"Gheorghe Asachi" Technical University of Iași

Faculty of Automatic Control and Computer Engineering

Department of Computers

Habilitation Thesis

Summary

RAM Memory Testing and Reliability Engineering in Complex Systems

Doctoral field

Computers and information technology

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Brief Introduction

The habilitation thesis entitled "RAM Memory Testing and Reliability Engineering in Complex Systems" brings together the author's most important scientific results since the defense of his doctoral thesis in 2001. The issue addressed in the thesis falls within the research field dedicated to increasing testability, reliability and safety in operation, essential requirements for real-time systems with high dependability.

The habilitation thesis spans 219 pages and is structured in three distinct parts, as follows:

Part I. RAM Memory Testing and BIST-RAM Logic Design

Part II. Reliability Performance Evaluation in Large Networks

Part III. Optimal Allocation of Reliability in Complex Redundant Systems

As the three parts are self-contained, the equations, figures and tables are numbered independently within each part. Also, a separate list of references, numbered in reverse chronological order, has been prepared for each part of the thesis. In the reference list, the author's name is highlighted in bold.

Each part of the thesis includes its own specific notation and nomenclature. The generally accepted English notations for the problem under study are mentioned in the text, but distinguished by italics.

Each of the three parts concludes with a summary of the author's main contributions, the papers in which these results have been disseminated, and the research directions that the author intends to continue or deepen.

The importance and actuality of the topics addressed in the thesis are supported by an extensive documentation, reflected by the list of references that encompasses papers published in the most prestigious journals in the studied field, including many recent works.

The extent of the thesis, the 194 mathematical equations and the 101 figures and 52 tables reflect the complexity of the topics covered. The habilitation thesis is the result of the author's scientific activity carried out over a period of over 20 years. The close connection between the issues addressed here and the didactic activity of the author in all these years is highlighted at the end of the thesis.

Part I

RAM Memory Testing and BIST-RAM Logic Design

➢ Brief presentation of the research area

The first direction of research addressed by the author in the habilitation thesis covers the problem of RAM memory testing. This aims to cover complex patterns of harder-to-detect defects that reflect the interference between two or more physically adjacent memory cells.

As shown in the International Technology Roadmap for Semiconductors (ITRS) series and further continued in the International Roadmap for Devices and Systems (IRDS) series, edited by the IEEE Computer Society, in System on Chip (SoC) or Network on Chip (NoC), the memory part has an increasing weight, currently covering 75-85% of the integrated surface. This trend is a consequence of increasing memory requirements for real-time applications that must provide more and more facilities. Therefore, the most efficient testing of the memory part is necessary to achieve competitive costs for circuits that are safe in operation and highly reliable.

The studied problem particularly concerns complex coupling fault patterns involving several neighboring physical memory cells, known in the literature as NPSF (Neighborhood Pattern Sensitive-Faults) fault patterns. Such models comprise three, four or five physically adjacent memory cells and cover a multitude of physical imperfections that may occur in the manufacturing process, such as: discontinuities on the metallization routes, short circuits, resistances or parasitic capacities, electromagnetic influences especially at high working frequencies, or parameters sensitive to temperature variation.

The research of the author and his collaborators from the “Gheorghe Asachi” Technical University of Iași concerns precisely these complex defect models, and significant theoretical and practical contributions have been made

to all of them by proposing new high-performance testing methods and algorithms.

The defect models studied are found both in SRAM (Static Random-Access Memories) type memories, and especially in DRAM (Dynamic Random-Access Memories) type memories where the integration density is even higher.

Since these defect models require knowledge of the internal structure or geometry of the memory (or even better, the correspondence between logical cell addresses and physical addresses), in order to know which cells are physically adjacent, the proposed algorithms target the testing performed in the manufacturing process of memory circuits and less the tests performed afterwards, especially when these circuits are integrated into digital systems. This point is reinforced by the fact that efficient testing of high-capacity memory circuits can only be accomplished using self-test logic integrated with the memory itself.

