Finite State Machine Watermarking Scheme using Genetic Algorithms for IP Cores Protection

by

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Acronyms

Acronym	Definition
FSM	Finite State Machine
ISFSM	Incompletely Specified Finite State Machine
CSFSM	Completely Specified Finite State Machine
STG	State Transition Graph
FT	Flow Table
IP	Intellectual Property
RTL	Register Transfer Level
GA	Genetic Algorithm
SoC	System on Chip
NP	Non-deterministic Polynomial time Problem
HDL	Hardware Description Language
VHDL	Very High Speed Integrated Circuit Hardware Description Language
PM	Process-Module
BT	Binary Tournament
RW	Roulette-Wheel Selection
DFS	Depth-First-Search
WG	Watermark Graph
MSE	Mean Square Error
PSNR	Peak Signal-to-Noise Ratio
dB	Decibel

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Abstract

This thesis proposes an improved procedure to watermark Intellectual Property Cores at Register Transfer Level using Genetic Algorithms. First, watermarking signature and Intellectual Property Core's behavioral description are translated into Finite State Machines in preparation for merging. The resulting Finite State Machine contains the watermarked Intellectual Property Core maintaining its original functionality without disruption. Next, a reduction procedure is applied to the watermarked design. At this stage, dealing with *hanging* states is challenging, if any of these is deleted, the watermark could be removed and possibly the original Intellectual Property Core functionality would not be disrupted. Both Finite State Machine merging and reduction are NP-Complete problems. In this study an improved objective function is proposed to accurately model the Finite State Machine reduction problem while applying Genetic Algorithms as optimization techniques at both stages. Empirical results show a significant improvement in terms of the number of final *hanging* states and watermark embedding strength as regards previous reported approaches.

Results of applying the proposed technique to watermark a number of Finite State Machines are presented and discussed.

Resumen

Esta tesis propone un procedimiento para insertar marcas de agua en IP Cores a nivel de transferencia de registros usando Algoritmos Genéticos. Primero, la firma y la descripción del comportamiento del IP Core son traducidos a máquinas de estados finitos para después ser fusionadas. La máquina de estados finitos resultante contendrá el IP Core firmado manteniendo la funcionalidad original sin ninguna alteración. Después, es aplicado un procedimiento de reducción de estados al diseño firmado. Un reto importante en esta etapa es el de lidiar con estados colgantes, que son un subconjunto de estados pertenecientes a la máquina de estados de la firma, y que al eliminar cualquier de estos estados, la marca de agua puede ser eliminada sin alterarse la funcionalidad original. Ambos problemas de fusión y reducción, son NP-completos. En este estudio se ha propuesto una función objetivo mejorada para modelar adecuadamente el problema de reducción aplicando algoritmos genéticos como técnicas de optimización en ambas etapas.

Resultados empíricos muestran mejoras significativas en términos del número final de estados colgantes y en la fuerza de la firma embebida en comparación con enfoques reportados en la literatura.

Chapter 1

Introduction

Throughout history, watermarking has been widely used for copyright protection. Existing techniques essentially consist in taking advantage of high information redundancy and susceptibility ranges of human's eye and ear. Inserting the watermark out of perception boundaries, allows the human to not discern any variation of the digital media even after been watermarked [29].

In the area of embedded systems, specially in the last pair of decades, the use of Systems on Chip (**SoC**), has impacted profoundly and became widespread alongside manufacturers. Intellectual Property (**IP**) Cores, reusable logic units, are widely used in electronic design. Thus, their authenticity is at risk when licensing to a second party or during redistribution [54].

There are two types of IP Cores, hard and soft cores. Hard cores are the physical description of some chip and they are commonly offered in binary representation [32]. Soft cores, on the other hand, are descriptions at higher levels. They can be distributed as netlists, representing the logical implementation at gate-level. These kinds of core give the original developer certain security when distributing multiple times due to the their high reverse engineering complexity. Soft cores have an even higher description level. Register Transfer Level (**RTL**) permits designers to develop their designs in a Hardware Description Language (**HDL**), such as VHDL and Verilog.

The technique proposed in this study inserts the watermark at synthesizable RTL by modifying its behavioral description. The proposal extracts and merge Finite State Machines (**FSMs**) from the IP Core and the watermark respectively. To achieve this, it is proposed to merge both FSMs using a Genetic Algorithm (**GA**). Media watermarking permits to lose data with little information, nevertheless, circuit watermarking must contain all of its original data at the end the signature must be difficult to remove, an issue which is tackled by a FSM reduction also based in GAs. It is also proposed an improvement when designing objective functions aimed to state reduction by reducing the space of satisfaction.

Among other advantages, IP Cores watermarking by merging and reducing involving FSMs leads to enhance heat and power dissipation [55] and an effective use of chip area by reducing the number of flip-flops and gates needed for implementation [5], fewer states permit handling a less significant number of don't cares. Furthermore, as pointed out by Christoforos, digital sequential systems operating over several time steps, can lead to a state-transition fault usually handled by merging the original FSM into a larger one that identifies and corrects errors [14].

1.1 MOTIVATION

IP reuse is becoming more and more common nowadays, however, sharing IP Cores in this competitive market can lead to copyright issues. Inserting a signature into the circuit behavior results in a secure way to share this information.

It has been previously proposed by several authors, techniques to watermark FSMs [2,6,15,34,54], however, it has been observed previous to the FSM merging, a set of *hanging* states, a group of states from the signature which are not *deeply* embedded (Defined in Section 2.1.1). It was noted that if any of these states is deleted, the watermark vanishes, in some cases without disrupting the original functionality, allowing to copyright infringements.

1.2 Goals

The main goal is to watermark IP Cores by FSMs merging using GAs, achieving invariance of the original design by not disrupting the primary functionality. The original functionality must be lost if someone tries to delete any part of the signature. That is, signature and design must be tightly bound.

The particular objectives are:

- To obtain a merged FSM containing the original functionality within the watermark.
- To analyze critical scenarios which could cause losing the watermark.
- To analyze the proposed objective functions oriented to FSM state-reduction in the literature to better understand the behavior and propose a better way to narrow the search space.
- To improve the state-reduction process.
- To conduct a comparative empirical analysis related to deterministic and genetic approaches to merging and reduction processes.
- To define a selection criteria of the most appropriate combination of algorithmic techniques that solve specific merging and reduction problems.

1.3 Methodology

Below the methodology of the proposed approach will be explained.

FSMs extraction

The first step is to extract the FSM which represents the IP Core behavior, then, it is translated into a FSM the watermark. Both steps are described in Sections 3.1 and 3.2 respectively.

Embedding procedure

After obtaining both FSMs, they are merged to obtain a single FSM with the signature embedded. That is, after the embedding procedure, the IP Core FSM will be already watermarked. Nevertheless, after this merging process, a state-reduction is performed. In Section 3.3.1 a deterministic merging method is described. In Section 3.3.2 a GA based approach is described.

Objective function

In Section 3.4.2 a GA based state-reduction of the watermarked FSM is presented. To obtain the objective function, a base function was proposed and the behavior of different state-reduction functions was analyzed to, based on their behavior, to define the coefficients of said function.

FSM reductions

There are two different types of FSM reduction. First there is a state-reduction proceeding which is aimed to fuse all compatible states with two different approaches, one deterministic described in Section 3.4.1, and a GA based approach, described in Section 3.4.2. The second type of FSM reduction is oriented to transitions, this reduction is performed by combining similar transitions by regrouping, this method is explained in Section 3.6.

SELECTING THE BEST RESULT

As seen above, deterministic and stochastic approaches to perform different proceedings are used. Thus, there will be 4 different watermarked FSMs and it will be necessary to choose the most convenient. In Section 3.5 is presented an equation to select the best result.

1.4 CONTRIBUTION TO KNOWLEDGE

Limiting the search space of the objective function that evaluates the possible solutions from the GA focused on state-reduction of FSMs, from fitting the model of a plane of a set of equations that describe the problem.

Empirical analysis of the use of stochastic techniques, particularly GAs aimed to optimize FSM merging and state reduction processes.

The presence of *hanging* nodes is critical during watermarking process. Previous studies by other authors do not address this issue, and to the best of our knowledge, it is the first time that *hanging* states are considered, how these states would affect the watermarking process and how stochastic techniques such as GAs deal successfully with them.

1.5 THESIS ORGANIZATION

Chapter 2 reviews previous work and theoretical framework related to the method presented in this thesis. In Chapter 3 each developed algorithm is described; going through FSMs extraction, merging, reduction and re-translation to Hardware Description Language (**HDL**); signal validations and synthesis verification is also presented. In Chapter 4 statistical justifications and experimental results are presented.

Finally, in Chapter 5 the conclusions drawn during this project are presented.

Chapter 2

Literature review

This chapter introduces several concepts related to the proposed watermarking scheme based on Genetic Algorithms (**GA**) for Intellectual Property (**IP**) Core protection. It also presents an extensive literature review of closely related topics together with several authors and state of the art research in order to contextualize this thesis work.

2.1 Basic concepts

In this section, basic terminology required to fully understand the method proposed in this research is described.

2.1.1 Finite state machine basis

A finite state system can be modeled by one or more Finite State Machines (**FSM**) that produce outputs on their transitions after receiving inputs [33].

An FSM M is a quintuple

$$M = (I, S, O, \delta, \lambda)$$

where I is a finite set of input symbols, S is a finite set of states and O is a finite

set of output symbols.

$\delta: S \times I \rightarrow S$ is the next state function.

$\lambda: S \times I \rightarrow O$ is the output function.

When the FSM is in a current state $s_i \in S$ and receives an input $a_i \in I$, it moves to the next state by $s_{i+1} = \delta(s_i, a_i)$ with $s_{i+1} \in S$ and gives as output $b_i = \lambda(s_i, a_i)$ with $b_i \in O$.

Let $M(S, E)$ be a FSM, where E are the transitions. Each transition $e(s_i, s_{i+1}) \in E$ with s_i and $s_{i+1} \in S$, represents state s_i is a *fanin* of state s_{i+1} and state s_{i+1} is a *fanout* of state s_i.

FSMs can be represented as State Transition Graphs (**STG**) and Flow Tables (**FT**). STGs are directed graphs whose vertices and edges correspond to states and state transitions from the FSM respectively [9]. As the STG of an FSM is a directed graph, graph theory concepts and algorithms are useful in FSM's analysis. A FT is a table with rows representing states and columns representing input symbols; an intersection of a row with a column corresponds to a next state and an output.

An FSM is a Completely Specified Finite State Machine (**CSFSM**) if there is a specified next state by the state transition function and a specified output by the output function for any state and its input. Otherwise, when there are states with an input that do not have a specific next state or output, the FSM is an Incompletely Specified Finite State Machine (**ISFSM**) [22].

Any pair of states s_i and s_j from S are compatible, if and only if, for every input sequence the next state and the output of s_i are the same as s_j.

$$\lambda(\delta(s_i, a_{(n+1)}), a_1 ... a_n) = \lambda(\delta(s_j, a_{(n+1)}), a_1 ... a_n) \tag{2.1}$$

A states set $C_i = \{s_{i1}, s_{i2}, ..., s_{in}\}$ is called a compatible class if every pair of states

is compatible [48]. C_{ij} is the *next states* set of C_i for every input a_i in I. It is said that C_{ij} is implied by C_i for every input a_i in I. P_i is the set of all compatibles C_{ij} implied by C_i, such that C_i and P_i are disjoint, that is, the cardinality of C_{ij} is greater than 1, $C_{ij} \not\subset C_i$ and $C_i \not\subset C_{ik}$ if $C_{ik} \in P_i$. A compatible C_i dominates a compatible C_j if $C_j \subset C_i$ and $P_i \subset P_j$. A compatible class which is not dominated by any other is called compatibility prime class (PC). A set of compatible states C_i is maximal if it is not a subset of another set of compatible states. A set of compatibles $C = \{C_1, C_2, ..., C_n\}$ is closed if, for each element $C_i \in C$, the implied $C_{ij} \forall a_i$ is also an element of C.

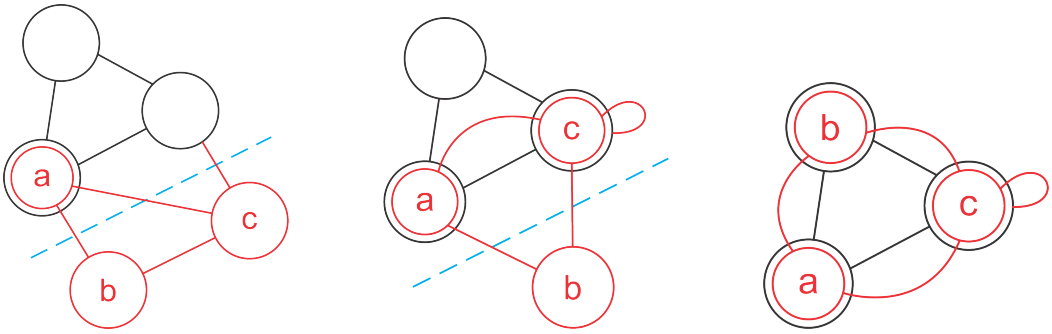
Let $M = (I, S, O, \delta, \lambda)$ and $M' = (I, S', O, \delta', \lambda')$ be two FSMs with same input and output sets. If for every state s in S and for every input a in I, it holds that $\delta'(\phi(s), a) = \phi(\delta(s, a))$ and $\lambda'(\phi(s), a) = \lambda(s, a)$ and ϕ is a bijective mapping from S to S', then M and M' are isomorphic, that is, both FSMs have the same number of states and are identical, except for the name of the states.

In a given FSM M formed by two merged FSMs M_i and M_w, ***hanging*** states, as called in this thesis, are a subset of states from M_w that can be pruned from M without disrupting M_i. For example, in Figure 2.1 are shown three examples of an FSM M formed after merging M_i and M_w with three states each. States and transitions from M_i are shown in black and states and transitions from M_w in red. In Figure 2.1a are two *hanging* states which can be pruned by the doted line. In Figure 2.1b is only one *hanging* state, and in Figure 2.1c there are no *hanging* states.

2.1.2 WATERMARKING CONCEPTS

In digital systems, a watermark is a kind of mark embedded in a digital signal within the signal itself. Its principal goal is to insert retrievable secret data related to the actual content of the shared media.

Watermarking may be used to verify ownership as a copyright protection by a



(a) FSM with two *hanging* states

(b) FSM with one *hanging* state

(c) FSM with no *hanging* states

Figure 2.1: *Hanging* states example

detection algorithm which extracts the watermark. In FSM watermarking, the mark, recalled as signature, is represented in FSM form. The way to insert the secret data is by merging both FSMs.

There are some important properties in FSM watermarking. The watermark should have a low overhead in area and resources, it must be robust, verifiable, difficult to remove, and overall, it must have fidelity.

FSM watermarking evaluation is defined as follows [57].

- Fidelity: This is the most important criteria. If the watermark process destroys the functional correctness, it is useless to distribute the core. Digital media watermarking is a process that affects the signal, nevertheless, in FSM watermarking it is admissible to insert new data, but keeping the original functionality.
- Resources overhead: Many watermark algorithms need some extra resources. Some for the watermark itself, some because of the degradation of the optimization results from the design tools.
- Verifiability: The watermark should be retrievable and also it should be embedded in such a way that simplifies the verification of the authorship.

- Difficult to remove: The watermark should be resistant against removal attack. The effort to remove the watermark should be greater than an effort needed to develop a new core or removal of watermark should cause corruptness of the functionality of the core. Watermarks which are embedded into the function of the core are more robust against removal than additive watermarks.

- Strong proof of authorship: The watermark should identify the author with a strong proof. It should be impossible that other persons can claim the ownership of the core.

- Robust: Meaning that even after adding new transitions or states, the signature should remain. The watermark procedure must be resistant against tampering.

In his work, Kalker provided the following watermarking definitions [27]:

- *"Robust watermarking is a mechanism to create a communication channel that is multiplexed into original content"*, and which capacity *"degrades as a smooth function of the degradation of the marked content"*.

- *"Security refers to the inability by unauthorized users to have access to the raw watermarking channel"*. Such an access refers to trying to *"remove, detect and estimate, write and modify the raw watermarking bits"*.

There are three types of attacks against FSM watermarking [39].

- Removal attack: Removal attacks are aimed to completely or partially remove the signature from the watermarked FSM. There are two kinds of removal attacks. The watermarked FSM can either have states deleted, or they can be masked in such a way that the signature is no longer retrievable. These types of attack do not need to know the input signal needed to obtain the signature back.

- Embedding attack: Embedding attacks are aimed to reinsert a signature into the watermarked design. This is possible by searching a new sequence of states that will be considered as the new watermark, or by embedding a completely new signature.

- Read-back Attack: Read-back is a feature that is provided for most FPGA families. This feature allows to read a configuration out of the FPGA for easy debugging. The idea of the attack is to read the configuration of the FPGA through the JTAG or programming interface in order to obtain secret information.

2.1.3 Evolutionary algorithms

Evolutionary Algorithms (**EA**) are described in [40] as follows.

- *"EAs are non-deterministic techniques that follow the Darwinian Principle of Evolution. A population is randomly or under certain conditions created and formed by individuals. Competition for survival among individuals determines which ones will reproduce and pass their genetic material to new individuals in following generations"*.

