Worst-Case and Average-Case Analysis of n-Detection Test Sets
Irith Pomeranz, Sudhakar M. Reddy

To cite this version:
Irith Pomeranz, Sudhakar M. Reddy. Worst-Case and Average-Case Analysis of n-Detection Test Sets. DATE’05, Mar 2005, Munich, Germany. pp.444-449. hal-00181554

HAL Id: hal-00181554
https://hal.archives-ouvertes.fr/hal-00181554
Submitted on 24 Oct 2007

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Worst-Case and Average-Case Analysis of n-Detection Test Sets

Irith Pomeranz1
School of Electrical & Computer Eng.
Purdue University
W. Lafayette, IN 47907, U.S.A.

and

Sudhakar M. Reddy2
Electrical & Computer Eng. Dept.
University of Iowa
Iowa City, IA 52242, U.S.A.

Abstract
Test sets that detect each target fault n times (n-detection test sets) are typically generated for restricted values of n due to the increase in test set size with n. We perform both a worst-case analysis and an average-case analysis to check the effect of restricting n on the unmodeled fault coverage of an (arbitrary) n-detection test set. Our analysis is independent of any particular test set or test generation approach. It is based on a specific set of target faults and a specific set of untargeted faults. It shows that, depending on the circuit, very large values of n may be needed to guarantee the detection of all the untargeted faults. We discuss the implications of these results.

1. Introduction
Under an n-detection test set, each target fault is detected n times, by n different test vectors. If a fault has fewer than n different test vectors that detect it, all its test vectors are included in an n-detection test set. The motivation for the use of n-detection test sets is that by increasing the number of detections of target faults, the likelihood of detecting unmodeled faults and defects is increased as well. In addition, generation of n-detection test sets for a specific fault model requires only minor modifications to a test generation procedure for the same fault model. This is typically simpler than writing a test generation procedure for a new fault model. Generation of n-detection test sets and their advantages in detecting unmodeled faults and defects were studied in [1]-[7].

Determining a value for n is typically done based on tester memory and test application time constraints. Since the size of a compact n-detection test set increases approximately linearly with n, n ≤ 10 appears to have become the accepted bound on n. Several questions arise when n is restricted. (1) How much unmodeled fault or defect coverage is missed by restricting n. (2) How much higher should n be in order to eliminate the fault or defect coverage loss. The latter is important in deciding whether higher values of n should be considered.

A model for estimating the defective part level after the application of a given test set was given in [3] and [4].

The model is based on the numbers of times fault sites are activated and observed by the test set, which are improved by n-detection test generation. This model can provide answers to the questions above with respect to a given test set. However, it was not used for providing general answers that are independent of the test set or the test generation procedure used. In addition, to answer the second question it would be necessary to perform test generation for increasing values of n, and the bound on n is unknown a-priori.

In this work we investigate a method of analysis to answer both questions in a way that is independent of any particular test set or test generation procedure. We perform the analysis by considering a specific set of target faults for n-detection test generation (single stuck-at faults), and a specific set of untargeted faults (four-way bridging faults [8], [9]). The four-way bridging fault model was used for developing manufacturing tests for static defects in industrial designs [9], [10]. Bridging faults were also used earlier as surrogates for unmodeled defects in estimating the defect coverage obtained by a given test set [3], [4]. The questions we answer become the following. (1) How much untargeted fault coverage (coverage of four-way bridging faults) is missed by restricting n. (2) How much higher should n be in order to ensure that all the untargeted faults (all the four-way bridging faults) are detected.

We investigate both a worst-case analysis and an average-case analysis to answer these questions. The worst-case analysis assumes that if it is possible to generate an n-detection test set that will fail to detect an untargeted fault, such a test set will be generated. The average-case analysis provides the probabilities that an arbitrary n-detection test set will detect untargeted faults. The worst-case analysis and its results are described in Section 2. The average-case analysis and its results are described in Section 3. The results of Sections 2 and 3 are analyzed in Section 4, and additional results, using a stricter definition of an n-detection test set, are presented to support the analysis.

