

Performance Evaluation of Two Allocation Schemes for Combinatorial Group Testing Fault Isolation

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Abstract - Two fault isolation approaches based on Combinatorial Group Testing (CGT) are presented. Although they both share the basic principle of grouping suspect resources into subgroups for testing, they differ in the allocation strategy used to achieve that grouping. Equal share CGT approach is analyzed first, results shown successful fault isolation in 85% of the runs. An average of 3.65 groups and 362 test vectors were needed to isolate a single fault with an average of 2.95 discrepant outputs in each run. After that, Interleaved CGT approach is proposed along with analytical demonstration of its strengths and weaknesses. Finally, future research framework is suggested to experimentally compare the two approaches.

1 Introduction

Adaptive fault detection and isolation methods for Field Programmable Gate Arrays (FPGAs) have been growing in importance especially in mission-critical domains. The design of dependable systems optimized for availability, reliability, and performance is crucial for applications that require fast recovery with minimal human intervention. For example, deep space satellites such as Stardust utilize over 100 FPGA devices to support multi-purpose tasks [1] and need to operate in various environmental extremes such as high radiation bursts and thermal fatigue conditions. Under such circumstances, the need for an efficient fault detection and isolation scheme becomes inevitable.

While most conventional approaches like redundancy and BIST provide fault detection and isolation capabilities, they suffer from the following two major limitations:

I. Offline isolation: In which the hardware has to be taken off service during fault isolation. This implies suspending the functional throughput during the isolation process, which in turn reduces device availability for mission-related tasks.

II. Exhaustive testing: By stress-testing individual resources with non-functional test vectors. Input/output pairs must be generated beforehand in such a way that guarantees best coverage of all resources under test. Fault detection latency might be increased by extensive testing thus degrading device reliability.

This paper presents a fault isolation approach based on CGT algorithm that mitigates the shortcomings of the conventional approaches. Availability is maximized by keeping the devices online during the fault isolation process. In addition, the usage of functional dataflow inputs makes it possible to detect and isolate faults without altering the normal throughput of the device, hence increasing device reliability.

Combinatorial group testing algorithms rely on the combinatorial aspects of the problem [2] by performing tests on groups of individuals at each step of the solution. The presented approach has shown that faulty resources in FPGA device can be isolated with the aid of CGT based approach.

The solution starts by initially considering all resources as suspect, and then proceeds by narrowing the suspect pool with each group of testing, until eventually isolating the single faulty resource. Two alternative versions of the method are presented:

- I. Equal Share Allocation: In which the suspected resources are divided into equal subsets, and assigned to one individual in the population, meaning that each suspected resource is covered by exactly one individual.
- II. Interleaved Allocation: Where the suspect resource subsets are shared among individuals. The sharing degree is controlled by a *Coverage Factor (CF)* which determines how many individuals utilize each resource in the suspect pool.

The remainder of the paper is organized as follows: Section 2 provides details about the equal share allocation scheme along with experimental

analysis of its performance. Section 3 proposes the new interleaved allocation scheme. Section 4 concludes the paper by comparing the two methods in term of efficiency and best/worst case scenarios and suggests directions for future research.

2 Equal Share Allocation Scheme

The Equal Share Allocation Scheme divides the resource suspect’s pool into equal subgroups (shares) and assigns each share to a different individual in the population. Therefore, each *Look Up Table (LUT)* in the suspect pool is said to be “covered” by one individual. The selection of which individual to configure on the device in order to apply test vectors is done randomly, for a population of R individuals, each will have an equal probability to be picked and tested.

2.1 Allocation Strategy

Assuming a suspect pool of N LUTs, Equal share scheme divides the N LUTs equally among R individuals. Each individual will comprise M suspect resources, where $M = N/R$. The CGT-based algorithm involves applying test vectors to each individual and then comparing the output to a predetermined set of correct outputs. If a discrepancy is detected, the suspect pool can drastically drop from N LUTs to M LUTs. New groups can then be formed by dividing the new suspect pool with M resources into R individuals again, and so on until the single faulty LUT is isolated. On the other hand, no reduction in the suspect’s pool can be gained if no discrepancy is detected. This can happen when the faulty resource is not utilized in such a way to signify erroneous output or when the applied test vectors fail to articulate the fault.

Figure 1 shows N suspect LUTs divided among a population of R individuals, where each individual exclusively covers M suspect LUTs.

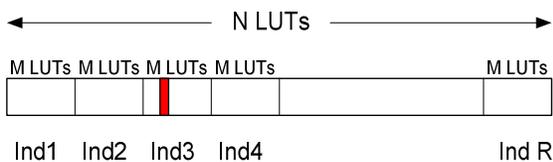


Figure 1: Equal Share Allocation Scheme

If the faulty LUT is used exclusively by Ind3 as shown in Figure 1 (denoted by the highlighted rectangle), and the applied test vectors articulated the

existence of the fault, the current group can be terminated and new one can be formed with a new suspects pool consisting of all the M LUTs used by Ind3.

