Coverage-Directed Stimuli Generation for Characterization of RF Amplifiers

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***Abstract*—Functional coverage allows to measure the progress in verification and as a consequence allows to ensure high verification quality. However, this requires significant manual effort in particular to achieve high coverage.**

In this paper we propose a coverage-directed stimuli generation approach for the characterization of *Radio Frequency* (RF) amplifiers. An output coverage analysis in combination with error calculation steers the stimuli generation towards coverage closure. We provide a case study using three industrial *Low Noise Amplifiers* (LNAs) to demonstrate the applicability and efficacy of our approach.

I. INTRODUCTION

Verification of *Analog Mixed Signal* (AMS) *System-on-Chips* (SoCs) has become a very difficult task. This is due to 1) potentially infinite scenarios resulting from the continuous nature of the analog signals, 2) slow SPICE level simulations [1], and 3) often manual observation of the *Design Under Verification* (DUV) output.

Fortunately, the abstraction of SystemC AMS *Virtual Prototypes* (VPs) offer a good trade-off between design accuracy and simulation speed [2]. The early availability, support for SystemVerilog-like assertions/checkers [3], and significantly faster simulation speed as opposed to SPICE simulations [4] allows these models to be used as a reference for functional verification of the SoC at lower abstractions, i.e., the transistor level. Hence, their functional correctness is inevitable.

In digital designs, functional coverage – a measure if all the features of the design have been verified [5] – is used as a metric to establish high verification quality. However, it is not very well understood for *Analog Mixed Signal* (AMS) [6]. Although, some work has been done in this direction (e.g. [7]), still significant manual effort is required to achieve high coverage. Furthermore, considerable time is required to find ways to close the loop of coverage analysis and stimuli generation. *Coverage-directed stimuli generation* (CDG) is a technique to automate the feedback from coverage analysis to stimuli generation. As a consequence, CDG helps to reach uncovered coverage quickly.

Contribution: In this paper, we propose the first automated coverage-directed stimuli generation approach for the characterization of *Radio Frequency* (RF) amplifiers (which include *Power Amplifiers* (PAs), *Low Noise Amplifiers* (LNAs), *Driver Amplifiers* (DAs) etc).

Based on the functional coverage notions introduced in [7], first an output coverage analysis is introduced in the feedback path which looks for coverage holes – specifications which were not satisfied. The coverage holes are then used to find the "nearest" DUV output. This step ensures efficient convergence. Second, based on the coverage holes, an error is calculated to systematically guide the feedback path in generation of new stimuli parameters. In case of positive error, the stimuli parameters are refined (increased step size) and in case of negative error, the stimuli parameters are reduced (decreased step size). We use three industrial LNAs as a case study to show the automated progression over multiple iterations.

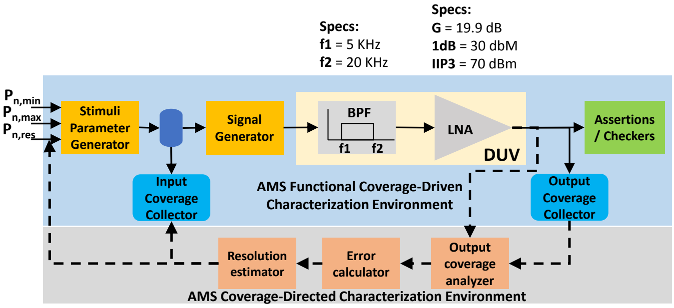

Fig. 1. AMS coverage-directed characterization Environment - LNA: Low Noise Amplifier, BPF: Band-Pass Filter, res: resolution

II. COVERAGE-DIRECTED CHARACTERIZATION

A. AMS Verification Environment and Deficiencies

Fig. 1 shows a verification environment with a coverage model surrounding an AMS DUV – LNA. It consists of the light blue elements in Fig. 1: A stimuli parameter generator, input coverage collector, and a signal generator on the input side, the DUV, assertions/checkers, and an output coverage collector on the output side.