2. Worst-case analysis
Let $F = \{f_0, f_1, \ldots, f_{k-1}\}$ be the set of faults for which n-detection test generation is carried out (the set of target
If the number of detections of \( f_i \) \( N \) can detect \(( \ref{1} \) and \( \ref{15} \), without detecting \( f \) possible to detect \( f \) either input vector \( 6 \) or input vector \( 7 \) will be included in \( g \) and \( 7 \), and the set \( g \) of input vectors \( = \{0,1,\cdots,15\} \) be the size of the intersection \( l_1, a_1,l_2,a_2 \). The fault is activated when \( l_1 = a_1 \) and \( l_2 = a_2 \). It then results in \( l_1 = a_1 \) in the faulty circuit. We use the decimal representation of the input vectors to represent \( U \). For the circuit of Figure 1 we have \( U = \{0,1,\cdots,15\} \).

The bridging fault \( g_0 = (9,0,10,1) \) is detected by the set of input vectors \( T(g_0) = \{6,7\} \). In the first three columns of Table 1 we show all the single stuck-at faults in \( F \) that are detected by at least one of the input vectors 6 and 7, and the set \( T(f_i) \) for every such fault \( f_i \). Considering \( f_0 = 1/1 \) with \( T(f_0) = \{4,5,6,7\} \), we note that it is possible to detect \( f_0 \) twice, using test vectors 4 and 5, without detecting \( g_0 \). A third detection of \( f_0 \) will require that either input vector 6 or input vector 7 will be included in the test set, thus guaranteeing that \( g_0 \) will be detected. Considering \( f_1 = 2/0 \) with \( T(f_1) = \{6,7,12,13,14,15\} \), it is possible to detect \( f_1 \) four times, using test vectors 12, 13, 14 and 15, without detecting \( g_0 \). A fifth detection of \( f_1 \) will guarantee that \( g_0 \) will be detected.

\[ g_j \in G \]

\( T(f_i) \cap T(g_j) \neq \emptyset \) for every \( f_i \in F(g_j) \). Let \( N(f_i) \) be the size of \( T(f_i) \), and let \( M(g_j,f_i) \) be the size of the intersection \( T(f_i) \cap T(g_j) \). We can detect \( f_i \) \( N(f_i) - M(g_j,f_i) \) times without detecting \( g_j \). If the number of detections of \( f_i \) is increased to \( N(f_i) - M(g_j,f_i) + 1 \), \( g_j \) is guaranteed to be detected. We denote \( N(f_i) - M(g_j,f_i) + 1 \) by \( n_{min}(g_j,f_i) \). This is the minimum value of \( n \) for which detection of \( f_i \) guarantees detection of \( g_j \). Considering all the faults in \( F(g_j) \), we define \( n_{min}(g_j) = \min\{n_{min}(g_j,f_i): f_i \in F(g_j)\} \). This is the minimum number of detections \( n \) that guarantees detection of \( g_j \) by an \( n \)-detection test set for \( F \).

In Table 1 we show the values of \( n_{min}(g_0,f_i) \) considering all the faults in \( F(g_0) \). Based on the information given in Table 1, we have \( n_{max}(g_0) = 3 \). Thus, in order to guarantee that an arbitrary \( n \)-detection test set will detect \( g_0 \), \( n \) must be larger than or equal to three.

Results of the computation of \( n_{min}(g_j) \) for the combinational logic of MCNC finite-state machine benchmarks are shown in Tables 2 and 3 (at the end of the paper). In Table 2 we are interested in faults out of \( G \) that are guaranteed to be detected by any \( n \)-detection test set for \( n \leq n_{max} \). Here, \( n_{max} \) is a constant for which it is practical to generate an \( n \)-detection test set \( (n_{max} = 10 \) in our experiments). In Table 3 we are interested in faults out of \( G \) that require large values of \( n \) to guarantee that they will be detected by an \( n \)-detection test set. We report in Table 3 on faults that are guaranteed to be detected by an \( n \)-detection test set only if \( n > n_{max} \). We only include in Table 3 circuits for which such faults exist.

