HyHOPE: Fast fault simulator with efficient simulation of hypertrophic faults

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Abstract: In sequential circuit fault simulation, hypertrophic faults, which result from a lengthened initialisation sequence in faulty circuits, usually produce a large number of fault events during simulation and require excessive gate evaluations. These faults degrade the performance of fault simulators attempting to simulate them exactly. In the paper, an exact simulation algorithm is developed to identify hypertrophic faults and to minimise their effects during fault simulation. The simulator HyHOPE, based on this algorithm, shows that the average speed-up ratio over HOPE for test vectors generated by STG3 is 1.65. Furthermore, the results indicate that the performance of HyHOPE is close to the approximate simulator, in which hypertrophic faults are simply dropped when they become potentially detected.

1 Introduction

Fault simulation has played a major role in VLSI testing. Its applications range from grading the quality of test sets to incorporating ATPG in test generation [17–20]. As the size of VLSI circuits grows larger, efficient fault simulation algorithms have been developed to meet the challenge [1–16]. These algorithms are highly refined for their domains of application. In this paper, we are mainly concerned with fault simulation algorithms for single stuck-at faults of synchronous sequential circuits.

One popular simulation algorithm is the concurrent fault simulation algorithm [13]. In concurrent fault simulation, a descriptor for a faulty circuit is present in the fault list of a gate only if the faulty-circuit status is different from that of the good circuit. A fault copy for a gate is simulated only when the fault is in the fault list, and a logic event or a fault event of this gate input occurs. The major advantage of concurrent fault simulation is its versatility. It is applicable to mixed-level circuits, various numbers of signal values and any gate delay model [14]. However, it requires large memory, and its performance is slower than the other fault simulation algorithms to be discussed below.

Most recently developed fault simulation algorithms are based on the single-fault propagation algorithm

ROOFS [3]. In single-fault propagation [1], faults are simulated one at a time, and only the difference between a faulty circuit and the good circuit is simulated. Furthermore, only a linked list is maintained for each faulty circuit to record its difference in status from the good circuit. Within the circuit, one set of fault-status words is maintained and shared by all faults. Hence, the memory requirement is much lower than for concurrent fault simulation. To efficiently simulate one fault after another without restoring status, for each simulated fault of each time frame, ROOFS assigns a unique simulation ID to indicate whether the fault-status word belongs to the currently simulated faulty circuit. Using this technique, the number of gate evaluations is significantly reduced.

Based on ROOFS, various parallelisation techniques have been proposed to improve performance further. Two fault simulators endeavour to parallelise the test vectors: PSF [6] and PARIS [7]. The major difference between PSF and PARIS lies in their way of grouping test vectors into a packet, or computer word. In PSF, the test sequence is partitioned into consecutive subsequences, whereas a packet in PARIS represents consecutive test vectors. Owing to a different test sequence arrangement, PSF performs multiple-pass simulation, and PARIS performs multiple iterations for a packet to obtain accurate results. Both PSF and PARIS can achieve significant speed-up over ROOFS, although their performance is somewhat correlated with the circuit types.

PROOFS [3, 4] is the parallel-fault enhancement of ROOFS. In PROOFS, a packet of 32 active faults is injected and simulated together using bit parallelism of computer word operation. In addition to simulating faults in parallel, PROOFS dynamically arranges the faults in a packet such that only the active faults are simulated. An even more efficient parallel-fault simulator, HOPE, is proposed in Reference 5. In HOPE, an active fault at a time frame is categorised as a single-event fault, if the fault effect originates only from the fault site, i.e. the present state of the faulty circuit is the same as that of the good circuit. The single-event faults are then simulated with sophisticated techniques similar to those found in combinational fault simulation. The results in Reference 5 show that, on average, 67% of faults are screened out, and a speed-up of 2 is obtained, compared with PROOFS.

Despite these sophisticated techniques, the efficiency of the fault simulated algorithms above depends on the

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degree of difference between a good circuit and its faulty versions, i.e. the fault effects. For most faults, the fault effects are few in number, and these simulators attain high efficiency by evaluating only a small number of gates for each fault. However, there are usually some faults in a circuit that take a longer sequence and are difficult to initialise. Hence, while a good circuit is initialised, these faults produce a great number of unknown values (X s), which are evidently different from good circuit values. As a result, a simulator taking advantage of such differences ends up heavily loaded with a large number of gate evaluations for the hypertrophic faults. Such faults are named hypertrophic faults in Reference 10. In HOPE, almost half the fault events are from such hypertrophic faults on ISCAS89 benchmark circuits, with test sequences generated by the reversed-time-approach test generator STG3 [18–20]. Its performance suffers greatly from these faults. This phenomenon has long been known, and the traditional way of dealing with hypertrophic faults is to drop these faults as potentially detected once the faulty X s propagate to POs along with known good circuit values. Accuracy is thus sacrificed for higher simulation speed.

