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Robust Reconfigurable Scan Networks

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Keywords—Reconfigurable Scan Networks, selective hardening, multi-objective optimization, synthesis

I. INTRODUCTION

Reconfigurable Scan Networks (RSNs), as standardized by IEEE Std. 1687 [1] and IEEE Std. 1149.1 [2] and shown in Fig. 1, efficiently access instruments, which are used to support dependable operation and diagnosis of devices, through a number of scan segments. Control primitives configure a scan path through the segments, and thereby determine the currently accessed instruments. The scan multiplexers select certain branches depending on the control signal value.

Hardening the most critical instruments and the corresponding scan segments against permanent faults is not enough to ensure robust access to the instruments since a single fault in RSN the control logic may corrupt scan paths and make certain instruments inaccessible. This affects two major tasks:

- **Post-silicon validation:** A fault in an RSN may prevent accessing a major part of instruments, such that only incomplete data can be extracted.
- **Runtime operation:** The device operation may be guided by runtime-adaptive instruments, e.g., Adaptive Voltage and Frequency Scaling (AVFS) or error rate adaption.

Inaccessibility of such critical instruments due to a single fault in the RSN may cause a system failure.

The impairment of the system operation due to inaccessibility of an instrument via an RSN, can be used as a weight of the instrument. A cost function defining the importance of an RSN primitive can be computed by summing up the weights of those instruments, which are inaccessible if the primitive is defect. Minimizing the cost function value for all the RSN primitives keeps the most critical instruments and a major part of the remaining instruments accessible, thereby the scenarios above are addressed. To minimize the cost function, faults in RSNs can be tolerated, or avoided as proposed in this paper.

Using conventional approaches, such as Triple Modular Redundancy (TMR) [3], for the entire RSN requires high hardware costs. In [4], single faults are tolerated by augmenting the initial RSN with minimized additional connectivities. This approach requires diagnostic support [5], complicates routing for test [6–9], and also access in the presence of a fault, and does not consider the criticality of the components.

The probability of defects can be reduced by hardening some components and cells locally. The existing approaches in the field of design-for-manufacturability [10] can reach as far as applying TMR locally to single cells [11]. They decrease the probability of defects and do not affect test and diagnostic procedures but increase power consumption and area overhead. Hardening a few carefully selected components, while leaving the remaining device unprotected, still reduces the probability of a system failure and has acceptable costs [12]. Hardening is usually applied for soft error mitigation [13], but these are efficiently tolerated in RSNs by repeating a failing pattern, and are therefore, out of the scope of this paper.

This paper presents the first solution to synthesizing cost-efficient robust RSNs. Even in the presence of defects, a robust RSN not only enables an efficient post-silicon validation with reliable access to the major part of the instruments but also provides runtime access to the most critical instruments. The presented selective hardening scheme is supported by an exact analysis, which assesses the criticality of a fault in any RSN primitive, as shown in Section IV. The criticality is calculated as a weighted sum of the instruments, which become inaccessible due to a fault in a given primitive. For each instrument, the accessibility for observation and control are considered separately to reflect the different requirements of a specific instrument. Based on the criticality analysis, a minimized number of RSN primitives is selected and hardened to reduce the damage caused by defects, as described in Section V. A trade-off between reducing the hardware costs of hardening and minimizing the remaining damage of defects is investigated by using an evolutionary algorithm [14, 15] for generating close-to-pareto-optimal solutions.

II. METHOD OVERVIEW

The presented scheme has the following major goals:

![Fig. 1. Considered system](image-url)
• **Precise Criticality Analysis:** The criticality of scan primitives should be carefully assessed, and the most critical primitives in the RSN for the correct system operation should be identified, as shown in Section IV.

• **Cost-effective Selective Hardening:** The scheme should dramatically decrease the damage of defects in RSNs for the system operation, while minimizing the hardware costs, as shown in Section V. The trade-off between the criteria above is investigated. The scheme is independent of the actual hardening technique to be used, e.g. in [10].

• **Access Patterns Compatibility:** The resulting RSNs must follow the initial RSN topology. They should not only be compatible with the existing access, test and diagnosis procedures [6–8, 16, 17], but also be able to use the same access patterns as the initial unhardened RSN.

