A System-Level Platform for Dependability Enhancement and its Analysis for Mixed-Signal SoCs

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Abstract— **The long-term functionality of any electronic system poses some requirements on the dependability of that system. Especially for critical systems it is becoming a crucial property with increasing system complexity and shrinking technology dimensions. Analog and mixed-signal systems are an important part of these critical systems. Until now little effort has been put into dependability of analog and mixed-signal systems, especially front/back-ends. This paper presents a new system-level platform for enhancing and analyzing the dependability of analog and mixed-signal front-ends in SoCs. Markov analysis has been used to theoretically investigate the dependability enhancement of these analog and mixed-signal front-ends based on this platform. Simulations in VHDL-AMS have also been conducted for an example target system consisting of a temperature sensor, operational amplifier and ADC to illustrate this platform. The gain parameter of the whole system, taken as an example of potential dependability hazard, has been investigated and enhanced based on this platform. The results show that this proposed platform is effective and has the potential to investigate and enhance dependability at system level.**

Keywords- analog and mixed-signal dependability; system-level platform; self-calibration; self-diagnosis; redundancy; Markov analysis; behavioral modeling

I. INTRODUCTION

Analog and mixed-signal front/back-ends, being an important part of most critical systems, especially in automotive, medical and mission-critical systems, have received little attention with regard to dependability. Studies have shown that with increasing complexity of systems and shrinking technology dimensions, dependability attributes like reliability, maintainability, and availability are becoming increasingly important [1].

It has been shown in [2] that the main causes of reliability degradation in ICs, like Negative Bias Temperature Instability (NBTI) and Hot Carrier Injection (HCI), are not only important in digital circuits but also have a significant effect on the performance of analog and mixed-signal systems as well. Since most analog circuits require matched parameters, therefore any mismatch induced by the above-mentioned effects can cause a change in their performance parameters.

These studies lead to the conclusion that in a similar way as low power, low noise, high resolution, and high speed have become important for many applications, dependability is also becoming an important design axis. Unfortunately, there is very little literature available regarding dependability of analog and mixed-signal circuits. Mostly efforts have been made to address NBTI, HCI and Time Dependent Dielectric breakdown (TDDB) effects in the early stages of the transistor design to tackle reliability issues [3]. Reliability, being only one attribute of dependability, implies that a lot of effort is required at design stage to address the life time dependability issues of a product.

Therefore, in order to start investigating these dependability issues, their negative effects and possible solutions, there is a need to address them via model-based descriptions that characterize the system performance as a function of operating conditions in order to lay a foundation for dependable system design.

This type of model-based approach is used in this paper to support a system-level platform to analyze the dependability enhancement of a conventional analog and mixed signal front-end. However, before discussing this system-level platform and different models, it is important to discuss the general definition of dependability and its most important attributes from a heterogeneous system point of view which are discussed in the next section. Section III describes the proposed platform and its principle of operation. Subsequently section IV and V will develop some basics on Markov analysis and its usage to analyze the dependability of the whole system. In the last sections simulation results and conclusions are presented.

II. DEPENDABILITY

In general, dependability of a system is defined as its trustworthiness that in a given environment the system will operate as expected and will not fail during its normal operation [4]. More precisely, it represents the property of the system that integrates attributes like availability, reliability, maintainability, safety, security and survivability [5-7].

In this paper, the focus will be on some important attributes of dependability, more specifically availability, reliability, and maintainability. Where *reliability* represents the continuity of correct service, *maintainability* represents the ability to undergo repair and modifications,

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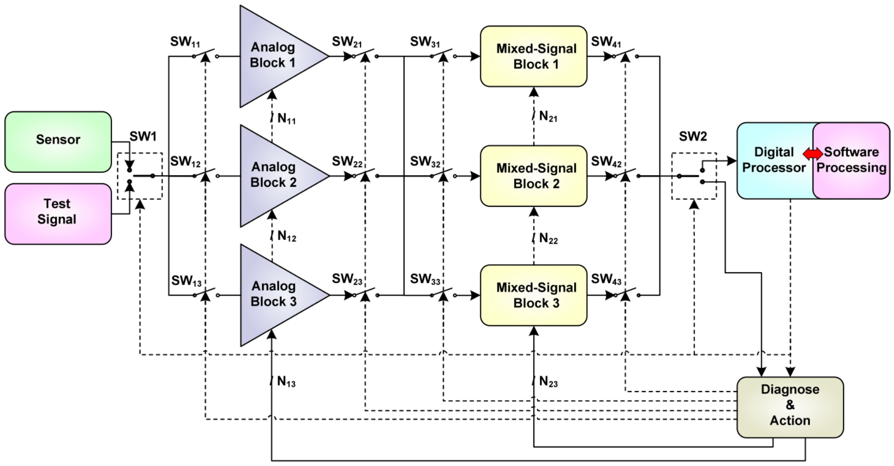

