Towards Evaluating Fault Coverage of Protocol Test Sequences*

Jinsong Zhu and Samuel T. Chanson

Department of Computer Science, University of British Columbia
Vancouver, B.C., Canada V6T 1Z4

In this paper, we investigate the quality of a given protocol test sequence in detecting faulty implementations of a specification. The proposed method differs from the conventional simulation method in that it is not necessary to consider various forms of fault combinations and is guaranteed to identify any faulty machines. Preprocessing and backjumping techniques are used to reduce the computational complexity of the method. We have constructed a tool based on the model and used it in assessing several test sequence generation techniques. Our experience shows that the method is both effective and efficient for even real life protocols.

Keyword Codes: C.2.2; C.2.m

Keywords: Protocol Specification and Testing; Fault Models; Fault Coverage

1. Introduction

Test sequence generation for communication protocols has been an active research area. However, the evaluation of the fault coverage for a given test sequence remains an open problem. Only a few methods such as the W method [5] and the DS method [9] have been proven to generate test sequences that can uniquely identify a finite state machine (FSM) under test. However, the W sequence is typically a lot longer than those generated using other methods, and many of the finite state machines simply do not possess a DS sequence [10]. On the other hand, other methods with better applicability and produces shorter sequence length, such as the UIO method [12] and a group of UIO-based optimization methods [1, 4, 11, 13], cannot in general guarantee to produce a checking experiment for a particular machine [17, 19]. The reason is that these methods are all based on a correct specification but unlike the W and DS methods, cannot guarantee an equivalence mapping between the specification and a machine that accepts the sequence. Therefore, in principle one needs to check the coverage of a given test sequence generated by these methods.

In [6, 15], a simulation method was proposed to estimate the fault coverage of a given test sequence. Based on a classification of faults, it randomly generates faulty machines to see if they can be defeated by the test sequence. The number of machines that cannot be defeated is used as a measure of fault coverage. A limitation of the method is that because of the complicated fault behaviors, it is difficult, if not impossible, to come up

*This work was partially supported by a grant from the Canadian Institute for Telecommunications Research under the NCE program of the government of Canada.

with a complete fault classification. The sampling of a small fraction of all cases also means the results must be interpreted with some degree of uncertainty.

In [18], a method was proposed for test sequence generation. The idea was to generate machines that accept ² an initial test sequence, and then incrementally add new subsequences to distinguish the machines until only one machine (the specification machine) is left. In this paper we extend this idea to coverage evaluation. A test sequence to be evaluated is used as the initial sequence. All machines that accept the sequence are referred to as *indistinguishable*. The number of indistinguishable machines, say k , with regard to a test sequence is used as a measure of its fault coverage. Obviously, the smaller the value of k , the fewer the machines that cannot be detected by the test sequence as faulty. This technique will uncover all faults and eliminates the need to explicitly consider various fault combinations.

We also propose a new method that fully takes advantage of the properties of the deterministic Finite State Machine (FSM) to overcome the problem of high computational complexity in [18]. By studying these properties, we found that techniques such as domain reduction and backjumping (see Section 3) can effectively prune the search space and substantially improve performance. Even a large real life protocol like NBS TP4 can be efficiently handled (see Table 2). This was a significant proof of the effectiveness of our method.

The rest of the paper is organized as follows. Section 2 contains a description of the underlying model and the properties of the deterministic FSM which forms the foundation of our coverage evaluation methodology detailed in Section 3. Section 4 shows the effectiveness of the method for a real life ISDN (Integrated Services Digital Network) protocol and Section 5 gives some empirical performance of the algorithms. Finally, Section 6 concludes the paper.

2. The Underlying Model

The underlying model in our study is a deterministic FSM. It is used in modeling the control part of a protocol (other techniques have been proposed for testing the data part, see for example [16, 3]). A deterministic FSM can be represented by a quintuple $M = \langle Q, X, Y, \delta, \lambda \rangle$, where Q, X, Y are the internal states, input alphabet and output alphabet respectively. δ (the *next state function*) is a mapping of $Q \times X$ into Q , and λ (the *output function*) is a mapping of $Q \times X$ into Y . The functions δ and λ can be extended for an input sequence $\sigma = x_1x_2...x_k$ as usual: $\delta(q_1, \sigma)$ is the final state after σ is applied to state q_1 , and $\lambda(q_1, \sigma)$ denotes the corresponding output sequence. That is, $\lambda(q_1, \sigma) = y_1y_2...y_k$ where $y_i = \lambda(q_i, x_i)$ and $q_{i+1} = \delta(q_i, x_i)$ for $i = 1, ..., k$, and $\delta(q_1, \sigma) = q_{k+1}$.

