GENERATION OF FEASIBLE TEST SEQUENCES FOR EFSM MODELS

Ali Y. Duale and M. Ümit Uyar

Electrical Engineering Department

The City College of the City University of New York

[duale, umit]@ee-mail.engr.ccny.cuny.edu

Abstract A method that enables the generation of realizable test sequences from a class of EFSMs is presented. If the interdependencies among the variables used in the actions and the conditions of EFSMs are not considered during test generation, the test sequences may be unrealizable in a test laboratory. Algorithms for the detection and elimination of inconsistencies from the EFSM models are presented. Once inconsistencies are eliminated, realizable test sequences can be generated from the resulting consistent EFSM by using the methods available for FSM models.

Keywords: conformance testing, EFSM, Estelle, FSM, VHDL.

1. INTRODUCTION

The aim of conformance testing is to detect errors and increase the level of confidence on an implementation. A major challenge in conformance testing of complex communication systems is the development of methods that automatically generate test sequences with minimum lengths while maximizing the fault coverage. The automation of test generation from the extended finite-state machines (EFSMs) is mainly impaired by the existence of *inconsistencies* among the variables used in the actions and conditions of the EFSM models.

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The specifications written in formal description languages such as VHDL and Estelle are typically modeled as EFSMs.

Conformance test generation from the finite-state machine (FSM) or labeled transition system (LTS) models has been an active research area [2, 6, 9, 10, 11, 13, 17, 18, 19]. However, generating feasible test sequences from the EFSMs still remains as an open research problem. Although several researchers made significant contributions towards testing EFSM models [3, 4, 12, 14, 15, 16, 19, 20], the inclusion of infeasible paths in the test sequences may be inevitable as long as the underlying models are EFSMs. Without a proper analysis of the interdependencies among the variables used in the actions and conditions of the EFSMs, considerable effort may be wasted on test generation since infeasible portions of these test sequences will be discarded later. The method presented in this paper enables the generation of only feasible test sequences from a class of EFSMs. It is assumed that the specification consists of a single process with linear actions and conditions. It is also assumed that pointers, recursive functions, and syntactically endless loops are not present in the specification.

The methodology presented here first considers the inconsistencies caused by the actions of the EFSM (if any), and proceeds with the elimination of inconsistencies among the conditions of the EFSM (if any).

The examples presented in this paper are based on VHDL. However, the algorithms are applicable to all EFSMs with the aforementioned properties. Currently, these algorithms are being applied to solve the *conflicting timers problem*, which arises when a protocol has multiple timers running concurrently. Due to the conflicting timers, a test sequence of a protocol such as the Estelle specification of the MIL STD 188-220 [8] may be interrupted by unexpected timeouts. Preliminary results show that generating test sequences for the MIL-STD 188-220 after eliminating the timer inconsistencies significantly improves the test coverage by including more transitions into the test sequences without timer interruptions [7].

The rest of the paper is organized as follows. Section 2. provides background information. Analysis of inconsistencies in EFSM models is presented in Section 3.. An example is worked out in Section 4.. Concluding remarks are given in Section 5..

2. PRELIMINARIES

The control structure of a communication protocol can be modeled as an FSM whereas the data portion of a protocol is usually modeled as an EFSM.

An $FSM = \langle S, I, O, \delta, \lambda \rangle$ where S, I, O, δ , and λ are a finite set of states, a finite set of inputs, a finite set of outputs, a state transition function such that $\delta: S \times I \rightarrow S$, and an output function such that $\lambda: S \times I \rightarrow O$, respectively. An $EFSM = \langle S, I, O, X, P, B, T \rangle$ where S, I , and O are defined as in an FSM;

X, P, B , and T are a set of variables, a set of parameters associated with the input set, a set of Boolean expressions which reference to a memory location, and a set of actions of the EFSM that consists of spontaneous transitions (ST) and input transitions (IT), respectively.

Both FSMs and EFSMs can be represented as directed graphs. A graph $G(V, E)$ is a structure defined by two nonempty sets, V and E . The elements of V and E are called *nodes* (or *vertices*) and *edges*, respectively. A pair of ordered nodes, (v_i, v_j) , of a *directed* graph describes an edge $e_k \in E$ which leaves v_i and terminates on v_j . The nodes v_i and v_j are called the *head* and the *tail nodes* of e_k , respectively.

A *path* (P) in $G(V, E)$ is a non-null sequence of consecutive edges. If the starting and ending nodes of a path (i.e., v_1 and v_r) are the same, the path forms a *loop*. For simplicity, throughout this paper, the term *loop* refers to the VHDL *while/for* constructs, rather than the ordinary loops. (The algorithms are applicable to both graphs with the ordinary loops and *while/for* loop constructs.) A node in G is assumed to be identified as the *initial node* from which all other nodes are reachable, and vice versa. $G'(V', E')$ is called a *subgraph* of $G(V, E)$ (expressed as $G'(V', E') \subseteq G(V, E)$) if:

$$V' \subseteq V \text{ and } E' \subseteq E : \forall e'_i \in E' \text{ tail}(e'_i), \text{ head}(e'_i) \in V'$$

3. INCONSISTENCIES

One of the major differences between the FSMs and EFSMs stems from the memory (i.e., the variables used in conditions) associated with the EFSMs. Unlike FSM graphs, the traversal of an edge $e_k = (v_i, v_j)$ of an EFSM graph mainly depends upon the condition and action variables of the edges in the paths leading to v_i . In an EFSM graph, the traversal of an edge leaving a node v_i may not be possible due to the conflicting conditions of the path(s) from v_0 to v_i , whereas for an FSM graph all paths are feasible. The complexity of testing EFSM models increases when one or more variables used in the edge conditions can assume multiple values at the same node.

A comprehensive analysis of the inconsistencies among the actions and conditions of the EFSM models is given in the subsequent sections. To improve readability, a simple example is chosen in this paper; however, the example is designed to depict the inconsistencies commonly present in real-life communication protocol specifications (e.g., MIL-STD 188-220).