In this paper, we propose a novel and exact fault simulation algorithm to identify hypertrophic faults during fault simulation and to simulate efficiently hypertrophic faults for sequential circuits, such that their adverse effect on performance is minimised. Based on the simulation algorithm proposed, the reduction of gate evaluations resulting from hypertrophic faults is three-fold:

- (a) The algorithm performs gate evaluation only when there is a difference with the previous time frame rather than with the good circuit.
- (b) Each fault is simulated in parallel with logic simulation.
- (c) The faulty circuits of various hypertrophic faults are simulated in parallel for an even greater reduction.

From this algorithm, a fault simulator for efficient and exact hypertrophic fault simulation, HyHOPE, is implemented on the framework of HOPE. The experimental results show that HyHOPE reduces above 40% of gate evaluations for faulty-circuit simulation of HOPE, and the average speed-up ratio over HOPE for test vectors generated by STG3 is 1.65. Furthermore, the results indicate that the performance of HyHOPE is close to an approximate version of HOPE, in which potentially detected faults are dropped.

2 Hypertrophic faults

In this Section, the behaviour of hypertrophic faults and their identification will be described. Furthermore, the key observation for reducing the hypertrophic fault effect will be discussed.

2.1 Definition

Hypertrophic faults [10] are faults that lengthen the initialisation of faulty circuits and, during this period, cause the status of many gates in the faulty circuits to remain unknown (X s), when the good circuit has been initialised. In general, such hypertrophic faults in a circuit are few in number and are usually associated with control lines, such as faults on reset lines. However, their fault effects, or difference from a good circuit, spread widely at each time-frame and generate a great number of fault events and gate evaluations, such that the performance of fault simulators is significantly degraded. The degradation in

performance stems from the fact that modern fault simulators count precisely on the small difference between the good circuit and its faulty versions. This difference is small for nonhypertrophic faults, which form the majority, and these fault simulators achieve good efficiency. The opposite characteristic of hypertrophic faults seriously affects the attainable efficiency of these simulators.

To handle hypertrophic faults, two approaches have been taken in the literature. One approach is to handle these faults implicitly, through either dynamic fault ordering [11] or dynamic fault grouping [12]. Both manipulate the ordering or group of faults during simulation to reduce the fault events. This approach is intuitive, but the improvement is not significant. In particular, the results of Reference 12 show that the number of fault events can only be reduced about 17% for two of the benchmark circuits and, for the other circuits, dynamic fault grouping gives an even smaller reduction.

Another approach is to relax the detection condition from sure detection to potential detection. A fault is surely detected if the fault produces a complementary value of the good circuit at primary outputs. A fault is potentially detected if there exists a primary output whose faulty-circuit value is unknown when the good-circuit value is known. As most hypertrophic faults are also potentially detectable, if a fault is dropped when it is potentially detected, the simulation time will be significantly reduced. Once it has been dropped, a potentially detected fault's detectability remains uncertain, even though some faults still have the possibility of being surely detected in later time frames. Accuracy is thus traded for faster simulation time. The simulation result is approximate rather than exact.

We propose an exact fault simulator that minimises the simulation requirement for hypertrophic faults. First, the identification of hypertrophic faults will be described.

2.2 Identification

The first step when handling hypertrophic faults is to identify these faults during the simulation. There have been a few methods to identify a hypertrophic fault. It can be either simply a fault that has been potentially detected or, as in Mozart [10], a fault whose difference from the good circuit is comparable in size to the good-circuit events. These methods are more suitable for approximate fault simulation, in which these identified faults are dropped.

To simulate hypertrophic faults exactly without incurring much overhead, these faults should be identified based on the estimation of X s at the next time frame. The number of flip-flops at which the faulty-circuit values are unknown and different from those of the good circuit is a good estimate for this purpose. Since from more X s at FFs, it is more likely that the difference with good circuit at the next time frame will be larger. If such a fault count is larger than a predetermined threshold value, the fault is identified as hypertrophic. The lower the threshold value, the sooner a hypertrophic fault is identified. However, there is a risk that some faults will be incorrectly identified as hypertrophic. Hence, the threshold value is a trade-off between these two extremes. In our implementation, the threshold value is empirically determined as 5% of the number of flip-flops in a circuit. The overhead for identification is negligible compared with the entire simulation time.

2.3 Key observation

Once the hypertrophic faults have been identified, an effective simulation algorithm can be developed to simu-

late them exactly. The simulation algorithm is based on the following observation: In event-driven simulation algorithms (logic or fault simulation) gate evaluation is required for a gate if any event occurs in the gate inputs. In other words, gate evaluation is required if the gate input status is different from the reference circuit status. The reference circuit can be the same circuit in the previous time frame, as in logic simulation, or the good circuit in the same time frame, as in ROOFS. Hence, a fault simulation algorithm is more efficient if it has fewer fault events. The following observation shows that hypertrophic fault events can be reduced if a proper reference circuit is chosen:

Key observation: A hypertrophic fault tends to have fewer events with respect to the same faulty circuit in the previous time frame than with respect to the good circuit. Furthermore, these events are highly correlated with the logic events of the good circuit. In other words,

$$|E_{f-g}| \gg |E_f - E_g|$$

where E_{f-g} are the events corresponding to the difference between the faulty circuit and the good circuit in the current time frame; E_f are the events corresponding to the difference in the faulty circuit between the current time frame and the previous time frame, E_g are the logic events corresponding to the difference in the good circuit between the current time frame and the previous time frame; and the minus sign in $E_f - E_g$ is the set difference.