Figure 1. Proposed platform for dependability evaluation

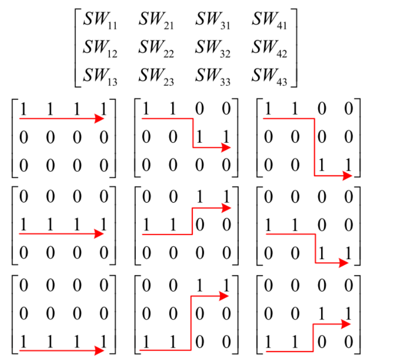

Figure 2. Switch Matrix and the possible active paths

and *availability* represents the readiness for correct service of the system [5]. These attributes are probabilistic quantities that overall determine the dependability and relate to probabilistic quantities like "Mean Time To Failure" (MTTF) "Mean Time To Repair" (MTTR), and "Mean Down Time" (MDT) [4, 6].

One approach to evaluate the dependability of a system is based on actual measurements, while another uses a number of abstract models to investigate the system-level reliability, maintainability, availability [8-11] and makes use of model-based fault injection techniques [12]. In this paper, model-based techniques have been used to analyze the dependability enhancement based on the proposed platform.

III. Proposed Platform

Despite the fact of increased cost and area, adding component redundancy to systems is an established way of providing fault-tolerant systems especially in safety/mission critical systems and therefore an approach to enhance system dependability. Furthermore it has been shown, for instance, in [13, 14] that different parameters of analog and mixed-signal circuits can be digitally programmed or tuned. Fig. 1 shows such a system where redundancy as well as digital programming/tuning capabilities of different analog and mixed-signal components have been utilized to propose a platform for system-level dependability analysis and enhancement.

The "Diagnose & Action" block is responsible for diagnosing the system dependability based on different system performance parameters and for taking actions accordingly to maintain the dependability level of the whole system. The switches SW_1 and SW_2 are used to switch between the normal and diagnosis modes whereas the switch matrix, composed of switches SW_{11}, SW_{12}, ... SW_{43}, is used to select different combinations of analog and mixed-signal blocks to form different active paths as shown in Fig. 2 (1 = switch closed, 0 = switch open). To avoid single point of failure and to achieve desired dependability these switches are made fault tolerant. Each active path consists of one "Analog Block" and one "Mixed-Signal Block". The influence of each performance parameter, like gain, offset etc., on dependability can be checked either at individual block or at each active path level by using the switch matrix.

Let us consider that initially all the blocks are fully dependable [4] and switches SW_{11}, SW_{21}, SW_{31}, and SW_{41} are closed to form an active path from switch SW_{11} to switch SW_{41} via switches SW_{21} and SW_{31} (Fig. 2). During the lifetime of the system the "Digital Processor" block will activate the "Diagnose & Action" block at predefined regular intervals of time and at the same time will switch SW_1 and SW_2 into the diagnosis mode. In diagnosis mode, the "Diagnose & Action" block will first try to verify the components of the current active path (in the present case this active path is from switch SW_{11} to switch SW_{41} via switches SW_{21} and SW_{31}) for their performance parameters. If the dependability of the system, according to different performance parameters of each block in this active path, is correct then the "Diagnose & Action" block will take no action; if there are some mismatches between the expected and measured values then it will take actions accordingly.

The dependability of each active path can be tuned back to its normal value by tuning blocks that are present in this active path via available digital programming/tuning capabilities. Since normally these blocks have their nominal tuning range [13, 14], each active path can be tuned back up to a specific level to try to regain system dependability. The purpose of the switch matrix is to provide greater flexibility and tuning space for the "Diagnose & Action" block. It could be achieved by using these redundant (identical) and tunable analog and mixed-signal blocks in order to maintain the system dependability. The basic idea behind this scheme is first to tune each component to maintain the dependability requirements of the whole system and once a component is out of its tuning range then replace this with a new/fresh (redundant/spare) component.