This verification environment enables thorough and systematic characterization of the LNA. However, it requires significant manual effort to achieve high coverage which becomes the bottleneck. Hence, we extend the verification environment by several components as shown in the Fig. 1 gray area. They form the basis for our proposed AMS coverage-directed characterization approach as detailed in the next section.

B. Proposed Approach

The overall proposed coverage-directed characterization approach for RF amplifiers approach is shown in Fig. 1. Initially, the resolution *res*, total number of iterations N, and parameters switch S are set. Parameters define one stimuli signal, e.g., amplitude (A), frequency (f), phase (φ) etc of a sine wave as shown in Eq.1.

$$f(t, A, f, \varphi) = A \times sin(2\pi ft + \varphi) \tag{1}$$

Resolution refers to the step-size between two stimuli signals. N controls when to end simulation in case the specification is not reachable with any stimuli, e.g., defect in DUV. S iterates over parameters periodically.

First, *stimuli parameter generator* generates the stimuli parameters w.r.t. the given input parameters and initial resolution. The *signal generator* generates the input stimuli w.r.t. the stimuli parameters and gives them as input to the DUV. The output of DUV goes to *assertions/checkers* to verify if the DUV is performing correctly. Additionally, the DUV output is collected in the *output coverage collector*. Afterwards, the new proposed *coverage analysis* starts. It consists of three main components, 1) output coverage analyzer, 2) Error calculator, 3) and resolution estimator. They are detailed as follows:

Output coverage analyzer: The analysis is executed in two stages, 1) the output coverage report is searched for coverage holes, 2) the nearest value to the coverage hole is searched in the complete DUV output. The analyzer searches for the first coverage hole and chooses it as a coverage goal. It looks for the nearest value in the DUV output spectrum. This nearest value search is done to make the process systematic and to speed up convergence. On the contrary, if a random value is taken in to consideration, the process does not remain systematic and convergence takes significantly longer. Once the nearest value is found, it is forwarded to the *error calculator* along with coverage hole.

Error calculator: The error is calculated by taking a difference between nearest value and coverage hole.

$$Error\ (E) = coverage\ hole -\ \ nearest\ value \tag{2}$$

The error from Eq. 2 can never be 0 because it signifies verified specification. So, either the error will be positive or negative. The error is passed on to the *resolution estimator*.

Resolution estimator: The res of a parameter for the next iteration is calculated in this component. The error is used to estimate if the res should be increased or decreased, i.e., step-size should be made smaller or larger.

$$resolution\ = \begin{cases} increase & \text{if } E > 0 \\ decrease & \text{if } E < 0 \end{cases} \tag{3}$$

In each iteration, the amplitude *res* and frequency *res* are adjusted by 50% and 20% of the current value, respectively. This way, the resolution is systematically altered while slowly converging to 100% coverage.

The new step size for the parameters is set and next iteration starts. All the parameters are never adjusted simultaneously in any iteration, instead switch S regulates which parameter to adjust. S switches to a new parameter every 20% of iterations. After N iterations, if the convergence is not achieved, the simulation is terminated citing "potential defect in DUV". Otherwise, the simulation ends with the coverage reports (input, output, and cross-coverage).

III. EXPERIMENTAL RESULTS

TABLE I
SPECIFICATIONS OF THREE INDUSTRIAL LNAS

LNA	Gain			1 dB (dBm)	IIP3 (dBm)	Frequency		II (ohm)	OI (ohm)	Amplitude	
	min (dB)	typ (dB)	max (dB)			min (KHz)	max (KHz)			min (v)	max (v)
A	17	18.2	20	60.4	20	5	20	50	50	0	5
B	17	19.8	25	60.4	10	50	100	50	50	0	3.3
C	14	16	17.2	30	20.7	3	13	50	50	0	5