In other words, the research has focused in particular on the identification of test algorithms to be included in memory circuits with self-test facilities such as Built-in Self-Test RAM (BIST-RAM) devices. For all the proposed tests, a synthesis was made of the logical self-testing structure that the algorithms involve, in order to evaluate their efficiency from this point of view as well.

The research area regarding the testing of RAM memories has a pronounced interdisciplinary character, encompassing knowledge related to computer architecture, the design of digital systems, the testing of digital structures, etc. Also, simulation techniques play a central role in identifying efficient test algorithms and in benchmarking their performance in terms of coverage of the considered defect models.

- **Author's main contributions to the field of RAM memory testing**

In this section, the most important scientific contributions made by the author of the habilitation thesis in the field of RAM memory testing after the defense of the doctoral thesis are presented in summary.

A. Test Methodology and/or Testability Assessment Contributions

a) Developing the concept of fault primitives as a basis for defining coupling fault models involving multiple memory cells (in particular, three-cell coupling, four-cell coupling and NPSF models);

b) Introducing a systematic method to evaluate the performance of multi-run march memory tests in terms of their ability to cover coupling fault models involving multiple cells (simple coupling failures or linked coupling failures);

c) Narrowing down the set of primitive faults corresponding to a given fault model, the detection of which must be explicitly verified when evaluating the ability of a memory test to cover the considered fault model. To this end, the concepts of equivalence or dominance between certain sets of faults can be applied. This technique called "fault collapsing" greatly reduces the effort of testability analysis of memory tests. This technique has been applied to all extended coupling fault models presented in this thesis.

B. New Memory Tests for Coupling Fault Models

a) Proposing four optimal tests (SS2CF1-SS2CF4) for the extended two-cell coupling fault model;

b) Proposing a suboptimal test dedicated to the restricted two-cell coupling model (MT-2CF), as an alternative to the optimal March C test, compared to which it has some advantages for the implementation in BIST-RAM type structures;

c) Proposing a suboptimal test dedicated to the extended model of two-cell coupling (MT-E2CF), as an alternative to the optimal tests SS2CF1-SS2CF4, compared to which the implementation in BIST-RAM circuits is simpler;

d) Defining some three-cell coupling fault models for which several effective multi-run march memory tests are proposed, such as MT-R3CF for the restricted model and March SR3C (with March SR3C-1 and March SR3C-2 subvariants) for the extended model, which are the most effective tests currently known for these complex models;

e) Defining a complex model of four-cell coupling faults that concern configurations of four neighboring cells arranged in a square. For the restricted model, the near-optimal multi-run test MT- R4CF was proposed, and for the extended model, the near-optimal multi-run test MT-E4CF eas proposed;

f) Proposing the shortest memory test currently known (March-76N), which covers the complex model of NPSF. This multi-run march test uses 16 background patterns of size 3×3 and is dedicated to the reduced model of NPSF;

g) Proposing a new near-optimal memory test (MT_NPSF_81N) that covers the complex model of NPSF and which uses 4×4 memory initialization patterns, much more suitable for implementations in BIST-RAM structures than those of size 3×3. It should be noted that the most efficient test of this type known so far (which is based on background patterns of size 4×4) is the March 96N test, so with this new test the number of memory operations reduces from 96N to 81N;

h) Defining an extended NPSF-type model (ENPSF) for which a near-optimal multi-run march test (MT-ENPSF) is proposed.

C. Logical synthesis of the self-test structure for possible BIST-RAM architectures

For all the proposed memory tests, the author presents an analysis regarding the possibility of implementation in the self-test structure and performs the logical synthesis of the data generation block, depending on the address and the background. The author's study highlights the difficulty of implementing multi-run march tests using 3×3 background patterns, such as the March-76N test, which is the shortest test covering the reduced model of NPSF.

