Sequential n-Detection Criteria: Keep It Simple!

Ilia Polian[1] Martin Keim[2] Nicolai Mallig[1] Bernd Becker[1]

[1] Albert-Ludwigs-University
Georges-Köhler-Allee 51
79110 Freiburg im Breisgau, Germany
< polian, mallig, becker >@informatik.uni-freiburg.de

[2] Mentor Graphics Corp.
8005 SW Boeckman Road
Wilsonville, OR, 97070
martin_keim@mentor.com

1 Theory

The idea of n-detection is to exposure a target fault in n *different* ways [1, 3]. A major concern about the n-detection has been the question whether different test vectors really do excite the fault in different ways leading to different activation and propagation conditions [2]. A special problem was the lack of methodology for answering this question. Our goal was to develop such a methodology and to evaluate its usefulness.

In this paper, we propose four new criteria called *difference types* for a pair of sequences. Here, we only consider test sequences of equal length which are minimal in the sense that they do not contain a sub-sequence that also detects the fault. Thus, the detection takes place in the last time frame of the sequence. Given two sequences, both detecting the same stuck-at fault f, we define the following four difference types:

Type A: The circuit has two outputs i and j, so that one sequence detects the fault f at the output i (i. e. at the output i the response of the correct and the faulty circuit differ) but not at the output j, whilst the other sequence detects f at the output j and does not at the output i.

Type B: The circuit has an output i, so that one sequence, S, detects the fault f at this output, and the other sequence, T, does not. Additionally, there must not be another output j, at which the sequence S does not detect f and the sequence T does, i. e. the set of outputs, at which the former sequence detects the fault f, includes the set of outputs, at which the latter one does.

Type C: The circuit has an output i, so that both sequences detect the fault f at this output. However, for one sequence the value at the output i is 1 for the correct and 0 for the faulty circuit, and for the other sequence the correct value is 0 and the faulty value is 1.

Type D: The circuit has an output i, so that both sequences detect the fault f at this output. For at least one time frame *before the detection*, the values on this output differ for the two sequences.

Note that sequence's difference is defined with respect to the fault f. Two sequences, S and T, may be different according to type A wrt the fault f_1, different according to type B wrt the fault f_2, not different for any difference type wrt the fault f_3, and not detect at all the fault f_4.

All proposed difference types deal only with values on circuit outputs for different test sequences and the correct and faulty versions of the circuit (*black box* view of the circuit). We feel that criteria evaluating some conditions in the near surroundings of the fault f would be a more accurate approach, but we also think that the computational complexity of these evaluations would be very high. This is why we concentrate in this work on circuits modeled as black boxes.

Finally, we call two sequences *non-identical* if they have different Boolean values in the same position. We consider this as the most trivial criterion for difference.

We concentrate on *minimal-length* test sequences that are of the same length. To obtain such sequences, we symbolically generate the sequences for a given stuck-at fault by a standard BDD-based algorithm. For a given upper bound l, we try to construct a test sequence of length 1, 2, . . . , l, but terminate when we succeed and return the results . The described method guarantees to generate *all* test sequences of minimal length.

The goal of stuck-at n-detection is to detect many real defects. To measure the efficiency of a test set in detecting real defects, the following approach is often chosen: a *non-target fault model* is selected, and the coverage with respect to this model is measured. Ideally, the fault model should closely correspond to real world's defects.

In this work, we use a bridging fault-based non-target fault model (RBFM) for evaluating n-detect sequences.

2 Experimental Results

2.1 Different Sequences and RBFM Coverage

In the first experiment, we concatenated five minimal test sequences in various ways and studied the dependency between n-detection and RBFM coverage of the sequences. First, minimal test sequences were generated for each stuck-at fault.

Let a, b, c, d, and e be five pairwise different sequences with respect to a difference type. Then, we obtain by concatenation the following sequences: 'aaaaa', 'ababa', 'abcab', 'abcda', and 'abcde', and determine the RBFM coverage of these sequences.

The average fault coverage for all stuck-at faults in question is given in Table 1, and in Table 2, the *percental increase* of the average fault coverage compared to the average fault coverage of the sequence 'aaaaa' is reported. One may have expected that one difference type would turn out to be superior to the others in sense that a high number of subsequences *different* with respect to this type would lead to a noticeable better RBFM coverage. On one hand, there seems to be a larger percental increase for the criteria A and D compared to the criteria B and C. On the other hand, the fault coverages for the sequence 'aaaaa' differ for various criteria, and the largest percental increase seems to be achieved in

Proceedings of the Eighth IEEE International On-Line Testing Workshop (IOLTW'02)
0-7695-1641-6/02 $17.00

Circuit	Diff.	No of	RBFM FC for concatenated seq.				
	Type	Seq.	aaaaa	ababa	abcab	abcda	abcde
s298	C	2.00	62.30	75.95	75.95	75.95	75.95
s344	A	3.81	65.45	74.75	78.84	79.19	79.24
s344	B	3.17	69.33	76.86	78.82	79.83	79.83
s344	C	3.05	66.45	75.08	75.84	77.60	77.63
s344	D	3.79	68.30	78.79	81.19	82.49	82.93
s349	A	3.74	64.77	74.48	78.39	78.72	78.78
s349	B	2.96	70.53	76.98	79.20	79.89	79.91
s349	C	3.05	68.54	76.15	77.66	79.01	79.01
s349	D	3.76	68.53	78.50	80.87	82.28	82.76
s386	A	2.10	5.39	7.20	7.17	7.17	7.17
s386	B	2.27	5.03	6.50	6.63	6.67	6.67
s386	C	2.00	8.98	9.72	9.72	9.72	9.72

