A conformance testing for communication protocols modeled as a set of DFSMs with common inputs

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Abstract

In this paper, we propose an effective conformance testing method for a subclass of protocols modeled as a set of DFSMs. The number of test cases in the proposed method is only proportional to the *sum* of those of states and transitions in a given set of DFSMs. In our method, we find a characterization set for each DFSM, which is used to test the DFSM alone in Wp-method, and the union of the characterization sets is used as a characterization set for the total system. For a set of DFSMs with common inputs, there may exist two or more tuples of states that have correct responses against a given characterization set. So, in order to identify each state *s* in a DFSM, we find a characterization set with some specific properties. Then we select a suitable

tuple of states containing the state s , and identify the state s by checking their response to the characterization set.

Keywords

Verification, protocol testing, test case selection and test coverage

1 INTRODUCTION

Conformance testing for communication protocols is highly effective to develop reliable communication systems. There are many research efforts on generating conformance test cases mechanically, which are well known as the TT-method [7], W-method [1], DS-method [2], UIO-method [9], and so on. Furthermore, there are some research papers focusing on more effective methods for generating test sequences. These efforts were mainly made for communication protocols modeled as a single deterministic finite state machine (DFSM). Recently similar research efforts have been done on non-deterministic or concurrent models [4, 5, 6, 11, 12].

According to the progress of computer networks, many kinds of protocols, which use several channels in parallel, are proposed. For such a protocol, it is quite natural that a protocol with several channels is considered as a set of DFSMs, each of which controls one channel and competes with other DFSMs for taking common inputs. Since a common input is taken by some DFSMs, the whole behavior of a given set of DFSMs is non-deterministic.

As a conformance testing method for such a non-deterministic FSM (NFSM) model, there is the GWp-method [6]. Such a method can be applied to a set of DFSMs mentioned above. However, since, in general, all reachable tuples of states of the DFSMs are considered as the states of the total system, the number of states of the total system is proportional to the product of those of the DFSMs. So, the number of generated test cases is also proportional to the product of those of the DFSMs. One of the methods free from such a drawback is to carry out the conformance testing for each DFSM independently. For example, the testing method in [5] is based on this idea and it treats protocols with communications among FSMs and internal actions. Since this method is based on the TT-method, it cannot identify the state after each transition is executed.

In this paper, for a specification modeled as a set of DFSMs with common inputs, we assume that the implementation under test (IUT, for short) is also modeled as a set of DFSMs (sub-IUTs) where the number of states of each sub-IUT does not exceed that of the corresponding DFSM in the specification. Under this assumption, we propose a testing method based on the GWp-method where the number of test cases is only proportional to the *sum* of those of states and transitions in a set of DFSMs. It identifies all states of DFSMs and confirms all transitions even if the IUT has any number of faults.

The proposed method uses the union of characterization sets W_i for all DFSMs A_i as a characterization set for the total system. Here, we assume that we can generate a characterization set which can identify all states in each DFSM even if the common inputs in the characterization set are received by several DFSMs non-deterministically. In order to identify a state s of a DFSM, we select a suitable tuple of states containing the state s , and identify the state s by checking its response to the characterization set.

The paper is structured as follows. In Section 2, we explain the model used in this paper, and then we define its fault model. In Section 3, the outline of the GWp-method for testing NFSMs is explained. In Section 4, we propose a testing method. In Section 5, the correctness of the proposed testing method is described. An example is given in Section 6. We conclude the paper in Section 7.

2 A SET OF DFSMS WITH COMMON INPUTS

2.1 Specification and Its Implementation

Definition 1 (Finite State Machine) A finite state machine (FSM) is defined as the following 6-tuple,

$$A = (S, X, Y, \delta, \lambda, s_0)$$

Here, S , X and Y are a finite set of states, a finite set of inputs and a finite set of outputs, respectively. δ is a transition function ($S \times X \rightarrow S$), and λ is an output function ($S \times X \rightarrow Y$). s_0 is the initial state of A . $\square$