GAs are a subclass and the most known type of EAs [19]. A GA is a search heuristic inspired in the process of biologic evolution and natural selection and their molecular-genetic base. GAs do not guarantee to find the optimal solution of a certain problem as any other deterministic algorithm, if there is an algorithm to solve said problem. However, GAs do not attempt to enumerate all possible solutions of the problem. On the contrary, these heuristic algorithms have the ability to decide which solutions should survive the evolution process, based on "how close" they are from the best solution [17]. In Algorithm 1 is presented the general structure of a GA [19].

```
t ← 0
initialize P(t)
evaluate P(t)
while not termination conditions do
    recombine P(t) to yield C(t)
    evaluate C(t)
    select P(t + 1) from P(t) and C(t)
    t ← t + 1
end
```

Algorithm 1: GAs general structure.

Where $P(t)$ is the population for generation t and $C(t)$ is the offspring or new individuals. Below are described the main characteristics of the canonical GA with binary representation, 1-point crossover, and mutation by bit flip.

Initialization and representation

Initially, these algorithms randomly generate many individual solutions allowing to scatter solutions through the entire search space. The solutions are generally represented as chromosomes and typically defined with binary genes.

Selection

Each one of the chromosomes will be evaluated to define its aptitude with an objective function. During each generation, the entire population will be evaluated to select the fittest solutions.

Crossover operator

Next, pairs of individuals will suffer a matting process analogous to the natural reproduction. This recombination will generate a child solution. Recombination or crossover is a genetic operator to promote exploration of individuals throughout the search space. It implies significant changes at genotypic level which reflects larger

steps for exploring new solutions.

MUTATION OPERATOR

The offspring is later mutated to maintain genetic diversity or to be able to avoid convergence to local optima [40]. Mutation is a fine genetic operation which implies small probability based changes at the genotypic level which would reflect short steps for solutions moving throughout the search space.

FITNESS FUNCTION

Once applied the genetic operators, there will be selected the best individuals to conform the next generation population with the objective function mentioned above.

2.2 STATE-OF-THE-ART

This section provides a literature review concerning to IP Core watermarking. First, works related to IP Core protection and the different techniques developed during the years to signature embedding will be listed and commented. Then, different approaches to extract FSMs directly form IP Cores description will be enumerated. And finally, two different techniques to state-reduce FSMs, one deterministic and one stochastic, are described.

2.2.1 IP CORE PROTECTION

Several authors have proposed different approaches to merge FSMs or to embed signatures into IP Cores [2, 34], being the first one the proposal of Torunoglu and Charbon [52]. In a low level description, some authors have inserted the signature by controlling temperature radiation, electromagnetic radiation, power consumption

[56] or after synthesis by flip-flops rearranging [41]. At a higher level, there have been some other authors that insert the signature by merging internal FSMs or directing the configuration bit-file by fusing look-up tables, [26, 31]. Nevertheless, these methods are either slow or very difficult to implement. For example, monitoring power consumption to read out the signature takes several minutes, and monitoring radiation is not viable because new metal packages absorb radiation [57].

Some other authors have proposed to merge one or more FSMs found in VHDL coding at a Register Transfer Level (**RTL**) with a new FSM representing the watermark [2, 6, 15, 16, 34, 54]. Cui proposed a hybrid watermarking technique to double protect the design at two different abstraction levels, by inserting the watermark during the FSM design, it makes it more difficult to erase the watermark, and by inserting the watermark once the design is integrated into the System on Chip (**SoC**) the signature can be more easily identified [15, 16]. In Arunkumar approach, the signature bits are inserted into the outputs of the existing and free transitions of the STG obtaining a high tampering resistance, nevertheless, by not adding new transitions the approach can not be practical when dealing with CSFSMs [6]. Abdel et al. proposed the first public-key scheme, their approach utilizes coinciding and unused transitions to insert time-stamped authenticated watermark bits [2]. Lewandowski et al. proposed a greedy heuristic to solve the isomorphism problem when trying to match the IP FSM and the signature FSM, their justification is the high complexity when trying reverse engineering to retrieve and or delete the signature [34]. Xu proposed to insert the watermark bits into unused transitions when dealing with ISFSMs and later to convert this final FSM into a CSFSM; when dealing with CSFSMs, they proposed to insert all watermark bits into new transitions [54], nevertheless, this can lead to states than complain with the term of *hanging* states described in Section 2.1.1.

Although IP Core watermarking by FSMs merging can be translated as a subgraph matching problem [28], this novel method provides advantages when monitor-

ing SoC signals in real time.

Considering the above, in this work the signature is embedded by using FSMs merging. To make this possible, it is necessary to extract and latter to merge FSMs directly related to the behavioral description and the watermark. In the next subsection works related to FSM extraction will be commented.

2.2.2 FSM EXTRACTION

As described below, there have been several proposals to extract FSMs from VHDL coding at RTL. Some of them are focused in the coding structure, other ones in sentences and some others create their own models in a random fashion.

Liu proposed a method for extracting FSMs in Hardware Description Language (**HDL**) written at RTL by recognizing FSMs general patterns within the Process-Module (**PM**) graph [37] . These general patterns are derived from a relationship between FSM's current and next states, not the coding order. Thereby, neither hints nor comments are needed to recognize FSMs. Kubek proposed to define the central structure of the Finite State Control as a signal (or more signals) [30]. States are defined as a set of possible values of those signals. Transitions between states can be encoded by conditional statements like *if* and *case*. Pruteanu presented a tool capable to generate completely or incompletely FSMs, based on the list of arguments regarding the number of internal states, and the number of inputs and outputs [46]. Jnagal created POWDER, a program that generates random FSMs [24].

Based in literature review, it has been concluded that the best approach to extract an FSM from HDL coding, is to insert the signals into the FSM transitions. This will benefit the final number of states due to data will be contained not in states, but in transitions, letting to handle in a better way the number of *hanging* states, which according to the experimental analysis in this thesis, are considered to be the most vulnerable component of the watermarked FSMs.

2.2.3 FSM REDUCTION

FSMs model different structures functionality like circuits, networks, digital systems, control units, microprocessors and protocols. In digital systems, the outlining is generally represented in HDL coding and embedded into digital controllers which are later synthesized.

The use of these systems is so common nowadays that modern synthesizers extract FSMs from these codes to reduce them during the synthesis process, decreasing the use of silicon, among other advantages. The challenge in this research is facing the lose of states representing the signature embedded in the FSM when it is optimized by the synthesizer. Because of that, it is proposed to perform a post state-reduction of the watermarked FSM.

In state-based minimization, several authors have proposed techniques that require the enumeration of compatible sets trying to reach some maximal class with the minimum cardinality. Proposals from deterministic and GA based approaches are listed and discussed below.

COMBINATORIAL SCHEME

Because the signature's embedding is carried out by inserting new transitions, when the IP Core represents an ISFSM; and new transitions, new states and a control bit when it represents a CSFSM; redundant data which could be lost during the synthesizer optimization is inserted. The watermarked FSM will have the original functionality for any input signal, as long as the control bit had been set.

Combinatorial reduction consists in finding compatible states sets. This set of compatibles can be recombined in different configurations. The main goal consists in finding the prime compatibility class with minimum cardinality which covers the original functionality, therefore, the states set that solves the original problem, the

merged FSM in its minimal expression [48].

Since the 50's, Paull and Unger developed the general theory for ISFSMs and proposed a tabular technique to find compatibility classes of internal states from a FSM [42]. Nevertheless, their approach considers a large number of cases.

Later in the 60's, Grasselli and Lucio showed that only some compatibility classes need to be considered as members of a solution introducing the concept of prime classes which assures a minimal solution, and reducing this way the solution space size [21], a concept that gained certain strength among other authors [47].

Some authors like Avedillo et al. suggested the use of a set of maximal compatibles as the input set [8], nevertheless, it is not guaranteed that only using maximal compatibles there would be found a minimum closed cover class.

Several approaches, including the ones listed above, start with the strategy of satisfying the cover condition and then handle the closure condition (refer to Section 2.1.1 for details). Ahmad et al. proposed the idea of switching the order between the two conditions [5], they presented an algorithm that starts with the closure condition and then handle the cover condition.

Peña proposed an exact algorithm that is not based on the enumeration of compatible sets, and, therefore, its performance is not dependent on the number of prime compatibles [43].

State-minimization implies the resolution of an NP Problem [48]. In [13,18,48] the efficiency a GA performing a stochastic search to solve the conditions mentioned above was shown.

GENETIC SCHEME

Reduction of the number of states in ISFSMs implies solving a NP-Problem [5, 48]. Thus, some authors suggested GAs to solve this kind of problem [13, 48, 55]. In Sánchez proposal it is required to find all the elements of some compatibility class, and with it to generate a minimum closed cover class, including all the states of the original FSM, this class is called prime compatibility (see Section 2.1.1 for details) [48]. Sánchez proposed to use GAs due to the high complexity of finding the prime compatibility, this step is a combinatorial problem classified as NP hard [48]. In his approach, solutions represent compatibility classes.

Due to their evolutionary nature, GAs will search for solutions regard to the specific inner workings of the problem; specifically when solving combinatorial problems, GAs provide a great flexibility and do not require much problem-specific knowledge in order to get good solutions. Besides, these algorithms do not have much mathematical requirements about the optimization of combinatorial problems [19].

Yinshui et al. presented a GA for FSM encoding to minimize area and power dissipation [55]. In their work, chromosomes represent states sets as a string of decimals. Later, Chattopadhyay et al. used binary depiction [13]. Their approach reduces the number of nodes in the binary decision diagram representation of the FSM by using a GA based method for area and power minimization.

In the following chapter the proposed FSM watermarking scheme will be presented. Next, the evaluations will be analyzed. And finally, in Chapter 5, the conclusions will be discussed.

Chapter 3

FSM watermarking procedure

This chapter presents in an ordered manner the main stages of the proposed watermarking scheme and in particular, the evolutionary approaches proposed for Finite State Machine (**FSM**) merging and reduction stages.

In this thesis, a watermark is embedded within the circuits behavioral description, to secure ownership at a circuit level by using Combinatorial and Genetic Algorithms (**GAs**) to extract, merge and optimize FSMs representing the original behavior and the watermark.

The extraction of the original FSM is explained in Section 3.1, the translation of the signature FSM is explained in Section 3.2. Those FSMs are merged using two different approaches. The first approach is a combinatorial algorithm which operates in a greedy fashion [34] (see Section 3.3.1), the second one, is a GA that finds the most promising solutions, finding a solution in polynomial time [48] (see Section 3.3.2).

To secure signature's states remaining after synthesis, the merged FSM is state-reduce. The best solution must be selected after reduction, i.e., the solution with less *hanging* states remains to next stages.

The reduction also has a combinatorial approach which is explained in Section 3.4.1, and a GA based approach explained in Section 3.4.2.

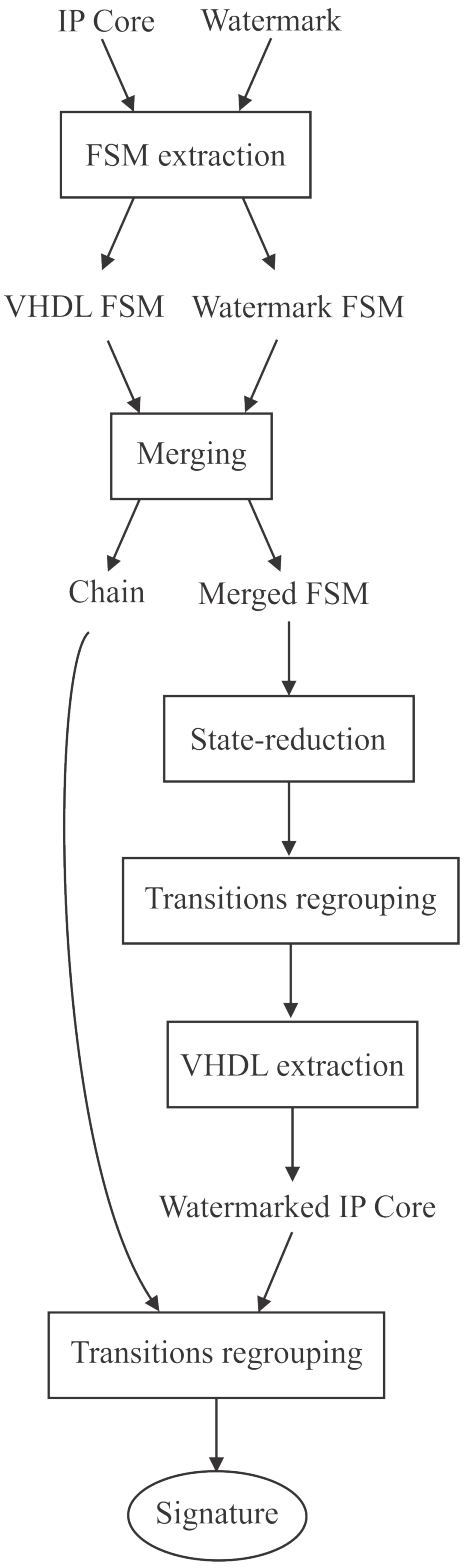


Figure 3.1: Watermarking Stages flow chart

It is necessary to properly combine adequate algorithms techniques in order to achieve the best possible solution (see Section 3.5); therefore, the next combinations are experimentally assessed:

a) Combinatorial Merging & Combinatorial Reduction

b) Combinatorial Merging & GA Based Reduction

c) GA Based Merging & Combinatorial Reduction

d) GA Based Merging & GA Based Reduction

The above procedure's combinations are investigated in order to determine which one provides the best performance in terms of copyright protection and FSM reduction.

All comparisons and experiments were made using FSMs from ACM/SIGDA benchmarks library [11], specially **LGSynth** series (High-Level Synthesis Workshops) from Collaborative Benchmarking and Experimental Algorithmics Laboratory granted by the Design, Verification and Test Division of Mentor Graphics Corporation. It was decided to use this benchmark due to its common use in literature.

3.1 Proposed FSM extraction

Intellectual Property (**IP**) Cores are regularly offered as synthesizable Hardware Description Language (**HDL**) at Register Transfer Level (**RTL**), typically in VHDL or Verilog, the dominant HDLs in the electronics industry. In this thesis, VHDL encoded IP Cores are used for the watermarking process.

The pseudo-code in Algorithms 2, 3 and 4 shows the steps followed to extract the FSM from the IP Core.

The first step consists in extracting an FSM from RTL VHDL [37]. If the FSM is an Incompletely Specified Finite State Machine (**ISFSM**), it is possible to insert

```
Input: Architecture
Output: Graph
List_of_processes ← FindProcesses(Architecture)
foreach process in List_of_processes do
    if process is triggered by a clock signal then
        process = Label as SEQ_P
    else
        process = Label as COM_P
    end
end
foreach a in List_of_processes do
    Graph ← InsertNode(node_a)
    foreach b in List_of_processes do
        Graph ← InsertNode(node_b)
        if there is a signal between a and b then
            InsertEdge(node_a, node_b)
            if b is called from a then
                node_a = Label as module
            else
                node_b = Label as module
            end
        end
    end
end
return Graph
```

Algorithm 2: Finding and labeling nodes.

extra transitions or states representing the watermark.

VHDL description will be modeled as a hierarchical modular graph, where each module will contain processes or more modules if necessary (see Figure 3.2a).

There are two different kinds of modules and processes, sequential and combinatorial. Modules with sequential label contain at least one sequential process, and modules with combinatorial labels, do not contain any sequential process.

Each process at RTL is represented in a Process-Module (**PM**) graph by a node as shown in Figure 3.3a. If there is a *fanout* or *fanin* from process a to process b, then a direct transition between their respective nodes is assigned. On the other hand, if

```
Algorithm TypeOfModule(Graph)
    foreach node in Graph do
        if node is labeled as module then
            if TypeOfModule(subgraph from node) then
                node.type = SEQ_M
            else
                node.type = COM_M
            end
        else
            if node is sequential then
                return true
            end
            return false
        end
    end
```

Algorithm 3: Modules labeling.

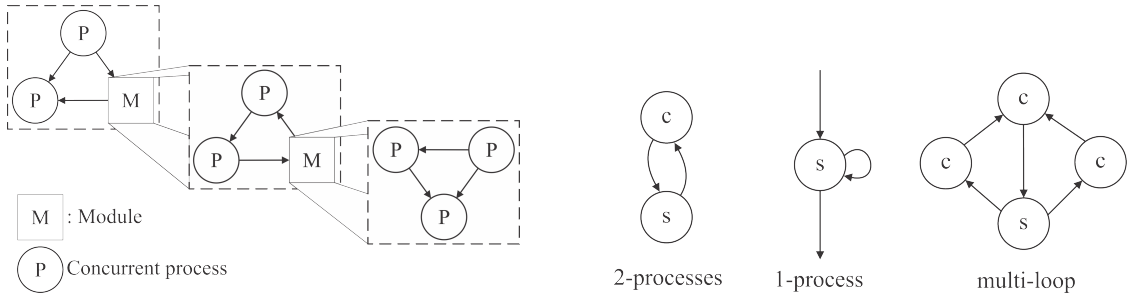
```
Input: Graph, List_of_loops
Output: G_IP(V, E)
foreach Loop in GetLoopPatterns(Graph) do
    if Loop is in List_of_loops then
        G_IP(V, E) ← Loop;
    end
end
return G_IP(V, E)
```

Algorithm 4: Loops recognition and FSM extraction.

process b is a function called from process a, then the respective node of process a will be labeled as a module and that module contains the process b respective node.