The validity of the observation can be demonstrated in Table 1 and will be further discussed in the gate evaluation analysis in Section 4.

Table 1: Hypertrophic fault events

Circuit	Number of hypertrophic faults	$ E_g $	$ E_{f-g} $	$ E_f - E_g $	$\frac{ E_f - E_g }{ E_{f-g} }$
s382	19	73459	3757416	71298	0.02
s444	19	73349	3270133	65341	0.02
s526	27	36177	1523038	88767	0.06
s1488	7	255948	1396374	121877	0.09
s35932	10	751122	2971640	458875	0.15

ation analysis in Section 4. In this Table, five ISCAS89 circuits with only hypertrophic faults are simulated with STG3 test vectors. The hypertrophic faults are identified as described previously. For each circuit, $|E_{f-g}|$ and $|E_f - E_g|$ of all identified hypertrophic faults are listed in columns 4 and 5, and their ratio is given in the last column. The ratio clearly shows that $|E_f - E_g|$ is far less than $|E_{f-g}|$, being less than 15% for all listed circuits.

From this key observation, an efficient simulation algorithm targeted for hypertrophic faults will be proposed in the following Section.

3 HyHOPE

3.1 Algorithm

The above observation suggests that the hypertrophic faults should be simulated in parallel with logic simulation. Based on the key observation, the reduction of gate evaluations for hypertrophic faults is achieved in three ways:

(a) Reduce the simulation loads of the hypertrophic fault by simulating only the difference between two consecutive time frames of a faulty circuit, instead of simulating its huge differences from the good circuit.

(b) Combine the simulation of hypertrophic faults with logic simulation.

(c) In addition, simulate the hypertrophic faults in parallel.

For non-hypertrophic faults, algorithms such as ROOFS-based algorithms are preferred, as these faults are only slightly different from the good circuit. Therefore the HyHOPE algorithm is as shown in Fig. 1.