Table 2 is organized as follows. After the circuit name we show the number of four-way bridging faults considered (detectable non-feedback four-way bridging faults between outputs of multiple-input gates). Under column \( n_{min}(g_j) \) we show the percentage of faults \( g_j \in G \) such that \( n_{min}(g_j) \leq n_{min} \). This is the percentage of faults for which an \( n \)-detection test set that guarantees their detection requires \( n \leq n_{min} \). If \( n = n_{min} \) results in 100% coverage of four-way bridging faults, we do not report on higher values of \( n \). For example, \( bbara \) has 858 faults in \( G \). Of these faults, 80.42% require \( n_{min}(g_j) = 1 \) to guarantee their detection, i.e., they will be detected by any 1-detection test set; 84.85% of the faults require \( n_{min}(g_j) \leq 2 \) to guarantee their detection, i.e., they will be detected by any 2-detection test set; 97.55% of the faults are guaranteed to be detected by any 10-detection test set.

Table 3 is organized as follows. After the circuit name we show the number of four-way bridging faults considered. Under column \( n_{min}(g_j) \) we show the number (and the percentage in parentheses) of faults

| Table 2: Faults with test vectors that overlap with \( T(g_0) = \{6,7\} \) |
|-----------------|-----------------|----------------|
| \( i \) | \( f_i \) | \( T(f_i) \) |
| 0 | 1/1 | 4 5 6 7 |
| 1 | 2/0 | 6 7 12 13 14 15 |
| 3 | 3/0 | 2 6 7 10 14 15 |
| 9 | 8/0 | 2 6 10 14 |
| 11 | 9/1 | 0 1 2 3 4 5 6 7 9 10 11 |
| 12 | 10/0 | 6 7 14 15 |
| 14 | 11/0 | 1 2 3 5 6 7 9 10 11 13 14 15 |
procedure 1 performs

\[ n \]

procedure 1 constructs

\[ n \]

assumes that as long as

\[ G \]

the probabilities of detecting the faults in

\[ G \]

To iterate in Section 2 is a worst-case analysis since it

\[ n \]

Nevertheless, there are non-trivial numbers of faults that

\[ G \]

For the last seven circuits in Table 3, even \( n = 100 \) is

\[ G \]

We show the distribution of \( n_{\min}(g_j) \) for dvram in

\[ G \]

Figure 2, considering faults for which \( n_{\min}(g_j) \geq 100 \).

\[ G \]

Figure 2: Distribution of \( n_{\min}(g_j) \) for dvram

3. Average-case analysis

The analysis in Section 2 is a worst-case analysis since it

assumes that as long as \( n \) is low enough to allow a fault

\[ g_j \in G \]

to escape detection, a test for \( g_j \) will not be

included in an \( n \)-detection test set. In practice, this worst

case may not happen. Our goal in this section is to obtain the

probabilities of detecting the faults in \( G \) by an arbitrary

\( n \)-detection test set, for different values of \( n \).

We construct several \( n \)-detection test sets randomly

for \( n = 1, 2, \cdots, n_{\max} \) using Procedure 1 given below.

Procedure 1 constructs \( K \) test sets \( T_0, T_1, \cdots, T_{K-1} \) for

\[ n \]

every value of \( n \). Initially, \( T_k = \phi \) for \( 0 \leq k < K \). Procedure 1 performs \( n_{\max} \) iterations where it considers every

test set. At the end of iteration \( n \), \( T_k \) is an \( n \)-detection test

set, for \( 0 \leq k < K \). In iteration \( n \), Procedure 1 considers

every fault \( f_i \in F \). For \( 0 \leq k < K \), if \( f_i \) is detected by \( T_k \)

fewer than \( n \) times, and \( T(f_i) \) contains tests that are not

included in \( T_k \) (i.e., \( T(f_i) - T_k \neq \phi \)), Procedure 1 selects a

test randomly out of \( T(f_i) - T_k \), and adds it to \( T_k \).

Procedure 1: Constructing \( n \)-detection test sets

(1) For \( k = 0, 1, \cdots, K-1 \), set \( T_k = \phi \). Set \( n = 1 \).

(2) For every \( f_i \in F \):

For every test set \( T_k, k = 0, 1, \cdots, K-1 \):

(a) Find the number of times \( f_i \) is detected by

\[ T_k \]

Let this number be \( n_{i,k} \).