Let us represent the condition of an edge as:

$$a_{00}x_0 + a_{01}x_1 + \dots + a_{0(m-1)}x_{m-1} < op > d$$

and the action of an edge as:

$$x_i = a_{01}x_0 + a_{11}x_1 + \dots + a_{1(m-1)}x_{m-1} + d$$

where m , op , and d are the number of variables, an operator, and a constant, respectively.

Definition 1 Condition inconsistency: *If there is no solution for the set of equations formed by the accumulated conditions of the edges of a sub-path $e_1 \cdot e_2 \cdot \dots \cdot e_i$ and an edge e_j , where $\text{head}(e_j)$ can be reached from $\text{tail}(e_i)$ or $\text{head}(e_j) = \text{tail}(e_i)$, then e_i and e_j are said to have a condition inconsistency.*

Definition 2 Action inconsistency: *If there is no solution for the set of equations formed by the actions of an edge e_i and the condition of another edge e_j , where $\text{head}(e_j)$ can be reached from $\text{tail}(e_i)$ or $\text{head}(e_j) = \text{tail}(e_i)$, then the two edges of e_i and e_j are said to have an action inconsistency.*

Definition 3 Consistent EFSM: *An EFSM which is free of both action and condition inconsistencies is called a consistent EFSM.*

In a consistent EFSM, the variables used in the conditions and actions do not impose any restrictions over the paths. Hence, all paths of the graph representation of a consistent EFSM are feasible.

In this paper, a depth-first (DF) and a modified breadth-first (MBF) graph traversals are used to detect inconsistencies together with *symbolic execution* and linear programming. Note that symbolic execution is utilized as a tool to detect inconsistencies, not as a test generation tool. For the inconsistency elimination, a graph splitting technique based on symbolic execution and linear programming [1] is introduced.

Once the inconsistencies are eliminated from an EFSM graph, realizable test sequences can be automatically generated from the resulting consistent EFSM by using the test generation methods available for FSM models (see for example [2] - [4], [6], [10] - [20]).

3.1 Definitions

Let us introduce the terms used throughout the paper as:

- $V_{v_i}^{reachable} \subseteq V$: set of nodes reachable from v_i without touching v_0 , the initial node.
- $E_{v_i}^{reachable} \subseteq E$: set of outgoing edges of $V_{v_i}^{reachable}$.
- $E_{v_i}^{out} \subseteq E$: set of outgoing edges of v_i .
- $E_{e_i \rightsquigarrow e_j}^{out} \subseteq E$: set of edges in the paths between $\text{tail}(e_i)$ and $\text{head}(e_j)$.
- $E_{v_i}^{in} \subseteq E$: set of incoming edges of v_i .
- $E_{v_i}^{in(T)} \subseteq E_{v_i}^{in}$: set of incoming edges of v_i that have already been traversed.
- $E_{v_i}^{in(NT)} = E_{v_i}^{in} - E_{v_i}^{in(T)}$: set of incoming edges of v_i that have not traversed.
- $Loop_{v_i} \in V$: node v_i is a loop entry/exit node.

- $V^{Loop_{v_i}} \subset V$: set of nodes that constitute the loop body whose entry/exit node is v_i .
- $E_{Loop_{v_i}}^{exit} \subset E$: set of outgoing edges of $Loop_{v_i}$ whose *tail* nodes are in the set $V^{reachable} - V^{Loop_{v_i}}$.
- $VAR = \{var_1, var_2, \dots, var_m\}$: set of variables used in the edge conditions and actions of $G(V, E)$.
- $VAR_{v_i}^{con-used} \subseteq VAR$: set of variables used in the conditions of outgoing edges of $V_{v_i}^{reachable} \cup \{v_i\}$.
- $VAR_{v_i}^{dif-modified} \subseteq VAR$: set of variables modified differently in the paths leading to v_i .

$$\bullet \text{ Cons}(e_k, e_r, v_i) = \begin{cases} 1 & \text{if traversing } e_k \text{ or where } e_r, \text{tail}(e_k) = \\ & \text{tail}(e_r), \text{ does not make } e_j \in E_{v_i}^{out} \\ & \text{infeasible} \\ 0 & \text{otherwise} \end{cases}$$

For simplicity, the notations $v_{i(s)}$ and v_i as well as $e_{i(s)}$ and e_i will be used interchangeably where appropriate.

3.2 Detection and Removal of Inconsistencies

The algorithms presented in this paper eliminate the inconsistencies by creating new nodes and edges, which increases the size of the original graph. However, these new nodes and edges are created only when necessary. Therefore, although the well-known state explosion cannot be avoided for all EFSMs, the unnecessary growth of the state space is prevented. For the cases where the state explosion is unavoidable, the size of the new graph is constantly monitored as the algorithms eliminate the inconsistencies.

3.2.1 Action Inconsistencies. Variables modified in the paths leading to a node v_i may cause action inconsistencies with the condition of another edge e_r , where $head(e_r) \in V_{v_i}^{reachable}$. Therefore, the effects of the variables modified differently by the actions of the paths leading to a node v_i on the conditions of the edges reachable from v_i need to be analyzed.

In general, the effects of edge actions on variables (i.e., variable modifications) can be represented as matrices. For an EFSM graph with m variables, $var_1, var_2, \dots, var_m$, a pair of matrices $A(m \times m)$ and $\tilde{B}(m \times 1)$ called the *modification matrix* and the *modification vector*, respectively, are defined.

The *accumulated effects* of the actions in the paths leading to a node v_i can be represented by a set of *Action Update Matrix* pairs defined as:

$$AUM(v_i, J) = \{A_{v_i,0}, \tilde{B}_{v_i,0}, A_{v_i,1}, \tilde{B}_{v_i,1}, \dots, A_{v_i,J-1}, \tilde{B}_{v_i,J-1}\}$$

where $A_{v_i,k}$, $\tilde{B}_{v_i,k}$, and J are the k^{th} modification matrix, k^{th} modification vector ($0 \leq k < J$), and the number of AUM pairs associated with v_i , respectively. The symbolic values of a variable var_r are represented in the r^{th} rows in $AUM(v_i, J)$. Only one AUM pair, where A and $\tilde{B}$ are initialized to the identity matrix and to a zero vector, respectively, is created for the initial node.