Based on the previous discussion, it is apparent that this allocation scheme can have two contrasting effects on the performance of the CGT:

- Maximal possible gain if the fault is articulated by the test vectors. This case is what makes the technique very efficient since the suspect list is reduced by a factor of R (from N suspect resources to M), in the best case leading to the formation of only $\text{Log}_R N$ groups.
- Minimal possible gain if the fault is not articulated by the test vector. In this case, the algorithm will finish testing all individuals in the population without detecting any discrepancy, and thus new groups must be formed out of the same N suspected LUTs, without achieving any gain from the previous stage.

The best case for this allocation scheme is to reduce the suspect list by a factor of R for each testing group, while the worst occurs when the fault is not articulated and the suspect list remains unchanged.

2.2 Experimental Setup

The circuit used to evaluate the Equal share CGT approach is a DES-56 encryption circuit. The circuit was implemented using VHDL. Xilinx ISE design tools were used to place and route the design, targeting Virtex II Pro FPGA device.

The *Fault Injection and Analysis Toolkit (FIAT)* [3], which has been developed for conducting fault isolation experiments, was used to model faults and evaluate testing results in order to assess the performance of the CGT approach. FIAT is a set of *Application Programmer Interfaces (APIs)* implemented using Python language to interact with the Xilinx ISE tools to inject and evaluate faults.

2.3 Results

Three experiments were conducted with population sizes of 15, 20, and 25 individuals. Each individual required 304 LUTs and was implemented on a square-area of 25X25 LUTs, making the resource utilization approximately 50%. Each experiment featured 20 different runs with the same experimental settings. Table 1 shows the experimental results for the three runs, the following four findings can be extracted:

Table 1: Results of three CGT experiments with different population size

Population	Isolation results		Number of groups						Required Test vectors	Discrepancies
	Success	Fail	3	4	5	6	Mean	SD		
15	17	3	0	13	6	1	4.35	0.587	247.4	3.7
20	17	3	14	6	0	0	3.3	0.470	311.9	2.55
25	17	3	14	6	0	0	3.3	0.470	525.3	2.6

- Isolation ability: Equal share CGT was able to isolate the single fault in 85% of the experiments. Varying the population size did not affect the ability of the CGT to isolate the fault at the end. However, it might be possible that the reason is the narrow adjustment of the population size in each consecutive experiment.
- Average number of groups: Population size is crucial with respect to the number of groups needed to isolate the fault. No solution could be achieved in the 15-individual experiment in less than four groups, while it became possible when the population size was increased to 20 or 25 individuals. Figure 2 shows a bar graph depicting the total number of runs for each group count.

Figure 2 shows that no run in the 15-individual case has achieved a solution in three groups, most of the runs ended with four and five groups. On the other hand, the 20 and 25-individual case achieved isolation with four runs at maximum. The CGT was able to isolate the single stuck-at fault in an average of 4.35 groups for the 15-individual case, this number was reduced to 3.3 for the 20 and 25 individuals cases.

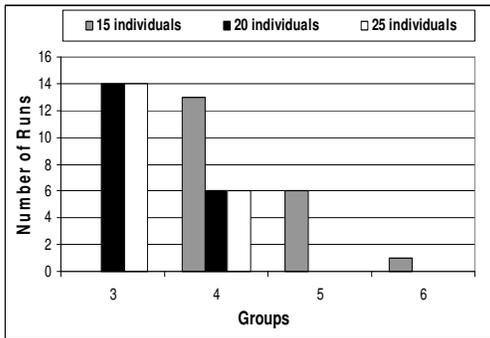


Figure 2: Total number of runs for each group count

- Average number of test vectors: The average number of test vectors needed in each experiment is proportional to the population size. The algorithm divides the suspect list into all available individuals and applies test vectors to each physical realization of the application. Consequently, more individuals imply more test vectors.

- Discrepancies: Represents the average number of discrepant outputs in each experiment. The number of discrepant output quantifies the reliability of the system because it tells what percentage of the time the system was able to respond with good output to some input.

3 Interleaved Allocation Scheme

In this scheme, each LUT in the suspect pool is used by more than one individual in the population. This means that the suspect resource groups used by individuals have to be interleaved. The rationale behind adopting this scheme is to reduce the chance that a faulty LUT is not articulated by test vectors within a specific configuration. If the probability that a faulty LUT is not articulated by one configuration is P , then the probability that it is not articulated by two independent configurations becomes $P \times P$. This improvement is attained at the expense of the maximal isolation progress rate achieved in the equal share approach.