(b) If \( n_{i,k} < n \) and \( T(f_i) - T_k \neq \phi \):

Select a test \( t \in T(f_i) - T_k \) randomly.

Add \( t \) to \( T_k \).

(3) Set \( n = n + 1 \). If \( n \leq n_{\max} \), go to Step 2.

Using the test sets \( T_0, \cdots, T_{K-1} \) produced by Procedure 1 for every value of \( n \), we estimate the probability that an arbitrary \( n \)-detection test set will detect a fault

\[ g_j \in G \]

as follows. For every \( n \)-detection test set \( T_k \) such that \( g_j \) is detected by \( T_k \) (i.e., \( T(g_j) \cap T_k \neq \phi \)), we increment a count \( d(n, g_j) \) by one. We define the probability of detecting \( g_j \) by an arbitrary \( n \)-detection test set as

\[ p(n, g_j) = d(n, g_j)/K. \]

For illustration, we consider the example circuit of

\[ G \]

In Table 1 we show \( n \)-detection test sets for \( n = 1 \) and 2. For each value of \( n \) we have \( K = 10 \) test sets. We consider the fault \( g_k \) with \( T(g_k) = \{12\} \). For this fault, \( n_{\min}(g_k) = 4 \). For \( n = 1 \), the set \( T(g_k) \) has a non-empty intersection with \( T_3 \) and \( T_7 \). We obtain \( d(1, g_k) = 2 \) and \( p(1, g_k) = 0.2 \). For \( n = 2 \), the set \( T(g_k) \) has a non-empty intersection with \( T_3, T_4, T_5 \) and \( T_7 \). We obtain \( d(2, g_k) = 4 \) and \( p(2, g_k) = 0.4 \).

Table 4: Test sets for example circuit

| \( k \) | \( n=1 \) | \( T_k \) | \( n=2 \) |
|-------|--------|--------|--------|
| 0     | 6 8 10 13 | 2 5 6 8 10 12 13 14 |
| 1     | 0 2 7 11 13 | 0 2 4 5 7 9 10 11 13 14 |
| 2     | 3 6 8 13 | 3 4 5 6 8 9 11 13 14 15 |
| 3     | 4 5 11 14 15 | 0 3 4 5 8 9 10 11 14 15 |
| 4     | 5 6 8 10 15 | 2 5 6 8 9 10 12 15 |
| 5     | 0 5 7 9 10 11 12 | 0 5 6 7 9 10 11 12 14 |
| 6     | 4 8 9 11 14 15 | 4 5 8 9 10 11 14 15 |
| 7     | 1 3 4 6 8 12 | 1 3 4 6 8 9 10 12 13 14 |
| 8     | 3 5 7 8 9 13 14 | 3 4 5 7 8 9 10 13 14 |
| 9     | 2 5 6 8 9 15 | 2 4 5 6 8 9 10 14 15 |

We computed \( p(n, g_j) \) using \( K = 10000 \) test sets for

\[ n = 1, 2, \cdots, n_{\max} \] where \( n_{\max} = 10 \). We report the results considering only faults \( g_j \) that are not guaranteed to be detected by a 10-detection test set, and considering only circuits that have such faults. In addition, we only report the results for \( n = 10 \) (the detection probabilities for lower values of \( n \) are lower). The results are shown in Table 5 (at the end of the paper). After the circuit name we repeat

\[ G \]

the number of faults that are not guaranteed to be detected by a 10-detection test set (the number of faults with
Proceedings of the Design, Automation and Test in Europe Conference and Exhibition (DATE’05)

1

\[ n_{\min}(g_i) \geq 11 \]. We then show the numbers of faults for which the probability of detection \( p(10,g_j) \) is at least 1, 0.9, 0.8, \ldots, 0.1, 0. We do not enter a number for a given probability if all the faults have a higher probability of detection. The fault with the lowest probability for \( ex\_2 \) has \( p(10,g_j) = 0.052 \). The two faults with the lowest probabilities for \( bbse \) have \( p(10,g_j) = 0.093 \) and 0.091. The fault with the lowest probability for \( cse \) has \( p(10,g_j) = 0.043 \).

