The constant C is computed using conversion gain of the mixer. Assuming a narrowband system, the conversion gain is effectively constant over the range of frequencies of interest. For $x_1(t) = V_m \cos(2\pi f_m t+\phi_m)$ and $x_2(t) = V_n \cos(2\pi f_n t+\phi_n)$, the intermodulation spectrum is generated at $f = |f_m \pm f_n|$ frequencies. Hence, the conversion gain and –1dB compression point with respect to the RF input and IF output characterize the behavioral model of the mixer. The computation complexity for generating the mixer output spectrum is $O(N^3)$, where N is the number of tones present at the mixer signal-input.

4. *Oscillator*: The behavioral model of frequency synthesizer or oscillator is realized as a set of amplitude values [$X(f)$] corresponding to different frequencies. The peak amplitude value corresponds to the local oscillator frequency; the amplitudes adjacent to the frequencies fall of according to the values calculated from the phase-noise of local oscillators.

The current behavioral models used for representing the non-linear system are simple and approximate. However, this does not significantly affect the quality of the tests derived (see Results in Section 6). This is because in general, the above approximations *preserve the relative "goodness"* of one test stimulus choice versus another. Hence, the test choices made with the above behavioral models are quite close to those that would have been made if accurate simulation had been used (the latter would be difficult in practice due to the large simulation times involved). The accuracy of such behavioral models is called into question only when the test generation algorithm is close to convergence. Hence, the quality of the test results (Section 6) is quite close to the optimal. With more accurate behavioral models, more accurate test stimulus generation can be performed.

Figure 5 shows, as an example of RF system-under-test, the behavioral model of the receive channel used for simulation of a narrow-band RF subsystem and computation of gain and IIP3 specifications for the same.

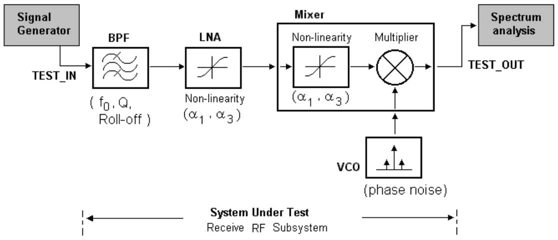

Figure 5. Behavioral modeling of system-under-test

Figure 6 through Figure 9 show the amplitude vs. frequency values at the outputs of different sub-modules for the RF subsystem shown in Figure 5 as an example of behavioral level simulation.

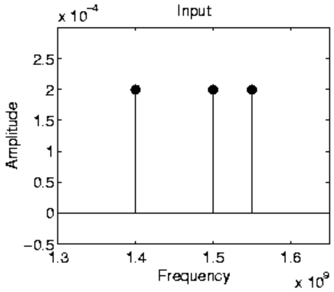

Figure 6. Example behavioral simulation: Spectra of 3 equal amplitude input tones

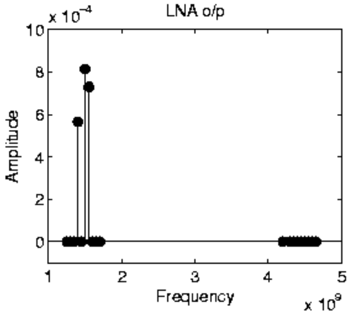

Figure 7. Example behavioral simulation: LNA o/p spectrum

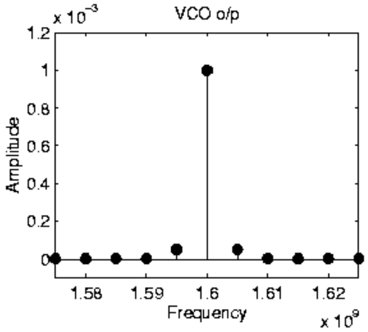

Figure 8. Example behavioral simulation: LO spectrum

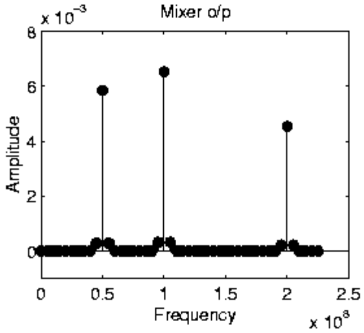

Figure 9. Example behavioral simulation: Mixer o/p spectrum

5. Test generation and test validation

An iterative greedy algorithm is used to select the parameters of the test stimulus, which is used to performing specification test of RF sub-systems. The goal of the test generation algorithm is to determine the optimal test stimulus waveform and the corresponding test response spectrum from which the specifications of system-under-test can be predicted as accurately as possible. A multi-tone sinusoidal waveform $X(t)$ is selected:

$$X(t) = \sum_{k}^{N} V_k \cos(2\pi f_k t + \phi_k) \qquad \textbf{(4)}$$

where,

V_k = amplitude for the k-th tone,

f_k = frequency of the k-th tone,

ϕ_k = phase difference of k-th tone with the first tone,

N = max. number of tones to be present in $X(t)$; $N \geq 2$.