A number of techniques are available for analyzing the dependability of a system, for example stochastic Petri nets, fault-trees, reliability block diagrams and Markov analysis. In this paper, Markov analysis will be used because of its simplistic modeling approach, repair/replace mechanism

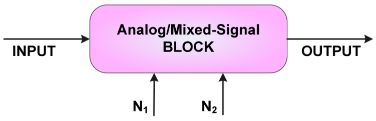

Figure 3. Block diagram of an analog/mixed-signal block with digital tuning knobs (N_1, N_2)

Table 1. Fault-free states as function of tuning knobs

N_1 N_2	State
0 0	1
0 1	2
1 0	3
1 1	4

inclusion, dynamicity, and modest computationally expensive requirements. In the next section, the necessary background on Markov analysis is provided which is further used to study the dependability enhancement of the proposed platform.

IV. Markov Analysis

Markov analysis starts with formulating a Markov state model by breaking the whole system into a number of states represented by circles (bubbles). These circles are then connected by directional arcs representing the transition rates (in our case failure and repair rates; failure per hour and repair per hour) at which the system moves from one state to another state. In general, these transition rates can be time varying, allowing the Markov state model to represent a variety of different densities for times spent in a state before the system moves to the next state [10]. Solution of such a state model using the state-space approach then predicts the probability that the system will be in various states after any specified time interval. The sum of these probabilities over non-failure states then yields the system reliability [11].

The basic assumption in Markov analysis is that the behavior of the system in each state depends on the present state of the system and not on the previous state or the time at which it reached the present state. In dependability engineering, this assumption is satisfied if all events (failures, repairs, etc.) in each state occur with constant occurrence rates. This means the time spent in each state follows an exponential distribution.

Mathematically, the Markov model is completely described by its transition matrix A(t) where, for every $i \neq j$ the ij^{th} entry represents the transition rate from state i to state j, and, for every $i = j$, the ij^{th} entry is represented by minus the sum of the entries in the rest of the i^{th} row. The diagonal entries are such that each row of A(t) sums to zero. The behavior of the Markov state model is then governed by the following differential equation [10]:

$$\frac{dP(t)}{dt} = P(t) * A(t) \tag{1}$$

where $P(t)$ is an $1 \times n$ row vector, $A(t)$ is an $n \times n$ matrix and n is the number of states in the system. The solution of (1), which gives the probability in each state of the system, is given by:

$$P(t) = P(0) * [e^{A(t)*t}] \tag{2}$$

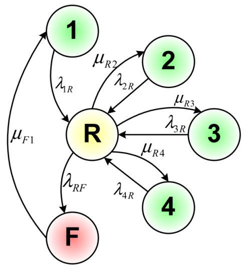

Figure 4. Markov state space model for an analog/mixed-signal block

where $e^{A(t)*t}$ is an $n \times n$ matrix and $P(0)$ is an $1 \times n$ initial probability row vector describing the initial state of the system.

V. Dependability Analysis of the Proposed Platform

In order to use Markov analysis to analyze the dependability of the proposed platform let, as an example, each analog and mixed-signal block has two digital tuning knobs (ports), as shown in Fig. 3, that are used to tune its dependability back to its normal value. This means that every analog or mixed-signal block has four different states, as shown in Table 1, where each state corresponds to a unique value of its digital tuning knobs (ports) and represents a fault-free state of the corresponding block.

In order to formulate a Markov state model for this block two more states are introduced. State R which corresponds to a state where a block is being repaired and a state F which represents a failed state in which case the block can not be further repaired by digital tuning knobs (ports) but could be replaced by a spare block. A Markov state model of this block, now consisting of six states as described above, is shown in Fig. 4.

In Fig. 4, λ_{ij} represents failure rates and μ_{ij} represents repair/replace rates. For example, λ_{1R} represents the failure rate from state 1 to state R; similarly μ_{R2} represents the repair rate from state R to state 2. Whereas, only μ_{F1} represents the replacement rate from state F to state 1. It has been shown in [10] that Markov state models with exponential repair-time densities will give the same results for steady-state probabilities as the more complicated non-exponential repair-time densities. Therefore instead of using more complex failure-time and repair-time densities, exponential time densities, where both failure rates and repair rates are constant, will be used to study the steady-state probabilities. For example if λ is a constant failure rate and μ is a constant repair rate then $\lambda e^{-\lambda t}$ and $\mu e^{-\mu t}$ will be the exponential failure and repair time densities respectively. The state transition matrix of this Markov state model (Fig. 4) with constant failure and repair/replace rates is:

$$A = \begin{bmatrix} -\lambda_{1R} & \lambda_{1R} & 0 & 0 & 0 & 0 \\ 0 & -\mu_{R2}-\mu_{R3}-\mu_{R4}-\lambda_{RF} & \mu_{R2} & \mu_{R3} & \mu_{R4} & \lambda_{RF} \\ 0 & \lambda_{2R} & -\lambda_{2R} & 0 & 0 & 0 \\ 0 & \lambda_{3R} & 0 & -\lambda_{3R} & 0 & 0 \\ 0 & \lambda_{4R} & 0 & 0 & -\lambda_{4R} & 0 \\ \mu_{F1} & 0 & 0 & 0 & 0 & -\mu_{F1} \end{bmatrix}$$