**Example:** In Fig.1, m1 is a regular scan multiplexer, and m2 is hardened. The multiplexer m1 might propagate the data from wrong scan-input, while m2 remains functionally correct, and faults due to a defect in m2 are avoided.

**III. MODELING**

An RSN is modeled as a directed graph \( G = (V, E) \) with vertices \( V \) and edges \( E \), as shown in Fig. 2 for the RSN from Fig. 1. Each vertex models a scan primitive (segment or multiplexer), a fan-out, or represents a primary scan-input or output. Each edge represents a direct connectivity between the vertices. Segment Insertion Bits (SIB) insert a sub-RSN into the path or bypass in based on the control signal value. It is modeled as a combination of a scan segment and a multiplexer.

**Fig. 2. RSN graph:** the stem region of \( f_0 \) is shown with grey color

If at least two disjoint paths exist between the source \( s \) and the destination \( d \), then \( s \) is a reconvergent fan-out stem, and the \( d \) is its reconvergence gate [18]. In RSNs, only multiplexers are reconvergence gates. A reconvergence gate, which does not reach any other reconvergence gate of a fan-out stem, is called a closing reconvergence. A stem region includes all such primitives reachable from a given fan-out stem, such that its closing reconvergence is reachable from these primitives.

So-called hierarchical series-parallel RSNs have first been introduced in [19] to allow scalable processing of RSNs.

**Definition 1:** A Series-Parallel (SP) RSN graph is an RSN graph, which consists of two vertices connected via a single edge, or a composition of two SP-RSNs \( G_1 \) and \( G_2 \):

- **Parallel:** The source of \( G_1 \) is identified with the source of \( G_2 \): the sink of \( G_1 \) is identified with the sink of \( G_2 \).
- **Series:** The sink of \( G_1 \) is identified with the \( G_2 \) source.

Although most RSNs can be directly represented as hierarchical SP graphs, additional steps might be required to obtain a hierarchical representation. Then an SP-RSN model is obtained by adding a minimized number of virtual vertices into the initial graph. This representation is only used for the analysis, and does not require any physical changes, since in the resulting hardened RSN the applied changes are reverted [19]. A binary decomposition tree is built for an SP-RSN model, shown in Fig. 3. The blue "S" vertices stay for serial connections, the green "P" vertices – for parallel ones.

**Fig. 3. Annotated binary decomposition tree for Fig. 1.** Since all the paths through the segment \( c2 \) traverse the multiplexer \( m_0 \), then \( m_0 \) dominates \( c2 \). The segment \( c2 \) belongs to such stem region, where the \( m_0 \) is a closing reconvergence. Then, \( m_0 \) is referred as a parent of \( c2 \), and \( c2 \) is referred as a 1-child of \( m_0 \). The multiplexer \( m_2 \) dominates \( m_1 \), but is not its parent, so the multiplexers are neighbors.

**IV. CRITICALITY ANALYSIS**

**A. Explicit Criticality Specification**

An explicit criticality specification reflects the damage caused by the inaccessibility of specific instruments. It is implemented as a list of instruments, where each instrument \( i \) is associated with a pair of non-negative damage weights. The first one \( d_{oi} \) defines the damage of losing the observability, while the second one \( d_{si} \) – the damage of losing the settability of the instrument. The exact values of the damage weights are specified by a system designer, e.g.:

- **Sensors:** A relatively low value of \( d_{oi} \) can be assigned to the damage of unobservability of one of many interchangeable sensors. If multiple sensors are inaccessible, the damage is more severe and is calculated as a sum of the sensors' weights. If the settability of sensors is not required then \( d_{si} \) is set to zero or close-to-zero.

- **Runtime-adaptive instruments:** The settability of a runtime-critical instrument is important for a correct system operation, and the corresponding damage weight \( d_{si} \) is set to a relatively high value. At the same time, the damage due to its unobservability \( d_{oi} \) is relatively low.

The damage weights of the instruments are annotated at the corresponding segments in the binary decomposition tree. To ensure the accessibility of the most critical instruments, the damage weight of any of those instruments, whose unobservability may lead to a system failure, should be at least as high as the sum of the damage weights of all other "uncritical" instruments. The same applies for the settability weights.