The lower limit of the $\{V_k's\}$ is determined by the noise floor referred at the input of the system. The upper limit is bounded by the minimum input amplitude level that saturates any of the internal sub-modules of the RF sub-system. The lower and upper bounds of $\{f_k's\}$ are determined by the frequency range of operation for the sub-system. It may be noted that the higher the value of N, the higher the difficulty of applying the test stimulus from the signal generator. The case $N = 2$ is the minimum value of N, for which the test stimulus undergoes the changes due to both inter-modulation effects arising from the system non-linearity and the gain. Furthermore, since the CUT response spectrum measured by the swept-tuned spectrum analyzers does not contain the phase information [6], for the test architecture as shown in Figure 2, the ϕ_k's can be removed from the test optimization variable space. Hence, in the algorithm $\phi_k = 0$, $\forall\ k$, is assumed. However, when using FFT spectrum analyzers, ϕ_k's can be included into the test optimization space to optimize the relative phase differences among the test tones for increased test accuracy.

The core test generation algorithm consists of iterative greedy search operation, which attempts to compute the optimal values of $[\{V_k, f_k\}$'s$]$ for a given N such that the error in the system specification prediction is minimum.

5.1. Test generation algorithm

The proposed test generation algorithm is a variant of gradient search [4] algorithm, which is described next.

```
BEGIN
  // algorithm parameters:
  $P$ = nominal value of the behavioral parameters
  $P_M$ = Perturbation vectors in $P$ for modeling regression eqn.
  $S_M$ = Specification values of the system corresponding to $P_M$
  $P_E$ = Perturbation vectors in $P$ for evaluating regression eqn.
  $S_E$ = Specification values of the system corresponding to $P_E$
  $Cost_2 = 0$
  Input N (of Eqn (4))
  do
    begin
    initialize [{$V_k$,$f_k$}'s] of Eqn (4) with some starting values
                                       within the search space
    $OUT_M$ = test response output spectrum for $P_M$
    Create regression model representing $f: OUT_M \rightarrow S_M$
    $OUT_E$ = test response spectrum for $P_E$
    $S_E'$= evaluate $f: OUT_E$          // i.e. predict specifications
                                       // using regression models
    Compute differences between ($S_E$ and $S_E'$)
                      //i.e. error in specification prediction
    $Cost_2$ = max of errors normalized w.r.t. nominal specs.
    if ($Cost_1 > Cost_2$)
      then
        Perturb the current optimization point [{$V_k$,$f_k$}'s]
        Compute the direction of –ve max gradient for $Cost_1$
                                       in [{$V_k$, $f_k$}'s] space
        Select new [{$V_k$, $f_k$}'s] along the –ve max gradient
```

```
      else
          Select new [{$V_k$, $f_k$}'s] along the previously
                                    computed –ve max gradient
      endif
      Cost2 = Cost1
   while(gradient for Cost1 is zero); // i.e. local minimum
END
```

The non-linear regression equations in the algorithm are computed using multivariate regression (MARS) computation engine, which attempts to map the variations in the measurement variables (amplitude spectrum of the CUT) onto the variations in the specifications of the CUT.

Figure 10 shows an example of cost minimization during the test generation from the behavioral simulation using two tones. The specification prediction error is used as the cost to be minimized. The test generation searches for the optimal stimulus in a three-dimensional amplitude and frequency space. In this example, the frequency of the first tone was taken as the fundamental frequency of the system, i.e. 1500 MHz. The *y* and *z* axes represent amplitudes of two tones; the *x* axis represents the frequency of the second tone. The search algorithm is started using an initial guess (1.4GHz, 1.3mV, 1.1mV). As the algorithms proceeds, it searches for the minimum cost and finally it reaches a local minimum at (1.36GHz, 1.2mV, 1mV), as shown in Figure 10. Hence, the final optimal stimulus consists of two tones at 1.36GHz and 1.50GHz, of amplitudes 1mV and 1.2mV, respectively.