The number of AUM pairs associated with v_i solely depends on the number of different ways in which the actions of the edges leading to v_i modify variables. If the overall variable modifications of the actions of any two paths leading to v_i are the same, only one AUM pair is sufficient to account for the effects of the actions in the two paths. Therefore, only unique AUM pairs are associated with v_i .

In general, after traversing an edge $e_k = (v_i, v_j)$, new AUM pairs are formed for v_j by applying the actions of e_k to the $AUM(v_i, J)$. Depending upon the net modification on $AUM(v_i, J)$ by the actions of e_k , the number of new AUM pairs formed for v_j may be less than or equal to that of v_i .

3.2.1.1 Detection of Action Inconsistencies. In this paper, a two-phase MBF graph traversal is designed to handle the detection of the action inconsistencies. The two phases of the MBF graph traversal will be referred to as P1-MBF and P2-MBF. Phase one of the MBF graph traversal, P1-MBF, can be viewed as the main graph traversal from which the P2-MBF may be invoked multiple times.

In the P1-MBF graph traversal, certain restrictions are imposed on the traversal of some edges as described below:

- The traversal of the edges of $E_{Loop_{v_i}}^{exit}$ is postponed until the edges of $(E_{Loop_{v_i}}^{out} - E_{Loop_{v_i}}^{exit})$ are traversed.
- The traversal of the outgoing edges of $v_j \in V^{Loop_{v_i}}$ is postponed until the edges of $(E_{Loop_{v_i}}^{in} - \{e_m = (v_x, v_y) : v_x \in V^{Loop_{v_i}}\})$ are traversed.
- The analysis of a loop (except for nested loops) whose entry/exit node is $loop_{v_i}$ is avoided if there is a non-traversed edge $e_m = (v_x, v_y)$, where $v_x \notin V^{Loop_{v_i}}$ and $Loop_{v_i} \in V_{tail(e_m)}^{reachable}$. Upon traversing an edge $e_k = (v_x, Loop_{v_i})$, it is checked if the following condition is true:

$$\begin{aligned} & \exists e_r = (v_y, v_w) \in E_{v_w}^{in(NT)} \text{ such that} \\ & (Loop_{v_i} \in V_{v_w}^{reachable} \wedge Loop_{v_i} \notin V^{Loop_{v_w}} \wedge head(e_r) \notin V^{Loop_{v_w}}) \end{aligned} \quad (1)$$

If statement (1) is true, the traversal of the edges of $E_{Loop_{v_j}}^{out}$ is postponed. As can be seen from (1), for nested loops, an inner loop is analyzed before traversing certain incoming edges of the outer loop entry/exit node.

In the P1-MBF graph traversal, upon traversing an edge $e_k = (v_x, v_y)$, it is checked if an action inconsistency between the edges in the paths leading to v_y and an edge $e_r = (v_w, v_z)$ reachable from v_y exists. The detection of action inconsistencies starts with checking the number of AUM pairs associated with v_y . If there is more than one, the effects of $\text{AUM}(v_y, J)$ on the conditions of $E_{v_y}^{\text{reachable}}$ must be analyzed. Such analysis becomes complicated when the paths between v_y and v_w contain loops.

When a node with multiple AUM pairs is visited by using P1-MBF, the P2-MBF graph traversal is initiated. If there is a loop in the path(s) between v_y and $\text{tail}(e_i)$, P2-MBF aims to postpone the analysis of the effects of the $\text{AUM}(v_y, J)$ on the conditions of $e_i \in E_{v_y}^{\text{reachable}}$ until this loop is completely analyzed. To cope with the difficulty of analyzing the effects of the $\text{AUM}(v_y, J)$ on the conditions of $E_{v_y}^{\text{reachable}}$, P2-MBF allows the traversal of each edge of a loop body at most once. In the P2-MBF graph traversal, edges of $E_{\text{Loop}_{v_i}}^{\text{exit}}$ are not traversed until the loop whose entry/exit node is Loop_{v_i} is completely analyzed by P1-MBF. In addition, unlike P1-MBF, the loop iterations are not advanced during the P2-MBF graph traversal.

In P2-MBF, the traversal of a given path terminates if at least one of the following statements is true:

- an action inconsistency is detected
- the path contains a loop entry/exit node Loop_{v_i} where
 - all edges in $(E_{\text{Loop}_{v_i}}^{\text{out}} - E_{\text{Loop}_{v_i}}^{\text{exit}})$ are traversed or
 - another entry/exit node $\text{Loop}_{v_j} \in V^{\text{Loop}_{v_i}}$ is visited by traversing an edge $e_k = (v_x, \text{Loop}_{v_j})$

The action inconsistency detection algorithm is given in Figure 1, where the first *while* loop is P1-MBF and the *if* statement within the second *while* loop implicitly represents P2-MBF. The algorithm stops after finding the first action inconsistency. If there is no action inconsistency, the algorithm stops upon completing the traversal of the graph in the MBF manner.

3.2.1.2 Elimination of Action Inconsistencies. The algorithm Figure 2 eliminates an action inconsistency between $e_k = (v_x, v_y)$ and $e_r = (v_w, v_z)$ of a loop-free graph by placing them into two separate subgraphs to prevent these two edges from being included in the same path. The two subgraphs are formed by splitting nodes and edges of $(\{v_y\} \cup V_{v_y}^{\text{reachable}})$ and $(E_{v_y}^{\text{out}} \cup E_{v_y}^{\text{reachable}})$ such that each subgraph contains either e_k or e_r but not both. When a node $v_{i(s)}$ is split, the new duplicate of v_i is denoted as $v_{i(s^*)}$, where s^* represents the number of times that $v_{i(s)}$ is split. Similarly, the duplicate of an edge e_i is denoted in the same manner (i.e., $e_{i(s^*)}$).