➢ **Further research**

a) For the three-cell coupling fault model with physically neighboring memory cells, no optimal or suboptimal memory test has been identified so far. The difficulty in this case derives from the fact that this complex fault model

covers several configurations, four or even six, as presented in this thesis. The author of the habilitation thesis aims to intensify the research within a wider team that includes colleagues specialized in search techniques specific to artificial intelligence, in an attempt to identify even more efficient tests than those presented in the thesis (MT-R3CF and MT-E3CF);

b) For the memory cell configurations considered in static coupling fault models, the author proposes to expand the research with the aim of identifying the most effective tests for dynamic faults as well. In all cases, easy-to-implement test algorithms in BIST-RAM structures will be sought.

Part II

Reliability Performance Evaluation in Large Networks

➢ Brief presentation of the research area

The second area of research addressed by the author in this habilitation thesis concerns the issue of reliability performance evaluation in large communication systems, systems modeled as stochastic networks. The difficulty of this problem, which requires the use of algorithms with NP-hard complexity, has two objective causes: (1) the large number of states through which a network can evolve and (2) the very high level of redundancy ensured by the nature of the network. To illustrate these aspects, let us consider the simplest case (but also the most common in practice) where only two states are considered for an element in the network: good operation and failure. This means that the state of an element in the network can be described by a logical variable (binary state network). If the network comprises n nodes and m arcs, then the number of possible states is 2^{m+n}, which for a complex network becomes an extremely large number.

Regarding redundancy it is obvious that there are many possible communication routs between any two nodes in the network. Thus, communication between two nodes is guaranteed if at least one of these routes is functional. As a result, when evaluating the reliability of a connection between two nodes in the network, one of the most difficult problems in the field of probability theory occurs, i.e., determining the probability of the occurrence of events that are not mutually exclusive. For this purpose, SDP (Sum of Disjoint Products) algorithms are used, which are known to be NP-hard.

For these extremely difficult problems, special emphasis is placed on approximate evaluation methods that can reduce the complexity in the case of large networks.

In this area of research regarding the evaluation of reliability in complex networks, the research of the author of the habilitation thesis focused on the following directions:

a) Searching for exact reliability evaluation algorithms for systems with a network structure by successively applying the total probability formula and some series-parallel reduction rules;

b) Identifying new, more efficient SDP algorithms based on multiple variables inversion techniques (MVI);

c) Searching for efficient approximate methods to accurately assess the reliability of a network connection, which explicitly consider both the possibility of interruption of network lines and the possibility of node failure;

d) Developing techniques to accelerate Monte Carlo simulation algorithms for estimating reliability performance in large networks;

e) Adapting specific methods for assessing the reliability of the connection between two nodes to the study of extended connections that concern several nodes in the network;

f) Identifying new methods for approximate reliability assessment in large networks using network decomposition techniques.

- **Author's main contributions to the field of reliability assessment in complex networks**

a) Proposing a new method of transforming a structure function (as an expression of the studied connection) into an equivalent form with mutually exclusive terms. Specifically, the author of the habilitation thesis and his collaborator Sabina Adriana Floria propose a new method for the algebraic extraction of mutually exclusive terms, based on an MVI technique (called NMVI) that applies equally to structure functions composed of minimal paths or minimal cuts. Based on this method, the authors develop an efficient SDP algorithm, also called NMVI, with superior performance to other algorithms of this type, for which they received the best paper award at the 2017 INISTA Conference in Poland. The author appreciates that the NMVI algorithm is a remarkable result, which is useful in solving any problem involving the calculation of the probability that at least one of a set of non-mutually exclusive events will occur;

b) Proposing a method for approximate reliability assessment in large-scale networks, where, for high accuracy, the fact that nodes in the network are subject to failure is directly and explicitly considered, i.e., a network model known as “stochastic network with unreliable nodes”. Compared to exact approaches, this approximate method provides a reduction of computational time of up to 40%. This method is published in the journal Complexity, in the Q2 area quartile;

c) Carrying out an in-depth study on the convergence of estimators when evaluating the performance by means of Monte Carlo simulation and the relationship between simulation time and estimation accuracy;

d) Proposing techniques to accelerate Monte Carlo simulation algorithms to reduce simulation time for reliability assessment in large-scale networks. Quantitative evaluations highlight that applying these techniques reduces simulation time to less than 25% compared to basic (crude) Monte Carlo simulation;