Liu et al. observed that process signals have combinatorial loops that can be represented in three different patterns [37]. They also found that only three of these loops are valid to represent an FSM, see Figure 3.2b.

The next step consists on finding these patterns and to label the involved nodes in each loop as an individual FSM traversing the PM graph in a Depth-First-Search (**DFS**) fashion as shown in Figures 3.3b and 3.3c. The FSM is represented in *kiss2* format, a standard FSM format [3].



(a) Modules in HDL **(b)** Valid FSM loop patterns in RTL VHDL

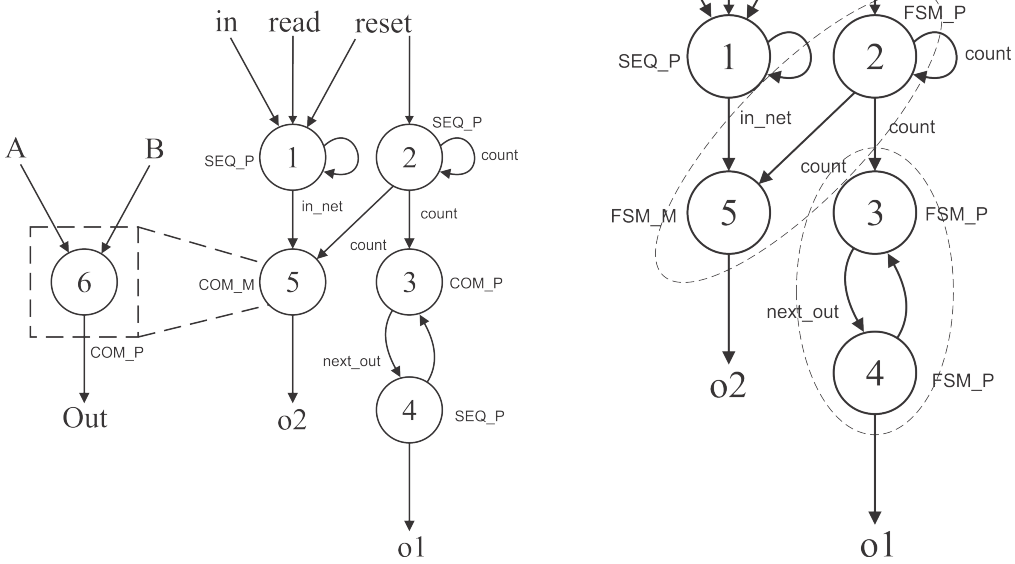
Figure 3.2: Loop patterns

So far, one out of two FSMs that will be merged has been extracted. This FSM represents the IP Core behavior, in the next section the translation from a file into the second FSM that will represent the signature, and their subsequent merging will be explained.

3.2 Proposed watermark translation

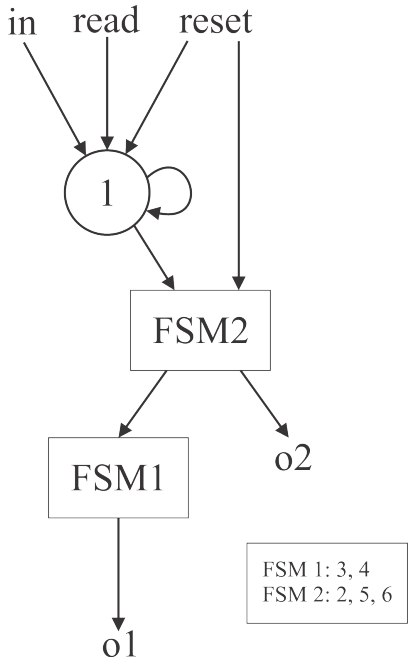
After FSM extraction from the IP Core, the next step is to construct a Watermark Graph (**WG**). Algorithm 5 shows the pseudo-code used to translate a watermark file into a FSM.

In [34], Lewandowski proposed to hash the watermark using RIPEMD-160 (**R**esearch and Development in Advanced Communications Technologies in Europe **I**ntegrity **P**rimitives **E**valuation **M**essage **D**igest in its 160 bits version). RIPEMD-160 is a cryptographic hash function which maps any data, in this case the watermark file, of any size, to a fixed 160 bits length binary chain [45]. It does not matter if the original size of the watermark file is less than or greater than 160 bits. This way, to insert any format file of any size as signature is now plausible. Besides, by hashing with a widely used hashing function, the proposed algorithm can be compared with others in literature, moreover, a fixed 160 bits length signature provides enough data to demonstrate that the number of *hanging* states can be minimized even with high



(a) Original PM graph

(b) PM graph loop patterns



(c) Final PM graph FSMs

Figure 3.3: Loop patterns and FSM recognition

Input: Watermark_file
Output: Watermark_graph $G_w(V, E)$, Bit_chain
Hex_string ← RIPEMD-160(Watermark_file)
foreach Hex *in* Hex_string **do**
  $G_w(V)$ ← InsertNode(New_vertex)
  if Hex $\not\subset G_w(E)$ **then**
    input ← RandomInput()
    $G_w(V)$ ← InsertNode(Temp_vertex)
    New_edge ← RenewEdge(New_vertex, Temp_vertex)
    New_edge.Input(Input)
    New_edge.Output(Hex)
    $G_w(E)$ ← InsertEdge(New_edge)
    Bit_chain ← Concat(Bit_chain, input)
  else
    New_vertex = a $\Rightarrow G_w(Hex) : (a, b)$
  end
end
return $G_w(V, E)$, Bit_chain

Algorithm 5: Translating a watermark into a FSM.

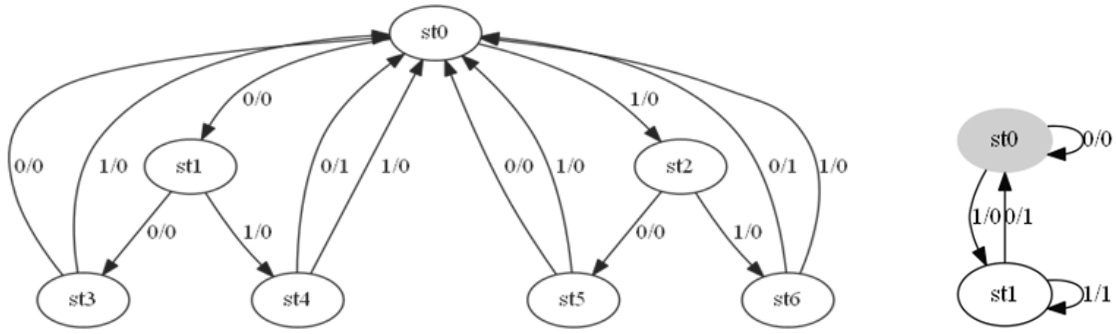
quantity of information.

The obtained binary chain from RIPEMD-160 is sectioned depending on the original FSM output length n, i.e. 160 bits will be separated in n bits packages resulting in $m = \lceil \frac{160}{n} \rceil$ total packages.

The number of new possible packages (transitions) to embed in the new State Transition Graph (**STG**) will be directly proportional to the total number of transitions m. The worst case scenario is when all bit packages are different. If n is greater than 5, then there will be more possible packages, than packages themselves. For example, if the original FSM has outputs of $n = 8$ bits length, then there will be $m = 20$ packages to insert, but $2^n = 256$ different packages to choose, that is, there are more possible packages than packages needed to embed the watermark. This scenario is shown in Table 3.1, there are only 5 possible cases where all packages could be inserted, nevertheless, 2 of them 5 have nearly zero probabilities of happening.

m	n	2^n	P
160	1	2	~ 1
80	2	4	0.6623
54	3	8	0.2235
40	4	16	0.0827
32	5	32	1.8004×10^{-13}
27	6	64	not possible
23	7	128	not possible
20	8	256	not possible
$\vdots$	$\vdots$	$\vdots$	$\vdots$
$m > 20$	$n > 8$	$2^n > 256$	not possible

Table 3.1: Probabilities of inserting all the packages.



(a) Original FSM **(b)** Signature

Figure 3.4: FSMs to be merged

Transitions only contain output strings, the input string depends on the original FSM, unless that not all the transitions could be merged, in that case the input would be randomly chosen. The building algorithm iterates through all packages inserting them into the new STG, saving the bit chain which satisfies the desired output. In Figure 3.4b an FSM with a hash chain 011100 is shown, the satisfying bit chain would be the input 111000, i.e., starting from *st0*, input 111000 would return 0 at the first transition because input 1 in *st0* has as output 0 and next state *st1*, the next transition would return 1 following the same principle, as well as the rest of transitions. Table 3.2 shows the next states.

At this stage, there are already two FSMs to later be merged. After the

Actual State	Input	Output	Next State
st0	1	0	st1
st1	1	1	st1
st1	1	1	st1
st1	0	1	st0
st0	0	0	st0
st0	0	0	st0

Table 3.2: Transitions to obtain satisfying chain from Figure 3.4b

merging process, the original functionality will remain; containing the watermark as new transitions or states, assuming they are not already contained, which is highly improbable.

3.3 FSM MERGING

The proposed method merges two FSMs: one corresponding to the IP Core module and one that represents the watermark. After fusing both of them, the resulting FSM maintains the original functionality together with the owner's signature. Two different approaches to merge the STGs are used, however, it will only remain the one with lower number of *hanging* states as will be explained in Section 3.5.

3.3.1 COMBINATORIAL MERGING

The first approach, based on Lewandowski et al. proposal [34], is a combinatorial merging with minor variations. Finding the most similar subgraph from the original FSM and the watermark FSM. This approach can be translated as an isomorphism problem, a well known NP-Complete problem [5]. Thus, they proposed a greedy algorithm designed to solve a subgraph matching problem.

The approach finds the highest degree node in the original FSM and then selects from the FSM watermark, the node with minimum cost to match with. This process will iterate recursively through all adjacent nodes. Algorithm 6 shows the pseudo-code used during this approach to merge FSMs in a combinatorial fashion.

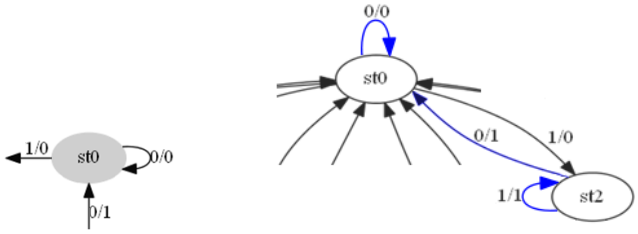
Input: $G_{IP}(V, E)$, $G_w(V, E)$, Bit_chain
Output: $G_m(V, E)$
$N_{IP} \leftarrow$ MaxDegreeNode(G_{IP})
$N_w \leftarrow$ MinMatchCost(Max, G_w)
$G_m \leftarrow N_{IP}$
r $\leftarrow$ G_{IP}.GetInputsLength()
q $\leftarrow$ -r
while *card*(UnmatchedNodes(G_w)) ≥ 1 **do**
  foreach node *in* MaxDegreeNode(UnmatchedNodes(N_{IP})) **do**
    New_vertex $\leftarrow$ MinMatchCost(N_w)
    $G_m(V) \leftarrow$ InsertNode(New_vertex)
    New_edge $\leftarrow$ RenewEdge(New_vertex, NextState(New_vertex))
    Input $\leftarrow$ Bit_chain[(q $\leftarrow$ (q+r)):r]
    New_edge.Input(Input)
    New_edge.Output(N_w.Output())
    $G_m(E) \leftarrow$ InsertEdge(New_edge)
  end
  $N_{IP} \leftarrow$ NotYetMatched(MaxDegreeNode(G_m))
end
return $G_m(V, E)$

Algorithm 6: Combinatorial FSM merging.

For example, Figure 3.4a shows the FSM extracted from a random IP Core, and Figure 3.4b shows the FSM obtained from the signature which is desired to merge with. For simplicity, let rename the states from the watermark FSM adding a W letter to the left, and for the IP Core FSM an I letter, leaving as result W_{st0} instead st0 for the watermark FSM, and I_{st0} instead of st0 for the IP Core FSM, and so on. Following the combinatorial merging approach, the highest degree nodes from the watermarked FSM is found, in this case there are only two states, and both have the same number of transitions, thus, W_{st0} is selected to start. W_{st0} has to be assigned to a corresponding I_{state}, thus, the FSM IP Core is traversed, looking for

the node with minimum cost to match with, i.e., the most similar, it must contain as many as possible transitions equal to W_{st0}.

For this particular case, it is needed to find an I_{state} with one loop transition with input 0 and output 0, a fan-out transition with input 1 and output 0, and finally a fan-in transition with input 0 and output 1. Basically, something similar to Figure 3.5a.



(a) W_{st0} state **(b)** I_{st0} pair candidate to W_{st0}

Figure 3.5: Don't care minimization

Starting from I_{st0}; it is notorious its lack of loop transitions as needed, but it do has a fan-out transition 1/0 as W_{st0}, if this state ended up being our I_{state} to pair to, then it would be necessary to insert extra transitions as shown in Figure 3.5b. Nevertheless, in Figure 3.4a can be seen that inserting loop transition 0/0 collapses with fan-out 0/0 transition in direction to I_{st1}. For that same reason, in this particular example, after searching from maximum to minimum degree order, and traversing recursively through all over the span from each state, it was not possible to found correspondence between states from both FSMs, concluding that graph 3.4a is a Completely Specified FSM (**CSFSM**). To overcome this issue, it was added an extra input bit for control as seen in Figure 3.6. Concluding that any subgraph from Figure 3.4b is isomorphic to Figure 3.4a graph, and moreover, that not all states from graph 3.4b can be related to any I_{state}, brings us to insert this extra W_{states} into graph 3.4a as new I_{states}, besides its own transitions as seen in Figure 3.6.

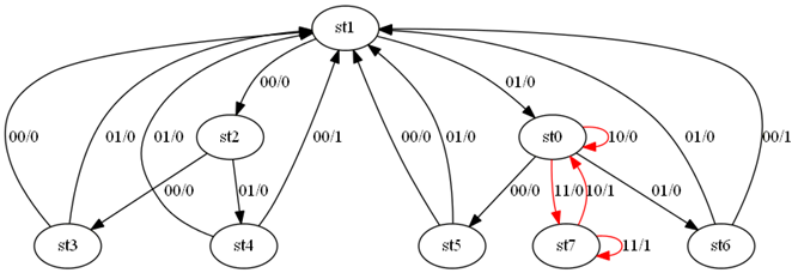


Figure 3.6: Combinatorial FSM merging

3.3.2 GA BASED MERGING

The second approach is a GA. It was decided to use an evolutionary algorithm to merge both FSMs due to the isomorphism problem and its NP-Complete nature. The number of possible combinations increases rapidly while adding states to the solution. For example, if it is chosen the FSM "*scf*" from LGSynth89 benchmark with its 121 states, the number of possible combinations to merge the signature would be:

$$ {}_nP_r = \frac{n!}{(n-r)!} \tag{3.1} $$

with n equal to the number of states of the IP Core and r equal to the number of states of the signature. If the signature has 2 states, then the number of combinations would be 14520, with three states almost 2 millions, with four states more than 200 millions, and with ten states it would be a number of 21 digits.

To solve this issue, the GA will only consider the best adapted possible solutions by qualifying their fitness, without ignoring enormous quantities of solutions. The pseudo-code of the GA based approach is shown in Algorithm 7 and 8.

In GAs, a random population is initialized following the representation explained below. The selection criterion considers the fittest individuals to mate and evolve to create the next generation.

Input: $G_{IP}(V, E)$, $G_w(V, E)$, Bit_chain
Output: $G_m(V, E)$
a ← G_{IP}.CountStates()
b ← G_w.CountStates()
r ← G_{IP}.GetInputsLength()
q ← -r
Chrom[ ] ← Merging(G_{IP}, $G_w(V, E)$)
for i:0 *to* a-1 **do**
    Pos_hot ← FindHot(Chrom[i×b+1:i×b+b])
    if *Pos_hot* ≠ *-1* **then**
        New_vertex ← MatchNodes(G_{IP}[i], G_w[Pos_hot])
        $G_m(V)$ ← InsertNode(New_vertex)
        New_edge ← RenewEdge(New_vertex, NextState(New_vertex))
        Input ← Bit_chain[(q ← (q+r)):r]
        New_edge.Input(Input)
        New_edge.Output(N_w.Output())
        $G_m(E)$ ← InsertEdge(New_edge)
    end
end
if *UnmatchedNodes(G_w).Count()¿1* **then**
    foreach node *in UnmatchedNodes(G_w)* **do**
        New_vertex ← node
        $G_m(V)$ ← InsertNode(New_vertex)
        New_edge ← RenewEdge(New_vertex, NextState(New_vertex))
        Input ← Bit_chain[(q ← (q+r)):r]
        New_edge.Input(Input)
        New_edge.Output(N_w.Output())
        $G_m(E)$ ← InsertEdge(New_edge)
    end
end
return $G_m(V, E)$

Algorithm 7: GA based FSM merging.

```
Algorithm Merging(G_IP, G_w(V, E))
    bits ← G_IP.GetInputsLength()
    pop ← population size
    samples ← number of experimental samples
    gens ← number of generations
    for p:1 to samples do
        new_pop[ , ] ← GenBin(bits, pop)
        for i:1 to gens do
            for j:1 to pop do
                x_temp ← pga(new_pop[i, j]).x
                f_temp[ ] ← pga(new_pop[i, j]).f
            end
            add_fit ← ∑ f_temp[ ]
            min_f ← f_temp[ ].Min()
        end
    end
    return x_temp[min_f]
Procedure PGA(pop)
    new_gen ← Crossover(pop)
    new_gen ← Mutate(pop)
    fit ← ∑ Hanging States ⇒ new_gen
    return fit, new_gen
```

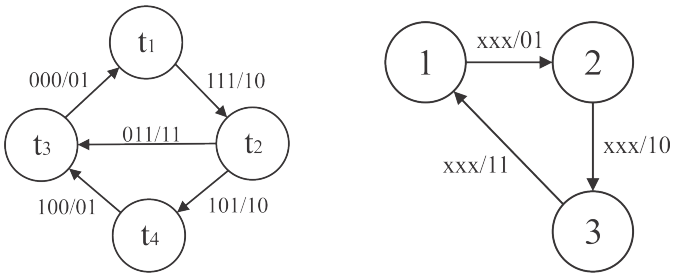
Algorithm 8: Genetics from GA based FSM merging.