Only the edges of $E_{v_y}^{\text{in}} = (E_{v_y}^T \cup E_{v_y}^{NT})$ that do not conflict with the edges in $E_{v_w}^{\text{out}}$ are duplicated during the splitting. However, it is not apparent if placing

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Action Inconsistency Detection
begin
  input:  $G(V, E)$ 
  output:  $E^{conf}$ 
  goal: to detect an action inconsistency
  Let  $Conf(e_i, e_j) = 1$  if by traversing  $e_i$ ,  $e_j$  becomes infeasible;
   $E^{conf} = \emptyset$ ;
   $v_x = v_0$ ;
   $V = V - \{v_x\}$ ;
   $DONE\_MBF = False$ ;
  while  $((NOT\ DONE\_MBF) \wedge (V \neq \emptyset))\{$ 
    while  $((E_{v_x}^{out} \neq \emptyset) \wedge (NOT\ DONE\_MBF))\{$ 
      traverse  $e_k = (v_x, v_y) \in E_{v_x}^{out}$ ;
       $E_{v_x}^{out} = E_{v_x}^{out} - \{e_k\}$ ;
      if  $((VAR_{v_y}^{diff-modified} \cap VAR_{v_y}^{con-used} \neq \emptyset) \wedge$ 
         $(\exists e_r = (v_w, v_z) \in E_{v_y}^{reachable} : Conf(e_k, e_r) = 1))\{$ 
         $E^{conf} = \{e_k\} \cup \{e_r\}$ ;
         $DONE\_MBF = True$ ;
       $\}$ 
     $\}$ 
    select a new node  $v_x \in V$  as determined by the MBF;
     $V = V - \{v_x\}$ ;
   $\}$ 
  return  $E^{conf}$ ;
end

```

Figure 1. Action Inconsistency detection algorithm.

copies of the edges in $E_{v_y}^{NT}$ in the same subgraph with $e_k = (v_x, v_y)$ will cause action inconsistencies. Copies of such edges are temporarily included in the same subgraph with e_k .

The effects of the actions of $E_{v_w}^{depend}$ on the outgoing edges of $v_w \in V_{tail(e_k)}^{reachable}$ must be analyzed later when each edge in $E_{v_w}^{depend}$ is traversed, where $E_{v_w}^{depend}$ is the set of edges temporarily included in the subgraph containing e_k . When an edge $e'_{i(s^*)} \in E_{v'_{w(s^*)}}^{depend}$ is traversed, it is checked if the

actions of $e'_{i(s^*)}$ are inconsistent with the conditions of the outgoing edges of $v'_{w(s^*)}$. If they are, $e'_{i(s^*)}$ is removed from the graph. Recall that $v'_{w(s^*)}$ is one of the copies of $v_{w(s)}$ whose outgoing edges conflicted with $e_{k(s)}$.

The graph splitting is slightly different when an action inconsistent is detected by traversing $e_k = (v_x, v_y)$, where v_y is a loop entry/exit node, as will be described later.

Since the graph topology changes with the creation of the new edges and nodes, the action inconsistency detection algorithm should be re-invoked after each graph split. As defined in Section 3.1, a path from v_i to v_j cannot include v_0 . Hence, the inconsistency removal algorithm does not split v_0 .

As for the loop-free graphs, the action inconsistency detection is performed by using the two-phase MBF graph traversal with P1-MBF and P2-MBF. For

Action Inconsistency Elimination

input: $e_k = (v_x, v_y)$ and $e_r = (v_w, v_z)$, where an action inconsistency exists between e_k and e_r

goal: to eliminate the inconsistency between e_k and e_r by creating two subgraphs such that each subgraph contains either e_k or e_r , but not both

begin

Split $v_{y(s)}$ into two nodes as: $v'_{y(s)}$ and $v'_{y(s^*)}$;

Split $\forall v_{i(s)} \in V_{v_{y(s)}}^{reachable}$ into two nodes as:

$$v'_{i(s)} \in V_{v'_{y(s)}}^{reachable} \text{ and } v'_{i(s^*)} \in V_{v'_{y(s^*)}}^{reachable};$$

Split $\forall e_{m(s)} = (v_{i(s)}, v_{j(s)}; L_{e_{m(s)}}) \in E_{v_{y(s)}}^{reachable}$ into two edges as:

$$e'_{m(s)} = (v'_{i(s)}, v'_{j(s)}; L_{e_{m(s)}}) \in E_{v'_{y(s)}}^{reachable} \text{ and}$$

$$e'_{r(s^*)} = (v'_{i(s^*)}, v'_{j(s^*)}; L_{e_{m(s)}}) \in E_{v'_{y(s^*)}}^{reachable};$$

Split $\forall e_{m(s)} = (v_{i(s)}, v_{y(s)}; L_{e_{m(s)}}) \in E_{v_{y(s)}}^{in(T)}$ such that

$\text{Cons}(e_{m(s)}, e_k(s), v_w(s)) = 1$, into two edges as:

$$e'_{m(s)} = (v_{i(s)}, v'_{y(s)}; L_{e_{m(s)}}) \in E_{v'_{y(s)}}^{in} \text{ and}$$

$$e'_{m(s^*)} = (v_{i(s)}, v'_{y(s^*)}; L_{e_{m(s)}}) \in E_{v'_{y(s^*)}}^{in} \text{ where } v_w(s) \text{ is the node}$$

whose outgoing edges are inconsistent with $e_k(s)$;

Create a duplicate of $\forall e_{m(s)} = (v_{i(s)}, v_{y(s)}; L_{e_{m(s)}}) \in E_{v_{y(s)}}^{in(T)}$ such that

$\text{Cons}(e_{m(s)}, e_k(s), v_w(s)) = 0$ as:

$$e'_{m(s)} = (v_{i(s)}, v'_{y(s)}; L_{e_{m(s)}}) \in E_{v'_{y(s)}}^{in};$$

Split $\forall e_{m(s)} = (v_{i(s)}, v_{y(s)}; L_{e_{m(s)}}) \in E_{v_{y(s)}}^{in(NT)}$ into two edges as:

$$e'_{m(s)} = (v_{i(s)}, v'_{y(s)}; L_{e_{m(s)}}) \in E_{v'_{y(s)}}^{in(NT)} \text{ and}$$

$$e'_{m(s^*)} = (v_{i(s)}, v'_{y(s^*)}; L_{e_{m(s)}}) \in E_{v'_{y(s^*)}}^{depend} \text{ (defined below);}$$

end

Figure 2. Action inconsistency elimination algorithm.

simplicity, only loops with single entry/exit nodes are considered in this paper. Note that syntactically endless loops are not considered in this paper.