If a state of an FSM is designated as the initial state (denoted as q_0), the FSM is said to be *initialized*. For simplicity, we will use initialized FSMs in the examples throughout this paper. The method is also applicable to uninitialized FSMs as long as a test sequence for each possible initial state is available.

An FSM is deterministic if any input symbol fed to the FSM causes a unique transition,

²“Accept” here means the machine transfers to a valid state after the input sequence is applied, and generates the exact output sequence as specified in the test sequence.

i.e.,

$$\forall q_i, q_j, q_k \in Q \quad \forall x \in X \quad (\delta(q_i, x) = q_j \wedge \delta(q_i, x) = q_k \Leftrightarrow q_j = q_k). \quad (\text{P1})$$

It can be derived from P1 that if two states produce different outputs for the same input, then the two states must be distinct, i.e.,

$$\forall q_i, q_j \in Q \quad \forall x \in X \quad (\lambda(q_i, x) \neq \lambda(q_j, x) \Rightarrow q_i \neq q_j). \quad (\text{P2})$$

A corollary of P2 is that if two states produce different output sequences under the same input sequence, then the two states must be different. Let X^* denote the set of finite-length input sequences, then

$$\forall q_i, q_j \in Q \quad \forall \sigma \in X^* \quad (\lambda(q_i, \sigma) \neq \lambda(q_j, \sigma) \Rightarrow q_i \neq q_j). \quad (\text{P3})$$

For a given input output sequence, if we do not limit the number of states and the input alphabet, there would be an infinite number of automata that “implement” the sequence and the number of indistinguishable FSMs would be infinite. We therefore only consider indistinguishable FSMs which have the same input alphabet as the specification FSM and which contain at most i states more than that of the specification, where i is a small integer. We will study the cases $i = 0$ and $i = 1$ as examples. For $i = 0$, conformance checking can be done using the usual machine equivalence algorithm [6, 15] (note that V-equivalence [5] is used in this study as the equivalence relation between two automata), since in this case, conformance means equivalence, and vice versa. For $i > 0$, the generated FSM is minimized before being checked. Other faults considered in this study are the usual ones, i.e., output faults, transfer faults, and their combinations.

To avoid equivalent states, the FSM is assumed to be minimal. This is justifiable because we can always reduce an FSM to its minimal form [8]. Furthermore, testing can only determine an implementation’s conformance up to the level of equivalence. The machine should also be strongly connected and fully specified. Strong connectivity ensures each state can be reached from any other state³ For partially specified machines, we use the completeness assumption that the machine will remain in the present state without producing any output (or *null* output) for any unspecified input.

In the following sections, we shall also use the graph representation G of an FSM. G is a directed graph (V, E) , where the vertex set V denotes the set of states, and the edge set E represents the transitions, i.e., $V = \{q_0, \dots, q_{n-1}\}$, $E = \{(q_i, q_j) | i, j \leq n-1 \text{ and there is a transition from } q_i \text{ to } q_j\}$. An edge from q_i to q_j , which receives input a_k and produces output o_l , is labeled by $(q_i, q_j; L)$ where $L \equiv a_k/o_l$, the input part of L is denoted $L^{(i)} \equiv a_k$, and the output part of L is $L^{(o)} \equiv o_l$.

3. Coverage Evaluation Methodology

As mentioned in Section 1, the coverage of a test sequence is measured by the number of indistinguishable machines which have the same input alphabet as the specification FSM and with an upper bound on the number of states. The problem thus becomes how to generate these indistinguishable machines under the given conditions. This problem

³The strong connectivity assumption can be replaced by a weaker one where every state can be reached from the initial state.

can be viewed as the reverse procedure of test sequence generation. The test sequence can be thought of as an unfolding of the FSM. The idea is to “collapse” the test sequence back to one or more FSMs which may or may not conform to the original specification. A FSM so constructed is called a *solution* with the given input alphabet and number of states. If only one solution is obtained, then it must conform to the specification and the number of indistinguishable FSM is zero. In other words, the coverage is 100%.

A FSM is said to have a *reset capability* (or *resettable*) if a special input signal ri always correctly sets the machine to its initial state q_0 from any state. Otherwise, it is called a *resetless* machine. In the following procedure we will study resettable machines only. For resetless machines, the entire test sequence can be considered as a single subsequence and is therefore a special case of the first situation.

For a resettable machine, a test sequence consists of test subsequences which start from q_0 . Based on the properties of the deterministic FSM, we can construct a *test tree* with these subsequences as follows. The root of the tree is q_0 . Each node corresponds to a state in the specification. The edges from a node to its children represent outgoing transitions from the corresponding state for each input symbol. Input symbols at every node are arranged in a fixed order to avoid isomorphic trees. The depth of the tree is the length of the longest subsequence. For a resetless machine, the test tree degenerates to a simple path. Figure 1 shows a sample FSM (taken from [17]), its UIO test sequence, and the corresponding test tree. Clearly, this tree can be constructed efficiently (in polynomial time) from the test sequence. The properties P1 and P2 guarantee a unique tree for a given test sequence.