min: minimum, typ: typical, max: maximum, II/OI: Input/output impedance

TABLE II
LNA CASE STUDY - GAIN (G) PROGRESS OVER MULTIPLE ITERATIONS

LNA	Iterations															TI	T (s)
	1			2			3			4			5				
	Ares (v)	Fres (Hz)	cov (%)	Ares (v)	Fres (Hz)	cov (%)	Ares (v)	Fres (Hz)	cov (%)	Ares (v)	Fres (Hz)	cov (%)	Ares (v)	Fres (Hz)	cov (%)		
A	1	1000	21	1.5	1000	24	2.25	1000	39	3.37	1000	42	5	1000	44	13	8.2
B	1	5000	14	0.5	5000	19	0.75	5000	20	1.12	5000	28	0.56	5000	30	15	18.1
C	3	6000	33	1.5	6000	33	2.25	6000	83	1.12	6000	83	1.68	6000	100	5	0.19

Ares: Amplitude resolution cov: Coverage Fres: Frequency resolution TI: Total Iterations T: Time

We consider three industrial LNA models, i.e. the SystemC AMS behavioral models are designed using [8]. The specifications given in Table I. Columns 2-4 show gain (G) in dB, column 5,6 show 1 dB compression point and *input third-order intercept point* (IIP3) in dBm, respectively. Column 7,8 show frequency in *kilohertz* (KHz), column 9,10 show input/output impedance in *ohms*, and last two columns show allowed input signal amplitude range in volts (v). Different LNAs are selected to show that regardless of the underlying specifications, coverage closure is achieved. Table II shows first 5 iterations and the coverage progression for reference. Column1 shows the LNA models, column 2,3 shows amplitude resolution (Ares) and frequency resolution (Fres), respectively, and column 4 shows total coverage (cov) achieved. The second last column shows the total iterations (TI) required to achieve coverage closure. The last column shows total time (T). It takes 13 iterations to achieve 100% coverage of gain (G) for *LNA A* in 8.2 seconds. *LNA B* achieves 100% coverage in 15 iterations and 18.1 seconds. *LNA C* is able to achieve 100% coverage in only 5 iterations. Interestingly, some iterations do not show any increase/decrease in coverage (column 4,7 and column 10,13 of *LNA C* in Table II). This is because of the stimuli parameters not refined enough to cover output specifications. The proposed approach can be efficiently used for achieving hard-to-reach coverage cases without manual observation.

Future work: In future, we plan to use statistical and probabilistic models (Bayseian networks) to close the loop between coverage data and the directives to the stimuli generator.

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REFERENCES

[1] L. W. Nagel, "SPICE-simulation program with integrated circuit emphasis," *Electronics Research Laboratory, Univ. of California, Berkeley*, 1973.

[2] M. Barnasconi, C. Grimm, M. Damm, K. Einwich, M. Louërat, T. Maehne, F. Pecheux, and A. Vachoux, "SystemC AMS extensions user's guide," *Accellera Systems Initiative*, 2010.

[3] *IEEE SystemVerilog*, IEEE Std. 1800, 2005.

[4] M. Barnasconi, "SystemC AMS extensions: Solving the need for speed," *DAC*, 2010.

[5] A. Piziali, *Functional verification coverage measurement and analysis*. Springer Science & Business Media, 2007.

[6] A. Fürtig, G. Gläser, C. Grimm, L. Hedrich, S. Heinen, H.-S. L. Lee, G. Nitsche, M. Olbrich, C. Radojicic, and F. Speicher, "Novel metrics for Analog Mixed-Signal coverage," in *DDECS*, 2017, pp. 97–102.

[7] M. Hassan, D. Große, T. Vörtler, K. Einwich, and R. Drechsler, "Functional coverage-driven characterization of RF amplifiers," in *FDL*, 2019, pp. 1–8.

[8] K. Kundert, "Accurate and rapid measurement of IP2 and IP3," *The Designers Guide Community, www. designersguide. org/Analysis/intercept-point. pdf*, 2002.