PREDICTING RELIABILITY OF MMICS USING MONTE CARLO ANALYTICAL TECHNIQUES (PART 2 OF 3)

Aris Christou
RIAC (University of Maryland)

Part 1 of this article, published in the 1st Quarter 2008 issue of the RIAC Journal, addressed the methodology used to estimate monolithic microwave integrate circuit (MMIC) high temperature performance. The current article covers the MMIC model development. The final part, to be published in the 3rd Quarter 2008 RIAC Journal, will discuss validation of the MMIC reliability model.

MMIC Circuit Reliability Model

The Given Conditions for MMIC Reliability Model

In general, several conditions must be given in order to establish a practical MMIC circuit reliability model, and these are summarized as follows:

1) The MMIC system is composed of m statistically-dependent subsystems (or stages, Figure 1), while the ith ($i = 1, \ldots, m$) subsystem (or stage) consists of n_i statistically-dependent and non-repairable components. Therefore, the MMIC system consists of "n" components where:

$$n = \sum_{i=1}^{m} n_i$$

and where each component is in either a failed or operating state.

2) Dependent failures can be due to a common cause (the failure of multiple components due to a single mechanism such as catastrophic or environmental failure), to interactions within a subsystem, and to interactions between subsystems. Due to the component failure interaction, the failure rate of the component (or subsystem) would increase once the neighboring components (or subsystems) have failed.

3) A single failure mechanism can affect several components, and a given component can be affected by several mechanisms and these mechanisms are statistically-independent.

4) Failure rate (λ) of a component, i, would be the sum of λ_{ii} (due to failure mechanism for component i itself), λ_{ij} (due to interaction by component j) and λ_{cc} (due to a common cause such as catastrophic failures which result in system failure as a *wh*ole). The interactions between passive components will be neglected.

5) Figure 2 shows the reliability schematic of a transimpedence amplifier (TIA) MMIC system. The effects of interactions among series connections may be neglected, since the path associated with the failed component has also failed. For example, if component 5 in Figure 2 has failed, the path (5-6) through it has also failed (open circuit). Component 6 is assumed to be non-operating. The interaction caused by components 5 and 6 therefore can be ignored.

6) The effects due to interactions are the same for the surviving components for the same subsystem. However, the effects of interactions among parallel active redundant FETs will be taken into account. As known, the stress of an active redundant component will increase once the neighboring components have failed. The stress will also increase with respect to the number of failed components, and this causes the survivors to have a higher failure rate. Referring to Figure 2:

$$\lambda_2 > \lambda_1 > \lambda_0$$

where

λ_2 is the failure rate of component 9 (or 10) for given failed paths 1-2 and 7-8,

λ_1 is the failure rate of component 9 (or 10) for given failed path either 1-2 or 7-8, and

λ_0 is the failure rate of component 9 (or 10) for no failed path.

7) The effects due to interactions are the same for the surviving components for the same subsystem. For example, if component 7 (or 8) has failed, its effects on components 1, 2, 9 and 10 are the same.

8) Interactions among components and subsystems are estimated through correlations determined experimentally if it is possible, or may be estimated by SPICE circuit analysis.

9) The failure distribution function is given for each independent component. It can be a mixture of several known failure distribution functions, i.e.,

$$f = a_1 f_1 + a_2 f_2 + \cdots + a_n f_n$$

where a_i is the fraction of the effects due to failure distribution function f_i and $a_1 + a_2 + ... + a_n = 1$. The weighting factors, however, must be modified after each component failure.