Figure 1. Test tree corresponding to the UIO test sequence

Now we assign each node a variable v_i , with i numbered according to the node's breadth-first traversal order in the tree (see Figure 1). v_0 is always assigned to the root q_0 . Where there is no ambiguity, we shall use the term node and variable interchangeably. The number of variables l (other than v_0) can be determined by a breadth-first traversal of the tree. For example, in Figure 1, $l = 12$. Initially, each variable can represent any state. Suppose the specification FSM has n states: $Q = \{q_0, q_1, \dots, q_{n-1}\}$, then the domain of each variable is Q . A consistent instantiation of all variables constitutes a so-

lution FSM, which is either the specification FSM or an indistinguishable machine. If we search all variables to generate the solutions as was done in [18], the computational complexity would be $O(n^l)$. The following techniques are used to reduce the computational complexity.

(1) Preprocessing: Although the domain of each variable is Q , the deterministic property will often restrict the values that a variable can assume. For example, according to P2, a variable cannot take on the value (i.e., a state) of a previous variable unless they are equal. In the extreme case, each variable may only have one value, representing the given FSM. We reduce the domains of the variables in the breadth-first order. For each variable v_i , we can obtain a set of variables, called unequal variables of v_i , whose indices are smaller than i and whose values are different from that of v_i . Variables that can only have one value constitute the unique set. Initially, the unique set contains v_0 only. The uniqueness of a variable v_i can be determined by examining its set of unequal variables. If this set contains the current unique set, then v_i must itself be a uniquely determined variable and is added to the unique set. To prevent isomorphic solutions, the unique state q_j assigned to v_i is chosen such that j is the smallest index not yet assigned. For example, if v_i is the first one that differs from v_0 , then it is assigned q_1 . The first variable that is distinct from v_0 and v_i is then assigned the next unassigned state, q_2 . A variable that is not in the unique set but has some unique states in its set of unequal variables can have these unique states removed from its domain. This is because it is not possible for the variable to assume any of these values. This procedure is performed until all variables have been processed. The results are a reduced domain and a set of unequal variables for each variable. The preprocessing phase often prunes the search space significantly and saves considerable time in the subsequent searches. Furthermore, for any variable v_j which is not uniquely determined, its set of unequal variables can help to reduce the search space dynamically, since it will not be necessary to assign v_j a value which has already been assigned to any of its unequal variables.

(2) Backjumping: During searching, when a variable cannot be assigned any value which is consistent with the previous assignments (a *dead-end* situation), we can jump back to the variable which causes the inconsistency rather than backtracking one step at a time as is usually done. This idea is widely used in solving search problems [7]. The point is to go back to the source of failure as far as possible. In our problem, when a variable is instantiated, it may be forced to take a value in one of two ways. First, it may only take a single value if its domain size is one. Second, the assignment of a previous variable which has the same input symbol may force it to assume the same value in order to be consistent with the properties of the deterministic FSM. Such value-forced variables cannot be the source of failures, so when a dead-end is encountered, they need not be reconsidered in selecting candidates. This situation will occur very frequently when the test sequence contains many identical transitions.

The algorithms for preprocessing and backjumping search are given below.

Algorithm-PREP: Domain reduction of node variables

Input: Node variables $v_i, i = 1, \dots, l$

Output: Reduced domain D_i for each v_i and its unequal variables NEQ_i .

Step 1: Generate unequal variables:

Initially, the set of unequal variables for each v_i , $NEQ_i = \emptyset$.

```

for every  $v_i (1 \leq i \leq l)$  do
  for every  $v_j$  with  $j < i$  do
    if  $(v_i \neq v_j)$  then
      add  $v_j$  to  $NEQ_i$ .

```

Step 2: Reduce domains of variables:

Initially, the set of uniquely determined variables $U = \{v_0\}$, state set $S = \{q_1, \dots, q_{n-1}\}$, and the domain for $v_i (i = 1, \dots, l)$ is $D_i = S \cup \{q_0\}$.

```

for every  $v_i (1 \leq i \leq l)$  do
  if  $U \subset NEQ_i$  then begin
    add  $v_i$  to  $U$ ;
     $D_i \leftarrow \{q_k\}$ ,  $k$  = the smallest subscript in  $S$  ;
     $S \leftarrow S - \{q_k\}$ ;
    for all  $v_j \in NEQ_i$  do
       $D_j \leftarrow D_j - \{q_k\}$ ;
  end else
    for all  $v_j \in NEQ_i$  do
      if  $v_j \in U$  then
         $D_i \leftarrow D_i - D_j$ ;