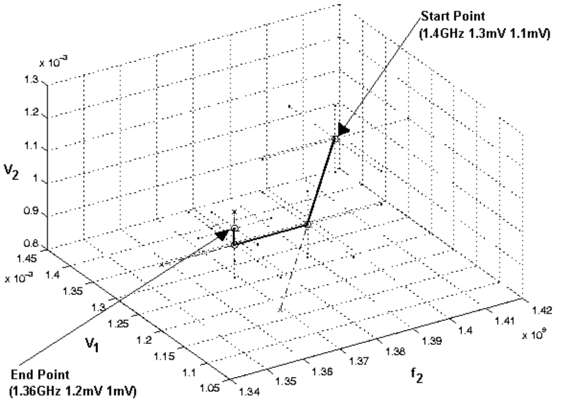

Figure 10. Example of prediction accuracy minimization of the test generation algorithm.

5.2. Test validation using transistor level simulations

The test stimulus generated by the algorithm is validated against the transistor level parameter perturbations as follows.

Due to process variations, the circuit components and the process parameters have non-zero tolerance values, which in effect may cause the system to fail with respect to some of its specifications. For test quality validation, the circuit (LNA, Mixer etc) component values (e.g. area of the transistors, values of R, L and C's in the modules) are perturbed and system-specifications are computed for each such perturbation. In addition, the output spectrum is recorded for these multi-parameter perturbations. Although, in real manufacturing process, these parameters may vary in a correlated way, random multi-parameter perturbations are used in this validation approach. The random multi-parameter perturbations of the circuit and process parameters represent the maximum degrees of freedom in which the system can fail (since, each parameter can vary independently of the other) and, hence, represent the worst case for test quality validation. The mapping $f: \mathbf{P} \rightarrow \mathbf{M}$ (see section 2) is constructed by building a regression model between the spectral components of the observed response and the specification of the system under test. For validation, the same function $f: \mathbf{P} \rightarrow \mathbf{M}$, computed as discussed above, is used to predict the specifications of the system under test from the observed response. The predicted values are compared with the corresponding specification values. If there exists a high degree of correlation between the subsystem test specifications and the response corresponding to the applied multi-tone test, there is little or no deviation between the predicted specification values and the specification values computed from simulation. Large deviations between the predicted and the simulated specification values would imply that the selected stimulus and the regression model have poor fitness for the RF subsystem under test.

In case of a high degree of fitness, the regression model and the selected test stimulus can be used together for simultaneous test of multiple specifications during the system-level test of RF subsystem of a wireless receiver in a real manufacturing process. In addition, a high degree of fitness of the stimulus and regression models would validate the approach of generating test stimulus for test of system-specifications using behavioral simulations. In the next section, using the proposed methodology, it is shown that, it is possible to track the specifications of the RF subsystem with high accuracy.

6. Experimental results

In this section, a case study is shown using the receive channel of a transceiver as the system under test, on which the proposed test generation and test validation method have been applied (Figure 11).

The circuit component (R, L, C) values and sizes of the transistors of different sub-modules are varied to form the parameter space for the transistor level description of the system. In this experiment, the tolerance in the parameter values is assumed 10% around their respective design values. System gain and system IIP3 are chosen as the specifications of interest. The nominal value of system gain is 22dB and system IIP3 is –12dB for –10dBm input level.

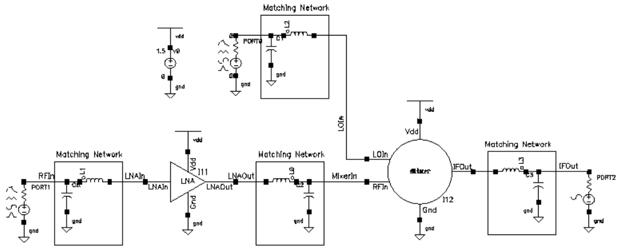

Figure 11 Block level diagram of the RF subsystem

The test stimulus used had two tones, one at 1.5 GHz of 1.2 mV and the other at 1.36 GHz, the amplitude being 1.0 mV. The main features of the test stimulus obtained from the test generation algorithm are:

- The stimulus consists of large-signal input tones, which try to extract the non-linearity of the system.
- The input frequencies need not be strictly in-band tones.
- Unlike conventional specification test, it may contain unequal amplitudes for different tones.
- The stimulus is used to compute the linear (e.g. system gain) and non-linear (e.g. IIP3) specifications simultaneously.

The fast, greedy algorithm used in the presented work may converge at a local minimum during test optimization. However, the gradient search algorithm implementation serves the purpose of a fast optimization toolbox in the presented test generation paradigm. Other global minimum search algorithms may be used, trading off the test convergence time for better test accuracy, without introducing any change in the methodology presented for alternate test generation.