Table 1: RBFM Fault Coverage, average numbers

Circuit	Diff.	FC Increase compared to aaaaa			
	Type	ababa	abcab	abcda	abcde
s298	C	21.90	21.90	21.90	21.90
s344	A	14.21	20.46	21.00	21.08
s344	B	10.87	13.70	15.15	15.15
s344	C	12.98	14.13	16.77	16.81
s344	D	15.37	18.87	20.78	21.43
s349	A	15.00	21.03	21.53	21.64
s349	B	9.15	12.29	13.26	13.30
s349	C	11.10	13.30	15.29	15.29
s349	D	14.54	18.01	20.06	20.76
s386	A	33.52	32.97	32.97	32.97
s386	B	29.22	31.69	32.42	32.42
s386	C	8.32	8.32	8.32	8.32

Table 2: Percental increase of the average

Circuit	Diff.	No of	RBFM coverage of sequence...				
	Type	Seq.	1	2	3	4	5
s298	C	2.00	85.32	84.60	84.60	84.60	84.60
s344	A	3.81	79.85	80.93	80.60	80.30	79.93
s344	B	3.17	81.97	82.33	82.32	81.77	81.77
s344	C	3.05	82.28	81.81	82.02	81.55	81.72
s344	D	3.79	83.96	83.99	84.39	84.25	84.01
s349	A	3.74	80.96	80.34	80.41	80.82	80.52
s349	B	2.96	82.75	82.45	82.35	82.08	81.95
s349	C	3.05	83.10	82.59	83.08	82.75	82.75
s349	D	3.76	84.42	84.00	84.03	83.95	83.72
s386	A	2.10	8.80	8.45	8.44	8.44	8.44
s386	B	2.27	7.89	7.50	7.67	7.67	7.67
s386	C	2.00	11.16	12.69	12.69	12.69	12.69

Table 3: Difference type-based N-detection, average

Circuit	Diff.	FC increase compared to $s_1r_1r_2r_3r_4$			
	Type	2	3	4	5
s298	C	-0.75	-0.75	-0.75	-0.75
s344	A	1.36	0.95	0.58	0.11
s344	B	0.44	0.42	-0.24	-0.24
s344	C	-0.57	-0.32	-0.88	-0.68
s344	D	0.03	0.51	0.35	0.06
s349	A	-0.76	-0.67	-0.17	-0.54
s349	B	-0.37	-0.49	-0.82	-0.97
s349	C	-0.61	-0.02	-0.42	-0.42
s349	D	-0.49	-0.46	-0.55	-0.83
s386	A	-3.99	-4.17	-4.17	-4.17
s386	B	-4.91	-2.73	-2.73	-2.73
s386	C	13.71	13.71	13.71	13.71

Table 4: Increase of the average, %

cases where the coverage for 'aaaaa' is low. Thus, we conclude that *none of the presented four difference types seems to be clearly superior to others regarding accuracy in predicting non-target fault coverage.*

2.2 Difference Type-Based n-Detection Sequence Generation

In the second experiment, we tried to guide the n-detection test sequence generation by our difference types and evaluated the efficiency of so-obtained sequences. For each stuck-at fault and for each difference type we generated five *different* sequences s_1, s_2, s_3, s_4, and s_5. Furthermore, we generated a pool of additional test sequences, for which no information is collected, whether or not they are different according to type A – D. From this pool, we selected randomly four sequences r_1, r_2, r_3, and r_4.

Next, we constructed five sequences: $s_1r_1r_2r_3r_4$ (1), $s_1s_2r_1r_2r_3$ (2), $s_1s_2s_3r_1r_2$ (3), $s_1s_2s_3s_4r_1$ (4), and $s_1s_2s_3s_4s_5$ (5) by concatenation, and estimated the defect detection efficiency by determining the RBFM coverage.

The average numbers are reported in Table 3, and the percental increase of the average fault coverage (compared to the average fault coverage of the sequence $s_1r_1r_2r_3r_4$) is presented in Table 4.

Both, improvement and deterioration of the fault coverage on average can be observed. However, no sensible regularity is visible. This suggests that the variations are within statistical noise. The statistical independence of n detections does not seem to rise when using the difference types.

We conclude that the proposed difference types are not suited for generating test sequences with higher RBFM coverage. More precisely, this means that the statistical independence of n-detection sequences generated by concatenating of n non-identical sub-sequences, is already sufficiently high. In contrast, taking sequences, which are *different* according to type A, B, C, or D, does not seem to improve the efficiency.

On the other hand, the first experiment demonstrated that applying the same sequence several times leads to decreasing fault coverage compared to applying non-identical sequences. Thus, it is important to use non-identical sequences. However, the simplest definition of *difference* seems to be as competitive as sophisticated definitions.

Altogether, our results show that the simplest n-detection criterion, taking non-identical sub-sequences, does a good job and that no sophisticated criteria are needed to achieve high defect coverage.

References

[1] S.C. Ma, P. Franco, and E.J. McCluskey. An experimental chip to evaluate test techniques experimental results. In *Int'l Test Conf.*, pages 663–672, 1995.

[2] I. Pomeranz and S.M. Reddy. On n-detection test sequences for synchronous sequential circuits. In *VLSI Test Symp.*, pages 336–342, 1997.

[3] S.M. Reddy, I. Pomeranz, and S. Kajihara. On the effects of test compaction to defect coverage. In *VLSI Test Symp.*, pages 430–435, 1996.