```

In Step 1, the set of unequal variables for each variable is generated. The **if** statement is executed $l(l-1)/2$ times. The evaluation of the condition $v_i \neq v_j$ is based on property P3. Since input sequences starting from a node constitute a subtree rooted at that node, the evaluation can be performed by comparing two subtrees rooted at v_i and v_j respectively. The comparison can be done by means of a breadth-first search algorithm for the subtree. When comparing two nodes, property P2 is used. When a pair of distinct nodes is found, the two subtrees are distinct (P3). However, when subtrees are incomplete, the node with an absent edge is not considered distinct from its corresponding node where the edge is present. For example, in Figure 1, although v_2 has no edge corresponding to a , we cannot conclude v_2 must be different from v_0 . Similarly, v_5 may possibly be equal to v_2 . The time complexity of tree comparison is at most $O(l)$. Hence, the complexity of Step 1 is $O(l^3)$.

The domains are reduced in Step 2 using the NEQ sets. If NEQ_i contains the current uniquely determined variables, v_i itself becomes a member of U . For each member v_j of U , the domains of v_j 's NEQ variables can be reduced by removing v_j 's corresponding value. The idea is that if a variable is not equal to a uniquely determined variable, it cannot assume the unique value of that variable. The complexity of this step is $O(l^2)$. Thus, the overall complexity of Algorithm-PREP is $O(l^3)$. Note that the test tree has to be constructed from the test sequence before using this algorithm.

Algorithm-SEARCH: Backjumping search to find solutions

Input: Node variables with reduced domains and the original specification

Output: The set of indistinguishable FSMs

Initially, the index of variables $i = 1$. A stack is used to store intermediate steps.

```

1.   $c_i \leftarrow \text{get\_candidate}(v_i)$ ;
2.  if  $c_i = \text{NONE}$  then begin
3.    /* dead-end encountered */
4.     $i \leftarrow \text{popstack}$ ;
5.    if stack is empty then
6.      exit with no more solutions;
7.    goto 1;
8.  end
9.  else begin
10.   if  $c_i$  is not a forced candidate then
11.     pushstack( $i$ );
12.      $i \leftarrow i + 1$ ;
13.   if  $i = l + 1$  then begin
14.     /* a solution is found */
15.     record the solution;
16.     check its conformance with the specification;
17.      $i \leftarrow \text{popstack}$ ;
18.   end
19.   goto 1; /* go on searching */
20. end

```

The procedure *get_candidate* in line 1 selects a consistent value for v_i from its domain (we shall say that v_i is instantiated). The reduced domain and the set NEQ_i both help reduce the number of candidates. During the instantiation process, it builds up a partial solution FSM with the values of variables up to v_i , one by one. To determine a consistent value of v_i , let v_p be v_i 's parent node in the test tree, and the I/O label from v_p to v_i be x/y . Suppose v_p has the value q_p which is a state in the partial FSM. If q_p has no outgoing transition labeled x/y , then we get a value for v_i which is the next state (say q_t) in its domain, and a new transition from q_p to q_t is added to the partial FSM. Otherwise, v_i is forced to be $\delta(q_p, i)$ in the FSM, because for a label x/y from a state q_p we can have at most one transition (refer to P1). The partial FSM is constructed incrementally until all variables are assigned consistent values, at which time the FSM becomes a final solution. To avoid isomorphic solutions, when instantiating v_i , only one value out of a set of equivalent candidates is selected. The candidates are equivalent in the sense that they represent equivalent states in the current partial FSM. If one of the equivalent candidates fails, the others will fail too. This fact is used to reduce the domains to be searched dynamically. *Get_candidate* returns NONE when no consistent value of v_i can be found. This is the dead-end situation so backjumping is invoked. Since a forced variable cannot be the source of a failure as mentioned before, line 11 only pushes an unforced variable onto the stack for subsequent backtracking. In line 13, $i = l + 1$ means all variables have been successfully instantiated, and a solution is found. Line 16 checks the solution's conformance with the specification using Dabbura and Sabnani's algorithm [6]. A non-conforming solution represents an indistinguishable FSM.