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All faults are in the regular fault list FL;
For each test vector {
    simulate good circuit and hypertrophic faults in parallel;
    drop detected hypertrophic faults;
    while (there are faults in FL not simulated for this vector) {
        simulate fault(s) with the ROOFS-based algorithm;
        identify hypertrophic faults;
        for each identified hypertrophic fault{
            mark the fault as hypertrophic fault;
            remove it from FL;
        }
    }
}

```

Fig. 1 HyHOPE algorithm

This simulation algorithm is essentially to simulate hypertrophic faults, as in the classical parallel-fault simulation [16], in which all faults are grouped into packets, and each packet of faults is simulated in parallel with the good circuit. The classical parallel fault simulation is not efficient, because most faults are non-hypertrophic and produce a difference from the good circuit smaller than that from the faulty circuits in the previous time frame. On the other hand, only the hypertrophic faults are in parallel simulated with the good circuit in HyHOPE. The key concept of the HyHOPE algorithm is that, by identifying the hypertrophic faults, we are able to simulate both kinds of fault, hypertrophic and non-hypertrophic, in the most efficient way.

3.2 Implementation

In this Section, the implementation of HyHOPE is given.

The proposed algorithm for simulating hypertrophic faults can be incorporated with existent fault simulators, such as ROOFS, and its parallel-fault versions, PROOFS and HOPE. We developed our simulator HyHOPE upon HOPE because the latter has the best performance and, most importantly, its source has been made publicly available by its authors.

In HyHOPE, procedures for hypertrophic fault identification and processing are built upon the original simulation mechanism of HOPE. Therefore the proven techniques of HOPE, such as using single-fault propagation to screen out single event faults with a short propagation path and using parallel-fault simulation to simulate multiple event faults and stem faults, are retained in HyHOPE for non-hypertrophic faults. All faults in the regular fault list are initially classified as non-hypertrophic. After a packet of faults has been simulated, the hypertrophic fault identification procedure is invoked to identify hypertrophic faults. The identified faults are then removed from the regular fault list into a hypertrophic fault list. At the next time frame, the faults in the hypertrophic fault list are simulated in parallel with the logic simulation. The original procedure for logic simulation is enhanced such that the good circuit and faulty circuits of hypertrophic faults can be simulated simultaneously. A fault in the hypertrophic fault list remains in the list until the fault is detected and dropped.

Accordingly, some data structures in HOPE are also modified. In HyHOPE, an extra word pair for each gate

is added to record in parallel the good-circuit status and the hypertrophic faulty-circuit status. This word pair is evaluated during the parallel simulation of good and hypertrophic faulty circuits. The first bit of the word pair is used to represent the good-circuit status. After the parallel simulation, its value is copied to original computer words representing the good-circuit status. The original good-circuit words are used for both parallel-fault simulation and single-fault propagation of non-hypertrophic faults, as in HOPE. It is possible to remove the original good-circuit words as, in HyHOPE, there is already a bit pair representing the good-circuit status. However, the good-circuit status then has to be retrieved during non-hypertrophic fault simulation and more overhead will be introduced in each gate evaluation. As the number of logic events is generally less than the number of fault events in sequential circuit fault simulation, we eliminate this overhead with a small increase in memory space.

In the present implementation of HyHOPE, the maximum number of hypertrophic faults to be simulated in parallel with logic simulation is limited by the given computer word length: 32 minus one for good-circuit simulation in our case. The hypertrophic fault identification procedure will not be invoked by HyHOPE when the number of currently simulated hypertrophic faults is equal to 31. The number limitation does not affect the performance of HyHOPE in the evaluation, as the number of hypertrophic faults is small in general, and the space is reused when some identified hypertrophic faults are detected. We would also like to point out that the hypertrophic fault packet size can be extended to more than one word, and many hypertrophic faults can be simulated simultaneously when more than 31 hypertrophic faults are identified.

4 Gate evaluation analysis

In this Section, the efficiency of various fault simulation algorithms will be discussed, based on analysis of the cases for which gate evaluation must be performed.

In event-driven simulation, a gate evaluation may occur when a value transition of a gate input between two consecutive time frames or a value difference between good and faulty circuits takes place. Table 2 shows all the cases for changing status at a gate input between two consecutive time frames T_{i-1} and T_i , for a fault. These cases are enumerated according to the four following conditions:

- the faulty-circuit status F_{i-1} is different from the good-circuit status G_{i-1} at T_{i-1} ,
- the good-circuit status is changed from T_{i-1} to T_i ,
- the faulty-circuit status is changed from T_{i-1} to T_i ,
- the faulty-circuit status F_i is different from the good-circuit status G_i at T_i .

A datum of value 1 in Table 2 indicates that a gate input meets the condition; otherwise, the value 0 is given. It is easy to see that four of the cases are not possible, and C_0 , C_6 and C_9 result in no gate evaluation in a worthy fault simulator.

For a given simulation algorithm, a case may or may not result in gate evaluation, and these characteristics determine the efficiency of the simulator. The simulation algorithms of ROOFS, concurrent-fault simulation and HyHOPE for hypertrophic faults are considered in this Section. Note that the discussion on ROOFS can also be applicable to its various parallelised versions, PROOFS and HOPE, because the parallelisation of faults can reduce but not completely eliminate the gate evaluations in the cases in Table 2.

In Fig. 2, the cases for which a simulation algorithm must perform gate evaluation are shown in the shaded area of the gate evaluation map. For example, a gate is evaluated in ROOFS for a fault if the gate has a gate input that falls into any of the cases C_3 , C_5 , C_7 , C_9 , C_{11} , C_{13} and C_{15} . In concurrent-fault simulation, gate evaluation is performed for a fault if any of the cases C_3 , C_5 , C_7 , C_{10} , C_{11} , C_{12} , C_{13} , C_{14} , C_{15} , and C_{6-9} occurs, where C_{6-9} is the case where a gate has inputs that satisfy both conditions of C_6 and C_9 . This is the case that a fault is in the fault list of the gate, and there are also logic events at gate inputs.

For both ROOFS and concurrent-fault simulation, these cases, indicated in their respective maps, are associated with gate evaluations independent of those of logic simulation, i.e. the gate evaluations of faults resulting from these cases must be performed in addition to those of Fig. 2a. On the other hand, for the hypertrophic faults in HyHOPE, they are simulated in parallel with logic simulation, and, hence, some of their gate evaluation cases coincide with those of logic simulation, as indicated in Fig. 2d. Therefore only the non-coincident cases, C_3 , C_{10} , and C_{11} , result in additional gate evaluations. As a result, it can be concluded that HyHOPE is superior to concurrent-fault simulation in dealing with hypertrophic faults, because the shaded area of the latter covers more than C_3 , C_{10} , and C_{11} and thus needs more gate evaluations than HyHOPE.

Table 2: Cases of gate evaluation

Case	Gate input status				Examples
	$F_{i-1} \neq G_{i-1}$	$G_{i-1} \neq G_i$	$F_{i-1} \neq F_i$	$F_i \neq G_i$	
C_0	0	0	0	0	0, x
C_1	0	0	0	1	impossible
C_2	0	0	1	0	impossible
C_3	0	0	1	1	$1 \rightarrow 1/0, x \rightarrow x/0$
C_4	0	1	0	0	impossible
C_5	0	1	0	1	$1 \rightarrow 0/1, x \rightarrow 0/x$
C_6	0	1	1	0	$0 \rightarrow 1, 1 \rightarrow 0$
C_7	0	1	1	1	$x \rightarrow 1/0, 0 \rightarrow 1/x$
C_8	1	0	0	0	impossible
C_9	1	0	0	1	$1/0, 1/x$
C_{10}	1	0	1	0	$1/0 \rightarrow 1, 1/x \rightarrow 1$
C_{11}	1	0	1	1	$1/x \rightarrow 1/0, 1/0 \rightarrow 1/x$
C_{12}	1	1	0	0	$1/0 \rightarrow 0, 1/x \rightarrow x$
C_{13}	1	1	0	1	$1/x \rightarrow 0/x, x/0 \rightarrow 1/0$
C_{14}	1	1	1	0	$1/0 \rightarrow x, 1/x \rightarrow 0$
C_{15}	1	1	1	1	$1/0 \rightarrow 0/1, 1/x \rightarrow 0/1$

The gate evaluation maps of ROOFS and HyHOPE show that, for hypertrophic faults, ROOFS has extra gate evaluations for C_5 , C_7 , C_9 , C_{13} and C_{15} , compared with

Fig. 2 Gate evaluation maps for various fault simulation algorithms

a Logic simulation

b ROOFS (all faults)

c Concurrent-fault simulation (all faults)

d HyHOPE (hypertrophic faults)

■ The darkly shaded area indicates the cases for which a simulation algorithm must perform gate evaluations

■ For concurrent-fault simulation, in addition to the dark shaded area, gate evaluation is required for the case C_{6-9} indicated by the lightly shaded area in c

■ Simulation for hypertrophic faults in HyHOPE is combined with logic simulation, as indicated by the dotted area in d

HyHOPE, whereas HyHOPE has an extra evaluation for C_{10} compared with HOPE. From Table 2, it can be seen that C_{10} occurs when the faulty circuit changes status while the good circuit remains unchanged. For hypertrophic faults, such an occurrence is far less likely than cases such as C_5 , C_9 and C_{13} , for which the faulty circuit is plagued by X s and the good circuit has known status. As a result, HyHOPE can achieve better efficiency than ROOFS for hypertrophic faults. As HyHOPE adopts the same algorithm as ROOFS for non-hypertrophic faults, the overall performance of HyHOPE is significantly better than ROOFS-based simulators, as will be demonstrated experimentally in the following Section.