For two states s and t , we say that s is *equivalent* to t if $\lambda(s, \sigma^i) = \lambda(t, \sigma^i)$ holds for any input sequence σ^i . We say that a FSM M_1 is *equivalent* to a FSM M_2 if the initial state of M_1 is equivalent to that of M_2 . A FSM M is said to be *minimal* if, for any two different states s and t of M , s is not equivalent to t . We say that a FSM M is *completely specified* (or *complete*) if both transition function and output function are defined for any pair of a state and an input. In this paper, if a FSM is not completely specified, we make the FSM complete as follows : For each pair of a state s and an input x whose transition and output functions are undefined, we add a new transition from s to itself whose output is empty and make the FSM complete. Here, we denote such an empty output by " ε ". For such a new transition x/ε from a state s , we say that the FSM *ignores* input x at state s .

A FSM is said to be *initially connected* if there exists a transition sequence from the initial state to any state of the FSM, where the transition sequence may be a null sequence.

A FSM is said to be *deterministic* if, for any pair of a state s and an input x , $\delta(s, x)$ and $\lambda(s, x)$ are uniquely defined. Such a FSM is called a deterministic

FSM (DFSM). A FSM that is not a DFSM is called a non-deterministic FSM (NFSM). If two non-deterministic transitions from a state have the same outputs b for an input a , then we say that the non-deterministic transitions (a/b and a/b) are non-observable. Otherwise (for example, a/b and a/c), we say that they are observable non-deterministic transitions. We say that a NFSM is observable NFSM (ONFSM) if all the non-deterministic transitions in the NFSM are observable [10].

Next, we define a set of DFSMs used in this paper. We call this model as *Coupled DFSMs*.

Definition 2 (Coupled DFSMs) *Coupled DFSMs* are a k -tuple,

$$A = (A_1, A_2, \dots, A_k)$$

where $A_1, A_2, \dots, A_k$ are DFSMs, respectively. Also, each $A_i (1 \leq i \leq k)$

$$A_i = (S_i, X_i, Y_i, \delta_i, \lambda_i, s_{i0})$$

must be a complete, initially connected and minimal DFSM. Furthermore, we suppose there is a reset operation so that the whole Coupled DFSMs are reset to their initial states at a time. $\square$

Here, an input such as $x \in X_i \cap X_j$ is called a *common input*. If a common input x is given to Coupled DFSMs from the external environment, one of DFSMs takes the input x non-deterministically and the chosen DFSM returns a response (output). Here, it is assumed that A_i is not chosen whenever A_j ignores the input x and A_j does not.

Definition 3 (Specifications of Communication Protocols) A specification of a communication protocol dealt with in this paper is given as Coupled DFSMs

$$A = (A_1, A_2, \dots, A_k)$$

consisting of k DFSMs. We also suppose that this specification does not contain any non-observable and non-deterministic transitions as a whole. $\square$

$A_i (1 \leq i \leq k)$ is said to be a *sub-specification* of A . Since we assume that a specification does not contain any non-observable and non-deterministic transitions, if there is a transition a/b in A_i , there may exist a transition a/c in A_j . However, there does not have to exist the same transition a/b in A_j .

Each implementation under test (IUT) I is given as follows.

Definition 4 (Implementation Under Test (IUT)) An implementation under test (IUT) I of a communication protocol is given as Coupled DFSMs consisting of k DFSMs

$$I = (I_1, I_2, \dots, I_k)$$

where each I_j must satisfy the following properties: I_j has the same set X_j

Figure 1 Example of Multi-Link Protocol.

Table 1 Inputs

Inputs	
1	link inc. req.
2	link dec. req.
3	data trans. req.
4,6,8	connect confirm
5,7,9	data trans. ack

Table 2 Outputs

Outputs	
1	connect confirm
2	data trans. ack
3,6,9	link inc. indication
4,7,a	link dec. indication
5,8,b	data trans. indication

Table 3 States

States	
0	disconnected
1	wait(connection)
2	connected
3	wait(data)

of input symbols as A_j . A set of output symbols in I_j is equal to the set $Y = Y_1 \cup Y_2 \cup \dots \cup Y_k$ that is the set of all output symbols used in the protocol. That is, there may exist a fault that I_j gives an output y such as $y \notin Y_j \wedge y \in Y_i$ ($i \neq j$). The number of states of each I_j does not exceed that $(|S_j|)$ of A_j .