REPRESENTATION

Binary representation has been used to represent the number of states, therefore the chromosome length is $n \cdot m$ bits, where n is the number of states in the signature's FSM, and m is the number of states in the RTL's FSM.

An example is given in Figure 3.7, a chromosome's genotype is 010|001|100|000, with length $3 * 4 = 12$. Every chromosome is formed by 4 packages with 3 genes each, in this particular case:

$$t = \{t_1, t_2, t_3, t_4\} = \{\underbrace{\overset{1\,2\,3}{(010)}}_{t1}, \underbrace{\overset{1\,2\,3}{(001)}}_{t2}, \underbrace{\overset{1\,2\,3}{(100)}}_{t3}, \underbrace{\overset{1\,2\,3}{(000)}}_{t4}\}$$



(a) IP-Core FSM **(b)** Signature's FSM

Figure 3.7: Merging example

where:
(010) = Represents node 2 of Signature's FSM matches node t_1.
(001) = Represents node 3 of Signature's FSM matches node t_2.
(100) = Represents node 1 of Signature's FSM matches node t_3.
(000) = Indicates node t_4 has no match.

This representation is called one-hot encoding [23], but also gray code or binary code can be used to minimize chromosome length and the size of the structure used to save the data flow. But the algorithm is explained using one-hot representation for simplicity.

CROSSOVER OPERATOR

After selection, recombination between individuals is carried out using single point crossover. A random position within 1 in n chances to be chosen, being n the number of genes, within the chromosome length is selected and genetic data is exchanged. For example, Figure 3.8 shows a crossover where 010 001 100 000 suffers a crossover at position 2 with 000 001 000 100 which returns 000 001 100 000, representing node $t1$ without matching, node $t2$ matched with node 3, node $t3$ matched with node 1, node $t4$ without matching and node 2 as *hanging* state; and chromosome 010 001 000 100, which represents node $t1$ matched with node 2, node $t2$ matched with node 3, node $t3$ without matching, node $t4$ matched with node 1 and no *hanging* states.

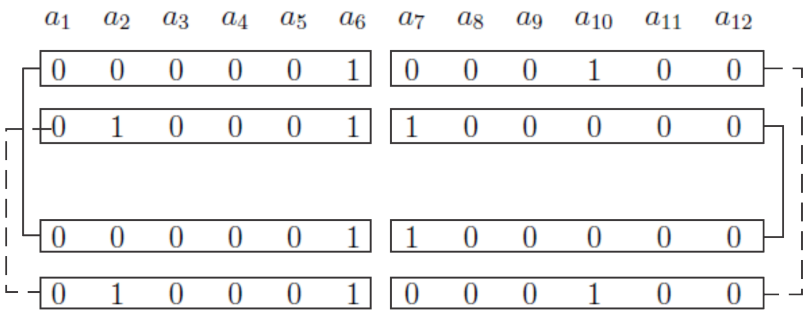


Figure 3.8: Crossover example at position 6.

MUTATION OPERATOR

In this stage, the chromosomes will suffer a mutation in one single gene. This mutation acts with a probability $\frac{1}{n}$ being n the number of genes, and inverts the information in the defined position. For example, if the chromosome 010 001 100 000 suffers a mutation in the gene 2, the new chromosome will be 000 001 100 000 as seen in Figure 3.9. Note that it has to be checked if the mutation does not entails to an invalid chromosome, it can be done simply by checking that a chromosome package has only one-hot, i.e., packages like 011 are taken as wrong; besides, in the whole chromosome should be only as much as n one-hot genes.

a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}
0	1	0	0	0	1	1	0	0	0	0	0
0	0	0	0	0	1	1	0	0	0	0	0

Figure 3.9: Mutation example at position 2.

FITNESS FUNCTION

The fitness function is directly proportional to the quality of a match, that is, it is intended to find some chromosome which has the minimum cost value depending on the *hanging* states. To do so, the function can be seen as a sum, with n equal to the

number of *hanging* states $\sum_{i=1}^{n} i$. In other words, it is intended to reduce the number of *hanging* states.

It can be seen that the *hanging* state $st7$ from the combinatorial merging (see Figure 3.6) because of the GA has disappeared in Figure 3.10.

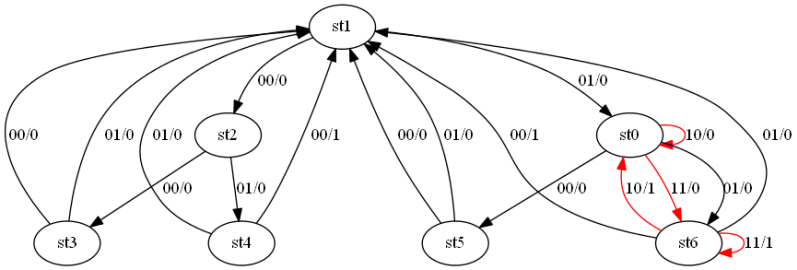


Figure 3.10: Genetic FSM Merging

At this point, there is already the watermarked IP Core, furthermore, it could be possible to translate its FSM to VHDL code. Nevertheless, as explained in Section 2.1.2, one main characteristic of watermarking is it's strength against attacks. In FSM watermarking, this so called attacks are carried out by removing *hanging* states which originally belonged to the watermark. Another issue of great importance are synthesis tools used in synthesis process because suboptimal STG representations are commonly generated to enhance effective use of chip area, as pointed out in [5, 43]. Thus, to ensure the watermark strength, these *hanging* states should be reduced to the minimum, or even better, completely removed when possible. To do so, the watermarked FSM is state-reduced. This process also involves two different approaches which are described below.

3.4 Watermarked FSM reduction

FSM state-reduction consists on finding the FSM that performs the original functionality with the minimum number of states. This minimal FSM, with the watermark already in it, is obtained by two different approaches, that is, there will be found

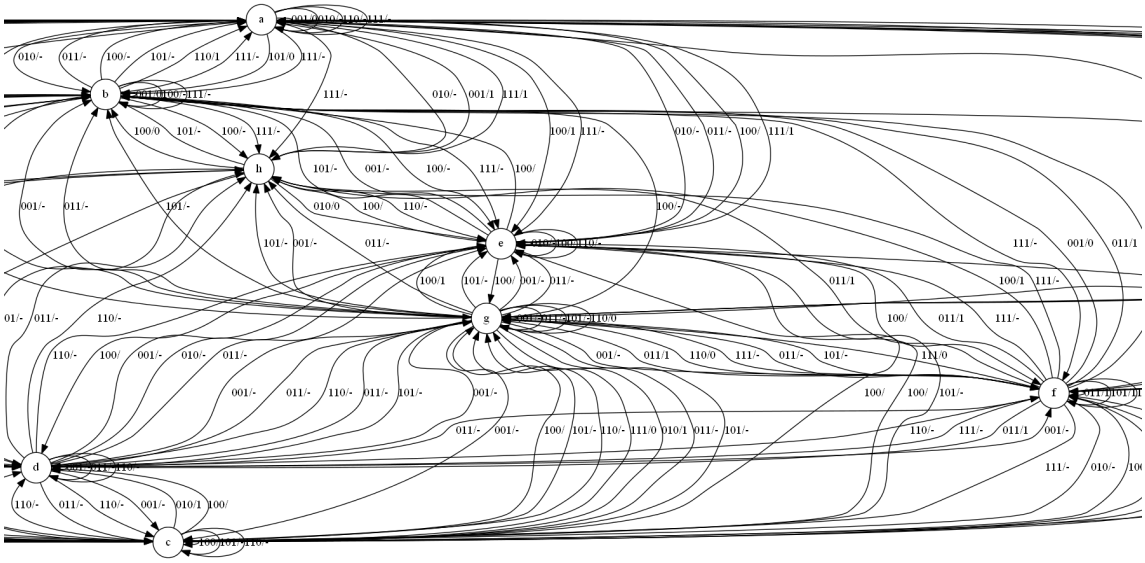


Figure 3.11: FSM to be minimized

two different results and the best of them will be chosen. The first approach is a combinatorial reduction, while the second one is a genetic reduction.

3.4.1 Combinatorial reduction

As explained in Section 2.1.1, any pair of states $(s_i, s_j) \in S$ is compatible if and only if their *output* and *next state* are exactly the same. The set composed entirely of compatible states is called compatible class $C_i = \{s_{i1}, s_{i2}, ..., s_{in}\}$ and the set of next states of this compatible class is called the implied C_{ij}. A set of compatibles $C = \{C_1, C_2, ..., C_n\}$ is closed if for each element $C_i \in C$, the implied C_{ij} is also an element of C. The pseudo-code of the combinatorial FSM reduction is shown in Algorithm 9.

Grasselli proposed a method to minimize the number of internal states and since its publication in 1965 it is the most widely used method to reduce the number of states in FSMs [21]. The method is described below. For a practical example, Table 3.3 shows the next-state flow table and Table 3.4 shows the output table of Figure 3.11 FSM to be minimized. Due to space, there is only shown part of Figure

```
Input: G_m(V, E)
Output: G_r(V, E)
N_t[ , ] ← Construct Next-State flow table from G_m
O_t[ , ] ← Construct output flow table from G_m
Q ← G_m.GetInputLength()
Q ← 2^Q
for j:2 to G_m.GetNumberOfStates() do
    for k:1 to G_m.GetNumberOfStates()-1 do
        if DctCompatibles(O_t[j,1:Outputs],O_t[k,1:Q]) then
            Compatibles[j, k] ← Label(∼)
        end
        else if DctIncompatibles(O_t[j,1:Os],O_t[k,1:Q]) then
            Compatibles[j, k] ← Label(×)
        end
        else
            Compatibles[j, k] ← NeededPairs(N_t[j,1:Q],N_t[k,1:Q])
        end
    end
end
for j:2 to G_m.GetNumberOfStates() do
    for k:1 to G_m.GetNumberOfStates()-1 do
        if Compatibles[j,k] has no labels then
            foreach pair in Compatibles[j,k] do
                if Compatible(pair) then
                    Compatibles[j,k] ← Label(∼)
                else
                    Compatibles[j,k] ← Label(×)
                end
            end
        end
    end
end
G_r ← ReduceStates(Compatibles[ , ])
return G_r(V, E)
```

Algorithm 9: Combinatorial FSM reduction.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7
a	a	-	d	e	b	a	-
b	b	d	a	-	a	a	-
c	b	d	a	-	-	-	g
d	-	e	-	b	b	-	a
e	b	e	a	-	b	e	a
f	b	c	-	h	f	g	-
g	-	c	-	e	-	g	f
h	a	e	d	b	b	e	a

Table 3.3: *Next-State* flow table

3.11 focusing in states, living out the rest of transitions. Note that Figure 3.11 does not have any relation with the global example used so far, and its only purpose is to show the complexity handled during minimization, being the FSM shown in Figure 3.11 one of the smallest treated during experimentation.

First, it is needed to place the symbol ($\sim$) in the corresponding cells in Table 3.5 where both states have a directly recognizable compatibility in the flow tables. For example, the pair of states (b, c) have the same *next states* as seen in Table 3.3 and same *output* as seen in Table 3.4. The same for directly recognizable incompatibility, for example, the states (a, c) are clearly incompatible, thus, the symbol ($\times$) is placed in its corresponding cell in Table 3.5.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7
a	0	-	0	1	0	-	-
b	0	1	-	-	-	1	-
c	0	1	1	-	-	-	0
d	-	-	-	-	0	-	-
e	-	-	-	-	-	-	1
f	0	-	1	1	1	0	-
g	-	1	-	1	-	0	0
h	1	0	1	0	-	-	1

Table 3.4: *Output* flow table

When compatibility or incompatibility are not directly recognizable then necessary conditions for compatibility are written. For example, states (a, b) are com-

patible only if states (d, a) are compatible also, thus, this new pair is written in the cell shared by b and a.

When the compatibilities table is finished, it is necessary to iterate for a second time to update it. For example, pair (e, f) needs pairs (c, e), (b, f) and (e, g) to be compatibles, but neither of them are, in this case the pair (e, f) must be updated to $(\times)$ as seen in Table 3.6.

	a	b	c	d	e	f	g
b	ad						
c	×	∼					
d	be	de ab	de ag				
e	ab ad	de ab ae	×	∼			
f	×	×	cd	×	ce bf eg		
g	∼	×	cd fg	de be af	×	eh	
h	×	×	×	∼	ab ad	×	×

Table 3.5: Compatibilities from Flow Tables 3.3 and 3.4 after 1 iteration

State pairs in Table 3.6 which do not have a $(\times)$ symbol are considered as compatibles. Finally, the table is scanned from bottom right to upper left corner to obtain the compatibility classes step by step as shown in Table 3.7.

The minimal covering class must be selected from the entire enumeration, that

	a	b	c	d	e	f	g
b	ad						
c	×	∼					
d	be	de ab	de ag				
e	ab ad	de ab ae	×	∼			
f	×	×	cd	×	×		
g	∼	×	cd fg	×	×	eh	
h	×	×	×	∼	ab ad	×	×

Table 3.6: Compatibilities from Flow Tables 3.3 and 3.4 after a second iteration

Step 1: $\{f, g\}$
Step 2: $\{f, g\}$,$\{e, h\}$
Step 3: $\{f, g\}$,$\{d, e, h\}$
Step 4: $\{c, f, g\}$,$\{d, e, h\}$,$\{c, d\}$
Step 5: $\{c, f, g\}$,$\{d, e, h\}$,$\{b, d, e\}$,$\{b, c, d\}$
Step 6: $\{c, f, g\}$,$\{d, e, h\}$,$\{a, b, d, e\}$,$\{b, c, d\}$,$\{a, g\}$

Table 3.7: Compatibility classes from table 3.6 after second iteration.

is, from all compatibility classes and their possible combinations, the maximal set must be selected which covers all original states in the minimal representation, or the subset with minimal cardinality. Comparing the reduced FSM from Figure 3.12 with the just merged FSM from Figure 3.10 can be seen a decrease in the number of states, furthermore, it has been even possible to get a lower number of states than

the original FSM as shown in Figure 3.4a. Must be clarified that this state-reduction is allowing to embed even deeper the watermark into the original FSM as observed in experimentation.

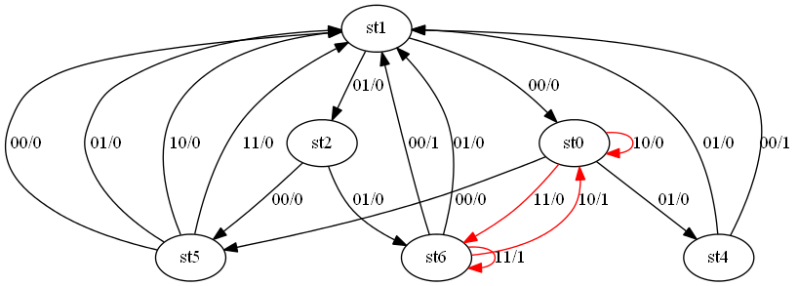


Figure 3.12: Combinatorial FSM Reduction

Even though there has been obtained a reduced watermarked FSM, there is a chance that the results can be improved by another reduction. This new step is a GA, which is explained below. In Section 3.5 it will be explained how to choose which result to keep to be translated to VHDL coding.

3.4.2 GA BASED REDUCTION

The pseudo-code of GA based FSM reduction is shown in Algorithm 10.

Input: G_m
Output: $G_r(V, E)$
Com_classes ← FindCompatibles(G_m)
Chrom[ ] ← Reduction(G_m, Com_classes)
for i:1 *to* Com_classes **do**
  if *Chrom[i] = 1* **then**
    CombineNodesFrom(Com_classes[i])
    UpdateGraph(G_r)
  end
end
return $G_r(V, E)$

Algorithm 10: GA based FSM reduction.