It is also interesting to compare ROOFS and concurrent-fault simulation in terms of gate evaluation maps. For lightly active faults, ROOFS is superior to the concurrent-fault simulation, because the restoration, C_{10} and C_{12} , is not required in ROOFS. As most faulty circuits are only slightly different from the good circuit, it can be concluded that ROOFS is more efficient than the concurrent-fault simulation. The conclusion is clearly demonstrated by the results in References 2 and 3, in which ROOFS had much fewer events than an existent concurrent-fault simulator CSIM [15] for all evaluated circuits. However, for hypertrophic faults, the area of $\{C_5, C_9, C_{12}, C_{13}\}$ is likely to be larger than others, as most of the faulty-circuit statuses of a hypertrophic fault remain unknown. Notably, the size of C_9 is conceivably large for a hypertrophic fault. Thus it would degrade the performance of ROOFS, and concurrent-fault simulation, although not as efficient as HyHOPE, might be more effective than ROOFS for hypertrophic faults, although there have not yet been any published results detailed enough to support this deduction.

The above analysis indicates that the simulation algorithm for hypertrophic fault in HyHOPE is superior to the concurrent-fault simulation and ROOFS. In the following Section, experimental results will be given to show that HyHOPE indeed has better performance than HOPE, a ROOFS-based simulator.

5 Experimental results

Our fault simulator HyHOPE was evaluated on ISCAS89 benchmark circuits [21] with test vectors generated by STG3 [18, 19] and a simulation-based ATPG [19]. First, we conducted the experiment with STG3 test vectors. Table 3 shows a summary of these circuits and

Table 3: Description of STG3 test vectors

Circuit	Number of vectors	Number of faults	Number of hypertrophic faults	Fault coverage, %	
				sure	potential
				HOPE	PTD
s208	111	215	24	63.72	72.09
s298	162	308	15	85.71	88.64
s344	91	342	29	96.20	97.95
s382	2463	399	19	90.98	94.74
s400	1282	424	19	82.78	86.56
s420	173	430	37	41.63	50.70
s444	1881	474	19	89.45	92.62
s526	754	555	27	75.32	78.38
s641	133	467	12	86.30	87.79
s713	107	581	37	80.90	83.13
s820	411	850	5	81.88	82.12
s832	377	870	5	81.38	81.49
s838	137	857	33	29.64	38.39
s953	16	1079	31	7.79	15.01
s1238	349	1355	2	94.69	94.69
s1423	36	1515	51	24.42	28.12
s1488	590	1486	7	92.60	92.80
s1494	469	1506	7	91.10	91.43
s5378	408	4603	38	74.02	75.32
s35932	86	39094	10	87.99	88.04

test vectors. Throughout all the experiments, the initial states of all the flip-flops were assumed to be unknown X s. The performance of HyHOPE was compared with those of HOPE and PTD, which is an option of HOPE to drop potentially detected faults.

Table 3 also shows the fault coverages of exact fault simulation, such as HyHOPE and HOPE, and the approximate fault simulation by PTD. As expected, PTD always gives an optimistic result. The difference can be significant, and more than 8% difference in fault coverage was observed for s208, s420, and s838. The number of hypertrophic faults identified and processed by HyHOPE is also given. For some circuits, this number is larger than 31, which means that, during the simulation, some identified hypertrophic faults were detected and their bit space was reused in the following time frames. It can also be seen that the hypertrophic faults are generally less than 5% of the total faults. In particular, the identified hypertrophic faults in s35932 are only 0.03%, yet almost half the fault gate evaluations were due to this small number of faults.

The run times of HyHOPE and HOPE on a SUN Sparc 2 workstation are reported in Table 4. The performance of HyHOPE can be clearly seen in this Table. The average speed-up ratio of HyHOPE over HOPE is 1.65. As shown in Table 4, HyHOPE is faster than HOPE for all but one circuit. For circuit s1238, HyHOPE is slightly slower than HOPE, because the circuit has no feedback loop, and there are very few

serious hypertrophic faults. The overhead for hypertrophic fault identification and processing makes the performance of HyHOPE slightly slower than HOPE. It is

Table 4: CPU times for STG3 test vectors

Circuit	CPU time, s			Speed-up over HOPE	
	HOPE	PTD	HyHOPE	PTD	HyHOPE
s208	0.33	0.20	0.25	1.65	1.32
s298	0.50	0.27	0.28	1.82	1.79
s344	0.35	0.22	0.25	1.59	1.40
s382	9.22	2.12	2.22	4.35	4.15
s400	6.15	2.08	2.27	2.96	2.71
s420	1.18	0.63	0.78	1.87	1.51
s444	10.12	3.67	3.77	2.76	2.68
s526	5.92	3.08	3.18	1.92	1.86
s641	0.60	0.42	0.52	1.43	1.15
s713	0.63	0.48	0.55	1.32	1.15
s820	2.18	1.47	1.63	1.48	1.34
s832	2.10	1.42	1.58	1.48	1.33
s838	2.93	1.70	2.18	1.72	1.34
s953	0.83	0.80	0.83	1.03	1.00
s1238	2.00	2.01	2.12	1.00	0.94
s1423	2.02	1.72	1.90	1.17	1.06
s1488	6.63	3.60	3.93	1.84	1.69
s1494	5.35	2.93	3.45	1.83	1.55
s5378	26.73	14.23	17.88	1.87	1.49
s35932	94.90	60.93	64.68	1.83	1.47
Average speed-up ratio				1.83	1.65

also interesting to note that, for circuits s382, s400 and s444, the speed-up ratios over HOPE are more than 2, and their identified hypertrophic faults are less than 5% of total faults. This is because, as discussed in Section 2, the hypertrophic faults, although few in number, produce a large number of unknown values that are different from the good-circuit values. Many of these faults can only be potentially detected. For instance, none of the identified hypertrophic faults in s35932 can be surely detected by the given test sequence. As a result, fault simulators, such as ROOFS and HOPE, that process the differences between faulty circuits and good circuits require a great number of gate evaluations for these faults. In HyHOPE, simulating these hypertrophic faults in parallel with the good circuit leads to a significant improvement.