We also suppose that there exists a reliable reset operation so that the whole Coupled DFSMs can be reset to their initial states at a time. $\square$

I_j ($1 \leq j \leq k$) is said to be a *sub-IUT* of I . As stated above, we suppose that both a specification A and an IUT I are modeled by the same number k of DFSMs, however, the internal states of I are not observable. That is, the IUT I is considered to be a black-box and will be tested. On the other hand, the specification A must be ONFSM as a whole, but the IUT I could have non-observable and non-deterministic transitions.

Definition 5 (Conformance of Communication Protocol) For a specification $A = (A_1, A_2, \dots, A_k)$ and an IUT $I = (I_1, I_2, \dots, I_k)$ of communication protocols stated above, we define that I is a correct implementation of A if each sub-IUT I_j of I is equivalent to the corresponding sub-specification A_j of A . $\square$

Figure 2 A Faulty IUT for Fig. 1.

2.2 Example Protocol in Our Model

We consider the protocol shown in Fig. 1 as an example. Fig. 1 represents a specification of a protocol which can dynamically vary the number of links between the lower and upper layers. On this specification, at most three links are set up by the orders from the upper layer, where the finite state control for each link is modeled as a DFSM. Table 1,2,3 represents the contents of inputs, outputs and states.

Whenever a “Link Increase request” is issued to this protocol by the upper layer, a link is newly set up by one of DFSMs which has not set up any link to the lower layer. In the case of “Link Decrease request” by the upper layer, one of DFSMs which has been holding a link to the lower layer cuts the link. Only executable DFSMs can compete with each other for these Link Increase/Decrease requests. That is, when an input 1 (“Link Increase request”) is issued, one of DFSMs with states where the input 1 is not ignored is chosen by non-deterministically and responds to the input 1. For example, in case that FSM2 is in the state where the input 1 is ignored (such as state 1 in Fig. 1), FSM2 is never chosen. If all DFSMs are in the states where the input 1 is ignored, we consider that one of them ignores the input 1. In this specification, we can easily check which DFSM responds to each Link Increase/Decrease request from its output. That is, the specification is modeled as an ONFSM as a whole. Fig. 2 is an example of a faulty implementation of the protocol shown in Fig. 1. Hereafter, we assume that the italic-faced *FSM_i* denotes a sub-IUT corresponding to the sub-specification FSM_i. At the tuple of states (0, 0, 0) of the Coupled DFSMs, their faults cannot be detected easily, since as a whole the outputs for the input 1 are the same as the specification (the set of 3, 6 and 9).

3 OUTLINE OF GWP-METHOD

The GWp-method[6] is an extended version of the Wp-method so that ONFSMs can be dealt with. In the GWp-method, testing consists of two parts : one is state identification whether there exist all states of the specification in a given IUT, and the other is confirmation of transitions whether all tran-

sitions of the specification are correctly implemented in a given IUT. Both of testing are carried out by checking whether the output sequences obtained by applying test sequences to the IUT are equal to those from the specification. Since an ONFSM has non-deterministic actions, in general, a number of variety of output sequences may be produced as the response for an input sequence. So, in the GWp-method, we give each test sequence to the IUT for several times. If the obtained set of the output sequences is not equal to that from the specification, we regard that the IUT has a fault. If the sets are the same, we regard that the IUT returns the correct response for the test sequence and continue the test using other test sequences. If the IUT returns the correct response for all test sequences, then we regard that the IUT is a correct implementation of a given specification.

The set of test sequences in the GWp-methods is given by constructing two kinds of sets of sequences : the *characterization set* (W set) and *state cover* (V set).