An Example

We shall use the FSM in Figure 1 to illustrate the above algorithms. Initially, $D_0 = \{q_0\}$, $D_i = \{q_0, q_1, q_2\}$ for $i = 1, \dots, 12$. From the tree, it can be seen that v_1 must be different from v_0 as their outputs to a are different. At this point, only v_0 is in the unique set U , so v_1 is also a uniquely determined variable. v_1 is then assigned q_1 , the next value in the state set. Next, v_2 is found to be distinct from v_1 because of their different outputs for ba . Therefore v_1 's value q_1 is removed from v_2 's domain. After all variables have been processed, their domains are found to be:

$$D_1 = \{q_1\}, D_2 = \{q_0, q_2\}, D_3 = \{q_0\}, D_4 = \{q_2\},$$

$$D_5 = \{q_0\}, D_6 = \{q_0, q_1, q_2\}, D_7 = \{q_1\}, D_8 = \{q_0\},$$

$$D_9 = \{q_0, q_1, q_2\}, D_{10} = \{q_0\}, D_{11} = \{q_0, q_1, q_2\}, D_{12} = \{q_0, q_1, q_2\}.$$

Note that the domains for most nodes have reduced, some of which have only one candidate. Those unreduced domains are all for leaf nodes since they have no outgoing edges (we'll see that this does not affect the search process). Now Algorithm-SEARCH is used to search for solutions. For the first five variables, only v_2 has more than one choice. We first choose q_0 , which is consistent with $v_1 = q_1$. The remaining variables are forced to take the values $q_1, q_1, q_0, q_1, q_0, q_1$, and q_1 respectively. Thus, we obtain our first solution:

$$v_0 = q_0, v_1 = q_1, v_2 = q_0, v_3 = q_0, v_4 = q_2, v_5 = q_0, v_6 = q_1,$$

$$v_7 = q_1, v_8 = q_0, v_9 = q_1, v_{10} = q_0, v_{11} = q_1, v_{12} = q_1.$$

Since all variables after v_2 were forced, the algorithm goes directly back to v_2 to find the next solution. The next candidate for v_2 is q_2 , which is also consistent with $v_1 = q_1$. The other variables are again forced to the same values, producing another solution:

$$v_0 = q_0, v_1 = q_1, v_2 = q_2, v_3 = q_0, v_4 = q_2, v_5 = q_0, v_6 = q_1,$$

$$v_7 = q_1, v_8 = q_0, v_9 = q_1, v_{10} = q_0, v_{11} = q_1, v_{12} = q_1.$$

It can be seen that the variables cannot take on any other value and so the algorithm terminates with two solutions. Figure 2 shows the two corresponding FSMs, with the first one an indistinguishable FSM, and the second one conforming to the specification. The

Figure 2. The two solutions for the UIO test sequence given in Figure 1

two solutions are both obtained backtrack-free, which means only $O(l)$ time is needed to get a solution. This is the best result we can hope for. We also observed that although domains for the leaf nodes cannot be reduced, they are usually forced to some values. For example, v_6 , v_9 , v_{11} , and v_{12} were all forced variables.

4. Q.931 Network Side Protocol as an Example

Figure 3. ISDN BRI network layer protocol (network side at the originating side)

The above example is too small to be practical. To show the effectiveness of the method to real life protocols, we take the example in [1], which is part of the ISDN Basic Rate Interface (BRI) D-channel signaling protocol. The state diagram of the protocol is shown in Figure 3 (taken from [1]). This protocol is defined in CCITT Recommendation Q.931 [2] (network layer) as a user-network interface. It describes the procedures for establishing, maintaining, and clearing basic circuit-switched voice connections. Only the network side of the Q.931 BRI for basic voice services at the originating end is considered here.

The notation used in Figure 3 is the same as in [1], i.e., the transition label $A?m_i/B!m_j$ is interpreted as receiving the input message m_i from FSM A, and sending the output message m_j to FSM B. Table 1 lists the UIO sequences for each state, and Table 3 gives all the test subsequences, with reset capability assumed. There are a total of 8 states, 14 inputs, 12 outputs, and 425 test steps (transitions).

Table 1. UIO Sequences for the FSM in Figure 3

State	UIO Sequence
N0	UI.1?setup_bad/UI.1!relcom
N1	UI.1?info/UI.1!info
N2	UI.1?info/null
N3	NI.2?netalert/UI.1!aler
N4	NI.2?netconn/UI.1!conn
N10	UI.1?connack/null
N12	T305!timeout/UI.1!rel
N19	UI.1?disc/null

A tool based on Section 3 has been implemented in C and runs on a Sun 4/30 workstation under Sun OS 4.1.1. It accepts as input a test sequence and a specification FSM and outputs all solutions found with the algorithms in Section 3. We applied the test sequence to the tool, and in less than a second, the unique solution was found backtrack-free, i.e., the coverage of the test sequence is 100%. This result is listed in Table 2 (see next section), among other experimental results.

5. Other Empirical Results

To collect more empirical results for problems of practical size, we conducted more experiments with examples taken from the literature. The actual computational cost is problem dependent. However, even though the complexity of Algorithm-SEARCH is $O(n^l)$ in the worst case when there is no reduction of domain for all variables and no forced variables, the results show that the complexity is far less in practice.