As mentioned in the literature review in Section 2.2.3, in 1959 Paull proposed a tabular technique to find compatibility classes of an FSM [42], and searching

Algorithm `Reduction(`G_{IP}, Com_classes`)`
- bits ← G_{IP}.GetInputsLength()
- pop ← Com_classes.Count()
- samples ← number of experimental samples
- gens ← number of generations
- α ← Number of maximal compatibles for which the closed condition is observed
- C ← pop – Chromosome length
- S ← Number of total states
- **for** p:1 *to* samples **do**
  - new_pop[,] ← GenBin(bits, pop)
  - **for** i:1 *to* gens **do**
    - **for** j:1 *to* pop **do**
      - x_temp ← PGA(new_pop[i, j]).x
      - f_temp[ ] ← PGA(new_pop[i, j]).f
    - **end**
    - add_fit ← $\sum$ f_temp[ ]
    - min_f ← f_temp[ ].Min()
  - **end**
- **end**
- **return** x_temp[min_f]

Procedure `PGA(pop)`
- new_gen ← Crossover(pop)
- new_gen ← Mutate(pop)
- β ← Number of maximal compatibles in new_gen
- γ ← Number of states which are covered by new_gen
- fit ← $\frac{5}{76}\left(-\frac{1.66\beta}{C}+\frac{\gamma}{S}+2\right)$
- fit ← fit × α
- **return** fit, new_pop

Algorithm 11: Genetics from GA based FSM reduction.

these classes is still used in state reduction due to its simplicity, exactitude and low computational cost. Later in 1965, Grasselli proposed the idea of minimizing the internal states of an FSM finding the set of prime classes with minimum cardinality [21]. Nowadays, efforts are focused on finding this minimal set.

One form to select the subset of compatibility classes from all possible combinations is by using GAs. Its goal is to prove some combinations and by discrimination

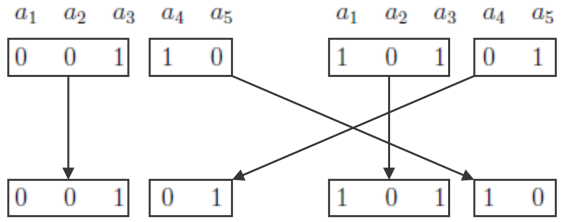


Figure 3.13: Crossover example at position 3

to select the best ones and use some characteristics to create new generations of possible solutions. Like Sánchez, the method proposed uses the same chromosome representation and operators [48], nevertheless, in this research a new fitness function that has shown a better performance is proposed.

CHROMOSOMES

Any possible chromosome is represented as a binary string and its length is always going to be the number of compatibility classes. For example, the chromosome

a_1	a_2	a_3	a_4	a_5
0	0	1	1	0

represents the compatibility classes from Table 3.7 in step 6 ($\{a, b, d, e\}$ and $\{b, c, d\}$), note that classes $\{c, f, g\}$, $\{d, e, h\}$, and $\{a, g\}$ would not be taken into account.

CROSSOVER OPERATOR

Mating will occur in a randomly chosen gene with a probability of 1 in n, being n the number of genes. For example, Figure 3.13 represents two chromosomes crossed at position 3.

MUTATION OPERATOR

This operator alters a selected gene with a probability of 1 in n. In Figure 3.14 is shown a chromose mutated at position 2.

a_1	a_2	a_3	a_4	a_5
0	0	1	0	1
0	1	1	0	1

Figure 3.14: Mutation example at position 2.

Resulting in compatibility classes $\{d, e, h\}$, $\{a, b, d, e\}$ and $\{a, g\}$ as maximal class.

FITNESS FUNCTION

To select the fittest solutions, a cost function is used which assigns a real value to each possible solution for selection after reproduction and survival for the next generation.

Sánchez proposed Equation 3.2, as the fitness function to minimize the number of final states in an FSM [48]. This function was used as a baseline to design an improved function to perform the state-reduction for the watermarked FSM.

$$F = C \cdot S \cdot \frac{\alpha}{\beta} + C - \beta + C \cdot \gamma \tag{3.2}$$

where:

C = Chromosome length.

S = Number of total states.

α = Number of maximal compatibles for which the closed condition is observed.

β = Number of maximal compatibles in the solution.

γ = Number of states which are covered by the solution.

Equation 3.2 can be rewritten as:

$$F = C \cdot \left[\left(\frac{S \cdot \alpha}{\beta} \right) - \left(\frac{\beta}{C} \right) + \gamma + 1 \right]$$

But it was noted that S is interacting with terms related to compatibility classes, rather than γ which is linked to states. Since the end of the 50's and beginning of the 60's, with the works of Paull and Grasselli [21,42], it was established that the terms to reduce the number of internal states of an FSM must remain even though their configuration changes, that is, the order of the terms and their respective coefficients can change, but not the terms themselves. Based on that premise, Equation 3.3 is the base function proposed where now γ is dependent of S and α is now independent. β/C and γ/S represent the percentage of classes and the percentage of states covered in the solution respectively.

$$F = \alpha - \frac{\beta}{C} + \frac{\gamma}{S} \tag{3.3}$$

To find the coefficients of Equation 3.3, different functions with the same variables were proven, and the results were mapped to a *cloud points*. Due to α, C and S are constants, there are only two variables, β and γ, thus the results are in $\mathbb{R}^3$, which means, the representation can be plotted as Figure 3.15. Some of the equations used to find the *cloud points* are shown below out of a total of 20 different configurations (refer to Appendix B to see the full list of equations).

$$F_1 = C \cdot S \cdot \frac{\alpha}{\beta} - \beta + C \cdot \gamma \qquad F_4 = \alpha \cdot \beta \cdot \gamma + \frac{C}{S}$$
$$F_2 = \frac{\alpha}{\beta} - \frac{\beta}{C} + \frac{\gamma}{S} + S \qquad F_5 = \frac{\alpha}{\beta} + \frac{\beta}{S} - \frac{\gamma}{C}$$
$$F_3 = \frac{\alpha}{\beta} - \frac{\beta}{S} \cdot C + \frac{\gamma}{S} - C \qquad F_6 = \alpha \cdot S + \beta \cdot \frac{\gamma}{C}$$

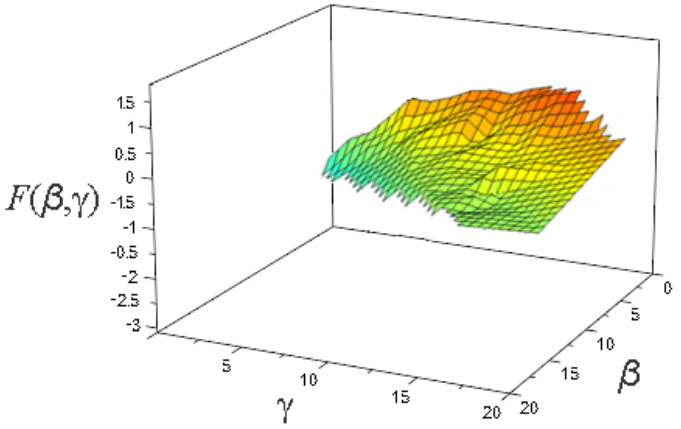


Figure 3.15: *Cloud points* from different configurations.

The *cloud* is very close to a sloped plane. A surface that can be approximated only with three points randomly chosen.

The three points are $P = (6, 8, 0)$, $Q = (2, 14, 0.8333)$ and $R = (12, 18, 0)$. The vectors $\vec{PQ}$ and $\vec{PR}$ can be calculated by the subtraction $Q - P$ and $P - R$, which are also on the plane.

$$\vec{PQ} = Q - P = (-4, 6, 0.8333)$$
$$\vec{PR} = R - P = (6, 10, 0)$$

With the cross product of these two vectors the orthogonal vector to the plane is obtained.

$$\vec{n} = \vec{PQ} \times \vec{PR} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ -4 & 6 & 0.8333 \\ 6 & 10 & 0 \end{vmatrix} \begin{matrix} \vec{i} & \vec{j} \\ -4 & 6 \\ 6 & 10 \end{matrix} = -8.333\vec{i} + 4.9998\vec{j} - 76\vec{k}$$

Then, the plane equation is:

$$z = Ax + By + C' = \left(\frac{1}{76}\right)(-8.333x + 4.9998y + 9.9996) \tag{3.4}$$

Let $x = \beta/C$ and $y = \gamma/S$, and since the plane is an approximation of the set of results of different fitness functions, the coefficients can be replaced as follows:

$$F = \alpha + \frac{5}{76}\left(-\frac{1.66\beta}{C} + \frac{\gamma}{S} + 2\right) \tag{3.5}$$

The plane equation has a Mean Square Error (**MSE**) of 0.0115 and a Peak Signal-to-Noise Ratio (**PSNR**) of 38.7851 dB with respect to the *cloud points*, values that were calculated as follows:

$$MSE = \frac{\sum_{i=1}^{n}\left(\left|\hat{Y}_i - Y_i\right|^2\right)}{n(n-1)}$$

$$PSNR = 20 \cdot log_{10}\left(\frac{max\left(\left|\hat{Y}\right|\right)}{\sqrt{MSE}}\right)$$

where $|\hat{Y}_i - Y_i|^2$ is the square difference between n *cloud points* $\hat{Y}$ and the interpolated sloped plane Y.

To reduce the MSE, the plane can be approximated by least squares fitting. Let again $x = \frac{\beta}{C}$ and $y = \frac{\gamma}{S}$ and:

$$\begin{bmatrix} \sum x_i^2 & \sum x_i y_i & \sum x_i \\ \sum x_i y_i & \sum y_i^2 & \sum y_i \\ \sum x_i & \sum y_i & \sum 1 \end{bmatrix} \begin{bmatrix} A \\ B \\ C'' \end{bmatrix} = \begin{bmatrix} \sum x_i z_i \\ \sum y_i z_i \\ \sum z_i \end{bmatrix}$$

which is equal to:

$$\begin{bmatrix} 10711.44165 & 21071.35575 & 1816.07197 \\ 21071.35575 & 47053.38285 & 4001.177778 \\ 1816.07197 & 4001.177778 & 568 \end{bmatrix} \begin{bmatrix} A \\ B \\ C'' \end{bmatrix} = \begin{bmatrix} 451.8089598 \\ 1254.968944 \\ 145.6158735 \end{bmatrix}$$

Then, $A = -0.0898$, $B = 0.0516$ and $C'' = 0.1804$, letting to:

$$F' = \alpha - 0.0898\frac{\beta}{C} + 0.0516\frac{\gamma}{S} + 0.1804 \tag{3.6}$$

which is now closer to each point in the *cloud points* with a MSE of 0.0113 and a PSNR of 38.9049 dB, which with the first approximation give differences of around 2×10^{-4} and 0.1198 respectively.

However, the terms of any of both plane equations can be used to replace the terms of the *fitness* function. This is possible because the aim of this approach is to adjust the results space, allowing to reduce the noise, thus, optimal solutions are more likely to be found, instead of being scattered through all the searching space.

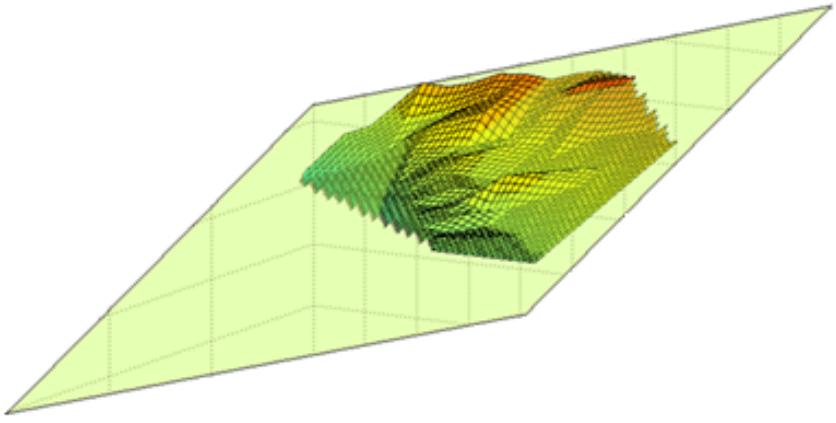


Figure 3.16: Plane interpolation from the *cloud points*.

When the algorithm reaches the stop condition (minimum cost value returned or number of generations), the chromosome with minimal cost value found will indicate the compatibility classes to take into account and thus the remaining states

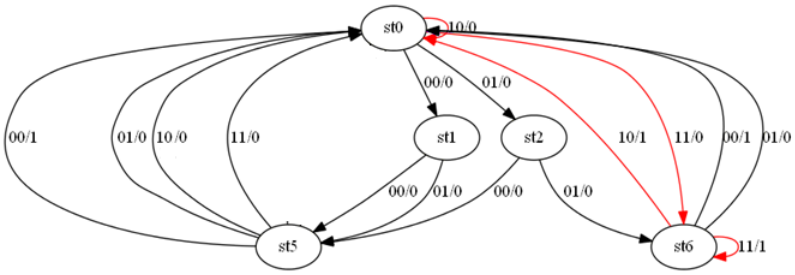


Figure 3.17: Genetic FSM Reduction

of the FSM.

So far, in the example of this chapter, that is, the merging process from Figure 3.4a and Figure 3.4b, there is already inserted the signature into the IP Core and also it has been reduced to decrease the riskiness of losing the watermark after synthesis by two different approaches. The final result after the GA approach is shown in Figure 3.17.

Now it is time to select which combination of approaches has to be kept to endure that the best result is chosen.

3.5 Selecting the best watermarked design

After reducing both FSMs with the different techniques, it is required to compare the results checking quantity of total final states and the number of *hanging* states to decide which FSM to keep as final result. Equation 3.7 will return a value between 0 and 1 if there are not *hanging* states, a value between 1 and 2 if there is one *hanging* state, a value between 2 and 3 if there are two *hanging* states, and so on. If there is a draw, that is, if for example, there are two different FSMs both with three *hanging* states but the first one with 5 final states and the second one with 4 final states, then equation 3.7 will return a value depending on the number of these final states, giving a lower result to the second FSM. In this case, it will return 3.765672465 for the FSM with 4 final states and 3 *hanging* states, and 3.804491726 for the FSM with

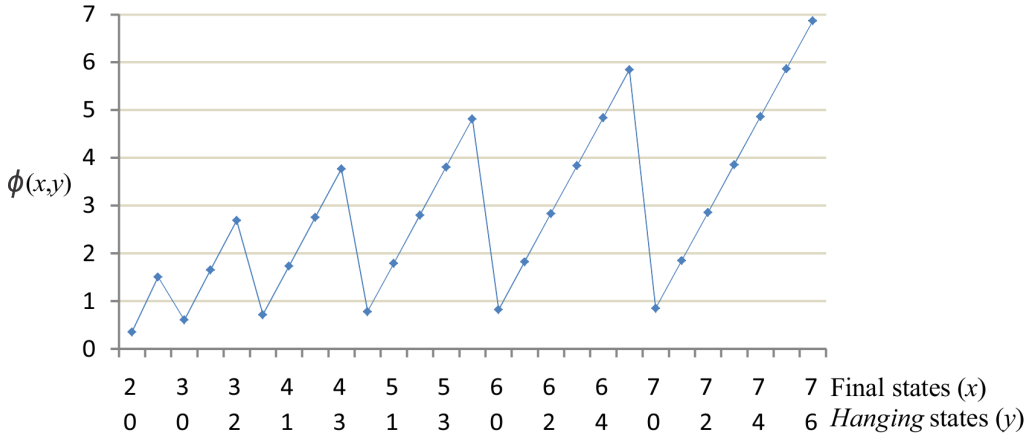
5 final states and 3 *hanging* states. Equation 3.7 compiles with superior horizontal asymptotes as shown in Figure 3.18a. These asymptotes prevent results from higher number of *hanging* states to interfere with results from smaller quantities of *hanging* states. This was achieved by the horizontal asymptotic behavior of the negative exponential $-exp(1/x)$, and the first term y which allows to increment the final value as new states are added to the final FSM. Adding a 2 at the end just adjusts the values between y and $y+1$, as shown in Figure 3.18a.

$$\phi(x,y) = y - \exp\left(\frac{1}{x}\right) + 2 \tag{3.7}$$

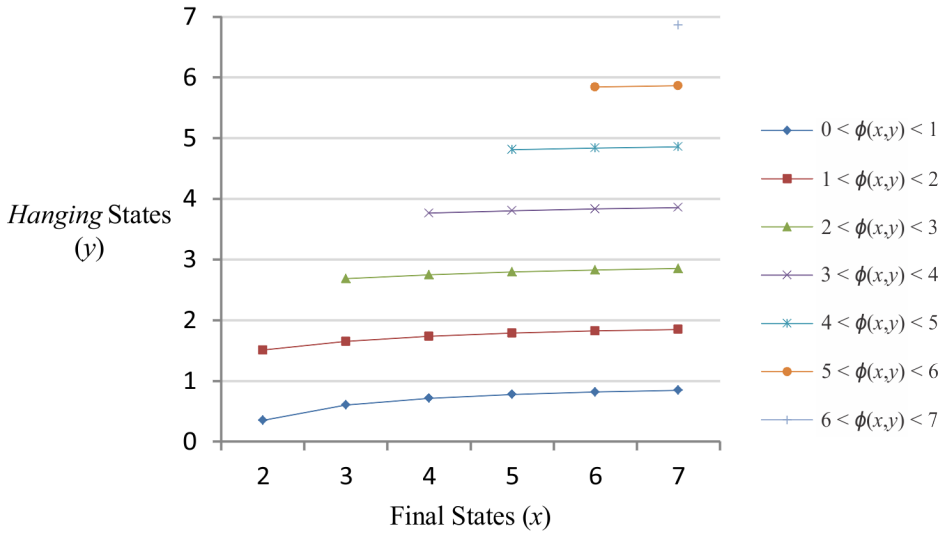
where $x : 1 < x < \infty$ is the number of final states and $y : 0 < y < x$ is the number of *hanging* states. In Figure 3.18a are plotted all possible solutions from $\phi(2,0)$ through $\phi(7,6)$. It is easy to notice that every solution of $\phi(x,y)$ has as horizontal asymptote $x+1$, this behavior is the result of $-exp(1/x)$.