For evaluation purposes, we also show the run time of the approximate fault simulator PTD in Table 4. As PTD drops the potentially detected faults, which are mostly hypertrophic faults, its performance can be used as a goal that an exact fault simulator of the same basic simulation mechanism strives to achieve. As expected, PTD outdoes its exact version HOPE by 83% on average, with some sacrifice in accuracy. When compared with HyHOPE, also based on HOPE, PTD is only slightly faster than the exact simulator HyHOPE. This indicates that HyHOPE not only preserves the accuracy but also has the performance approaching that of the approximate simulator.

To examine our proposed simulation algorithm for hypertrophic faults in detail, the number of gate evaluations for faulty-circuit simulation of HOPE, PTD and HyHOPE are listed in Table 5. For HOPE and PTD, the fault gate evaluations consist of single-fault propagation, candidacy test and parallel-fault simulation. The listed gate evaluations of HyHOPE consist of two parts: the column 'fault' in HyHOPE is the number of fault gate evaluations generated by non-hypertrophic faults that are simulated as in HOPE; and the column 'extra' lists the extra evaluations for simulating hypertrophic faults in parallel with logic simulation, as proposed in our simulation algorithm. Therefore the number of total fault gate evaluations with HyHOPE is the sum of these two numbers. From Table 5, it can be seen that more than 40% of fault gate evaluations in HOPE are reduced by HyHOPE on average, which is approaching the ratio achieved by PTD. Furthermore, there are many circuits, such as s382, s444, s526, s832, s1488 and s35932, where the efficiency of HyHOPE is very close to PTD.

A new version of HOPE, HOPE1.1 [12] incorporates three additional heuristics: functional injection; static ordering by fanout free region; and dynamic fault ordering of potentially detected faults. It appears that functional injection is the most effective of the three and is able to reduce fault site events. However, the overall improvement is not significant: 12%, except for two circuits, s5378 and s35932. The improvement of these two circuits mostly comes from functional injection, which is not implemented in HyHOPE. Even so, HyHOPE still has

Table 5: Number of gate evaluations for STG3 test vectors

Circuit	Number of gate evaluations for faults					Evaluation ratio over HOPE	
	HOPE	PTD	HyHOPE			PTD	HyHOPE
			fault	extra	total		
s208	21098	9506	9758	4572	14330	0.451	0.679
s298	30274	10140	9983	3627	13610	0.335	0.450
s344	22264	6603	6520	4681	11201	0.297	0.503
s382	610068	109252	105695	22767	128462	0.179	0.211
s400	434632	117698	116347	16644	132991	0.271	0.306
s420	108471	58920	64633	15103	79736	0.542	0.735
s444	712839	228080	219532	19595	239127	0.320	0.335
s526	397639	202697	197856	25673	223529	0.510	0.562
s641	36379	14605	14660	4627	19087	0.401	0.525
s713	38524	17768	18532	5422	23954	0.461	0.622
s820	187090	101708	102782	11867	114649	0.544	0.613
s832	175211	96420	97029	10444	107473	0.550	0.613
s838	298443	187776	230462	23910	254372	0.829	0.852
s953	53278	50003	51967	294	52261	0.939	0.981
s1238	117088	116352	117106	63	117169	0.994	1.001
s1423	128094	102125	108515	5251	113766	0.797	0.888
s1488	487501	153150	153486	41216	194702	0.314	0.399
s1494	405012	147095	147626	34201	181827	0.363	0.449
s5378	2038037	850656	1025816	110493	1136309	0.417	0.558
s35932	6149767	3424269	3557019	228301	3785320	0.557	0.616
Average evaluation ratio						0.494	0.595

fewer fault gate evaluations than HOPE1.1 for these two circuits, and the average speed-up for all circuits is 47% over HOPE1.1.

We also conducted the experiment with the test set generated by a simulation-based ATPG [19] (see Table 6). Although the general quality of this test set is comparable with that of STG3, for individual circuits, the fault coverage shows significant difference. However, HyHOPE still outperforms HOPE by an average speed-up of 1.90. It can be seen that, for most circuits, the number of identified hypertrophic faults is similar to that of STG3. The performance of HyHOPE is close to that of PTD, except for the circuit s1423. The discrepancy comes from the fact that many serious hypertrophic faults in the circuit are activated by this test sequence. The current implementation of HyHOPE can only simulate 31 hypertrophic faults in parallel. As a result, a few serious hypertrophic faults are simulated with non-hypertrophic fault simulation instead of the proposed efficient algorithm. For this case, the performance of HyHOPE can be further improved by extending the packet size for hypertrophic fault simulation, as described in Section 3.2. However, for most circuits in our experiment, the extension of packet size was not needed. From the above Tables, it is clear that the efficient hypertrophic fault simulation in HyHOPE leads to a significant improvement for both test sets generated by STG3 and the simulation-based ATPG.

A fair comparison of HyHOPE with other well-known ROOFS-based fault simulators, such as PARIS [7] and PROOFS [3, 4], can only be indirect, owing to the difference in the machines used and in implementation details. For PROOFS, fortunately, it has been reported in Reference 5 that HOPE had a speed-up advantage of 2. Therefore we estimate that HyHOPE could have a speed-up ratio of more than 3 over PROOFS, as we built HyHOPE on HOPE. In the case of PARIS, which exploits pattern parallelism, we compare HyHOPE with a simulator implemented according to the description in Reference 7 of PARIS*. The run time result with the STG3 test set is listed in Table 7. The diversified comparison results reflect the different natures of parallel fault in HyHOPE and parallel pattern in PARIS*. For the particular case of s1238, which contains no feed-back