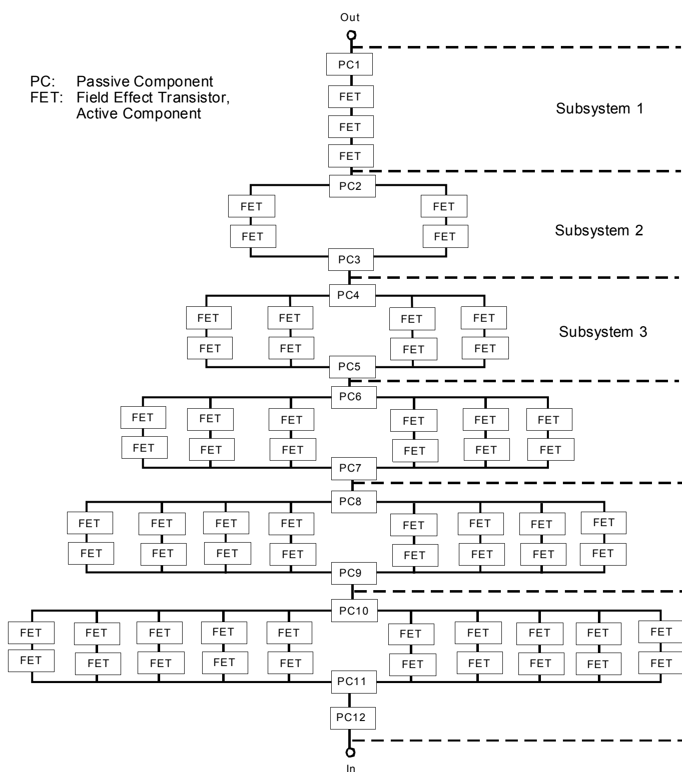

Figure 1: A Typical Reliability Block Diagram of a Multi-Stage MMIC

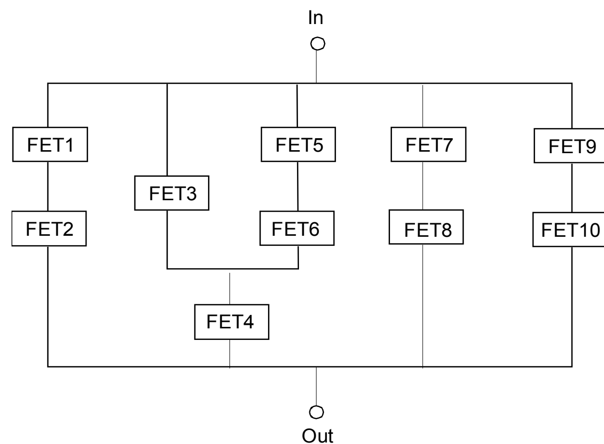

Figure 2: The Reliability Block Diagram of TIA

Procedures to Model MMIC Reliability

Two cases have been investigated, and the results as well as the procedures used are summarized as follows:

Case 1: If the interactions between components can be estimated by the correlation matrix obtained through SPICE circuit analysis or by experiment, then the steps to model the MMIC system reliability are:

1) Determine the interactions between components through SPICE circuit analysis so that the failure weighting factor $W(n_i, n_f)$ can be determined.

2) Identify the failure distribution function for each independent component. Based on the failure distribution function, select a random number for each component and through the inverse transformation method calculate a time to failure for each component. The time to failure t of a component (i.e., FET) related to a random number x is obtained by the proper selection of the distribution function.

3) If the predicted time to failure of a component is greater than a pre-specified life, then the component is operational, otherwise it is a failure. Identify the first failed component, and set the component time to failure to be T.

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4) Modify the remaining time to failure of the surviving components by $W(n_i, n_f)$. The new time to failure T_i' (i = 2, 3, 4, …, n, and n is the number of components consisting the MMIC circuit) will be

$$T'_i = T_{i-1} + \frac{\Delta T}{W(n_i, n_{i-1})}$$

or

$$T'_i = T_i + \Delta T \frac{1 - W(n_i, n_{i-1})}{W(n_i, n_{i-1})}$$

where ΔT is the difference between time to failure T_i of the surviving component i and time to failure T_{i-1} of the failed component i -1.

5) Step (4) is repeated until the modified T's of all components are obtained, determine the system's time to failure as the modified T' of the final failed component, compare it to the system's mission life, and record it as a success or a failure.

6) Step (2) is repeated until a statistically adequate sampling size is obtained.