In [6, 15], some examples were used for fault coverage evaluation using simulation. We applied our tool to the examples, and derived the same conclusions. The W, DS and UIO methods were evaluated in [15]. The conclusion was that they all had the same full coverage for strong conformance test. Nevertheless, since the number of all possible machines is $15^{10} (\approx 5.7 \cdot 10^{11})$ for the sample machine M (Fig.1 in [15]), and only 10^6 randomly generated machines were examined, the conclusion needs to be verified. With our tool, we were able to confirm that the three test sequences given in the paper did have a unique conforming solution (see Table 2 for FSM 1) and thus have a 100% fault coverage. The example in [6] (FSM 2) for UIO method also has a unique solution. An encouraging observation is that all solutions were obtained backtrack-free.

To further evaluate our tool, we studied the W method with one extra state (denoted as W^{+1} in Table 2), using the same sample FSM 1. The original example for the DS method in [9] (FSM 3) was also studied for both the DS and UIO methods, assuming it is resettable. Furthermore, two real protocols, the ISDN BRI network layer protocol [1] and a subset of the NBS Class 4 transport protocol (TP4) [14], were studied for the UIO and DS methods respectively. The fault coverages for these examples were all found to be 100%.

Table 2 summarizes the results of our experiments. In the table, (n, m, p, L) is the number of states, inputs and outputs for the example, and the length of the test sequence,

Table 2. Performance of our method on some examples

Example	(n, m, p, L)	Method	No. of Solutions	No. of Backtrackings	No. of Forced Cases	Time (s)
FSM 1 [15]	(5,2,3,29)	UIO	1	(0, 0)	(9, 9)	0.04
	(5,2,3,35)	DS	1	(0, 0)	(12, 12)	0.04
	(5,2,3,58)	W	1	(0, 0)	(18, 18)	0.05
	(5,2,3,130)	W ⁺	15	(0, 60)	(48, 558)	0.15
FSM 2[6]	(7,4,4,111)	UIO	1	(0, 15)	(38, 256)	0.13
FSM 3 [9]	(6,2,2,40)	UIO	1	(8, 59)	(35, 203)	0.09
	(6,2,2,62)	DS	1	(0, 0)	(25, 25)	0.07
ISDN BRI[1]	(8,14,12,425)	UIO	1	(0, 0)	(105, 105)	0.82
NBS TP4[14]	(15,27,26,4131)	DS	1	(105, 488)	(2874, 2909)	273.77

respectively. The solutions for the examples we tried are all unique and conform to the original specification (no indistinguishable solutions). Two numbers are recorded in the column for “No. of Backtrackings” and also the column for “No. of Forced Cases”. The first one is the number when the first solution is found, and the second when the algorithm stops. Forced cases occur when a variable is forced to a value during instantiation. The larger the number of forced cases, the better the gains from backjumping. The column “Time” is the number of seconds of CPU time consumed by the tool, including input and output processing. The results showed that the strategy of preprocessing and backjumping is surprisingly effective. Even a sizable real protocol like NBS TP4 can be handled efficiently. Considering the small number of backtrackings (many of which are backtrack-free) and the worst case complexity of n^L , the savings are substantial.

6. Conclusions

We have examined the issue of fault coverage evaluation of a given test sequence for deterministic FSMs. The metric for fault coverage is the number of indistinguishable machines and a tool has been constructed based on this model. Preprocessing and backjumping techniques have been proposed which reduce the complexity of finding indistinguishable FSMs substantially. The tool has been used in evaluating the quality of some test sequence generation techniques, and some previous results were confirmed. Other applications such as an evaluation of a group of UIO-based optimization techniques are reported in [19]. Since each indistinguishable FSM is explicitly generated, the tool is also useful in analyzing how a faulty machine could have escaped detection.

REFERENCES

1. A.V. Aho, A.T. Dahbura, D. Lee, and M.U. Uyar. An optimization technique for protocol conformance test generation based on UIO sequences and rural Chinese postman tours. *IEEE Transactions on Communications*, 39(11), November 1991.
2. CCITT Red Book, vol.III. *FASCICLE III.5 - Integrated Services Digital Network (ISDN) Recommendations (Study Group XVIII)*. 1984.
3. S.T. Chanson and J. Zhu. A unified approach to protocol test sequence generation. In *Proc. IEEE INFOCOM*, San Francisco, March 1993.