From Table 5 it can be seen that some of the faults in \( G \), that are not guaranteed to be detected by a 10-detection test set, have very high probabilities of being detected by such a test set. However, there are also non-trivial numbers of faults with lower probabilities. These faults may be left undetected by a 10-detection test set. Increasing \( n \) to detect such faults may sometimes require very high values of \( n \) as can be seen from Table 3. Overall, the average-case analysis is consistent with the worst-case analysis in pointing to the existence of untargeted faults that are not likely to be detected by a 10-detection test set.

4. Discussion

The results of the previous sections indicate the following.

An \( n \)-detection test set for a reasonable value of \( n \) (around \( n = 10 \)) is guaranteed to detect a high percentage of the untargeted faults, and will detect most of the remaining untargeted faults with a high probability. However, there are also faults that are likely to escape detection by an \( n \)-detection test set. The values of \( n \) required for such faults can be very high. Thus, increasing \( n \) is not likely to be an effective solution for improving the effectiveness of an \( n \)-detection test set.

In some situations the small loss in untargeted fault coverage may be acceptable. When it is not, direct test generation for additional fault models can be carried out. Alternatively, methods to improve the effectiveness of an \( n \)-detection test set can be used. To illustrate this point we use an alternate method to generate \( n \)-detection test sets, based on a different definition of an \( n \)-detection test set. The definition we used so far is the standard one. For completeness, we repeat this definition next.

Definition 1: Let \( T \) be a test set where no test is duplicated. A fault \( f \) is detected \( n \) times by \( T \) if \( T \) contains \( n \) tests that detect \( f \).

Under the alternate definition from [5], two tests that detect a target fault \( f \) are required to be sufficiently different in order to be counted as different detections of \( f \). The definition given in [5] is the following.

Definition 2: Let \( T \) be a test set where no test is duplicated. A fault \( f \) is detected \( n \) times by \( T \) if there exist \( n \) tests \( t_1, t_2, \ldots, t_n \) in \( T \) such that the following condition is satisfied. For every \( i \) and \( j \) such that \( 1 < i \leq n \) and \( 1 \leq j < i \), let \( t_{ij} \) be the test which is specified in bits where \( t_i \) and \( t_j \) are specified to the same value, and unspecified in other bits. The test \( t_{ij} \) does not detect \( f \).

Definition 2 simulates \( f \) under a test \( t_{ij} \) that contains the common bits of \( t_i \) and \( t_j \). If these bits are sufficient for detecting \( f \), then the two tests \( t_i \) and \( t_j \) are considered similar, and are not counted as two detections of \( f \). If \( t_{ij} \) does not detect \( f \), then \( t_i \) and \( t_j \) are considered sufficiently different, and they are counted as different detections of \( f \).

We use Definition 2 in Procedure 1 for the construction of \( n \)-detection test sets as follows. When we find the number of detections \( n_{ij} \) of a fault \( f_i \) under a test set \( T_k \), we use Definition 2 to compute \( n_{ij} \). If \( n_{ij} < n \), we find the tests out of \( T(f_i) - T_k \) that, if added to \( T_k \), will be counted as different detections of \( f_i \) according to Definition 2. If the number of detections of \( f_i \) cannot reach \( n \) according to Definition 2, we use Definition 1 instead. This is done to avoid situations where faults are detected much fewer than \( n \) times.

Results of average-case analysis based on Definition 1 and based on Definition 2 are shown in Table 6. In this case we used \( K = 1000 \) test sets for the analysis. On the first row for every circuit we show the results obtained using Definition 1, and on the second row we show the results obtained using Definition 2. We target the same set of faults in both cases.

Table 6 demonstrates that Definition 2 can improve the quality of an \( n \)-detection test set by increasing the probability that an untargeted fault will be detected by the test set. For example, out of the 474 four-way bridging faults with \( n_{\min} \geq 11 \), we use Definition 2 to compute \( n_{ij} \). Out of 381 faults are detected with probability greater than or equal to 0.8 by a standard 10-detection test set generated using Definition 1, whereas 440 faults are detected with probability greater than or equal to 0.8 if the test set is generated using Definition 2. The probabilities of detection given in Tables 5 and 6 can be used to calculate the probability that an untargeted fault escapes detection.