7) Calculate the reliability and MTTF by:

$$R = \frac{N_s}{N}$$

and

$$MTTF = \frac{\sum_{i=1}^{N} TTF_i}{N}$$

and the error by the function,

$$error = 200 \sqrt{\frac{R}{N(1 - R)}} \%$$

The flow chart for the methodology is shown in Figure 3. Two types of MMICs, which are the TIA (Transimpedence Amplifier) and LNAs (Low Noise Amplifier), have been analyzed by applying this method. The error function equation, as is noted, has been derived from the definition of failure rate $\lambda(t)$ which is:

$$\lambda(t) = \frac{N_f(t + \Delta t) - N_f(t)}{N(t)\Delta t}$$

The failure rate $\lambda(t)$ is an approximately inverse proportion to the surviving time to failure Δt for a fixed number of failures at time from t to $t + \Delta t$. If $\lambda(t)$ is increased by a weighting factor $W(n_i, n_f)$, then Δt will be reduced by a factor of $W(n_i, n_f)$. The new surviving time to failure, therefore, is modified by $\Delta t/W(n_i, n_f)$, and the modified time to failure will be determined by the error function. The relationship between the correlation coefficient and the weighting factor is obtained by assuming that the difference of time to failure between the surviving components and the failed component is proportional to the associated difference of current drift [Reference 7], i.e.,

$$\Delta TTF \propto \Delta I_d$$

We also note that error function equation is applicable for both the TIA and LNA. Based on the linear regression method, if two variables (FETs) have the same (current drift) dispersion, i.e., $S_i = S_j$ then the correlation coefficient is identical to the regression coefficient b_{ij} and b_{ji}, i.e., $r_{ij} = b_{ij} = b_{ji}$, and the following relation:

$$\Delta T_i = r_{ij} \Delta T_j$$

$$\Delta T_j = r_{ij} \Delta T_i$$

where ΔT_i (or ΔT_j) is the difference of time-to-failure between component i (or j) and the failed component j (or i) (Figure.4).

The equations can be generalized as:

$$T'_j = T_j - r_{ij}(T_j - T_i)$$

$$T'_i = T_i - r_{i,i-1}(T_i - T_{i-1})$$

Comparing equations, the relationship between the correlation coefficient and the weighting factor is determined by the following equation:

$$-r_{i,i-1} = \frac{1 - W(n_i, n_{i-1})}{W(n_i, n_{i-1})}$$

$$W(n_i, n_j) = \frac{1}{1 - r_{ij}}$$

Steps (4) and (5) can be explained as in Figure 4 in which the random times-to-failure generated can be arranged so that $T_1 < T_2 < ... < T_n$ and $W(1, 2, …, n - 1)$ is the weighting factor due to failure of components 1, 2, … , n - 1.