3.1 Allocation Strategy

The Coverage Factor (CF) indicates the number of individuals covering each resource in the suspect pool. For example, $CF = 2$ means that each suspect LUT is covered by two different individuals. In order to meet this constraint, the subgroups of suspects used by different individuals have to interleave. Figure 3 shows an example of the Interleaved allocation scheme with $CF = 2$ and population size = 5.

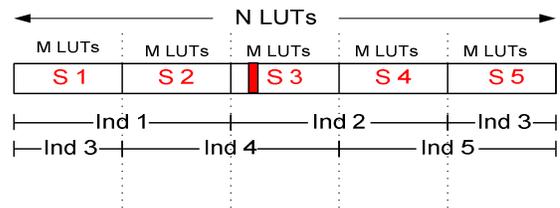


Figure 3: Interleaved Allocation scheme with $CF=2$

In the interleaved allocation scheme, the N LUTs have to be divided into M subgroups where $M = N/R$, each individual will utilize $2 \times M$ LUTs in order to meet the coverage factor requirement $CF=2$. A discrepancy will reduce the number of suspects to $2M$ rather than M

as in the equal share approach. However, a two-pass technique is used to improve the performance of the interleaved approach while maintaining a low probability that a fault LUT is not articulated. The two passes are described below:

Pass one: In this pass, the algorithm tries to reduce the suspect list from N to $CF \times N/R$ where CF is the coverage factor. In the $CF=2$ example shown in Figure 3, the target is to reduce the suspect list from N LUTs to $2M$ LUTs, this can happen as early as one discrepant output is detected. The advantage here is that there is less probability that a fault in an LUT is not articulated by a test vector as there are two individuals utilizing each suspect LUT. For instance, if the highlighted LUT in Figure 3 is the faulty one, two individuals (Ind2 and Ind4) have a chance to produce discrepant output.

Pass two: The goal of this pass is to reduce the size of the suspect list from $2M$ to M , and thus achieving the same maximal reduction attained in the Equal share approach. In order to achieve this target efficiently, a new data structure called *Interleaved Individuals Set (IIS)* is introduced to the CGT program to keep track of the interleaved individuals in a specific CGT configuration. Figure 4 shows the IIS for the configuration of Figure 3 with $CF=2$ and $R=5$.

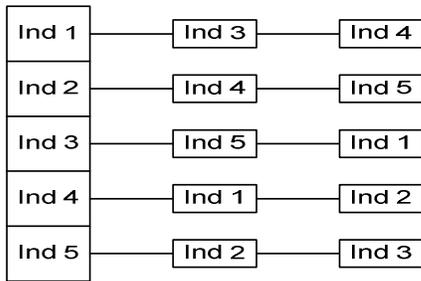


Figure 4: Interleaved Individual Set for configuration in Figure 3.

This data structure can be constructed at the beginning of each group when the individuals are configured and the suspect list is distributed among them. The purpose of the IIS is to improve pass 2 by expediting the process of narrowing the suspect list from $2M$ to M . This can be achieved by testing only those individuals that are interleaved with the one that showed discrepancy.

4 Conclusion

The equal share approach relies on a high-risk high-gain technique, in which each resource in the suspect list is utilized by one individual. Reduction in

the suspect list from M to M/R is achieved at the expense of a higher probability of unarticulated faults. Groups containing individuals with unarticulated faults lead to no improvement in suspect list reduction.

On the other hand, the interleaved allocation scheme adopts a low-risk approach by covering each suspected resource with two or more configurations, making it less probable that a group of testing yields no improvement. It can achieve the same fault isolation achieved in equal share approach by utilizing a design-time IIS data structure to keep track of the individuals that should be tested whenever a discrepancy is detected.

The equal share approach is a special case of the interleaved approach where $CF=1$, this might be useful to design one generic model for both approaches that is controlled by setting CF to 1 (equal share) or more (interleaved approach). This is our first recommendation for future work in this line of research. In addition, population size effect should be studied more to explore the effect of considerably high and low population sizes on the performance of both allocation schemes. Finally, Interleaved approach should be investigated with different values of coverage factor to see if it really adds more robustness to the conventional equal share CGT approach.

5 References

- [1]. Sharma, C. A. and R. F. DeMara (2006), "A Combinatorial Group Testing Method for FPGA Fault Location," in *Proceedings of the International Conference on Advances in Computer Science and Technology (ACST 2006), Puerto Vallarta, Mexico, 2006*.
- [2]. Du D and Hwang, F. K. (2000), "Combinatorial Group Testing and its Applications," *Series on Applied Mathematics volume 12*, World Scientific.
- [3]. Sharma, C. A. (2007), "FPGA Fault Injection and Analysis Toolkit (FIAT)."