e) Adapting the specific methods for evaluating the reliability of a connection between two nodes (two-terminal reliability evaluation) to the study of extended connections that concern several nodes in the network (k-terminal reliability evaluation). Detailed research on performance evaluation in complex networks, focusing on k-terminal network reliability evaluation problems, is a current interest of the author, with research results to be published soon;

f) Proposing and making a comparative analysis of methods for approximate evaluation of reliability performances in large-scale networks based on decomposition into subnetworks;

g) Proposing and evaluating a recursive reliability calculation algorithm for small and medium-sized networks based on the application of the total probability formula and some series-parallel reduction rules. This program was used by the author to verify and validate all studies performed by the other methods.

➢ **Further research**

a) All reliability studies presented in the thesis referred to networks with fixed topology, known a priori. In the case of ad hoc networks, but also in other situations, e.g., in sensor networks, the topology can have certain dynamics and, in these conditions, the classical methods for evaluating the reliability performance must be adapted to this new context. The author's future research will expand to cover these aspects of topology dynamics as well;

b) The author plans to conduct an in-depth study on accelerating the process of algebraic extraction of mutually exclusive terms by combining the NMVI algorithm with other known techniques.

Part III

Optimal Allocation of Reliability in Complex Redundant Systems

➢ Brief presentation of the research area

The third direction of research addressed by the author in this habilitation thesis concerns the optimal allocation of reliability in complex redundant systems. The reliability optimization problems (ROPs) that intervene in the design of complex systems are some of the most well-known research topics, to which special attention is still being paid today.

Depending on the intended solution for improving reliability, ROP problems are divided into three categories:

a) *Reliability Allocation Problems*, where the decision variables directly or indirectly reflect the reliability of the component elements of each subsystem;

b) *Redundancy Allocation Problems* (RAP), where the decision variables represent the number of components for each subsystem;

c) *Reliability-Redundancy Allocation Problems* (RRAP), where the decision variables reflect both the reliability of the component elements and the level of redundancy for each subsystem.

Practice has shown that the most difficult optimization problems belong to the RAP and RRAP types. In this thesis, RAP optimization problems are primarily addressed. These problems involve extremely complex, NP-hard search algorithms, as their solution space is very large.

The thesis focuses on the application of evolutionary algorithms and methods based on linear programming techniques. However, heuristic, engineering methods are also used, such as the analytical method based on Lagrange multipliers, to verify the solutions obtained or as part of a search strategy that combines several techniques. These directions of research with a pronounced interdisciplinary character were carried out by the author together

with Professor Florin Leon, from the "Gheorghe Asachi" Technical University of Iași, an expert in the field of artificial intelligence.

In this area of research that aims to identify optimal or suboptimal design solutions in accordance with reliability requirements, the author has mainly focused on the following topics:

a) Formulating complex RAP optimization problems for systems with a heterogeneous structure, which include most of the redundancy techniques encountered in practice. Compared to other issues encountered in the literature, the types of redundancy and reliability models considered by the author are the most comprehensive. These types of redundancy and the corresponding reliability models are presented in detail in the thesis;

b) Searching for the most efficient optimization methods based on evolutionary algorithms, for RAP-type problems, dedicated to the design of complex systems, with a heterogeneous structure and a large number of subsystems, of the order of tens or even hundreds;

c) Finding the most efficient methods for the RAP optimization problems based on linear programming techniques;

d) Adapting and extending the most effective optimization methods dedicated to cost-constrained RAP problems to solve multi-constraint optimization problems involving, e.g., cost, weight, and volume;

e) Adapting and extending the most efficient optimization methods dedicated to RAP problems to solve even more difficult RRAP optimization problems.