It is needed that results with 0 *hanging* states to remain between $\phi(x,y) = 0$ and $\phi(x,y) = 1$, this same principle goes to the rest of possible solutions. As seen in Figures 3.18a and 3.18b, the behavior of Equation 3.7 satisfies this principle. Thus, Equation 3.7 satisfies $\phi(x_i,y) < \phi(x_{i+1},y)$ and $y < \phi(x,y) < y+1$. Table 3.8 shows the results of $(x,y) = (2,0)$ to $(x,y) = (4,3)$, plotted in Figure 3.18a until $(x,y) = (7,6)$.

In the example used so far after merging and reducing the FSMs presented in Figure 3.4 from Section 3.2, the better FSM obtained is shown in Figure 3.12, the combination of techniques to reach this result was a genetic merging with a combinatorial reduction. The resultant FSM has less states than the original FSM shown in the Figure 3.4a, moreover, there is any *hanging* state related to the watermark, which means that the watermark has a better chance to remain after synthesis.



(a) Behavior of $\phi(x, y)$



(b) Horizontal Asymptotes of *Hanging* States

Figure 3.18: Asymptotes behavior

3.6 TRANSITIONS REGROUPING

Before converting the final FSM to VHDL coding, a regrouping is performed to minimize the number of transitions known as *don't care minimization* [36].

The main goal of *don't care minimization* is to reduce occupied area and possibly improve performance. The way to solve this is an exhaustive searching method.

x	y	$\phi(x, y)$
2	0	0.351278729
2	1	1.508175302
3	0	0.604387575
3	1	1.650141192
3	2	2.686458043
4	0	0.715974583
4	1	1.734719145
4	2	2.751151131
4	3	3.765672465

Table 3.8: $\phi(x, y)$ behavior

For example, if the next-state of *st0* is *st1* regardless the input from 0000 to 0101, and besides, the output is the same for every case, then the transition shown in Table 3.9a can be reduced as shown in Table 3.9b.

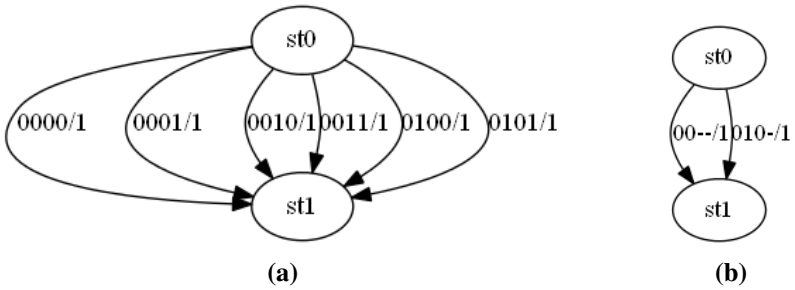


Figure 3.19: FSM before and after Don't Care Minimization

Table 3.10 shows minimization steps. All inputs related to *minimizable* transitions are sorted in ascending order. In the **first step** the first transition inputs are grouped where the **first bit** are the same. In the **second step** are grouped only the inputs where their **second bit** is the same, and so on. This regrouping will continue until each group contains only 2 or 1 input, when this happen, the bits at the position from the specific step will be necessarily different letting to create a new transition with a don't care bit.

Actual State	Next State	Input	Output
st0	st1	0000	1
st0	st1	0001	1
st0	st1	0010	1
st0	st1	0011	1
st0	st1	0100	1
st0	st1	0101	1

(a) Transitions **before** Don't Care Minimization

Actual State	Next State	Input	Output
st0	st1	00–	1
st0	st1	010-	1

(b) Transitions **after** Don't Care Minimization

Table 3.9: Transitions regrouping

When an insertion of a don't care bit is reached, then all results can be re-grouped similar to the first iteration, reducing the transition even more. Finally, if there are no more possible reductions then the algorithm stops and returns the transition reduced as the column **Result** from the example Table 3.10.

First Iteration			Second Iteration		Result
First Step	Second Step	Third Step	First Step	Second Step	
0000 0001 0010 0011	0000 0001 0010 0011	0000 0001 0010 0011	000- 001-	000- 001-	00–
0100 0101	0100 0101	0100 0101	010-	010-	010-

Table 3.10: Don't care minimization steps

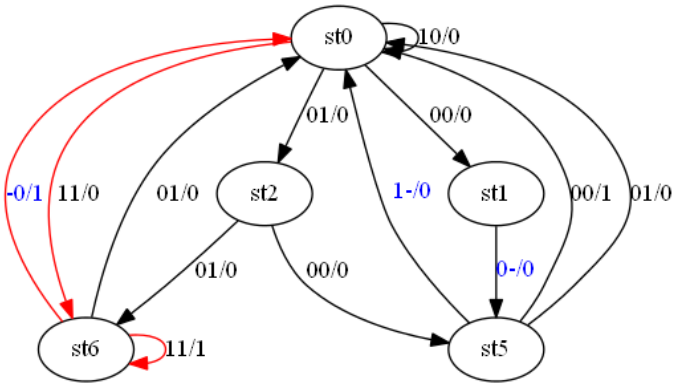


Figure 3.20: Don't care minimization of Figure 3.12

3.7 Validation

3.7.1 Original functionality

Most VHDL synthesizers extract FSMs found within the code to optimize and synthesize them side by side [37]. As a matter of fact, some synthesizers let to configure this process, for example, Leonardo Spectrum allows to set the FSM Extraction as *disabled* [1].

There are three ways to synthesize an FSM:

1. To omit any special synthesis directives and let the logic synthesizer operate on the state machine as though it were random logic. This will prevent any reassignment of states or state machine optimization. It is the easiest method and independent of any particular synthesis tool, but it is the most inefficient approach in terms of area and performance.

2. To use directives to guide the logic synthesis tool to improve or modify state assignment. This approach is dependent on the software used.

3. To use a special state-machine compiler, separated from the logic synthesizer, to optimize the state machine. It can then merge the resulting state machine

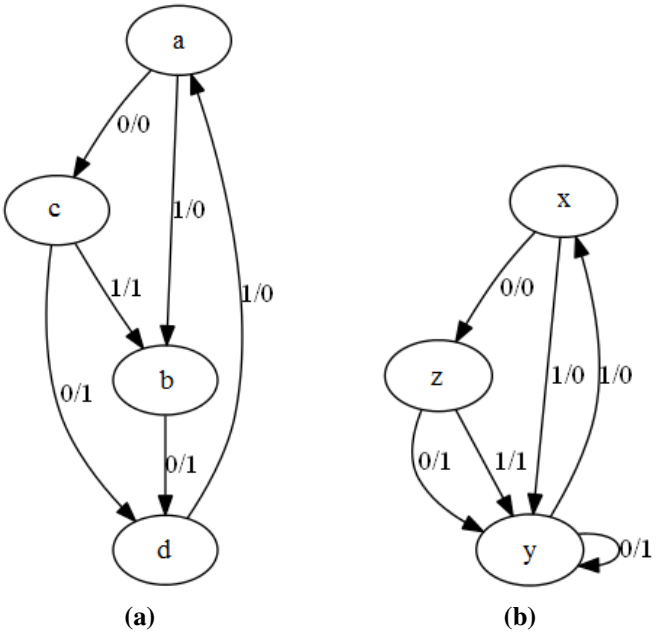


Figure 3.21: FSMs to validate

with the rest of the logic. This method leads to the best results but it is harder to use and ties the code to a particular set of software tools, not just the logic synthesizer.

An FSM compiler extracts the state machine. Some companies use FSM compilers that are separate from logic synthesizers because algorithms for FSM optimization are different from those for optimizing combinatorial logic.

To validate that the watermarked FSM has the original functionality, it is necessary to compare both FSMs [22]. Thus, a new method was proposed to perform this comparison.

First, a transition table is constructed for each FSM as shown in Tables 3.11a and 3.11b. Then, a table of compatibilities is constructed as Table 3.12a. Each column represents states from one FSM and rows are states from the other. In the example, rows represent states of Figure 3.21a and columns states of Figure 3.11b. Starting from upper-left corner to the bottom and then to the right, all pairs

	Next State		Output	
	0	1	0	1
a	c	b	0	0
b	d	-	1	-
c	d	b	1	1
d	-	a	-	0

(a) Flow table of Figure 3.21a

	Next State		Output	
	0	1	0	1
x	z	y	0	0
y	y	x	1	0
z	y	y	1	1

(b) Flow table of Figure 3.21b

Table 3.11: Flow tables

are noted of compatible states needed to make compatible the pair of states at the crossing point of that specific row and column. For example, pair (a,x) represented in cell (1,1) can be compatible because their outputs are the same, but they need pairs (c,z) and (b,y) to be compatible as well, thus, those pairs are listed in that specific cell. If there is a directly visible incompatibility, it is marked as $\times$, observe pair (a,y), in Table 3.11a the possible outputs of state a are different from the possible outputs of state y in Table 3.11b, thus, cell (1,2) of Table 3.12a is marked with $\times$.

a	cz by	×	×
b	×	dy	dy
c	×	×	dy by
d	ay	ax	×
	x	y	z

(a) First Iteration

a	✓	×	×
b	×	✓	✓
c	×	×	✓
d	×	✓	×
	x	y	z

(b) Second Iteration

Table 3.12: Compatibilities of Flow Tables 3.11a and 3.11b

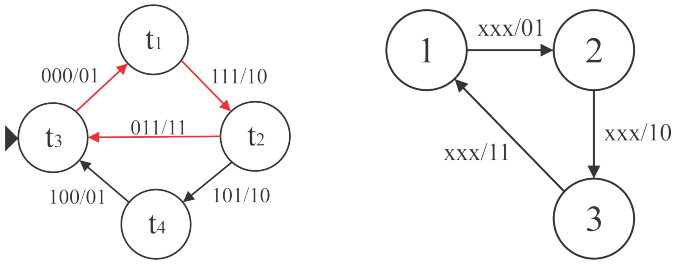
Next, the compatibilities table is updated following the same fashion, from upper-left to bottom-right as showed in Table 3.12b. If the pairs listed in the current cell are also compatibles, then this pair is also compatible, or incompatible otherwise. For example, cell (4,1) from Table 3.12a (or pair (d,x)) has to be marked as not compatible ($\times$) because the pair (a,y) is also not compatible. In contrast, pair (b,y)

is marked as compatible (✓) because (d,y) is also compatible.

Finally, if there is, at least, one compatible cell per column, then, the original functionality remains. That is, if every state represented by the columns have one or more compatible states, then the entire FSM is embedded into the final FSM. Although so far the merging process has been described as the signature FSM being merged into the original FSM, it can also be seen as the opposite, the original FSM being merged into the signature FSM.

3.7.2 SIGNATURE

To validate if the signature remains it is only necessary to feed the final FSM with the bit chain obtained by the method explained in Chapter 3.2. If the output is the same as the signature after been hashed, then the signature is still embedded and the authorship can be proved.



(a) FSMs merged **(b)** Signature

Figure 3.22: FSMs merging

For example, Figure 3.22b represents a watermark's FSM, and it is merged with the FSM on Figure 3.22a, also the bit chain obtained after hashing the signature is "011011", if state 1 from 3.22b is paired with state $t3$ from 3.22a the only one and necessary bit chain that satisfy the signature as output is "000111011". To prove it, the FSM is feeded with "000111011"; in the first impulse, "000" will return "01", then "111" will return "10", and finally "011" will return "11", which concatenated from the signature after hashing.

Chapter 4

Experimental results analysis

4.1 Experimental setup

All comparisons and experiments were made using Finite State Machines (**FSMs**) from ACM/SIGDA benchmarks library [11], specially **LGSynth** series (High-Level Synthesis Workshops) from Collaborative Benchmarking and Experimental Algorithmics Laboratory granted by the Design, Verification and Test Division of Mentor Graphics Corporation.

The experimentation were carried out with double precision. The machine used in every experiment has a machine *epsilon* in double precision of 2^{-53} with a minimum positive value in double precision of 4.94065645841247E-324. The processor is an Intel Core 2 Duo with a clock velocity of 1.5 GHz. The Operating System (**OS**) is Windows 7 of 32 bits with 3.00 GB of RAM memory available. The codification was written in C# 5.0 in .NET 4.5 using Visual Studio 2012.

The Genetic Algorithms (**GAs**) configuration used during experimentation is described below.

4.1.1 RANDOM SEEDS

New population of chromosomes are specified by 50 percent of probability by each gene. It was used the pseudo-random method of C# to obtain values between 0.0 and 0.99999999999999978 seeded from the system clock. If this pseudo-random value is greater than 0.5 then the gene is equal to 1, otherwise it is set to 0. Mutation and mating positions are set by the same pseudo-random method.

4.1.2 GA SPECIFICS FOR MERGING

Binary representation has been used to represent the number of states, therefore the chromosome length is $n \cdot m$ bits, where:

n = number of states in the FSM signature,

m = number of states in the RTL's FSM.

An initial population is defined by P individuals or solutions.

$$P = r! - \sum_{i=1}^{r-1} i! \text{ with } r = max(m, n) \tag{4.1}$$

Crossover operation works by exchanging genetic material between solutions, for example, an individual 010001100000 recombining at $2nd$ crossover position with individual 000001000100 results in offspring 010001000100 (node 2 matches node $t1$, node 3 matches node $t2$, node $t4$ has no match, etc) and 000001100000 (node $t1$ has no match, node 3 matches node $t2$, node 1 matches node $t3$, etc).

During mutation, it is necessary to check if a mutated offspring does not result in an invalid chromosome. This can be done by verifying that a chromosome package has only one-hot, for example, packages like 011 are considered invalid; moreover, a chromosome could represent a maximum of n one-hot genes. For example, if the chromosome 010001100000 is mutated at gene 2, the new chromosome would be

000001100000.

4.1.3 GA specifics for reduction

Any possible solution is expressed in binary form representing a combination of compatibility classes and its length is the total of those classes. There are 2^C individuals in the initial population with C being the number of compatibility classes. For mating, individuals exchange genetic material according to crossover probability at a random position. For example, chromosomes 00110 and 10101 recombined at position 3 would generate offspring 00101 and 10110. After, children are mutated by flipping genes according to mutation's probability, for example, chromosome 00101 mutated at position 2 would create chromosome 01101 resulting in compatibility classes C_2, C_3 and C_5 as maximal classes. The function on Equation 4.2 was used as objective function.

$$F = \alpha + \frac{5}{76}\left(-\frac{1.66\beta}{C} + \frac{\gamma}{S} + 2\right) \tag{4.2}$$

4.2 Reported results

The proposed method aims to insert information in FSM transitions, yet, reported results also show the number of states, transitions and bits that have been reduced.

As mentioned above, all results shown here were taken from the LGSynth benchmark library and compared with the best results found in literature. The proposals that were chosen to be compare with, are focused in FSM reduction, aimed to emphasize the final number of states, particularly of *hanging* states; and FSM watermarking to compare the number of final transitions, final states and number of bits embedded.

Original FSM			Watermarked FSM					
			Cui's Method		Proposed Method			
FSM	**St**	**Tr**	**FT_1**	**OH**	**FT_2**	**FS**	**OH**	**UT**
s27	6	192	194	101.04%	100	4	52.08%	51.55%
s386	13	3328	3333	100.15%	1686	30	50.66%	50.59%
bbara	10	253	258	101.98%	176	7	69.57%	68.22%
opus	10	640	649	101.41%	346	32	54.06%	53.31%
tbk	32	4096	4102	100.15%	2085	26	50.90%	50.83%

Table 4.1: Comparative table of number of final transitions from Cui's method inserting 128 bits [15], and the proposed method inserting 160 bits of FMS's.

In Table 4.1 comparative results of the proposed method with Cui's proposal are shown [16]. Column **St** is the number of original states; **Tr** is the number of original transitions; $\mathbf{FT}_1$ is the number of final transitions of Cui's proposal; $\mathbf{FT}_2$ and **FS** are the number of final transitions and states, respectively, of the proposed method; **UT** is the upturn (or improvement) of final transitions of the method proposed and Cui's proposal; and **OH** is the overhead (or the percentage of exceeding states) between final states of each method and the number of original states.

In Table 4.2 comparative results of the proposed method with Abdel's proposal are shown [2]. Column **St** is the number of original states; **Tr** is the number of original transitions; $\mathbf{FS}_1$ is the number of final states of Talaat's proposal; $\mathbf{FS}_2$ are the number of final states of the proposed method; **UT** is the upturn (or improvement) of final transitions of the method proposed and Talaat's proposal; and **OH** is the overhead (or the percentage of exceeding states) between final states of each method and the number of original states.

In Table 4.1, the proposed method has a less significant number of transitions than Cui's method. Besides, Table 4.2 shows there are less final states than Talaat's method in 6 out of 8 different experiments.