Definition 6 (Characterization Set) The *characterization set* W for a FSM is given as a set of input sequences called *characterization sequences*. Each state in a given FSM must be uniquely identified by observing the set of output sequences obtained by applying all input sequences in W. $\square$

Definition 7 (Transfer Sequences to Goal States) A *transfer sequence* to a state s in a FSM is an input sequence which makes the FSM move from the initial state to the goal state s . The set V of transfer sequences to all states in the FSM is called a *state cover*. $\square$

In NFSM models, there may exist several reachable states for a given transfer sequence because of non-deterministic behavior. Therefore, for an ONFSM, if the ONFSM does not produce the expected output sequence for a given transfer sequence, we decide that the ONFSM does not reach the expected state because of non-deterministic behavior, and try the test again.

Definition 8 (Test Suite) The test suite for state identification is the concatenation $V.W$ of V and W. The test suite for confirmation of transitions is defined as follows using V, W and X (the set of input symbols) : $V.X \oplus W = \{\sigma.w \mid \sigma \in V.X, s_0 \xrightarrow{\sigma} s_i, w \in W\}$ $\square$

4 PROPOSED TESTING METHOD

In the proposed method, for a specification $A = (A_1, A_2, \dots, A_k)$ and an implementation $I = (I_1, I_2, \dots, I_k)$ modeled as Coupled DFSMs, first, we give some conditions for the characterization set used in the testing. Then, using the characterization set satisfying the conditions, we will carry out the test

whose cost is proportional to the sum of the numbers of states and transitions in the DFSMs. Like the GWp-method, the proposed testing method is divided into the following two parts: (1) state identification and (2) confirmation of transitions.

4.1 Construction of Characterization Set

In the proposed method, for state identification, we assume that we can construct a characterization set W_i for each sub-specification A_i which satisfies the following two conditions(Def.9 and 10).

Definition 9 (Condition for common inputs) For each characterization set W_i containing common inputs, W_i must be able to identify each state in A_i even if A_i ignores the common inputs in W_i . $\square$

Then, we construct the following set W .

$$W = W_1 \cup W_2 \cup \dots \cup W_k$$

For each input sequence σ in W , let $\bar{\sigma}_i$ denote the input sequence obtained from σ by deleting all the input symbols which the sub-specification A_i cannot respond to. And let W'_i denote the set of $\bar{\sigma}_i$ for all input sequences σ in W . Here, we also treat each W'_i as a characterization set for A_i .

As an example, let's consider the protocol in Fig. 1. Suppose that the following characterization sets are constructed.

$$W_1 = \{35, 4, 5\}, W_2 = \{16, 7, 6\}, W_3 = \{18, 9, 8\}$$

Then, we obtain the characterization set W for the total system as follows:

$$W = \{35, 4, 5, 16, 7, 6, 18, 9, 8\}$$

Also, the characterization sets

$$W'_1 = \{35, 4, 5, 1\}, W'_2 = \{16, 7, 6, 3\}, W'_3 = \{18, 9, 8, 3\}$$

are obtained.

Here, we must take the above condition into consideration for the construction of W_1 . In Table 4, even if we make a smaller characterization set $W''_1 = \{35, 4\}$, it can identify four states of FSM1. But the common input 3 in W''_1 may be taken by one of other DFSMs, that is, in Table 4, the corresponding output 5 with underline may be changed to ε . In this case, we cannot distinguish state 2 from state 3. So it is necessary to construct the characterization set W_1 which can identify each state in FSM1 even for such a case. That is the reason why we add another sequence 5 to W_1 . By adding the sequence 5 to W_1 , we can distinguish state 2 from state 3 even if the common input 3 is taken by another DFSM. Also in Tables 5 and 6, we add sequences 6 and 8 to W_2 and W_3 , respectively, from the same reason.

Table 4 W_1

State	35	4	5
0	$\varepsilon\varepsilon$	ε	ε
1	$\varepsilon\varepsilon$	1	ε
2	$\underline{5}2$	ε	ε
3	$\varepsilon2$	ε	2

 Table 5 W_2

State	16	7	6
0	$\underline{6}1$	ε	ε
1	$\varepsilon1$	ε	1
2	$\varepsilon\varepsilon$	ε	ε
3	$\varepsilon\varepsilon$	2	ε

 Table 6 W_3

State	18	9	8
0	$\underline{9}1$	ε	ε
1	$\varepsilon1$	ε	1
2	$\varepsilon\varepsilon$	ε	ε
3	$\varepsilon\varepsilon$	2	ε