If by traversing an edge $e_k = (v_x, v_y)$, of a graph with loops, an action inconsistency is detected with one of the edges in $E_{v_y}^{reachable}$, then one of the following cases is true:

- **Case 1:** $v_x \notin V^{Loop_{v_i}}$.
- **Case 2:** $v_x, v_y \in V^{Loop_{v_i}}$ and $y \neq i$ (i.e., $\text{tail}(e_k)$ is not the loop entry/exit node).
- **Case 3:** $v_x, v_y \in V^{Loop_{v_i}}$ and $y = i$ (i.e., $\text{tail}(e_k)$ is the loop entry/exit node).

The method of graph splitting for Cases 1 and 2 is similar to that of the loop-free graphs except that if $Loop_{v_i}$ is split, a copy of each edge $e_r \in E_{Loop_{v_i}}^{out}$

is included in all new subgraphs. For Case 3, the following steps are taken to eliminate action inconsistencies:

- The loop is advanced one iteration by duplicating all nodes of $V_{Loop_{v_i}}^{reachable}$ and the edges of $E_{v_y}^{reachable}$ as: $V_{v_y(s)}^{reachable}$, $V_{v_y(s^*)}^{reachable}$, $E_{v_y(s)}^{reachable}$, and $E_{v_y(s^*)}^{reachable}$, respectively. Since a loop must have only one entry node, $\forall e_r = (v_x, v_y) \in E_{Loop_{v_i}}^{in}$: $v_x \notin V_{Loop_{v_i}}$ are not duplicated.
- The AUM pairs of $Loop_{v_i}$ are not updated.
- The tail node of $e_{k(s)}$ is changed to $Loop_{v_i(s^*)}$.
- To determine the exit condition(s) of the loop, the feasibility of the conditions of each edge in $E_{Loop_{v_i(s)}}^{out}$ is investigated. If the loop exit criterion is satisfied, the conditions of the edges in $(E_{Loop_{v_i(s)}}^{out} - E_{Loop_{v_i(s)}}^{exit})$ become infeasible. Otherwise, the edges in $E_{Loop_{v_i(s)}}^{exit}$ are infeasible. An edge whose condition is found to be infeasible is removed from the graph.

As in the case of loop-free graphs, these steps are repeated after each graph split.

Let us introduce the following definitions for any node $v_i \in V$:

- $AUM(v_i, J)[v_i \xrightarrow{SE} v_x]$: the resulting $AUM(v_x, J)$ after applying symbolic execution on $AUM(v_i, J)$ in the paths between v_i and $v_x \in V$.
- $E_{v_i}^{conf}(e_x \in E_{v_i}^{in}, e_r) \subseteq E_{v_i}^{in(T)}$: set of traversed incoming edges of v_i , where each edge conflicts with e_r after obtaining $AUM(v_i, J)[v_i \xrightarrow{SE} head(e_r)]$.
- $E_{e_k \leadsto e_r}^{conf}(e_x \in E_{e_k}^{out}, e_r)$: set of edges in the paths from $tail(e_k)$ to $head(e_r)$, where each edge conflicts with e_r after obtaining $AUM(tail(e_k), J)[tail(e_k) \xrightarrow{SE} head(e_r)]$.
- $E_{v_i \leadsto head(e_r)}^{inf}(v_i, head(e_r))$ set of edges, in the paths between v_i and $head(e_r)$, whose conditions are infeasible after obtaining $AUM(v_i, J)[v_i \xrightarrow{SE} head(e_r)]$.

After an action is detected and eliminated, the resulting graph $G'(V', E')$ is characterized as:

$$V' = (V - V_{v_y(s)}^{reachable} - \{v_{y(s)}\}) \cup V_I' \cup V_{II}', \text{ where}$$

$$V_I' = (\{v_{y(s)}'\}) \cup V_{v_y(s)}'^{reachable} \text{ and } V_{II}' = (\{v_{y(s^*)}'\}) \cup V_{v_y(s^*)}'^{reachable}$$

$$E' = (E - E_{v_y(s)}^{reachable} - E_{v_y(s)}^{in}) \cup E_I' \cup E_{II}', \text{ where}$$

$$\begin{aligned}
 E'_I &= (E_{v_{y(s)}}^{reachable} - E_{v_{y'} \sim tail(e_r)}^{inf(v_{y(s)}, tail(e_r))}) \cup E_{v_{y(s)}}^{in(NT)} \cup \\
 &\quad (E_{v_{y(s)}}^{in(T)} - E_{v_{y'}(s)}^{conf(e_x \in E_{v_{y(s)}}^{in}, e_r)}) \text{ and} \\
 E'_{II} &= (E_{v_{y(s)}}^{reachable} - E_{v_{y'}(s)}^{conf(e_x \in E_{e_k \sim e_r}^{out}, e_r)}) \cup E_{v_{y(s^*)}}^{in} \cup (\{e_k\} \cup E_{v_{w(s^*)}}^{depend})
 \end{aligned}$$

Due to the removal of edges with infeasible conditions from $G'(V', E')$, unreachable subgraphs may result. A simple DF graph traversal can be used to eliminate unreachable subgraphs from $G'(V', E')$. Furthermore, if the condition of an edge e_i cannot be satisfied due to the actions of another edge e_j , it is removed from the graph during the condition inconsistency analysis as described next.

3.2.2 Condition Inconsistencies. In this section, the detection and elimination of condition inconsistencies (if any) is considered, which is the next step after the action inconsistencies are eliminated from the EFSM model.

A test sequence generated from an EFSM should avoid including two or more edges with conflicting conditions. Since the conditions of the edges of a test sequence constitute a system of constraints, algorithms available for solving linear programming problems can be used in deciding whether a certain path predicate is feasible [1].