4. M.S. Chen, Y. Choi, and A. Kershenbaum. Approaches utilizing segment overlap to minimize test sequences. In *Proc. IFIP 10th Int. Symp. on Protocol Specification, Testing, and Verification*, 1990.
5. T.S. Chow. Testing software design modeled by finite-state machines. *IEEE Transactions on Software Engineering*, May 1978.
6. A. Dahbura and K. Sabnani. An experience in estimating fault coverage of a protocol test. In *Proc. IEEE INFOCOM*, 1988.
7. R. Dechter. Enhancement schemes for constraint processing: backjumping, learning, and cutset decomposition. *Artificial Intelligence*, 41(3):273–312, 1990.
8. A. Gill. *Introduction to the Theory of Finite State Machines*. McGraw-Hill Book Company, Inc., 1962.
9. G. Gonenc. A method for the design of fault detection experiments. *IEEE Transactions on Computer*, June 1970.
10. Z. Kohavi. *Switching and Finite Automata Theory*. New York: McGraw Hill, 1978.
11. R.E. Miller and S. Paul. Generating minimal length test sequences for conformance testing of communication protocols. *IEEE/ACM Trans. on Network*, February 1993.
12. K. Sabnani and A. Dahbura. A protocol test generation procedure. *Computer Networks and ISDN Systems*, 15:285–297, 1988.
13. Y.-N. Shen, F. Lombardi, and A.T. Dahbura. Protocol conformance testing using multiple UIO sequences. In *Proc. IFIP 9th Int. Symp. on Protocol Specification, Testing, and Verification*, 1989.
14. D.P. Sidhu and T.-K. Leung. Formal methods for protocol testing: A detailed study. Technical Report 86-23, Dept of Computer Science, Iowa State Univ., 1986.
15. D.P. Sidhu and T.-K. Leung. Formal methods for protocol testing: A detailed study. *IEEE Transactions on Software Engineering*, April 1989.
16. H. Ural and B. Yang. A test sequence selection method for protocol testing. *IEEE Transactions on Communication*, April 1991.
17. S.T. Vuong and W.Y.L. Chan. The UIOv-method for protocol test sequence generation. In *Proc. 2nd Int. Workshop on Protocol Testing System*, October 1989.
18. S.T. Vuong and K.C. Ko. A novel approach to protocol test sequence generation. In *Proc. GLOBECOM'90*, December 1990.
19. J. Zhu and S.T. Chanson. Fault coverage evaluation of protocol test sequences. Technical Report 93-19, Dept of Computer Science, Univ of British Columbia, June 1993.

Table 3. UIO-based Test Sequences for the FSM in Figure 3

```

r/- UI.1?setup_bad/UI.1!relcom UI.1?setup_bad/UI.1!relcom
r/- UI.1?info/- UI.1?setup_bad/UI.1!relcom
r/- UI.1?info_bad/- UI.1?setup_bad/UI.1!relcom
r/- UI.1?info_last/- UI.1?setup_bad/UI.1!relcom
r/- UI.1?rel/UI.1!relcom UI.1?setup_bad/UI.1!relcom
r/- UI.1?disc/- UI.1?setup_bad/UI.1!relcom
r/- T302?timeout/- UI.1?setup_bad/UI.1!relcom
r/- NI.2?netclear/- UI.1?setup_bad/UI.1!relcom
r/- NI.2?netalert/- UI.1?setup_bad/UI.1!relcom
r/- NI.2?netconn/- UI.1?setup_bad/UI.1!relcom
r/- UI.1?connack/- UI.1?setup_bad/UI.1!relcom
r/- T305?timeout/- UI.1?setup_bad/UI.1!relcom
r/- T308?timeout/- UI.1?setup_bad/UI.1!relcom
r/- UI.1?setup/UI.1!setupack UI.1?setup_bad/- UI.1?info/UI.1!info
r/- UI.1?setup/UI.1!setupack UI.1?setup/- UI.1?info/UI.1!info
r/- UI.1?setup/UI.1!setupack UI.1?rel/UI.1!relcom UI.1?setup_bad/UI.1!relcom
r/- UI.1?setup/UI.1!setupack T302?timeout/UI.1!prog.UI.1!disc T305?timeout/UI.1!rel
r/- UI.1?setup/UI.1!setupack NI.2?netclear/- UI.1?info/UI.1!info
r/- UI.1?setup/UI.1!setupack NI.2?netalert/- UI.1?info/UI.1!info
r/- UI.1?setup/UI.1!setupack NI.2?netconn/- UI.1?info/UI.1!info
r/- UI.1?setup/UI.1!setupack UI.1?connack/- UI.1?info/UI.1!info
r/- UI.1?setup/UI.1!setupack T305?timeout/- UI.1?info/UI.1!info
r/- UI.1?setup/UI.1!setupack T308?timeout/- UI.1?info/UI.1!info
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info UI.1?setup_bad/- UI.1?info/null
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info UI.1?setup/- UI.1?info/null
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info UI.1?info/null UI.1?info/null
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info UI.1?info_bad/UI.1!prog.UI.1!disc
   T305?timeout/UI.1!rel
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info UI.1?info_last/UI.1!disc NI.2?netalert/UI.1!alert
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info UI.1?rel/UI.1!relcom UI.1?setup_bad/UI.1!relcom
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info UI.1?disc/UI.1!rel UI.1?disc/null
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info T302?timeout/UI.1!prog.UI.1!disc
   T305?timeout/UI.1!rel
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info NI.2?netclear/- UI.1?info/null
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info NI.2?netalert/- UI.1?info/null
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info NI.2?netconn/- UI.1?info/null
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info UI.1?connack/- UI.1?info/null
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info T305?timeout/- UI.1?info/null
r/- UI.1?setup/UI.1!setupack UI.1?info/UI.1!info T308?timeout/- UI.1?info/null
r/- UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc UI.1?setup_bad/-
   NI.2?netalert/UI.1!alert
r/- UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc UI.1?setup/-
   NI.2?netalert/UI.1!alert
r/- UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc UI.1?info/-
   NI.2?netalert/UI.1!alert
r/- UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc UI.1?info_bad/-
   NI.2?netalert/UI.1!alert
r/- UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc UI.1?info_last/-
   NI.2?netalert/UI.1!alert