Definition 10 (Condition for response of other DFSMs) Let C_i denote the set of common inputs contained in W'_i . We assume that we can construct each W'_i such that every $A_j (j \neq i)$ has a state which ignores all common inputs in C_i . $\square$

For state identification, we only assume the above two conditions. However, for confirmation of transitions, we need a further assumption. If a state s in a sub-specification A_i ignores a common input x , and if another sub-specification A_j produces an output y at every state for the common input x . In this case, we cannot confirm logically that $s \xrightarrow{x/\varepsilon} s$ in A_i is correctly implemented. The IUT produces the same outputs as the total system even if I_i produces the output y for the input x at state s , since at any tuple of states containing state s , I_j produces the output y .

Therefore, we also give the following assumption for each sub-specification A_i .

Definition 11 (Assumption for each DFSMs) Let D denote the set of common inputs. We assume that every A_i has a state which ignores each common input in D . $\square$

In general, even if there exists a characterization set for each sub-specification, there may not exist a characterization set which satisfies the above three conditions. However, for most cases that there are not so many common input symbols in each characterization set, we believe that we can construct characterization sets which satisfy the above three conditions (for example, see an example in Section 6).

4.2 State Identification

We identify all the states in DFSMs as follows.

- Selection of tuples of states

Let s_j^i denote a state in $A_j (j \neq i)$ which can ignore all inputs in C_i . For each state s_p of A_i , we treat $ss_p^i = (s_1^i, s_2^i, \dots, s_k^i) (s_i^i = s_p)$ as the tuple of

states to identify the state s_p . Note that when we give any input in C_i to the tuple of states ss_p^i , only the state s_p of A_i can make a response.

- Giving test sequences

We give a test suite $V.W_i'$ to the tuples of states constructed above for several times. Here, each v_p^i in V is the sequence obtained by concatenating all transfer sequences $v_1^i, v_2^i, \dots, v_k^i$ for the states $s_1^i, s_2^i, \dots, s_k^i$ in ss_p^i . And we use the same v_p^i repeatedly while testing for a state. If we get an unexpected output sequence as the result for the transfer sequence v_p^i , we consider that non-deterministic behavior of Coupled DFSMs makes the IUT move to a tuple of states except ss_p^i and we try to give the transfer sequence v_p^i again. If we get the correct output sequence for v_p^i , then we observe a response of ss_p^i for each input of W_i' . If the obtained set of output sequences is not equal to that from the specification, we conclude that the IUT is faulty.

We apply the above method to all states in each sub-specification A_i ($1 \leq i \leq k$). If we cannot find faulty states, we conclude that we have identified all the states in the IUT.

As an example, we try to identify states of FSM1 in Fig. 1.

- Selection of tuples of states

The characterization set W_1' has common inputs $C_1 = \{1, 3\}$. For example, both state 1 of FSM2 and state 1 of FSM3 ignore these common inputs 1 and 3. So, we select a tuple of states (0, 1, 1) for identifying state 0 of FSM1. We select (1, 1, 1) for state 1, (2, 1, 1) for state 2 and (3, 1, 1) for state 3, respectively.

- Giving test sequences

We give the test suite $V.W_1'$ to the IUT for several times and observe a response from the IUT. This V is a set of transfer sequences to the chosen four tuples, for example, $V = \{11, 111, 1411, 14511\}$. For testing a tuples of states (2, 1, 1), if the output sequence for a transfer sequence 1411 is not 3169, we decide that we couldn't transfer the IUT to a tuple of states (2, 1, 1) because of non-deterministic behavior. Then we try the test again.

4.3 Confirmation of Transitions

For a transition $s_p \xrightarrow{x/y} s_q$ ($x \in X, y \in Y \cup \{\varepsilon\}$) in each sub-specification A_i , we confirm the transition by dividing the following two cases.

If the input x is not a common input, we give a test suite $v.x.W_i'$ where v is the same transfer sequence used to identify the state s_p .