loop, PARIS* behaves as PPSFP [9] and is very efficient. However, for some circuits, such as s298, s382, s444, s526, s1494, and s35932, PARIS* is clearly outperformed by HyHOPE. For some of these circuits,

Table 7: Comparison for STG3 test vectors

Circuit	CPU time		Time ratio
	PARIS*	HyHOPE	
s208	0.22	0.25	0.880
s298	0.82	0.28	2.929
s344	0.68	0.25	2.720
s382	7.37	2.22	3.320
s400	7.40	2.27	3.260
s420	0.65	0.78	0.833
s444	15.53	3.77	4.119
s526	12.05	3.18	3.789
s641	0.60	0.52	1.154
s713	0.75	0.55	1.364
s820	2.73	1.63	1.675
s832	3.27	1.58	2.070
s838	1.43	2.18	0.656
s953	0.37	0.83	0.446
s1238	0.60	2.12	0.283
s1423	4.03	1.90	2.121
s1488	13.10	3.93	3.333
s1494	12.95	3.45	3.754
s5378	10.88	17.88	0.609
s35932	1720.20	64.68	26.596

PARIS* is even inferior to its single-pattern version. The last observation has also been reported in References 7 and 8. Based on our comparison with PARIS*, it appears that HyHOPE delivers a consistently better performance. However, the comparative merits of parallel-fault simulation and parallel-pattern simulation deserve more thorough investigation.

In summary, HyHOPE improves the performance of HOPE by about 65%. Furthermore, the experiment shows that, with our efficient algorithm for simulating hypertrophic faults, the exact fault simulator can be almost as fast as the approximate one, without any sacrifice in accuracy.

6 Conclusions

The efficiency of modern fault simulation algorithms depends largely on the degree of difference between the

Table 6: Results for simulation-based ATPG test vectors

Circuit	Number of vectors	Number of hypertrophic faults	Fault coverage %		CPU time, s			Speed-up over HOPE	
			sure	potential	HOPE	PTD	HyHOPE	PTD	HyHOPE
s208	400	22	63.26	70.70	0.77	0.35	0.43	2.20	1.79
s298	350	15	85.71	88.67	0.88	0.40	0.47	2.20	1.87
s344	300	28	95.03	96.78	0.78	0.33	0.42	2.42	1.86
s382	1014	19	88.97	93.23	4.07	1.05	1.22	3.88	3.34
s400	1512	17	88.21	91.74	5.82	1.28	1.60	4.55	3.64
s420	200	41	40.70	48.84	1.28	0.67	0.83	1.91	1.54
s444	1692	19	85.87	90.93	7.53	1.82	2.13	4.14	3.54
s526	2682	27	79.28	82.34	13.28	3.15	3.77	4.22	3.52
s641	211	29	84.37	86.72	0.92	0.52	0.62	1.77	1.48
s713	350	17	81.76	83.13	1.45	0.85	1.03	1.71	1.41
s820	900	3	93.88	94.00	3.92	2.45	2.73	1.60	1.44
s832	703	3	91.61	91.84	3.22	2.10	2.22	1.53	1.45
s838	150	38	29.06	37.57	3.52	2.10	2.63	1.68	1.34
s953	156	31	8.34	20.85	6.13	5.17	5.83	1.19	1.05
s1238	500	3	91.44	91.44	3.15	3.15	3.25	1.00	0.97
s1423	1451	41	82.18	86.14	58.37	17.00	35.77	3.43	1.63
s1488	300	5	94.01	94.35	3.58	2.22	2.33	1.61	1.54
s1494	300	5	93.29	93.63	3.43	2.10	2.35	1.63	1.46
s5378	501	49	69.15	70.61	31.13	16.10	21.13	1.93	1.47
s35932	298	10	88.26	88.28	171.80	91.00	97.72	1.89	1.76
Average speed-up ratio								2.32	1.90

good circuit and its faulty versions, i.e. the number of fault effects. For most faults, the fault effects are few in number, and these simulators attain high efficiency by evaluating only a small number of gates for each fault. However, a small number of hypertrophic faults in a circuit may produce a great number of Xs, which are evidently different from good values. As a result, a simulator taking advantage of such a difference ends up heavily loaded with a large number of gate evaluations for the hypertrophic faults, which may account for as much as half the CPU time.

In this paper, we have proposed a novel and exact fault simulation algorithm to identify hypertrophic faults during the fault simulation and efficiently to simulate hypertrophic faults for sequential circuits such that their effect on performance is minimised. The reduction of hypertrophic fault events by the proposed simulation algorithm is threefold:

- (a) The algorithm simulates only those hypertrophic fault events resulting from a difference with the previous time frame rather than with the good circuit.
- (b) Each hypertrophic fault is simulated in parallel with logic simulation. The events can be significantly reduced by (a) and (b), as stated in the key observation.
- (c) In addition, these hypertrophic faults are simulated in parallel for even further reduction.

Based on this algorithm, a fault simulator HyHOPE for efficient and exact hypertrophic fault simulation has been implemented upon HOPE. The experimental results have shown that HyHOPE reduces by about 40% the fault gate evaluations of HOPE, and the average speed-up ratios over HOPE for STG3 test vectors and simulation-based ATPG test vectors are 1.65 and 1.90, respectively. Furthermore, the results have also indicated that the performance of HyHOPE is close to the approximate simulator without any sacrifice in accuracy. The proposed HyHOPE algorithm is targeted at the single stuck-at-fault model. We would like to point out that the proposed heuristics for hypertrophic fault simulation can be easily extended to fault simulation targeted at other fault models where hypertrophic fault effect may occur, such as transition fault [22, 23] and stuck-open fault [24].

7 References

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