```

Table 3. UIO-based Test Sequences for the FSM in Figure 3 (cont'd)

r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc UI.1?rel/UI.1!relcom UI.1?setup_bad/UI.1!relcom
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc UI.1?disc/UI.1!rel UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc T302?timeout/- NI.2?netalert/UI.1!alert
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netclear/UI.1!disc T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netconn/- NI.2?netalert/UI.1!alert
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc UI.1?connack/- NI.2?netalert/UI.1!alert
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc T305?timeout/- NI.2?netalert/UI.1!alert
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc T308?timeout/- NI.2?netalert/UI.1!alert
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert UI.1?setup_bad/- NI.2?netconn/UI.1!conn
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert UI.1?setup/- NI.2?netconn/UI.1!conn
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert UI.1?info/- NI.2?netconn/UI.1!conn
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert UI.1?info_bad/- NI.2?netconn/UI.1!conn
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert UI.1?info.last/- NI.2?netconn/UI.1!conn
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert UI.1?rel/UI.1!relcom UI.1?setup_bad/UI.1!relcom
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert UI.1?disc/UI.1!rel UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert T302?timeout/- NI.2?netconn/UI.1!conn
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netclear/UI.1!disc T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netalert/- NI.2?netconn/UI.1!conn
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert UI.1?connack/- NI.2?netconn/UI.1!conn
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert T305?timeout/- NI.2?netconn/UI.1!conn
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert T308?timeout/- NI.2?netconn/UI.1!conn
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn UI.1?setup_bad/- UI.1?connack/null
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn UI.1?setup/- UI.1?connack/null
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn UI.1?info/- UI.1?connack/null
r/-	UI.1?setup/UI.1!setupack UI.1?info.last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn UI.1?info_bad/- UI.1?connack/null

Table 3. UIO-based Test Sequences for the FSM in Figure 3 (cont'd)

r/-	UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn UI.1?info_last/- UI.1?connack/null
r/-	UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn UI.1?rel/UI.1!relcom UI.1?setup_bad/UI.1!relcom
r/-	UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn UI.1?disc/UI.1!rel UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn T302?timeout/- UI.1?connack/null
r/-	UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn NI.2?netclear/UI.1!disc T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn NI.2?netalert/- UI.1?connack/null
r/-	UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn NI.2?netconn/- UI.1?connack/null
r/-	UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn UI.1?connack/null UI.1?connack/null
r/-	UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn T305?timeout/- UI.1?connack/null
r/-	UI.1?setup/UI.1!setupack UI.1?info_last/UI.1!info.UI.1!callproc NI.2?netalert/UI.1!alert NI.2?netconn/UI.1!conn T308?timeout/- UI.1?connack/null
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc UI.1?setup_bad/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc UI.1?setup/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc UI.1?info/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc UI.1?info_bad/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc UI.1?info_last/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc UI.1?rel/UI.1!relcom UI.1?setup_bad/UI.1!relcom
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc UI.1?disc/UI.1!rel UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc T302?timeout/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc NI.2?netclear/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc NI.2?netalert/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc NI.2?netconn/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc UI.1?connack/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc T305?timeout/UI.1!rel UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?info_bad/UI.1!prog.UI.1!disc T308?timeout/- T305?timeout/UI.1!rel
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel UI.1?setup_bad/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel UI.1?setup/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel UI.1?info/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel UI.1?info_bad/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel UI.1?info_last/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel UI.1?rel/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel UI.1?disc/null UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel T302?timeout/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel NI.2?netclear/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel NI.2?netalert/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel NI.2?netconn/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel UI.1?connack/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel T305?timeout/- UI.1?disc/null
r/-	UI.1?setup/UI.1!setupack UI.1?disc/UI.1!rel T308?timeout/UI.1!rel UI.1?setup_bad/UI.1!relcom