**B. Fault Effects**

A single fault in an RSN might affect the intended connectivity properties of the instruments and might make the RSN disconnected. Next, the influence of specific faults in terms of graph connectivity is discussed.

1) **Scan Segments:** A fault \( f \) in a scan segment may break the integrity of all the scan paths, which traverse this segment. The existence of a faulty segment is modeled by removing the corresponding vertex from the RSN graph. The fault effect is isolated inside the branch controlled by the closest parental scan multiplexer of the given segment. The parental multiplexer is identified by traversing the binary decomposition tree in a reversed polish order starting from the affected segment. In the isolated branch, the segments located closer to the scan-output than the affected segment, are inaccessible for setting the value from the scan-in. In a decomposition tree, it is equivalent to removing the connectivity to the affected vertex and the segments on its right-hand side. This modified tree is further referred as a settability tree under a fault \( f \). The same idea is applied to build a observability tree under a fault \( f \). The segments located closer to the scan-in become unobservable and are disconnected in the observability tree.
2) Scan Multiplexer and SIB: In the event of a "stuck-at-
id" fault, a multiplexer will permanently select only one input, independent of the value driving its address control port. So, its opposite branch becomes inaccessible through this multiplexer. For all the primitives in this branch, a path cannot be sensitized to the inaccessible branch is removed from the binary decomposition tree as shown in Fig. 4.

Fig. 4. Due to a "stuck-at-1" fault of the multiplexer m0 from Fig. 1 the instruments i1, i2 and i3 become inaccessible.

A SIB affected by a "stuck-at-asserted" fault always provides access to the sub-RSN. If the SIB is "stuck-at-deasserted", access to the sub-RSN is never granted. Fault effects in SIBs are considered as a combination of those for a scan segment and a multiplexer.

C. Combining Topology Analysis with the Specification

The relative criticality of each scan primitive compared to other scan primitives is determined by the possible damage to the system, if the primitive is faulty. The damage $d_j$ of a primitive $j$ is calculated as a weighted sum of the instruments, which become inaccessible due the fault in this primitive:

$$d_j = \sum_{i=1}^{N} d_i * y_{i,j} + \sum_{i=1}^{N} ds_i * z_{i,j}$$

where $y_{i,j} := 1$ if the instrument $i$ becomes unobservable, when the primitive $j$ is defect; $z_{i,j} := 1$ if the instrument $i$ is not settable due to a defect in the primitive $j$.

The computation is done hierarchically, starting from the lowest left node of a binary decomposition tree and follows the order of a reverse polish notation. Thereby, the relative criticality of the primitives located in the lower levels of the tree is computed before the computation of their parents starts. For a series-parallel RSN, the values of $y_{i,j}$ and $z_{i,j}$ are efficiently assessed with the help of a decomposition tree:

- For a defect in primitive $j$, the value of $y_{i,j}$ is set to one, if the instrument $i$ is disconnected from the primitive $j$ in the observability tree. Otherwise, it is set to zero. Similarly, a settable tree is used to assess $z_{i,j}$.
- If a primitive $j$ is hardened, a fault $f$ is avoided and the initial decomposition tree is used to assess $y_{i,j}$ and $z_{i,j}$.

V. SELECTIVE HARDENING

The desired solution to the hardening problem should satisfy the following optimization criteria:

- A maximized number of instruments remains observable and settable through the RSN even in the presence of defects. The damage to the system operation is minimized:

$$\sum_{i=1}^{N} d_i \rightarrow \min$$

where $N$ is the total number of scan primitives;

- The total cost of hardening is minimized:

$$\sum_{i=1}^{N} c_i * x_i \rightarrow \min$$

where the weight $c_i$ is the hardening cost for a primitive $i$; the variable $x_i := 1$, if the primitive is hardened.

Although, we can directly control only the values of $x_i$, the interdependence between the values of variables $x_i$ and $y_{i,j}$ allows to implicitly control the values of $y_{i,j}$. If a certain primitive is hardened, it implies that a defect in this primitive cannot occur and the observability of its children is not affected. The same applies to the settability of the instruments.

Minimizing the costs of hardening increases in general the damage due to defects in the RSN, and vice versa. Therefore, a trade-off between these criteria is investigated by computing close to pareto-optimal solutions. The parameter space is explored by applying the evolutionary algorithm SPEA-2 [14] of the Opt4J framework from [20].