- **Author's main contributions to optimal reliability allocation in large hybrid redundant systems**

a) Devising an intuitive engineering method for determining a lower bound solution, i.e., the minimum values, for optimal redundancy allocation problems to ensure a required level of reliability. Identifying such a minimal solution is the first step in the optimization process. Based on this intermediate solution, the process of searching for the optimal solution is significantly reduced;

b) Developing a fast and efficient solution for solving RAP type problems in ~~the~~ case of systems with active redundancy based on the application of an analytical method (a Lagrange multiplier technique) as a first step followed by a search process with an original method called Pairwise Hill Climbing (PHC). Although dedicated to redundant systems with series-parallel structure, the efficiency of the PHC search process makes this hybrid method offer very good solutions also in case of redundant systems with spare components kept in passive or partially active state (i.e., standby redundancy allocation);

c) Formulating complex RAP-type optimization problems~~,~~ regarding the optimal allocation of redundancy in systems with heterogeneous structure, which is based on a comprehensive reliability model that covers most types of redundancy encountered in practice. Reliability calculation for redundant hybrid structures was performed based on Markov models. Compared to other problems found in the literature, the types of redundancy and reliability models considered by the author are the most comprehensive;

d) Expressing the RAP optimization problem as a Quadratic Unconstrained Binary Optimization (QUBO) problem, thus creating premises for a quantum solution on the D-Wave quantum computer;

e) Developing some effective optimization methods based on evolutionary algorithms for RAP-type problems dedicated to the design of complex systems, with a heterogeneous structure and a large number of subsystems (of the order of tens or even hundreds). In this regard, the RELIVE algorithm should be highlighted first, which combines the main global search with secondary local searches and, in addition, implements a technique of self-improvement of individuals that survive for several generations. The RELIVE algorithm also applies three types of mutations with different probabilities: Gaussian mutation, reset mutation, and pairwise mutation, designed specifically for problems with integer solutions;

f) Developing a zero-one integer programming formulation, intended to be solved with the lpsolve software application, particularly effective in solving RAP-type problems that arise in the design of complex systems with a

heterogeneous structure and a large number of subsystems. In case of complex systems, with a number of subsystems of the order of hundreds, this linear programming approach proved to be both fast and efficient, and offered the best solutions.

- **Further research**

In collaboration with Professor Florin Leon and by expanding the research team, the author of the habilitation thesis will continue the study of the optimal allocation of reliability in redundant systems with a hybrid structure, in several directions, as follows:

a) In all optimization problems addressed in this thesis, the type of redundancy for a subsystem is predetermined. But for some reliability models, this condition is too restrictive and can be relaxed. Therefore, the optimization process will be extended to find an optimal solution that addresses both the type of redundancy and the number of components for each subsystem;

b) Some redundant structures often adopt the technical solution where, in order to avoid common errors, the components are functionally compatible but constructively different and consequently have different reliability values. A research direction also looks at such redundant subsystems with a heterogeneous structure, where the components are no longer identical, but preserving the diversity of redundancy types considered in the studies so far;

c) In many cases, ROP optimization problems include multiple constraints. For example, maximizing reliability must take into account the maximum allocated budget, but at the same time weight or volume restrictions may also be imposed. The author aims to extend the research study in this regard as well. Also, under conditions of multiple constraints, optimization problems can be multi-objective. For example, the goal is to minimize the cost and volume of a product while ensuring a required reliability and a maximum allowable weight. Within an enlarged collective, the author's research will also expand in this direction;

d) The most important research direction, however, remains the extension of RAP-type optimization problems to RRAP-type problems, in which some decision variables express the reliability of the component elements, and others, the level of redundancy for each subsystem. In other words, to ensure the required reliability of the system at the subsystem level, either a direct increase in component reliability with additional cost (i.e., reliability allocation), or a redundancy-based reliability improvement (i.e., redundancy allocation) is accepted. Under these conditions, the optimization problem becomes much more complicated. Such a study, which preserves the diversity of redundancy types in the RAP problems presented in the thesis, is already underway, and although the problems are difficult, the results are promising.

Final remarks

The issues addressed in the thesis fall within the research field dedicated to increasing testability, reliability and safety in operation. The main topics addressed in the thesis are complex, with a pronounced interdisciplinary character. Consequently, mastering their complexity necessarily requires teamwork. The author of the habilitation thesis was able to coagulate a research team to successfully address these difficult topics. Next, the author aims to expand the research group to address the new directions of study.