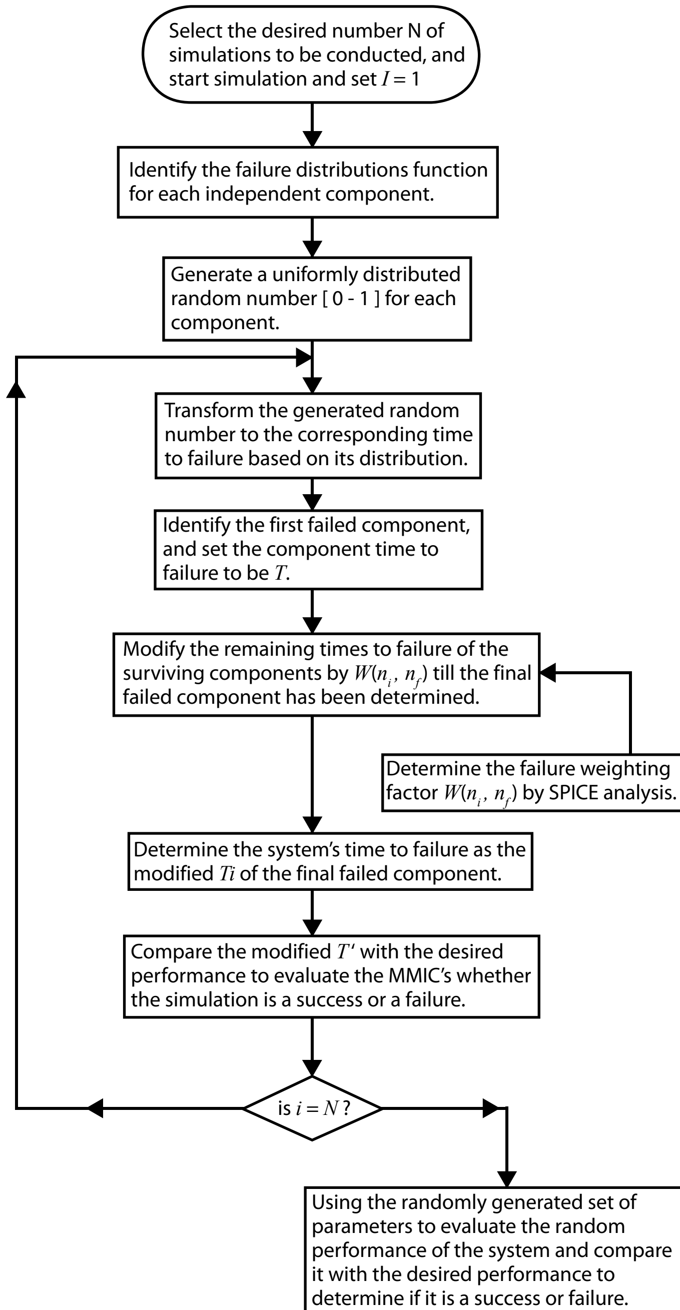

Figure 3: The flow chart for the reliability estimation of TIA and LNA holds.

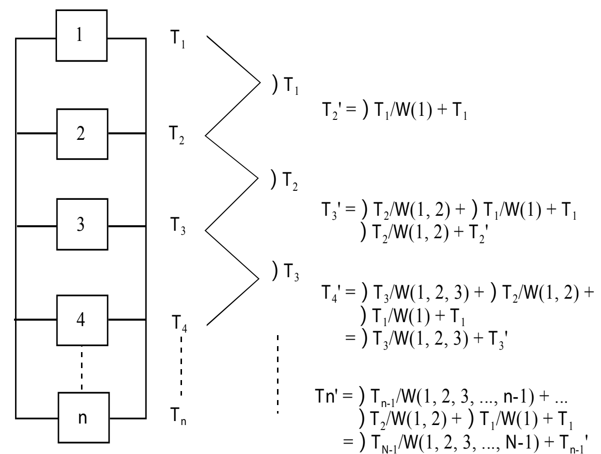

Figure 4: The Methodology to Determine the Time-To-Failure

Case 2: If the correlation between components can not be estimated by SPICE circuit analysis or any other method, then the steps to model the MMIC system reliability by Monte Carlo techniques can be stated as follows:

1) Determine from the MMIC circuit the specific groups of s-dependent components and groups of s-independent components, for example, FET1 through FET14 in Figure 5 are in an s-dependent group. The failure rate of a component in the s-dependent groups will be affected by the state (failed or operational) of any other components which are in the same group.

2) Identify the failure distribution function for each independent component. Based on the failure distribution function, select a random number for each component and through the inverse transformation method calculate a time to failure for each component.

3) If the predicted time to failure of a component is greater than a pre-specified life, then the component is operational, otherwise it is a failure. Determine in which s-dependent subsystem the failed components belong to if a failure has occurred, and then set the component failure time to be T.

4) If the failed components belong to an s-dependent group, then modify the remaining life of the surviving components in the same by $W(n_i, n_f)$. $W(n_i, n_f)$ is determined by assuming that the total stress upon the s-dependent subsystem (stage) is fixed and also the

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stress upon the component is proportion to the failure rate λ of the component. The new failure rate of the surviving component is obtained as:

$$n\lambda_0 = \left(n - n_f\right)\lambda'$$

$$\lambda' = n\left(\frac{\lambda_0}{n - n_f}\right)$$

where n is the total number of components in the MMIC system, n_f is the number of failed components, λ_o is the original failure rate, and λ' is the new failure rate. The weighting factor $W(n_i, n_f)$ is estimated by:

$$W\left(n_i, n_j\right) = \frac{n}{n - n_f}$$

The new time to failure can still be determined by the error function equation.

5) Step (4) is repeated until the modified T' of all groups is determined and then determine the system's time to failure from the modified T's and compare it to the system's mission life.