The edge conditions in a path from the starting node v_0 to a node v_i can be represented in matrices. A triplet of matrices are defined as C ($m \times p$), $\tilde{O}P$ ($p \times 1$), and $\tilde{D}$ ($p \times 1$), where m is the number of variables, p is the number of conditions in the path from v_0 to v_i , C is the coefficient matrix, $\tilde{O}P$ is the operator vector containing the relations of $=, <, >, \neq, \dots$, etc., and $\tilde{D}$ is the scalar vector containing the scalar values of the conditions in the path.

The AUM pairs discussed in Section 3.2.1 are applied to the edge conditions of the EFSM graph as follows. A single condition of an edge $e_r = (v_i, v_j)$ is in the form of $\tilde{C} * \tilde{V}(\tilde{O}P)\tilde{D}$. The condition of e_r will be modified based on the symbolic values of the variables var_0 through v_{m-1} , which are represented by the AUM(v_i, J). The current values of the variables including all the modifications represented by an AUM pair of v_i are in the form of: $\tilde{V} = A_{v_i, k} * \tilde{V} + \tilde{B}_{v_i, k}$. Substituting $\tilde{V}$ values in an edge condition will result in $\tilde{C}(A_{v_i, k} * \tilde{V} + \tilde{B}_{v_i, k})(\tilde{O}P)\tilde{D}$, which simplifies as $\tilde{E} * \tilde{V}(\tilde{O}P)f$, where $\tilde{E} = \tilde{C} * A_{v_i, k}$ is an m -element vector and f is a scalar. An edge $e_r = (v_i, v_j)$ whose condition is infeasible based on the AUM pairs of v_i is deleted from the graph. The values assumed by the variables used in the condition of e_r can be determined from:

$$C * \tilde{V} = C * (A_{v_i, k} * \tilde{V} + \tilde{B}_{v_i, k})$$

where C is the coefficient matrix for the condition of e_r and $0 \leq k < J$, where J is the number of AUM pairs associated with v_i .

The accumulated different conditions of the paths leading to v_i can be represented by a set of *Accumulated Condition Matrix* (ACM) triplets: $\text{ACM}(v_i, J) = (C_{v_i,0}, \tilde{O}P_{v_i,0}, \tilde{D}_{v_i,0}, C_{v_i,1}, \tilde{O}P_{v_i,1}, \tilde{D}_{v_i,1}, \dots, C_{v_i,J-1}, \tilde{O}P_{v_i,J-1}, \tilde{D}_{v_i,J-1})$, where $C_{v_i,k}$, $\tilde{O}P_{v_i,k}$, $\tilde{D}_{v_i,k}$, and J are the k^{th} coefficient matrix, k^{th} operator matrix, k^{th} scalar value matrix ($0 \leq k < J$), and the number of the ACM triplets associated with v_i , respectively.

3.2.2.1 Detection of Condition Inconsistencies. The condition inconsistency detection is performed by traversing the graph in a depth-first (DF) manner. Condition inconsistencies can be detected and eliminated by focusing on the ACM triplets of a node v_y , $\text{ACM}(v_y, J)$, one triplet at a time. Let $\text{ACM}(e_r)$ be the triplet representing the condition of $e_r \in E_{v_y}^{\text{reachable}}$. Furthermore, let $\text{VAR}_{e_i}^{\text{con-used}} \in \text{VAR}$ be the set of variables used in the conditions of $e_i \in E$. Once a node v_y is visited by traversing an edge $e_k = (v_x, v_y)$, each edge $e_r = (v_w, v_z)$, where $v_w \in V_{v_y}^{\text{reachable}}$, such that

$$\text{VAR}_{e_r}^{\text{con-used}} \cap \text{VAR}_{e_k}^{\text{con-used}} \neq \emptyset$$

is identified. The consistency between the conditions of e_k and e_r is then checked by concatenating $\text{ACM}(e_r)$ to the $\text{ACM}(v_y, p)$, where $0 \leq p < J$.

Let us introduce the following definition:

$$\text{Feas}(\text{ACM}(v_y, p), e_r) = \begin{cases} 1, & \text{if } \text{ACM}(v_y, p) \# \text{ACM}(e_r) \text{ has a solution} \\ 0, & \text{otherwise} \end{cases}$$

where $\#$ denotes concatenation of the two ACM triplets.

If the new constraints formed by $\text{ACM}(v_y, p) \# \text{ACM}(e_r)$ has a solution, e_r is said to be *consistent* with the edges whose conditions constitute $\text{ACM}(v_y, p)$. Otherwise e_r is *inconsistent* with the edges whose conditions constitute $\text{ACM}(v_y, p)$. The algorithm in Figure 3 stops when either a condition inconsistency is found or the DF graph traversal is completed.

3.2.2.2 Elimination of Condition Inconsistencies. A condition inconsistency between two edges $e_k = (v_x, v_y)$ and $e_r = (v_w, v_z)$ is eliminated by splitting the nodes $(\{v_y\} \cup \{v_i \in V_{\text{tail}(v_y)}^{\text{reachable}} : v_i \rightsquigarrow v_w\})$, with their incoming and outgoing edges, into two subgraphs such that each subgraph contains either e_k or e_r , but not both. The outgoing edges of the nodes $\{v_i \in V_{\text{tail}(v_y)}^{\text{reachable}} : v_i \rightsquigarrow v_w\}$ will be referred to as $E_{v_y \rightsquigarrow v_w}^{\text{out}}$. The condition inconsistency elimination algorithm is given in Figure 4.

Since the consistency of the edges of $E_{v_y}^{\text{in}(NT)}$ with $E_{v_w}^{\text{out}}$ cannot be decided during the graph splitting, copies of these edges are included temporarily in the

Condition Inconsistency Detection