This subsection explains how the algorithm is applied to the selective hardening problem. Each problem instance is modeled as a gene, which is represented as a list of binary values, which show whether a given primitive is hardened. The optimization algorithm includes the following steps:

1) Read the initial problem: The information about an RSN is provided, and any of the $r$ primitives may be hardened.
2) Generate the initial population: A diversified set of genes is generated, where random primitives are hardened.
3) Calculate the fitness function: The candidates are assessed with the criteria above. The dominant candidates are kept for mating, the dominated ones are dropped.
4) Check the termination criteria: If the allowed number of generations is exceeded, the computation terminates with a set of close-to pareto-dominant solutions.
5) Generate the next population: A limited number of individuals is selected from current population for mating.
6) Perform mating: Crossover and mutation are applied to the selected individuals with a determined probability:

- Individual bit mutation: A random bit is flipped.
- One-point crossover: First offspring: $n$ bits are taken from the first gene; another $r - n$ are taken from the second gene. Second offspring: vice-versa.

The computation continues from the step 3.

The RSN topology is not affected by the presented method, and the resulting RSNs are not only compatible with all the existing access, test and diagnosis procedures [6–8, 16, 17], but can also use the same access patterns, as the initial RSNs. If the initial RSN is security compliant [21] and/or testable [19], the presented scheme does not destroy these properties.

VI. EXPERIMENTAL RESULTS

Experiments are conducted on an Intel® Core™ i7-8565U CPU @ 1.80GHz × 8 with 16 GB of main memory. The RSN benchmarks are taken from the ITC'16 [22] and the DATE'19 [23] sets. Due to spacing constraints, only medium- and large-sized RSNs are considered. The number of scan segments (Column 1) and multiplexers (Column 2) are given in Table I.

The analysis has been conducted considering an explicit specification, where 70% of all the instruments have randomly assigned non-zero damage weights of losing their observability, and another 70% - of losing the settability. Also, 10% random instruments are set as important for observation, another 10% - control. The binary decomposition trees have been generated as in [19]. The primitives to harden are selected by using the evolutionary algorithm called SPEA-2 [14] implemented in the Opt4J framework from [20]. The parameters below have been used for the optimization:
The best damage-reducing solution, which requires at most 10% hardened primitives, is presented, in Columns 7 and 8.

The most cost-efficient solution for reducing the damage down to 10% of the initially assessed value (Column 5) in Columns 9 and 10.

All the important instruments remain accessible via the resulting RSNs. The procedure is completed in Column 11 and is acceptable for all the benchmarks.

VIII. CONCLUSION

A method to generate robust Reconfigurable Scan Networks is presented, which ensures reliable access to the most relevant instruments throughout the device lifetime. A minimized number of primitives uses hardened cells of high yield based on the precise criticality analysis, such that all the critical instruments and most of the remaining instruments are accessible through the RSNs even in the presence of defects. A trade-off between the hardening cost and the remaining damage of defects for the observability and the settable ability of the instruments is investigated by using an evolutionary algorithm and close to pareto-optimal solutions is computed. The experimental results show that efficient hierarchical processing enables scalability with the increasing RSN size and complexity. The resulting RSNs are compatible with the patterns, generated by the existing methods for the initial RSNs.

ACKNOWLEDGMENTS

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BIBLIOGRAPHY


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### TABLE I. Robust RSN Synthesis, SPEA-II, Varying Optimization Criteria

<table>
<thead>
<tr>
<th>Design(S)</th>
<th>Benchmark characteristics</th>
<th>Initial assessment</th>
<th>SPEA-II Generations</th>
<th>Minimize cost, Damage ≤ 10% Cost</th>
<th>Minimize damage, Cost ≤ 10% Damage</th>
<th>Execution time [m]</th>
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</thead>
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*Note: The values in the table represent the optimization criteria for different benchmark characteristics, with varying numbers of segments and multiplexers. The initial assessment shows the cost and damage combinations, while the SPEA-II Generations column indicates the optimization process iterations. The Minimize cost, Damage ≤ 10% Cost and Minimize damage, Cost ≤ 10% Damage columns present the optimized values, and the Execution time provides the duration for each optimization step.*