Original FSM			Watermarked FSM				
			Talaat's method		Proposed Method		
FSM	**St**	**Tr**	**FS_1**	**OH**	**FS_2**	**OH**	**UT**
mc	4	30	6	150.00%	20	500.00%	333.33%
lion	4	13	5	125.00%	4	100.00%	80.00%
dk27	7	8	9	128.57%	7	100.00%	77.78%
ex4	14	448	14	100.00%	30	214.29%	214.29%
s27	6	192	7	116.67%	4	66.67%	57.14%
s298	218	S/I	219	100.46%	190	87.15%	86.75%
tbk	32	4096	33	103.13%	26	81.25%	78.79%
bbara	10	253	12	120.00%	7	70.00%	58.33%

Table 4.2: Number of final states from Adbel's method inserting 40 bits [2], and the proposed method inserting 160 bits.

These reductions are important because fewer number of transitions and states in FSMs enhance heat and power dissipation and an effective use of chip area by reducing the number of flip-flops and gates needed for implementation, permitting handling a less significant number of don't cares and a lower number of state-transitions faults.

Table 4.3 shows size comparisons of FSMs before and after been watermarked. Column 2 shows the original number of states, column 3 shows the number of final states after watermarking, column 4 shows the overhead, and the last column shows the number of *hanging* states. So far, no other method has reported the number of these *hanging* states, for this reason, there are no other results for comparison. However, it can be concluded the efficiency of the proposed approach considering the values of the last two columns. There are only 3 out of 19 FSMs with *hanging* states and some overhead in the number of final states. That is, only 16% of these experiments have ended with some kind of size increment and *hanging* states. However, 84% of watermarked FSMs are obtained with strengthen security in case of attempt of copyright violation.

Original		Final FSM after inserting 160 bits		
FSM	**Original States**	**Final States**	**Overhead**	***Hanging* States**
bbara_bbtas	128	51	-60%	0
S298	218	190	-13%	0
donfile	24	14	-42%	0
modulo12	12	5	-58%	0
tbk	32	26	-19%	0
ex1	18	15	-17%	0
dk16	27	24	-11%	0
lion9	9	6	-33%	0
sse	13	10	-23%	0
mark1	12	10	-17%	0
s27	6	4	-33%	0
bbtas	6	6	0%	0
dk27	7	7	0%	0
lion	4	4	0%	0
train11	11	11	0%	0
Keyb	19	19	0%	1
dk512	15	16	7%	2
beecount	4	6	50%	2
ex7	4	6	50%	2

Table 4.3: Number of final *hanging* states.

4.3 STATISTICAL ANALYSIS

Even though data provided clear support, GAs have a stochastic and non-deterministic nature. A statistical significance test has been applied to establish if the fitness function associated to the GA is, at least, as good as the options proposed in literature.

In statistics, a result is statistically significant when it is not probable to happen randomly. Student's t-test is the most widely applied test to determine if two sets of

data are significantly different from each other [49], nevertheless, it needs the data to follow a normal distribution.

There are tests to avoid normal distribution, or nonparametric statistical tests like Wilcoxon signed-rank test [53].

4.3.1 WILCOXON SIGNED-RANK TEST

It has been proven by non-parametric statistical hypothesis Wilcoxon signed-rank test that experimental results shown in Tables 4.4 and 4.5 has statistically significant difference when comparing base function in Equation 4.3 with final function in Equation 4.4. Finally, final function in Equation in 4.4 was compared with Equation 3.2 proposed by Sánchez in [48].

$$F = \alpha - \frac{\beta}{C} + \frac{\gamma}{S} \tag{4.3}$$

$$F = \alpha + \frac{5}{76}\left(-\frac{1.66\beta}{C} + \frac{\gamma}{S} + 2\right) \tag{4.4}$$

Table 4.4 shows experiments with FSMs after been watermarked, **O** column is the number of original states, $\mathbf{F}_b$ is the number of states obtained after reduction with base function in Equation 4.3, $\mathbf{F}_f$ is the number of states obtained after reduction with final function in Equation 4.4, **D** is $\mathbf{F}_b$-$\mathbf{F}_f$ difference and **Index** and **Ranks** columns are inherited from Wilcoxon signed ranked test.

Ranks designated to indexes 1 to 5 are the same because the mean value is equal to Equation 4.5.

$$\left(\frac{1}{k}\right)\sum_{l=1}^{k} l = \frac{k+1}{2}, \text{if } k = 5 \rightarrow \frac{5+1}{2} = 3 \tag{4.5}$$

FSM	Index	O	F_b	F_f	D	Ranks
s27	1	6	4	5	-1	-3
s386	2	13	30	31	-1	-3
tbk	3	32	26	25	1	3
Opt_FSM	4	7	6	5	1	3
shiftreg	5	8	8	7	1	3
dk27	6	7	9	7	2	7
ex4	7	14	30	28	2	7
bbara	8	10	9	7	2	7
manual2	9	8	16	13	3	9.5
donfile	10	24	15	12	3	9.5
modulo12	11	12	12	5	7	11

Table 4.4: Sampling Population with watermark

The same principle is used to rank 6 through 8 and 9 through 10. $T = 6$ since $T = min\,(T_+, |T_-|)$ and $T_+ = 60$, $|T_-| = 6$. And $n_r = 11$, also:

$$\sigma_T = \sqrt{\frac{n_r\,(n_r+1)\,(2n_r+1)}{24}} \qquad \mu_T = \frac{n_r\,(n_r+1)}{4}$$

$$\sigma_T = 11.24722188 \qquad \mu_T = 33$$

Thus:

$$z = \frac{T - \mu_T - 0.5}{\sigma_T} \approx -2.445$$

Finally, if z value is replaced in Equation 4.6, the following p-value is obtained:

$$f(z) = \frac{1}{\sqrt{2\pi}} \mathrm{e}^{-\left(\frac{z^2}{2}\right)} \approx 0.0201 \tag{4.6}$$

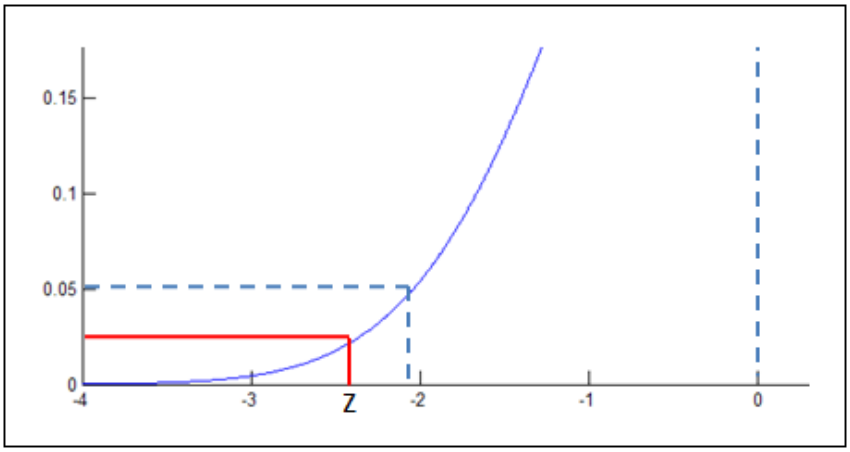


Figure 4.1: z value location in Normal Distribution and its p-value.

Thus, p-value is equal to $f(z) \approx 0.0201$ indicating null hypothesis H_0 probability, that is, the probability that there is no significant difference between samples. If p-value is equal to a probability of 2.01%, then the $p_{critical}$ is equal to 0.025.

Table 4.5 shows experiments with FSMs before been watermarked, **O** column is the number of original states, **S** is the number of states reported by Sánchez in [48] with Equation 3.2, $\mathbf{F}_b$ is the number of states obtained after reduction with base function in Equation 4.3, $\mathbf{F}_f$ is the number of states obtained after reduction with final function in Equation 4.4, $\mathbf{D}_1$ is the difference **S**-$\mathbf{F}_f$, $\mathbf{D}_2$ is the difference $\mathbf{F}_b$-$\mathbf{F}_f$ and **Index** and **Ranks** columns are taken from Wilcoxon signed ranked test.

Applying Wilcoxon test to $\mathbf{D}_1$ difference, a probability of the mean difference between the final function in Equation 4.4 and Equation 3.2 proposed by Sánchez in [48] of 0.0483 is obtained, that is, when results are different, there is a 96% of probability to found better results when using the equation proposed in this thesis.

In both ranking tests performed with **D** difference from Table 4.4 and $\mathbf{D}_1$ difference from Table 4.5, a p-value equal to 0.0201 is obtained, which represents a probability of the mean difference between the fitness function in Equation 4.4 and the base function in Equation 4.3 to be zero, with a probability of 2.01%, in other words, it means that the final function has 98% of probabilities to be better than

FSM	Index	O	S	F_b	F_f	D_1	D_2	Ranks
beecount	1	7	4	4	6	-2	-2	-1.5
ex5	2	9	4	6	8	-4	-2	-1.5
lion9	3	9	4	5	6	-2	-1	-3
ex7	N/A	10	4	6	6	-2	0	N/A
train11	N/A	11	4	6	6	-2	0	N/A
opus	4	10	9	9	8	1	1	4
bbara	5	10	7	7	5	2	2	6
ex3	6	10	4	10	8	-4	2	6
mark1	7	15	12	12	10	2	2	6
bbsse	8	16	13	13	10	3	3	9
ex1	9	20	18	18	15	3	3	9
sse	10	16	13	13	10	3	3	9
ex2	11	19	6	30	18	-12	12	11

Table 4.5: Sampling Population without watermark

the base function. That is, when Equation 4.4 has a different result to Equation 4.3, it has a 98% likelihood to be better, which is coherent due to both functions mostly have the same statistical difference after any number of tests because it is being compared to the same functions.

It has been experimentally and statistically demonstrated that the new Fitness Function proposed (Equation 4.4) obtains better results, either when comparing no-watermarked FSMs, or even when comparing watermarked FSMs with no-watermarked FSMs.

Chapter 5

Conclusions

Watermarking IP Cores by merging and state-reduction involving Finite State Machines using Genetic Algorithms leads to enhance heat and power dissipation and an effective use of chip area, besides, it also permits handling a smaller number of don't cares, all of that with a more secure embedded signature which can be extracted from any kind of file of any size. When found, even one FSM from HDL coding, is guaranteed to watermark the IP Core and to recover the signature without original functionality nor watermark disruption.

5.1 Remarks

This thesis presented a new approach to watermark IP Cores at a behavioral level by merging and reducing Finite State Machines using Genetic and deterministic algorithms. The proposed approach is based on previous proposals, achieving a stronger signature, mainly due to the proposed *post* state-reduction method and its new *fitness* function (see Equation 3.5 from Section 3.4.2).

This equation has been concluded after studying the behavior of several configurations of fitness functions with the same variables and interpolating its characteristic equation (see Section 3.4.2, equation 3.4). By doing this, it was possible to reduce the space of satisfaction instead of scatter the solutions through all the search

space. This conclusion aims to improve Finite State Machine merging by Genetic Algorithms as future work.

The proposed method consists in extracting and translating HDL code and some signature file into FSMs. Both FSMs are later merged and state-reduced by Discrete Combinatorial and Standard Genetic Algorithms. It was presented Equation 3.7 from Section 3.5, aimed to select which combination of algorithms has returned the best solution.

It also has been implemented a greedy *post* transitions-reduction based in a *don't care* approach and a VHDL translation from watermarked FSMs, as seen in Section 3.6.

5.2 Future work

It has been deduced that *hanging* states are the true responsible of weak watermarking and that reducing them to the minimum leads to a more secure signature. It also has been experimentally proven that reducing watermarked Finite State Machines does not imply to lose the original functionality neither its embedded signature. It was also proven that Sánchez proposal is an efficient way to find possible combinations of prime classes to solve the *post* states-reduction [48]. It is considered that their work deserves future research, being a new point of reference the fitness function proposed in this thesis.

5.3 Contributions

In this thesis it has been shown that it is possible to obtain watermarked FSMs with fewer states than an FSM without been watermarked. For example, difference column **D** in Table 4.4, shows that the reduction method proposed achieved similar

or better results, even tough the FSMs used have more information. Even more, in almost every case, the final FSMs ends with fewer states than before watermarking. To make this possible, a better *fitness* function has been proposed, showing better performance to state-reduce FSMs.

A proposal to find the coefficients related to objective functions aimed to state reduction as starting point by surface's fitting has been also presented. Optimal solutions are more likely to be found, instead of being scattered through all the searching space.

Moreover, in addition to reporting differences tables, the number of *hanging* states was also reported, a term defined in this thesis; and which to the best of the knowledge, has never been done. This is important, due to starting from this work, now it is possible to compare future with previous works concerning to FSM merging and watermarking mainly aimed to watermark robustness.

Appendices

Appendix A

Wilcoxon signed-rank test

Frank Wilcoxon [53] defined the signed rank test as follows:

Let n be the sample size, or number of pairs, and $2n$ the number of related pairs. To $i = 1, ..., n$, let $x_{1,i}$ and $x_{2,i}$ the measurements of each sample.

- H_0 (null hypothesis): The mean difference between pairs is zero.
- H_1 (alternative hypothesis): The mean difference between pairs is not zero.

1. To $i = 1, ..., n$, calculate $|x_{2,i} - x_{1,i}|$ and $sgn(x_{2,i} - x_{1,i})$, where sgn is the sign function.

2. Exclude the pairs with difference $|x_{2,i} - x_{1,i}| = 0$. And let n_r the size of the reduced sample.

3. Order the remaining n_r pairs in ascending order $|x_{2,i} - x_{1,i}|$.

4. Order the pairs by rank, starting with 1. The pairs receive as rank the average of all the ranks they span. Let R_i be the rank.

5. Calculate the statistical test W, as the sum of the ranks with sign.

$$W = \left| \sum_{i=1}^{n_r} [sgn(x_{2,i} - x_{1,i}) \cdot R_i] \right|$$

6. Bigger the n_r value, the sampling distribution of W converges to a normal distribution, thus, to $n_r \geq 10$, z value can be calculates as:

$$\sigma_T = \sqrt{\frac{n_r \left(n_r + 1\right) \left(2n_r + 1\right)}{24}}$$

$$\mu_T = \frac{n_r \left(n_r + 1\right)}{4}$$

$$z = \frac{T - \mu_T - 0.5}{\sigma_T}$$

Besides, it is possible to calculate the statistical test T as the minor of the sing rank sum, instead of statistical W.

$$T = min\left(T_+, |T_-|\right)$$

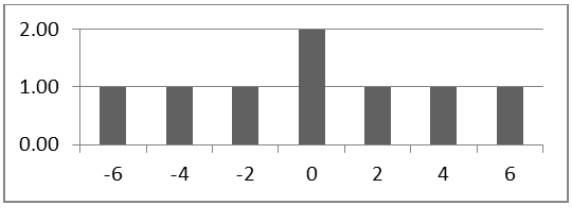
Where T_+ is the sum of the ranks corresponding to positive differences, and $|T_-|$ is the sum of the ranks corresponding to absolute negative differences. To values n_r very small, can be enumerated every possible combinations of sampling distribution T. Suppose, for example, $n_r = 3$ objects, whose absolute differences (with sign) produce the ranks 1, 2 and 3 as seen in table A.1.

Figure A.1a shows the sampling distribution of this situation, and Figures A.1b and A.1c show the corresponding distributions to $n_r = 4$ and $n_r = 5$ respectively.

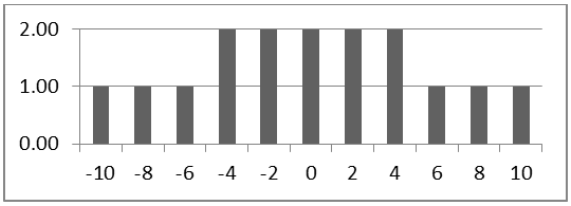
It is easy to notice that greater the n_r value, the sampling distribution T is

Ranks			W
1	2	3	
+	+	+	+6
-	+	+	+4
+	-	+	+2
+	+	-	0
-	-	+	0
-	+	-	-2
+	-	-	-4
-	-	-	-6

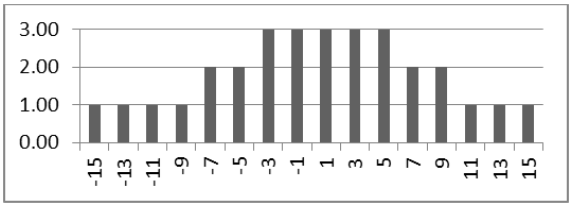
Table A.1: Possible differences from 3 ranks



(a) Distribution $n_r = 3$



(b) Distribution $n_r = 4$



(c) Distribution $n_r = 5$

Figure A.1: Distributions of n_r

converging to a normal distribution and satisfies the central limit theorem. Also, it

is known that the normal distribution equation is:

$$f(z) = \frac{1}{\sqrt{2\pi}} \mathrm{e}^{-\left(\frac{z^2}{2}\right)} \tag{A.1}$$

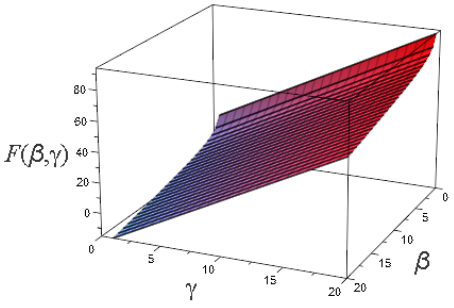
Finally, if the z value previously obtained is replaced in equation A.1, the p-value can be calculated to know the probability to be true of the null hypothesis H_0. If p-value is greater than $p_{critical}$ critical value, then H_0 is accepted, otherwise is rejected. Commonly in medicine, $p_{critical}$ is 0.01, in computer science is accepted 0.05.