```

begin
  input:  $G(V, E)$ , output:  $E^{conf}$ 
  goal: to detect a condition inconsistency
   $E^{conf} = \emptyset$   $v_x = v_0$ ,  $V = V - \{v_x\}$ ;
  DONE_DF = False;
  while ((NOT DONE_DF)  $\wedge$  ( $V \neq \emptyset$ )){
    while (( $E_{v_x}^{out} \neq \emptyset$ )  $\wedge$  (NOT DONE_DF)){
      traverse  $e_k = (v_x, v_y) \in E_{v_x}^{out}$ ;
       $E_{v_x}^{out} = E_{v_x}^{out} - \{e_k\}$ ;
      if (( $\exists e_r = (v_w, v_z) \in E_{v_y}^{reachable}$  where
        ( $VAR_{e_k}^{con-used} \cap VAR_{e_r}^{con-used} \neq \emptyset$ )  $\wedge$  (Feas(ACM( $v_y, p$ ) $e_r$ ) = 0))){
         $E^{conf} = \{e_k\} \cup \{e_r\}$ ;
        DONE_DF = True;
      }
    }
    select a new node  $v_x \in V$  as determined by the DF;
     $V = V - \{v_x\}$ ;
  }
  return  $E^{conf}$ ;
end
    
```

Figure 3. Condition inconsistency detection algorithm.

same subgraph with $e_k = (v_x, v_y)$. The influence of $E_{v_w}^{depend}$ on the conditions of the outgoing edges of $v_w \in V_{tail(e_k)}^{reachable}$ must be analyzed later when each edge in $E_{v_w}^{depend}$ is traversed, where $E_{v_w}^{depend}$ is the set of edges which are temporarily included in the subgraph containing e_k . An edge $e'_{i(s^*)} \in E_{v'_{w'(s^*)}}^{depend}$ whose condition is found to be inconsistent with the condition of an outgoing edge of $v'_{w(s)}$ is removed from the graph.

After a condition inconsistency is detected and eliminated, the resulting graph $G'(V', E')$ is defined as:

$$V' = (V - \{v_i \mid v_i \in V_{v_y(s)}^{reachable} \wedge v_i \rightsquigarrow v_w\} - \{v_{y(s)}\}) \cup V'_I \cup V'_{II}$$

$$\text{where } V'_I = (\{v'_{y(s)}\} \cup V_{v'_{y(s)}}^{reachable}) \text{ and } V'_{II} = (\{v'_{y(s^*)}\} \cup V_{v'_{y(s^*)}}^{reachable})$$

$$E' = (E - E_{v_y \rightsquigarrow v_w}^{out} - E_{v_{y(s)}}^{in}) \cup E'_I \cup E'_{II}, \text{ where}$$

$$E'_I = E_{v'_{y(s)}}^{in(NT)} \cup E_{v'_{y(s)}}^{in(T)} \cup E_{v'_{y(s)}}^{reachable} \text{ and}$$

Condition Inconsistency Elimination

input: $e_k = (v_x, v_y)$ and $e_r = (v_w, v_z)$, where a condition inconsistency exists between e_k and e_r

goal: to eliminate the inconsistency between e_k and e_r by creating two subgraphs such that each subgraph contains either e_k or e_r , but not both

begin

Split $v_{y(s)}$ into two nodes as: $v'_{y(s)}$ and $v'_{y(s^*)}$;

Split $\forall v_{i(s)} \in V_{v_{y(s)}}^{reachable} : v_i \rightsquigarrow v_w$ into two nodes as:

$$v'_{i(s)} \in V_{v'_{y(s)}}^{reachable} \text{ and } v'_{i(s^*)} \in V_{v'_{y(s^*)}}^{reachable};$$

Split $\forall e_{m(s)} = (v_{i(s)}, v_{j(s)}; L_{e_{m(s)}}) \in E_{v_{y(s)}}^{reachable} : \text{tail}(e_r(s)) \rightsquigarrow v_w$ into two edges as:

$$e'_{m(s)} = (v'_{i(s)}, v'_{j(s)}; L_{e_{m(s)}}) \in E_{v'_{y(s)}}^{reachable} \text{ and}$$

$$e'_{m(s^*)} = (v'_{i(s^*)}, v'_{j(s^*)}; L_{e_{m(s)}}) \in E_{v'_{y(s^*)}}^{reachable};$$

Split $\forall e_{m(s)} = (v_{i(s)}, v_{y(s)}; L_{e_{m(s)}}) \in (E_{v_{y(s)}}^{in(T)} - \{e_k\})$ into two edges as:

$$e'_{m(s)} = (v_{i(s)}, v'_{y(s)}; L_{e_{m(s)}}) \in E_{v'_{y(s)}}^{in(T)} \text{ and}$$

$$e'_{m(s^*)} = (v_{i(s)}, v'_{y(s^*)}; L_{e_{m(s)}}) \in E_{v'_{w(s^*)}}^{in} \text{ where } v_{w(s)} \text{ is the node whose outgoing}$$

edges are inconsistent with $e_k(s)$;

Split $\forall e_{m(s)} = (v_{i(s)}, v_{y(s)}; L_{e_{m(s)}}) \in E_{v_{y(s)}}^{in(NT)}$ into two edges as:

$$e'_{m(s)} = (v_{i(s)}, v'_{y(s)}; L_{e_{m(s)}}) \in E_{v'_{y(s)}}^{in(NT)} \text{ and}$$

$$e'_{m(s^*)} = (v_{i(s)}, v'_{y(s^*)}; L_{e_{m(s)}}) \in E_{v'_{w(s^*)}}^{depend};$$

end

Figure 4. Condition inconsistency elimination algorithm.

$$E'_{II} = E_{v'_{w(s^*)}}^{depend} \cup E_{v'_{y(s^*)}}^{in(T)} \cup \{e_k\} \cup (E_{v'_{y(s^*)}}^{reachable} - \{e_i \in E_{v'_{y(s^*)}}^{reachable} : \text{Feas}(\text{ACM}(v_y, p) \# \text{ACM}(e_i)) = 0\})$$

As for the action inconsistency detection and removal case, the algorithms restart after each graph split.

3.3 The Complexity of the Algorithms

The complexity of the action inconsistency detection and elimination is contributed by a two-phase MBF graph traversal, constructing the number of AUM pairs for each node, and executing the linear programming for each edge for each AUM pair.

The complexity for the two-phase MBF graph traversal is $O(E^2)$. For each node v_i , the number of AUM pairs is $\sum_1^{|V|-1} |E^{v_j \rightarrow v_i}| \times |\text{AUM}(v_j, J)|$ (where $|E^{v_j \rightarrow v_i}|$ is the number of edges from v_j to v_i) such that $\exists e_k = (v_j, v_i)$. Linear programming takes $\min(m^2, S^2)$ steps where m is the number of variables and S is the number of constraints [1].

Figure 5. a) An EFSM graph b) The resulting EFSM graph after the action inconsistencies are eliminated from the EFSM graph shown in Figure 5.a.