If the input x is a common input, we give a test suite $v.W_i' \cup v.x.W_i'$. Here, the transfer sequence v in this test suite is constructed as follows. We find a tuple of states $ss_p^i = (s_1^i, s_2^i, \dots, s_k^i)$ ($s_i^i = s_p$) where each state s_j^i of A_j ($j \neq i$)

ignores the common input x . Then, v may be any transfer sequence to ss_p^i . Here, the test suite $v.W$ is used to identify all states in the tuple of states ss_p^i (note that W is the union of all characterization sets W'_i for identifying each state s_j^i). The test suite $v.x.W'_i$ is used for confirming the transition and identifying the state which the sub-IUT I_i reaches after the transition is executed.

We apply the above method to all transitions. If the IUT is not faulty, we conclude that the implementation of transitions for the specification is correct.

Note that the numbers of test sequences used for identifying states and confirming transitions are proportional to the sum of those of states and transitions in DFSMs, respectively.

5 CORRECTNESS OF TESTING METHOD

5.1 Correctness of State Identification

For a specification modeled as Coupled DFSMs, we must take the following two notices. One is the existence of the common inputs. Assume that for an identification of a state s in A_i , we can observe the expected output 1 after providing an input x . At this time, the IUT may be implemented badly, since it is possible that A_i doesn't give the output 1 and the other A_j gives the output. This is the reason why we cannot identify a state even if we can observe the expected response for the IUT. The other is our assumption that the IUT may have non-observable and non-deterministic transitions. On this case, for a given transfer sequence, even if we can observe the expected output sequence, we cannot guarantee that the IUT is led to the tuple of states which we want to lead. The IUT may be led to several tuples of states.

For example, the response of a tuple of states $(2, 1, 1)$ for W'_1 is,

$$35/5\varepsilon, 4/\varepsilon, 5/\varepsilon, 1/\varepsilon$$

Here, a sub-IUT $FSM1$ may ignore the common inputs 1 and 3. Then the sub-IUT $FSM1$ has at least one of states which return the response like the following (there may exist both states) :

$$(35/5\varepsilon, 4/\varepsilon, 5/\varepsilon, 1/\varepsilon), (35/\varepsilon\varepsilon, 4/\varepsilon, 5/\varepsilon, 1/\varepsilon)$$

In order to consider all possibilities stated above, we introduce the state variables in Table 7 where the value of each variable is true if and only if there exists the corresponding state in the sub-IUT $FSM1$. The above condition can be expressed as the following logical formulas.

- For the tuple of states $(0, 1, 1)$, $\varphi_{11} \vee \varphi_{12}$
- For the tuple of states $(1, 1, 1)$, φ_{13}
- For the tuple of states $(2, 1, 1)$, $\varphi_{14} \vee \varphi_{15}$

Table 7 Var(FSM1)

Var	Response for W'_1
φ_{11}	35/ $\epsilon\epsilon$, 4/ ϵ , 5/ ϵ , 1/3
φ_{12}	35/ $\epsilon\epsilon$, 4/ ϵ , 5/ ϵ , 1/ ϵ
φ_{13}	35/ $\epsilon\epsilon$, 4/1, 5/ ϵ , 1/ ϵ
φ_{14}	35/52, 4/ ϵ , 5/ ϵ , 1/ ϵ
φ_{15}	35/ ϵ 2, 4/ ϵ , 5/ ϵ , 1/ ϵ
φ_{16}	35/ ϵ 2, 4/ ϵ , 5/2, 1/ ϵ

Table 8 Var(FSM2)

Var	Response for W'_2
φ_{21}	16/61, 7/ ϵ , 6/ ϵ , 3/ ϵ
φ_{22}	16/ ϵ 1, 7/ ϵ , 6/ ϵ , 3/ ϵ
φ_{23}	16/ ϵ 1, 7/ ϵ , 6/1, 3/ ϵ
φ_{24}	16/ $\epsilon\epsilon$, 7/ ϵ , 6/ ϵ , 3/8
φ_{25}	16/ $\epsilon\epsilon$, 7/ ϵ , 6/ ϵ , 3/ ϵ
φ_{26}	16/ $\epsilon\epsilon$, 7/2, 6/ ϵ , 3/ ϵ