As noted earlier, the analysis proposed requires information regarding which targeted and untargeted faults are detected by each input vector of the circuit, and hence can be directly used for circuits with small numbers of inputs. However, as the data in Table 6 shows, the analysis can be used to evaluate the relative effectiveness of different \( n \)-detection test generation methods. Additionally, one can partition a larger circuit into smaller subcircuits and apply the analysis to the subcircuits. Such analysis can be used to evaluate the effectiveness of a chosen value of \( n \), and to estimate the probability of untargeted faults escaping detection.

5. Concluding remarks

In order to restrict the test set size, \( n \)-detection test sets are typically generated for restricted values of \( n \). We
addressed the following questions related to this restriction. (1) How much unmodeled fault or defect coverage is missed by restricting $n$. (2) How much higher should $n$ be in order to eliminate the fault or defect coverage loss. Our analysis was independent of any particular test set. We used single stuck-at faults as target faults, and four-way bridging faults as untargeted faults for the purpose of this study.

Table 3: Worst-case numbers of detected faults (large $n$)

| circuit  | faults | $n_{\text{min}}(g_f)^{\infty}$ |
|----------|--------|-------------------------------|
| ex2      | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| train4   | 2469   | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| beccount | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| cse      | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| dvramp   | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| bbara    | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| ex4      | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| keyb     | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| opus     | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| bsse     | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| cse      | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) | 0 (0.00) |

We used both a worst-case analysis and an average-case analysis to provide answers for these questions. The worst-case analysis assumed that if it is possible to generate an $n$-detection test set that will fail to detect an untargeted fault, such a test set will be generated. The average-case analysis provided the probabilities for an arbitrary $n$-detection test set to detect untargeted faults.

References

[1] S. C. Ma, P. Franco and E. J. McCluskey, “An Experimental Chip to Evaluate Test Techniques Experiment Results”, in Proc. Intl. Test Conf., 1995, pp. 663-672.

[2] J. T.-Y. Chang, C.-W. Tseng, C.-M. J. Li, M. Purcell and E. J. McCluskey, “Analysis of Pattern-Dependent and Timing-Dependent Failures in an Experimental Test Chip”, in Proc. Intl. Test Conf., 1998, pp. 184-193.

[3] M. R. Grimalia, S. Lee, J. Dworkar, K. M. Butler, B. Stewart, H. Balachandran, B. Houchins, V. Mathur, J. Park, L.-C. Wang and M. R. Mercer, “REDO - Random Excitation and Deterministic Observation - First Commercial Experiment”, in Proc. VLSI Test Symp., 1999, pp. 268-274.

[4] J. Dworkar, M. R. Grimalia, S. Lee, L.-C. Wang and M. R. Mercer, “Enhanced DO-RE-ME based Defect Level Prediction using Defect Site Aggregation-MPG-D”, in Proc. Intl. Test Conf., Oct. 2000, pp. 930-939.

[5] I. Pomeranz and S. M. Reddy, “Definitions of the Numbers of Detections of Target Faults and their Effectiveness in Guiding Test Generation for High Defect Coverage”, in Proc. Conf. on Design Automation and Test in Europe, March 2001, pp. 504-508.

[6] C.-W. Tseng and E. J. McCluskey, "Multiple-Output Propagation Transition Fault Test", in Proc. Intl. Test Conf., 2001, pp. 358-366.

[7] S. Venkataraman, S. Sivaraj, E. Amyeen, S. Lee, A. Ojha and R. Guo, "An Experimental Study of n-Detect Scan ATPG Patterns on a Processor", in Proc. 22nd VLSI Test Symp., April 2004, pp. 23-28.

[8] S. Sengupta et. al., "Defect-Based Tests: A Key Enabler for Successful Migration to Structural Test", Intel Technology Journal, Q.1, 1999.