The complexity for the condition inconsistency detection and elimination is bounded by the number of times the graph is split. Therefore, for the general case, the complexity of algorithms for handling the action inconsistencies is exponential with respect to the number of simple paths (i.e., the number AUM pairs). Similarly, the condition inconsistency elimination can be exponential with respect to the number of graph splits. However, based on our experience with several protocols (even with nested and/or concatenated loops), the complexity of both algorithms and, hence, the size of the consistent graph are bounded by the number of different values each condition variable assumes.

4. EXAMPLE

In the EFSM graphs in all the figures, the condition and actions of an edge are inclosed in parentheses " $\dots$ " and curly braces " $\{\dots\}$ ", respectively.

In Figure 5 the $AUM(v_1, J)$ associated with v_1 is based on the $AUM(v_0, 1)$ and the actions of the edges between v_0 and v_1 (i.e., e_0 and e_1). The first AUM pair of v_1 ($A_{v_1,0}, \tilde{B}_{v_1,0}$)

$$A_{v_1,0} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \tilde{B}_{v_1,0} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Figure 6. The EFSM graph after the graph of Figure 5.b is split due to the condition of $e_{4(0)}$ (the subgraph starting from node $v_{1(0)}$ is shown).

Figure 7. The EFSM graph after the graph of Figure 6 is split due to the condition of $e_{4(3)}$ (the subgraph starting from the node $v_{1(0)}$ is identical to the subgraph starting from $v_{1(0)}$ of Figure 6).

is formed when e_0 is traversed. The values assumed by a , b , c , i , and $True$ after e_0 is traversed can be determined from:

$$\tilde{V} = A_{v_1,0} * \tilde{V} + \tilde{B} \quad (2)$$

where $\tilde{V}(m \times 1)$ is the vector for the variables. Equation (2) yields $a=a$, $b=I$, $c=c$, $i=i$, and $True = True$. Similarly, due to the action associated with e_1 , a new AUM pair $(A_{v_1,1}, \tilde{B}_{v_1,1})$, where $b=I0$, is formed for v_1 when e_1 is traversed. P1-MBF continues until the loop is advanced two iterations as shown in Figure 5b. The P2-MBF graph traversal is invoked upon visiting v_1 of Figure 5b. P2-MBF proceeds until $v_{5(2)}$ is visited. An action inconsistency is detected between the edges leading to $v_{1(0)}$ and the outgoing edges of $v_{5(2)}$. As a result, the graph of Figure 5b is split as shown in Figure 5.b. There are no action inconsistencies in the EFSM graph of Figure 5.b. The DF graph traversal of Figure 5.b proceeds with the edges of $e_{2(0)}$, $e_{3(0)}$, $e_{4(0)}$, $\dots$. The ACM triplet resulting from the traversal of the path $e_{0(0)} \cdot e_{2(0)} \cdot e_{3(0)} \cdot e_{4(0)}$ is:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad \begin{bmatrix} \leq \\ = \\ < \\ < \end{bmatrix} \quad \begin{bmatrix} 0 \\ 1 \\ 2 \\ 0 \end{bmatrix}$$

It is found that the edges $e_{4(1)}$ and $e_{5(1)}$ use the variable c in their conditions, which is also used in the condition of $e_{4(0)}$. Since the $ACM(v_{4(0)}, 1) \# ACM(e_{5(1)})$ system of constraints does not have a solution, there is a condition inconsistency between $e_{4(0)}$ and $e_{5(1)}$. To eliminate this condition inconsistency, the graph of Figure 5.b is split such that $e_{4(0)}$ and $e_{5(1)}$ are placed into two separate subgraphs as shown in Figure 6.

Similarly, when $e_{4(3)}$ of the graph of Figure 6 is traversed, the system of constraints formed by $ACM(v_{4(3)}, 1) \# ACM(e_{5(4)})$ has no feasible solution. As a result, the EFSM graph of Figure 6 is split. The graph of Figure 7 contains no inconsistencies. $\square$

5. CONCLUSIONS

The method presented in this paper enables the generation of realizable test sequences from a class of EFSMs. Due to the variable interdependencies among the actions and conditions, certain paths of an EFSM model may not be feasible. Algorithms to eliminate these inconsistencies from a class of EFSMs to produce consistent EFSMs are presented. The elimination of inconsistencies is achieved by using a graph splitting technique based on symbolic execution and linear programming. To avoid unnecessary state explosion, new nodes and edges are created only when needed during the inconsistency elimination. Although the well-known state explosion cannot be avoided for all EFSMs, the growth of the state space is limited. For the cases where the state explosion is

unavoidable, the size of the new graph is constantly monitored as the algorithms eliminate the inconsistencies.

Since consistent EFSMs behave like FSMs, the FSM-based test generation techniques can be used to generate feasible test sequences from the consistent EFSMs.

Currently this methodology is being applied to generate tests for the MIL-STD 188-220 protocol [7].

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