Table 9 Var(FSM3)

Var	Response for W'_3
φ_{31}	18/91, 9/ ϵ , 8/ ϵ , 3/ ϵ
φ_{32}	18/ ϵ 1, 9/ ϵ , 8/ ϵ , 3/ ϵ
φ_{33}	18/ ϵ 1, 9/ ϵ , 8/1, 3/ ϵ
φ_{34}	18/ $\epsilon\epsilon$, 9/ ϵ , 8/ ϵ , 3/b
φ_{35}	18/ $\epsilon\epsilon$, 9/ ϵ , 8/ ϵ , 3/ ϵ
φ_{36}	18/ $\epsilon\epsilon$, 9/2, 8/ ϵ , 3/ ϵ

- For the tuple of states (3, 1, 1), φ_{16}

In our proposed method, we have selected a state in A_j ($j \neq 1$) which ignores all the common inputs in W'_1 . So, each formula includes a state which returns the same response as the specification (e.g. φ_{11} for the tuple of states (0, 1, 1)), and it may include a state whose response for a common input is ϵ (e.g. φ_{12} for the tuple of states (0, 1, 1)).

For the sub-IUT FSM_2 , we can get the following logical product of formulas using state variables in Table 8.

$$(\varphi_{21} \vee \varphi_{22}) \wedge \varphi_{23} \wedge (\varphi_{24} \vee \varphi_{25}) \wedge \varphi_{26}$$

For the sub-IUT FSM_3 , we can get the following logical product of formulas using state variables in Table 9.

$$(\varphi_{31} \vee \varphi_{32}) \wedge \varphi_{33} \wedge (\varphi_{34} \vee \varphi_{35}) \wedge \varphi_{36}$$

On all of the cases, the formula for each tuple of states always has one state whose response is expected on the specification, and it may have another state whose response is equal to the expected response except that the output for the common input is changed to ϵ . And also, the set of formulas for one sub-IUT has no same state variables, that is, all state variables in the set of formulas are different. Since we assume that the number of states of each sub-IUT I_i does not exceed the number of states N_i of the corresponding sub-specification A_i , we must select at most N_i state variables to be true in order to make all of N_i formulas be true. So, we cannot select one state variable to be true so that two formulas can be true together. Then we must select only one of state variables in each formula to be true so that we make all of N_i formulas be true.

If we select the state variable whose response is not the expected output y but the empty output ϵ , we can consider that the output y , which we observed when we gave the characterization set to the IUT, was obtained from an other sub-IUT I_j . However, the formulas for the other sub-IUT I_j have only state variables whose response is expected on the specification or equal to the expected response except that the output for the common input is changed to ϵ . So, each state in the other sub-IUT I_j cannot produce the

output y . Also, because of the limitation on the number of state variables to be true, we cannot select so much number of state variables.

From the above, all we can do is to select the state variables whose response is equal to the expected response on the specification in order to make all formulas be true. That is the reason why our method is correct for state identification.

We can identify the following four states for $FSM1$.

$$\varphi11, \varphi13, \varphi14, \varphi16$$

We can also identify all states in $FSM2$ and $FSM3$.

Here, we can say something about non-deterministic behavior of the IUT. Until now, when we give the IUT a transfer sequence v which can make A_i move to s_p , we cannot guarantee that the state of the sub-IUT I_i is s_p truly. However, now we can say that (1) each sub-IUT I_i has a state corresponding to each state in the sub-specification A_i , and (2) we can exactly lead the state of a sub-IUT to any state by the transfer sequence used to identify the state.

5.2 Correctness of Confirmation of Transitions

From now, we explain why by our proposal method (by giving test suite $v.x.W_i$ or $v.W \cup v.x.W'_i$), we can check whether each transition $s_p \xrightarrow{x/y} s_q$ ($x \in X, y \in Y \cup \{\varepsilon\}$) in the sub-specification A_i is correctly implemented on the corresponding sub-IUT I_i .

(Case 1)

If the input x is not a common input, we give the IUT the test suite $v.x.W'_i$ where v is the transfer sequence used to identify the state s_p . We can guarantee that the starting state of the transition x/y is s_p truly since v is the sequence used to identify the state s_p . And by observing outputs from the IUT for $x.W'_i$, we can identify the state after x/y is executed.