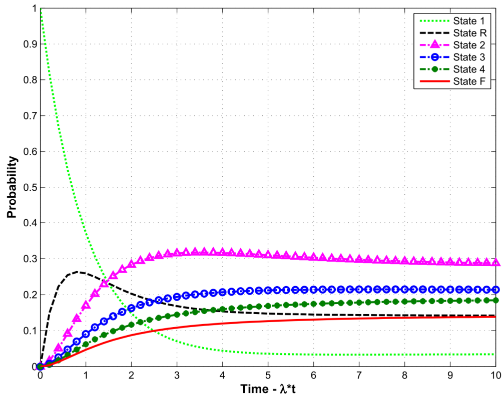

Figure 5. Probability of each state of the analog/mixed-signal block as a function of time (λ=1/1000)

By using this transition matrix in (1) a set of differential equations is obtained which can be solved numerically by using P(0)=[P_1 P_R P_2 P_3 P_4 P_F]=[1 0 0 0 0 0] as the initial state probabilities and the values of Table 2 as constant failure and repair rates. In Table 2 all the values are expressed as per hour. As an example, every fault-free state (i.e. 1, 2, 3, and 4) is assumed to have a failure rate of 1 failure per one thousand hours (1/1000). Therefore state 1 will fail in 1/1000 per hour while state 2 will fail once per two thousand hours. This is because of the fact that state 2 will be active only if state 1 will fail. Since state 2 will fail with the same rate as state 1 but will be active only when state 1 will fail therefore to use Markov analysis, where each current state is independent from the previous state, the failure rate for state 2 must be once per two thousand hours (1/2000). Similarly state 3 and state 4 will fail once in three and four thousand hours respectively. In a similar way, once a failure will occur from state 1 to state R it will be repaired to state 2; this means the repair rate from state R to state 2 will be once every thousand hours (1/1000) and the subsequent repair rate, to apply Markov analysis, for state 3 and state 4 will be once per two and three thousand hours respectively. Furthermore the replacement rate from state F to state 1 will be once in four thousand hours (1/4000).

The solution of the differential equations, discussed above, will provide the probability of the analog or mixed-signal block in each state as a function of time which is shown in Fig. 5. The sum of these probabilities over non-failure states (i.e 1, 2, 3, and 4) then yields the reliability of each analog or mixed-signal block. In order to calculate the reliability of the whole system, Reliability Block Diagrams (RBD) are used. RBDs are not used to calculate the reliability of a repairable system, but one can use RBDs under the assumption that each repairable block behaves like a non-repairable block and its reliability is independent from the reliability of the other blocks. This is accomplished by assigning μ_{F1} = 0 (i.e. no replacement) in the above transition matrix and recalculate the reliability of each repairable block and treat this enhanced reliability as the reliability of a non-repairable block.

The working principle of the proposed platform suggests that it can be considered as composed of two main blocks connected in series, as shown in Fig. 6, where each main block is composed of three parallel sub-blocks, each being

Table 2. Failure rate and repair/replace rate values

Parameter	Value/hr	Parameter	Value/hr
λ_{1R}	1/1000	μ_{F1}	1/4000
λ_{2R}	1/2000	μ_{R2}	1/1000
λ_{3R}	1/3000	μ_{R3}	1/2000
λ_{4R}	1/4000	μ_{R4}	1/3000
λ_{RF}	1/4000		