[9] V. Krishnaswamy, A. B. Ma, P. Vishakantaiah, "A Study of Bridging Defect Probabilities on a Pentium (TM) 4 CPU", in Proc. Intl. Test Conf., 2001, pp. 688-695.

[10] S. Chakravarty, A. Jain, N. Radhakrishnan, E. W. Savage and S. T. Zachariah, "Experimental Evaluation of Scan Tests for Bridges", in Proc. Intl. Test Conf., 2002, pp. 509-518.
### Table 6: Average-case probabilities of detection under Definitions 1 and 2

| circuit | faults | def | 1   | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 | 0.0 |
|---------|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| bbsse   | 21   | 1   | 8   | 14  | 16  | 16  | 18  | 19  | 20  | 20  | 21  |     |     |
|         |   2   |     | 10  | 18  | 19  | 20  |     |     |     |     |     |     |     |
|         | 172  | 1   | 115 | 143 | 147 | 150 | 152 | 153 | 153 | 153 | 156 | 170 | 172 |
|         |   2   |     | 130 | 156 | 161 | 163 | 164 | 165 | 165 | 165 | 165 | 171 | 172 |
| bbsse   | 2    | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 2   |     |
|         |       | 2    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |     |     |     |
| cse     | 79   | 1   | 50  | 76  | 77  | 77  | 77  | 77  | 78  | 78  | 78  | 79  |     |
|         |       | 2    | 66  | 78  | 78  | 78  | 78  | 78  | 78  | 78  |     |     |     |
| dvram   | 1653 | 1   | 1076 | 1493 | 1532 | 1564 | 1573 | 1610 | 1611 | 1618 | 1623 | 1637 | 1653 |
|         |       | 2    | 1382 | 1597 | 1620 | 1625 | 1628 | 1635 | 1643 | 1645 | 1649 |     |     |
| ex4     | 82   | 1   | 40  | 82  |     |     |     |     |     |     |     |     |     |
|         |       | 2    | 61  | 82  |     |     |     |     |     |     |     |     |     |
| ex6     | 16   | 1   | 1   | 14  | 15  | 15  | 15  | 15  | 15  | 15  | 15  | 16  |     |
|         |       | 2    | 2   | 16  |     |     |     |     |     |     |     |     |     |
| fetch   | 708  | 1   | 564 | 680 | 695 | 695 | 696 | 701 | 705 | 705 | 708 |     |     |
|         |       | 2    | 601 | 693 | 704 | 704 | 705 | 705 | 705 | 705 | 708 |     |     |
| keyb    | 474  | 1   | 186 | 371 | 381 | 418 | 424 | 429 | 434 | 443 | 446 | 453 | 474 |
|         |       | 2    | 274 | 426 | 440 | 458 | 461 | 465 | 468 | 470 | 473 | 473 | 474 |
| log     | 199  | 1   | 121 | 167 | 172 | 172 | 172 | 172 | 172 | 193 | 193 | 199 |     |
|         |       | 2    | 164 | 193 | 193 | 193 | 193 | 193 | 193 | 193 | 193 |     |     |
| mark1   | 100  | 1   | 50  | 87  | 93  | 93  | 95  | 98  | 98  | 98  | 100 |     |     |
|         |       | 2    | 59  | 90  | 95  | 95  | 95  | 95  | 95  | 95  |     |     |     |
| opus    | 49   | 1   | 15  | 40  | 46  | 47  | 49  |     |     |     |     |     |     |
|         |       | 2    | 27  | 44  | 46  | 47  | 49  |     |     |     |     |     |     |
| rie     | 1197 | 1   | 796 | 1046 | 1068 | 1070 | 1070 | 1134 | 1134 | 1134 | 1179 | 1179 | 1179 |
|         |       | 2    | 1071 | 1144 | 1146 | 1169 | 1177 | 1179 | 1179 | 1179 | 1179 | 1179 | 1179 |
| s1a     | 5934 | 1   | 3412 | 4984 | 5263 | 5432 | 5495 | 5599 | 5659 | 5777 | 5833 | 5879 | 5934 |
|         |       | 2    | 4617 | 5566 | 5673 | 5756 | 5794 | 5855 | 5891 | 5912 | 5924 | 5925 | 5934 |