(Case 2)

If the input x is a common input, we give the IUT the test suite $v.W \cup v.x.W'_i$. In general, when testing of state identification has not been finished, each sub-IUT may have a wrong state whose response is not equal to that on the sub-specification even if the response of the sub-IUT for all of W'_i is correct. But if testing of state identification has been finished, and if we can get the expected response, it shows the existence of the state of I_i corresponding to a state of the sub-specification A_i (because there are not any other possibilities). Then if we can observe the expected outputs when we give W for the tuple of states which the transfer sequence v leads ($ss_p^i = (s_1^i, s_2^i, \dots, s_k^i)$ ($s_i^i = s_p$)), we can guarantee that we have led the IUT to ss_p^i .

Next we explain why we can confirm transitions by the test suite $v.x.W'_i$ by dividing into three cases.

(Case 2.1)

We first consider the case that the state is changed by execution of the transition $s_p \xrightarrow{x/y} s_q (x \in X, y \in Y \cup \{\varepsilon\})$. Because we have constructed the tuple of states so that a state s_j^i can ignore the common input x , the output must be only y when the input x is given at ss_p^i . At this time, by observing the response for W'_i , we can check whether the common input x is taken into other DFSMs. If another DFSM takes the input x and produces the output y , and if the state s_p of the sub-IUT I_i is badly implemented as it can ignore the input x , then the response for W'_i is not for s_q but s_p , and then we can find the error.

(Case 2.2)

Secondly we consider the case that the state is not changed by execution of the transition $s_p \xrightarrow{x/y} s_q (x \in X, y \in Y \cup \{\varepsilon\})$, and the output y is ε . Since we have constructed the tuple of states ss_p^i so that every state in ss_p^i ignores the common input x , we can find the error if we cannot observe the output ε after giving x . We can also find the error that s_p and s_q are not the same if the response for W'_i is different from s_p 's response.

(Case 2.3)

Lastly, we consider the case that the state is not changed by execution of the transition $s_p \xrightarrow{x/y} s_q (x \in X, y \in Y \cup \{\varepsilon\})$, and the output y is not ε . On this case we can test in a similar way. We have constructed the tuple of states ss_p^i so that every state in I_j ($j \neq i$) ignores the common input x . On this case that the output y is not ε , however, we should consider that the IUT may be implemented as that state s_p of I_i can ignore the common input x and a state of another sub-IUT I_j can give the output y without changing its state. On the condition of $(s_p = s_q)$ and $(y \neq \varepsilon)$, we cannot deny such a possibility only by confirmation of the transitions of I_i . However the possible error is that the output y may be changed to ε like the testing for state identification. We can guarantee that there is not such a possibility by confirmation of all transitions in each sub-IUT I_j . That is, by confirming of the transitions at all states of each sub-IUT I_j , we can assure that each sub-IUT I_j can give either an output z which can be used only by A_j or only ε . So we can also assure that I_j cannot give the output y which can be used only by A_i , and finally we can guarantee that I_i gives the output y truly.

From the above, our proposal method guarantees that the implementation of transitions is correct.

6 EXAMPLE

We have applied our testing method to the abracadabra protocol. We have simplified an Estelle specification of the abracadabra protocol in [3] and modified it so that three sending processes run in parallel. Fig. 3 is its specification in our model where I/O symbols are represented symbolically. From this spec-

Figure 3 Example Spec. for Abracadabra Protocol.

ification, we have constructed characterization sets satisfying the conditions mentioned in Section 4.1.

7 CONCLUSION

In this paper, we propose a conformance testing method for communication protocols modeled as a set of DFSMs with common inputs. In the proposed method, we check each DFSM independently. So, the cost is only proportional to the sum of the numbers of states and transitions of DFSMs. Although we assume the existence of characterization sets which satisfy some conditions, we believe many communication protocols satisfy the conditions.

One of the future work is to extend the class of DFSMs so that we can treat the communications between DFSMs and internal actions in DFSMs.

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