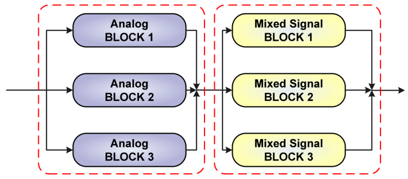

Figure 6. Reliability Block Diagram (RBD) for the proposed platform

independent from any other block and having the reliability as recalculated above. Therefore by using the principle of RBD, the overall reliability of each main block, being composed of three sub-blocks in parallel, can be calculated by using the following equation:

$$R(t) = 1 - \prod_{i=1}^{n} (1 - R_i(t)) \tag{3}$$

Here n represents the number of parallel sub-blocks. Similarly, once the reliability of each main block is calculated, the reliability of two main blocks connected in series can be calculated using the following equation:

$$R(t) = \prod_{i=1}^{m} R_i(t) \tag{4}$$

Here m represents the number of main blocks in series. Using these equations, the overall reliability of the whole system without and with repairable components is shown in Fig. 7. It is clear from this figure that the reliability of the whole system with repairable components (WRC) is increased as compared to reliability with non-repairable components (NRC). This reliability increase is directly related to the repair rate or the number of available repaired states (e.g. 2, 3, 4 in current case) and can be increased further either by increasing repair rate or by providing more repaired states.

The maintainability of the whole system, being the probability that the system is successfully repaired while it

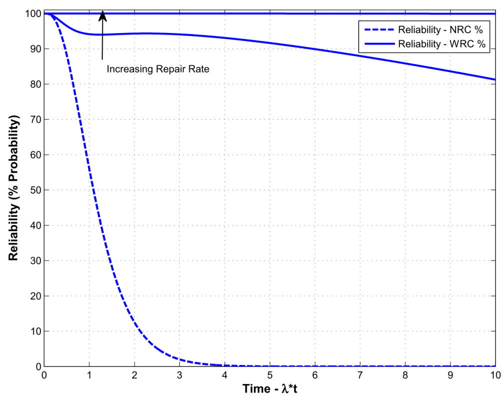

Figure 7. Reliability for the proposed platform (* NRC=No Repairable Components, WRC=With Repairable Components, λ=1/1000)

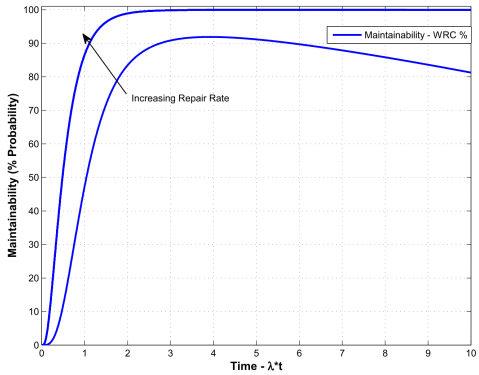

Figure 8. Maintainability of the proposed platform (λ=1/1000)

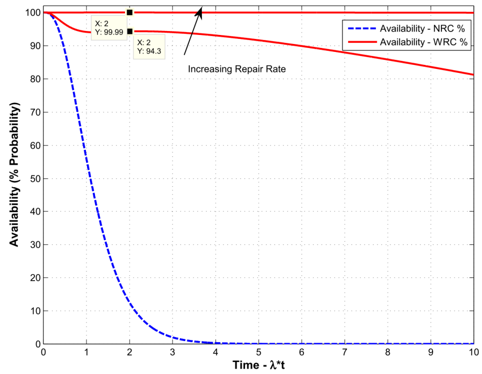

Figure 9. Availability of the proposed platform (λ=1/1000)

fails, can be calculated by estimating the contribution of the repair mechanism to decrease the unreliability (1-reliability) of the non-repairable component system. This can be accomplished by subtracting the sum of probabilities in state R and State F of a repairable component system from the probability of failure (unreliability=1-reliability) of the system with no repair mechanism for components. This difference gives the value of the probability of fault-free system that has been increased due to repair mechanisms which was not possible with non-repairable components. This is called the maintainability or the probability that the system was successfully repaired (i.e. it is in fault-free state) when it failed; this is a reason to enhance the reliability of the whole system which can not be otherwise achieved by a simple non-repairable component system. The maintainability (percentage probability as a function of time that the system will be repaired if it fails at that time) of the platform is shown in Fig. 8 which indicates that the maintainability of the whole system increases with increasing repair rate.

Similarly, the availability (percentage probability as a function of time that the system will be available for correct service at that time) of the platform can also be related to the probabilities in different states. The probability in states 1,2,3, and 4 gives the probability that the system will be correctly functioning (continuity of correct service) and the probability in states R, and F gives the probability that the system will not be functioning correctly (failure continuity). Therefore by having the probability of correctly functioning and the probability of not-correctly functioning (i.e. reliability and unreliability), the availability of the platform can be calculated by finding the ratio of probability that the system is correctly functioning to the total probability of being correctly functioning and not-correctly functioning. In other words, dividing the reliability of the system by the reliability plus the unreliability of the system that is shown in the following equation:

$$A = \frac{Reliability}{Reliability + Unreliability} \tag{5}$$

Since Reliability + Unreliability = 1 at a particular time, therefore the availability of the platform will also follow the same pattern as reliability (percentage probability as a function of time that the system will be correctly functioning at that time). Fig. 9 shows the availability of the platform and it clearly indicates that by increasing the repair rate, the availability of the whole system can be enhanced up to 99.99 percent.