6) Step (2) is repeated until a statistically adequate sampling size is obtained. The flow chart for the methodology is shown in Figure 6.

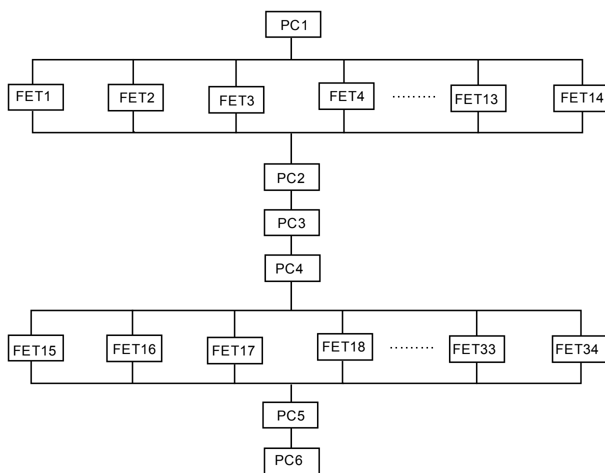

Figure 5: Reliability Block Diagram of the Low Noise Amplifier

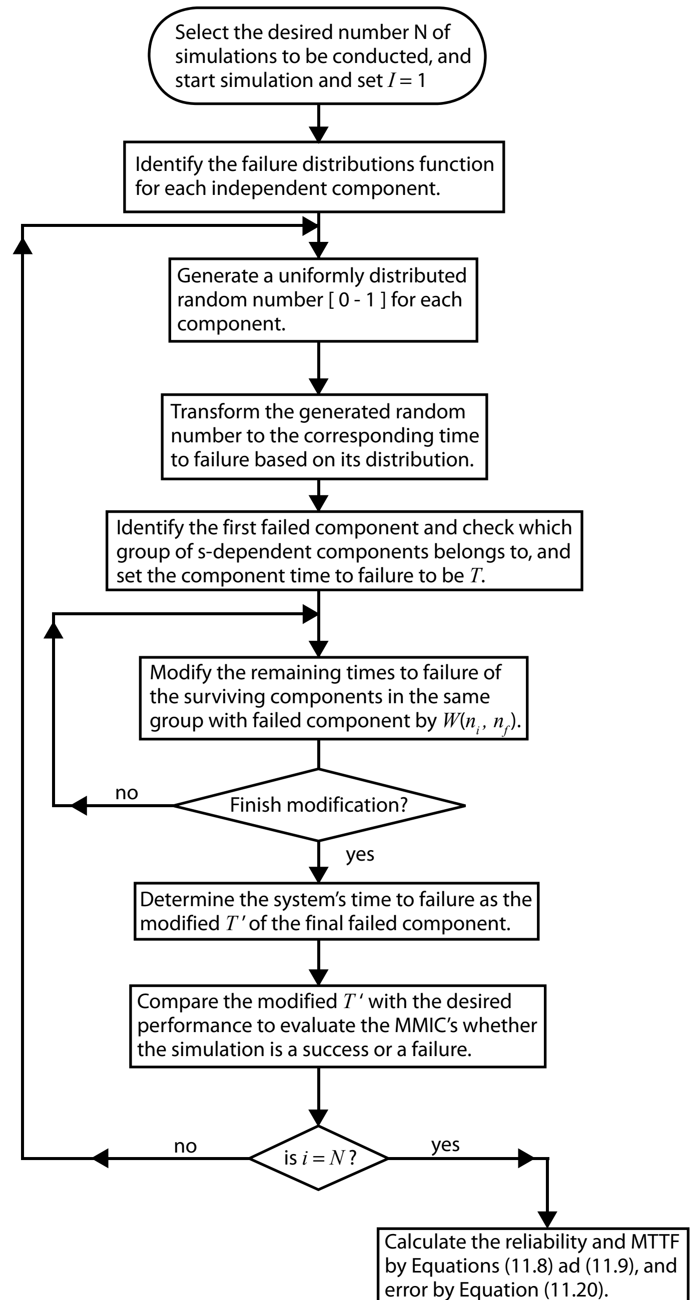

Figure 6: Flow chart for calculation of MTTF

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