Appendix B

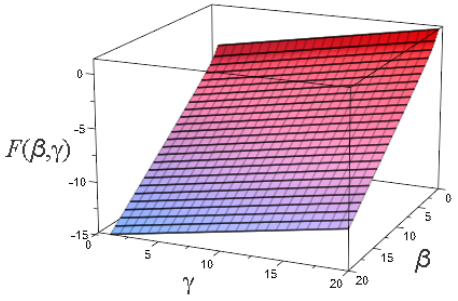
List of equations

The 20 equations used to obtain the *cloud points* are listed below with their respective characteristic graphs, α, C and S were fixed to the same value for each different graph. Due to that Genetic Algorithms (**GA**) are stochastic, each one of the equations was tested 5 times for each Finite State Machine (**FSM**). All the FSMs were taken from LGSynth benchmarks.

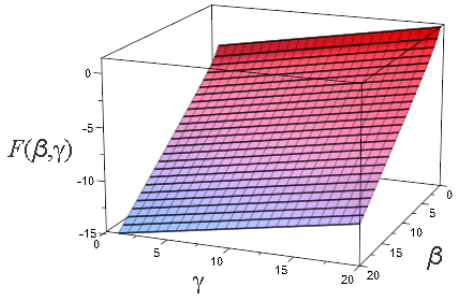
In Figure B.1 the sum of all the equations listed below is presented. As seen in Figure B.1, every equation has a similar behavior, except for F_{11} and F_{14} that have values $F(\beta, \gamma)$ up to 400. It was intended that the proposed equations span their values throughout all the search space. However, when these equations are bounded to values found during state-reduction for α, β, γ, C and S, they tend to behave similarly. This similar behavior was the key to find the *cloud points* presented in Figure 3.15 from Section 3.4.2. That is, even though their characteristic graphs are not exactly like the mentioned *cloud* due to this graphs span the entire surface by taking every possible $F(\beta, \gamma)$ value, when they are evaluated with values found during state-reduction, they create said *cloud* because now they are being only evaluated in such values.



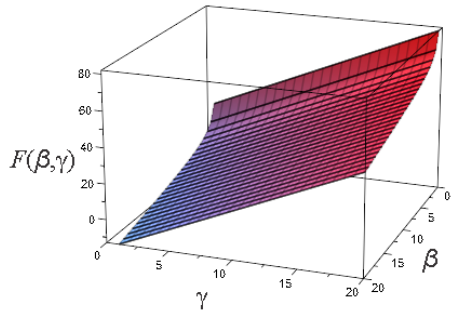
$$F_1(\beta,\gamma) = C \cdot S \cdot \frac{\alpha}{\beta} - \beta + C \cdot \gamma$$



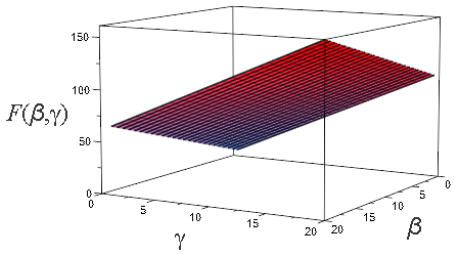
$$F_2(\beta,\gamma) = \frac{\alpha}{\beta} - \frac{\beta}{C} + \frac{\gamma}{S} + S$$



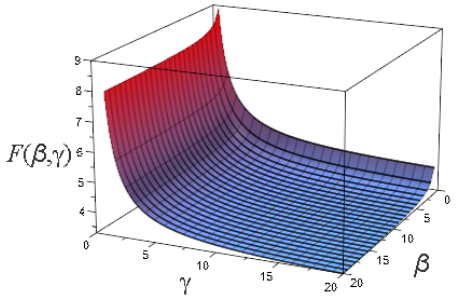
$$F_3(\beta,\gamma) = \frac{\alpha}{\beta} - \frac{\beta}{S} \cdot C + \frac{\gamma}{S} - C$$



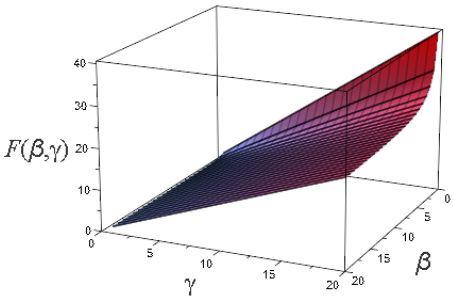
$$F_4(\beta,\gamma) = C \cdot S \cdot \frac{\alpha}{\beta} + C - \beta + C \cdot \gamma$$



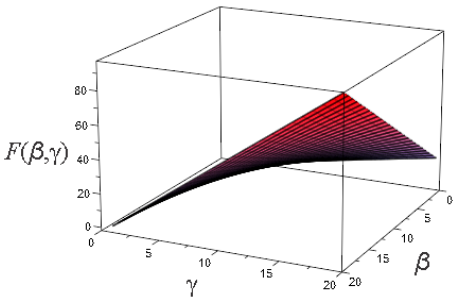
$$F_5(\beta,\gamma) = \alpha + \beta \cdot C + \gamma \cdot S$$



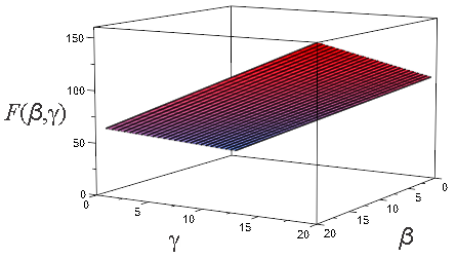
$$F_6(\beta,\gamma) = \frac{\alpha}{\beta} + \frac{S}{\gamma} + C$$



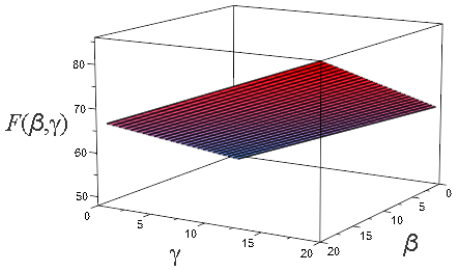
$$F_7(\beta,\gamma) = \frac{\gamma}{\beta} \cdot \alpha + \frac{C}{S} + \gamma$$



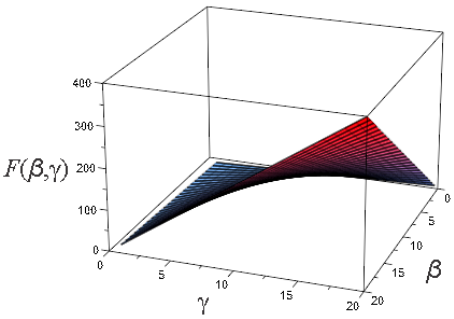
$$F_8(\beta,\gamma) = \alpha \cdot \beta \cdot \frac{\gamma}{S} - C + \gamma$$



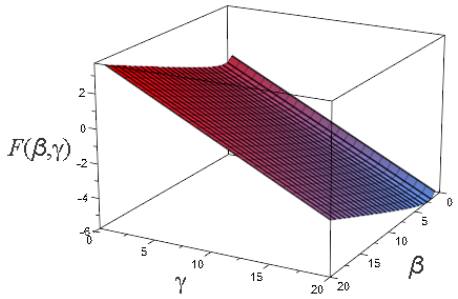
$$F_9(\beta,\gamma) = C \cdot \beta + S \cdot \gamma + \frac{\alpha}{C \cdot S}$$



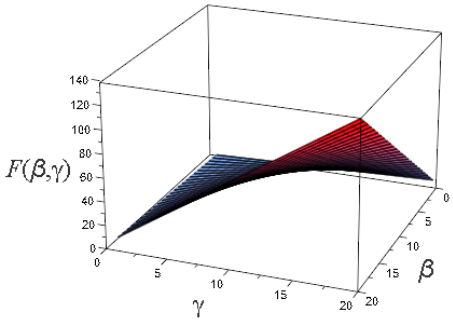
$$F_{10}(\beta,\gamma) = \alpha + \beta + \gamma + C \cdot S$$



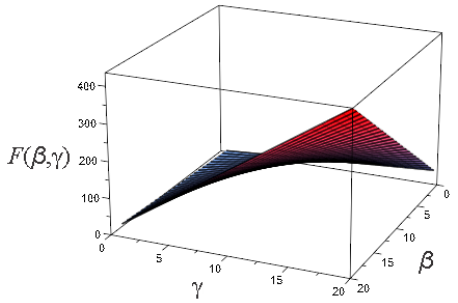
$$F_{11}(\beta,\gamma) = \alpha \cdot \beta \cdot \gamma + \frac{C}{S}$$



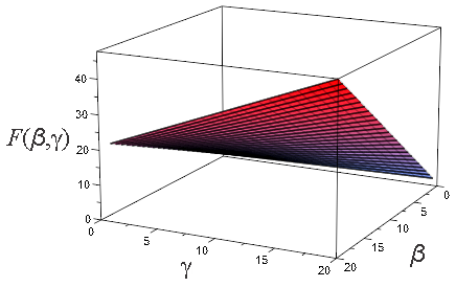
$$F_{12}(\beta,\gamma) = \frac{\alpha}{\beta} + \frac{\beta}{S} - \frac{\gamma}{C}$$



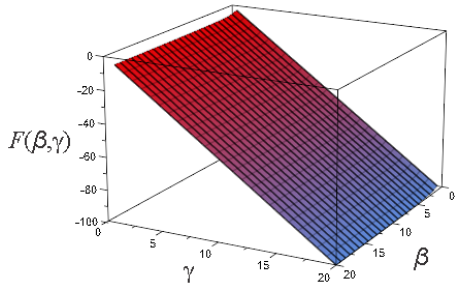
$$F_{13}(\beta,\gamma) = \alpha \cdot S + \beta \cdot \frac{\gamma}{C}$$



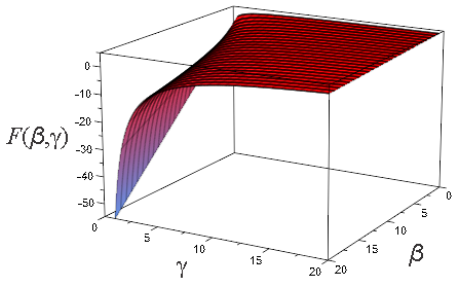
$$F_{14}(\beta,\gamma) = \alpha \cdot \beta \cdot \gamma + C \cdot S + \gamma$$



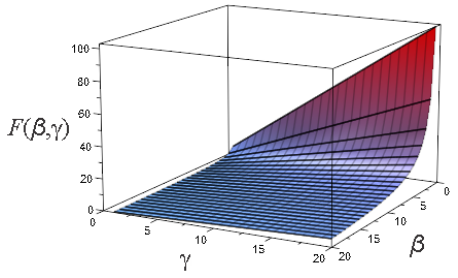
$$F_{15}(\beta,\gamma) = \alpha + \frac{\beta}{C} \cdot \frac{\gamma}{S} + \beta$$



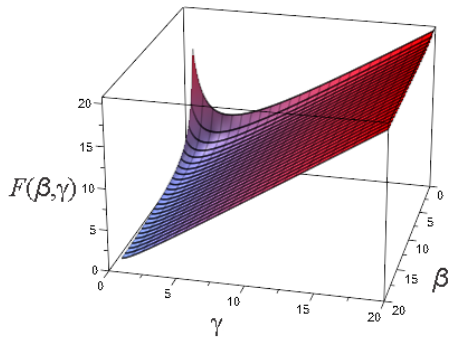
$$F_{16}(\beta,\gamma) = \frac{C}{\beta} + \alpha - \gamma \cdot S$$



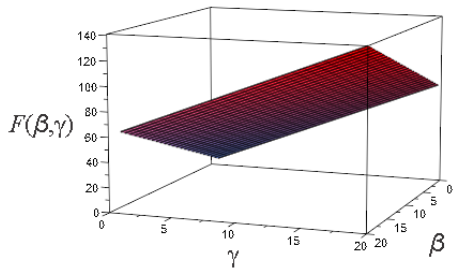
$$F_{17}(\beta,\gamma) = \frac{\alpha}{S} - \beta \cdot \frac{C}{\gamma} + S$$



$$F_{18}(\beta,\gamma) = \frac{1}{\beta}(\alpha \cdot C + \gamma \cdot S)$$



$$F_{19}(\beta,\gamma) = \frac{\alpha \cdot C \cdot S}{\beta \cdot \gamma} + \gamma$$



$$F_{20}(\beta,\gamma) = \beta \cdot C + \gamma \cdot S + \alpha - \gamma$$

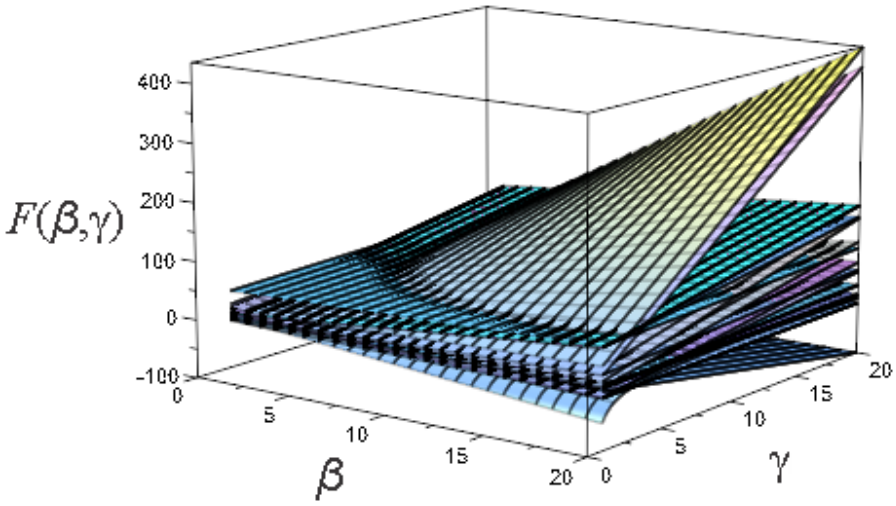


Figure B.1: Sum of all equations.

Appendix C

VHDL encoding

Even though, translating FSMs to VHDL is not part of the reported method, it has been implemented to return a *finished product* and is explained below. In some cases, the format to describe FSMs is *.dot* that is formed as follows:

```
digraph digraph_name{
    st0 -> st0 [label = "10\0"]
    st0 -> st4 [label = "01\0"]
    st0 -> st5 [label = "00\0"]
    st0 -> st6 [label = "11\0"]
    st1 -> st1 [label = "01\0"]
    .
    .
    .
    st6 -> st6 [label = "11\1"]
}
```

Where the transitions are described with format **actual_state ->** **next_state** [label = **"input\output"**]. Nevertheless, the most used format is *.kiss2* which is formed as follows:

```
.model model_name
```

```
.i 2
.o 1
.s 6
.p 17
.r st0
.start_kiss
    10 st0 st0 0
    01 st0 st4 0
    00 st0 st5 0
    11 st0 st6 0
    01 st1 st1 0
    .
    .
    .
    11 st6 st6 1
.end_kiss
```

Where **.i** is the input length, **.o** is the output length, **.s** is the number of states, **.p** is the number of transitions, **.r** is the initial state **.star_kiss** is the start of the listed transitions and **.end_kiss** is the end of the listed transitions.

In addition, the transitions are described with format **"x st*i* st*j* y"** where **x** is the transition's input, **st***i* is the actual state, **st***j* is the next state and **y** is the transition's output.

Thanks to *.kiss2* headers; VHDL inputs, outputs and signals can be directly declared as the code shown below representing the FSM from Figure 3.17 in Section 3.4.2.

```
ENTITY entity_name IS PORT{
```

```
INPUT1 : IN STD_LOGIC_VECTOR(1 DOWNTO 0);
OUTPUT1: OUT STD_LOGIC };
END entity_name;

ARCHITECTURE Behavior OF entity_name
IS TYPE State_type
state(st0, st1, st2, st3, st4, st5, st6);
BEGIN
    PROCESS(INPUT) BEGIN
case state is
    when st0 => if (INPUT1 = '10') then  *
        {OUTPUT1 = '0'; state <= st0}    *
    elseif (INPUT1 = '01') then
        {OUTPUT1 = '0'; state <= st4}
    elseif (INPUT1 = '00') then
        {OUTPUT1 = '0'; state <= st5}
    elseif (INPUT1 = '11') then
        {OUTPUT1 = '0'; state <= st6}
    when st1 => if (INPUT1 = '01') then
        {OUTPUT1 = '0'; state <= st1}
                .
                .
                .
    when st6 => if (INPUT1 = '11') then
        {OUTPUT1 = '1'; state <= st6}
    END PROCESS;
END Behavior;
```

After declaring **ENTITY**; the **PROCESSES** from the **ARCHITECTURE** are filled with *cases* which, at the same time, has *whens* to represent transitions. For example, the lines marked with a (*) symbol, indicate that when the *actual state* is **st0** with an **input** '01', the output will be '0' and the *next state* will return to **st0** as shown in Figure C.1.

Figure C.1: Next State example

Thus, it is only necessary to iterate through all states from the FSM to obtain its transitions and translate them into VHDL.

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