To fully understand the behavior and performance of this proposed platform, a simulation setup consisting of a single active path has been considered which is discussed in the next section.

VI. Simulation Setup

Fig. 10 shows the block diagram of the simulation setup where a conventional front-end composed of a temperature sensor, amplifier and analog-to-digital converter has been modeled at behavioral level in VHDL AMS [15-18]. For illustration purposes here only one active path has been considered which can be further extended to other active paths that can be selected using the switch matrix. To investigate the dependability of such a system (front-end) at system level, one first has to consider which performance parameters are crucial from a dependability point of view; subsequently the influence of that performance parameter has to be included in the behavioral models.

As an example the gain of the whole system (front-end) has been considered as an important dependability issue. Since OpAmps are mostly used in closed-loop configurations to maintain the gain based on negative feedback, therefore only ADC gain is likely to influence the overall gain of the system.

Fig. 11 shows the simulation results where the overall gain of the system (front-end) has been monitored by the "Diagnose & Action" block at regular intervals of time. Once degradation in gain due to the ADC has been diagnosed, proper repair actions by tuning the ADC gain back to its allowed value are taken by the "Diagnose & Action" block as encircled in Fig. 11.

These results show that by properly selecting a suitable regular interval of time for monitoring the gain of the whole system, being an important performance parameter for dependability of the whole system, can be tuned back to its normal value and hence in this way dependability of the whole system can be enhanced or maintained for a longer time as compared to a system with non-repairable components.

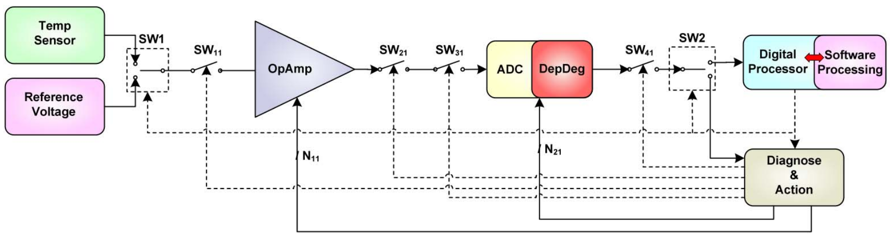

Figure 10. Simulation setup of the target system

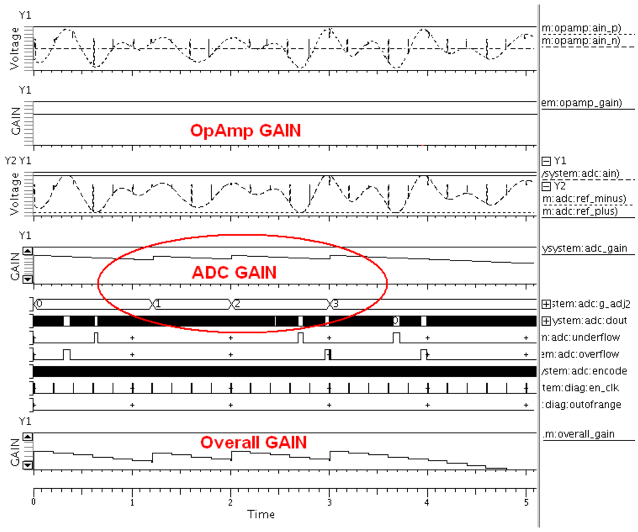

Figure 11. ADVance VHDL-AMS simulation of the target system

VII. CONCLUSION

In this paper we have proposed a system-level platform for dependability enhancement and its analysis for mixed-signal SoCs. Based upon Markov analysis reliability, maintainability, and availability being the important attributes of dependability have been calculated for this proposed platform. A target system consisting of a temperature sensor, operational amplifier and ADC has been simulated at the behavioral level to show how gain, being an important performance parameter in this case to influence dependability, can be analyzed and enhanced using this proposed platform. The results show that by utilizing the digital programming/tuning capabilities of different analog and mixed-signal circuits and the selection of a number of selectable active paths using the switch matrix provides a potential for the proposed platform to be used for dependability enhancement of future critical systems, especially for analog and mixed-signal front-ends.

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