Noise arising from the devices and parasitic elements present in the system was ignored during test generation using behavioral simulations. The test validation process uses transistor level simulation of the system and, hence, inherently takes into account the noise present in the system. The test generation approach is verified by injecting parametric failures in the form of random variations of the components around their nominal values. The specifications for these circuits are predicted with the regression model. Pass/fail decisions can be made using the predicted values and the error margins, which are shown in Table 2. The predicted system specifications are compared against the system specification information available from transistor level simulations. The predicted values exhibit close agreement with the specifications obtained from simulations and majority of the predicted specification data lie in the vicinity of the straight line with slope +1, which represents the locus of “ideal” predictions.

In the case study presented, every iteration during test generation for the RF subsystem using behavioral models for a two-tone test stimulus takes ~1 min, whereas the generation of the regression models from transistor level simulations (which is equivalent to one iteration for the test generation algorithm) takes ~10 hrs. Hence, the approach presented here shows significant reduction in test generation time by trading off simulation accuracy in the initial phase of test generation.

Figure 12 and Figure 14 show the tracking of the system gain and system IIP3 specifications. For a two-tone test, the proposed approach predicts the system-gain and system-IIP3 simultaneously, and it is possible to distinguish between faulty and fault-free circuits if the actual specification values do not lie within the prediction error margins around the upper and lower limits of their respective acceptance region. Figure 13 and Figure 15 show the percentage error in prediction with respect to the nominal values of specifications. The results are summarized in Table 2.

Table 2. Summary of the simulation results.

System Specification	Nominal value	Max. error in spec. prediction
Gain	22dB	±3.0% (±0.7dB)
IIP3	-12dB	±0.4% (±0.5dB)

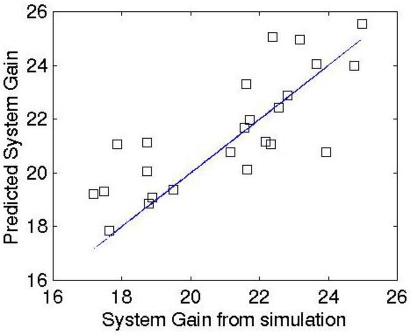

Figure 12. Tracking of system gain.

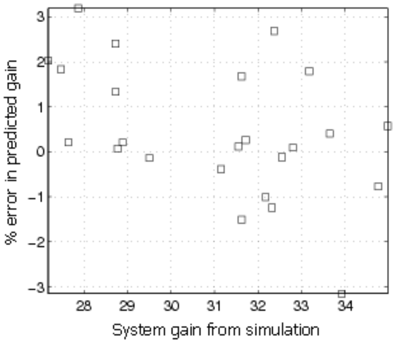

Figure 13. Percentage error in tracking of system gain.

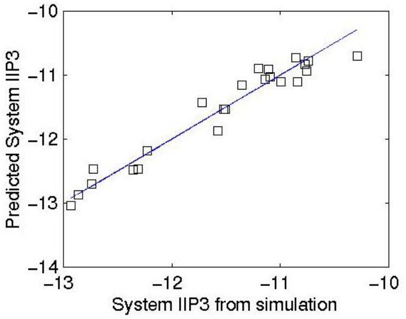

Figure 14. Tracking of system IIP3.

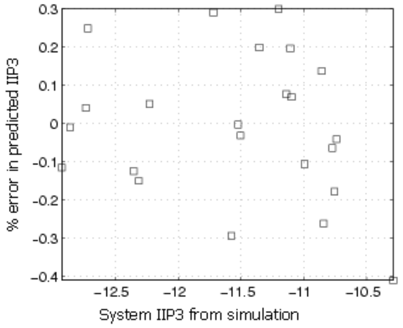

Figure 15. Percentage error in tracking of system IIP3.

In the presented work, the noise figure (NF), which is another important specification for the RF sub-system, was not considered. Alternate test generation for NF would require: behavioral modeling of the NF-vs-frequency information from the transistor level simulation, such that the measurement space (amplitude-vs-frequency) exhibits statistical (deterministic) trend for predicting the NF from behavioral simulation and the modeling incurs no significant increase in simulation time. Currently, the absence of an effective modeling approach satisfying the above constraint is prohibitive for the alternate test generation for NF.

7. Conclusions

In this paper, a new test methodology for RF sub-systems in narrow-band wireless transceiver like architecture is presented. The approach is based on applying multi-tone stimulus, measurement of the test response spectrum, and prediction of multiple system specifications simultaneously using statistical regression equations. A fast, iterative algorithm using behavioral level simulations of the system-under-test selects the optimum multi-tone stimulus for the proposed test approach. The statistical regression equations are constructed using transistor level simulation of the same system. Pass/fail test decisions can be made from the predicted specifications. The simulation results on a case study, using the receive channel of RF transceiver as the system under test, exhibit accurate tracking of the system specifications using the regression models generated using the presented approach.

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