PROGRESSIVE ON-THE-FLY TEST METHOD

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ABSTRACT

The development of communications systems demands testing. This paper presents a framework for testing on-the-fly, which relies on the identification of 3 types of tests and on their sequential execution.
The *ioco* conformance relation was adopted in order to assign verdicts.
A prototype tool is also presented that supports the proposed framework. This tool, named PROFYT, was developed based on the SPIN verifier and uses communicating FSMs to describe the specification. PROFYT was used to test Conference Protocol implementations on-the-fly and enabled us to conclude about the benefits of the test methodology proposed.

KEYWORDS

Protocol conformance, on-the-fly conformance, automatic testing.

1. INTRODUCTION

The development of communications systems demands testing. During decades, many testing methodologies were defined aimed at verifying the conformity of protocol implementations to their specifications [Brinksma et al., 1997], [Fernandez et al., 1997], [Raymond et al., 1998], [Lee et al., 1996] [Schmitt et al., 2000], [Gargantini et al., 1999], [Kerbrat et al., 1999], [Groz et al., 1999]. Further references can be found in [Brinksma et al., 2001] and [Petrenko, 2000]. One of the recent approaches consists in testing *on-the-fly* the implementation conformity [Vries et al., 2000]. Tools implementing the *on-the-fly* conformance testing approach, derive and execute tests in a single step; relying on some specification model, these tools explore the model not only to select the next message to be transmitted by the tester, but also to validate messages received from the implementation. Although appealing, this testing approach has some drawbacks such as: (1) the length of test traces and (2) the difficulty in reproducing detected failures [Vries et al., 2000]. Besides, the lack of test control may conduce to situations in which sever non-conformance cases are undetected, just because the test events selected randomly did not exercise some basic interoperability functions.

In this paper we present a new methodology which uses the on-the-fly approach, but reduces the problems mentioned. We also present a tool that implements the method, named PROFYT. This tool is based on the SPIN verifier and uses communicating FSMs as behaviour model. The validation of the method and the tool was based on the Conference Protocol; multiple faulty implementations were tested, and the cost of finding

faults is compared with the TorX [Vries et al., 2000] tool. The results obtained enabled us to conclude and quantify the benefits of the proposed approach.

This work is reported in 6 sections. Section 2 defines the communicating finite state machines. Section 3 presents the main contribution of this paper: the progressive test method, the test modes, and the algorithms implementing them. Section 4 presents the PROFYT tool, which implements the methodology proposed. Section 5 reports the results of evaluating our methodology and tool against the TorX tool. Section 6 concludes the paper.

2. COMMUNICATING FINITE STATE MACHINES

Communicating finite state machines are used to describe the behaviour of interacting processes [Lee et al., 1996], and can be extended with message queues and variables [Holzmann, 1991].

A message queue m is a triple $m = (U_m, N_m, C_m)$, where U_m is the set of messages, N_m is the maximum number of messages held by the queue, and C_m is the set of ordered sets of messages held by the queue; M denotes the set of queues used by a state machine, and $m \in M$. An ordered set of messages $c_m = < u_{m,1}, \dots, u_{m,i}, \dots, u_{m,k} >$ is an element of C_m, where $u_{m,i} \in U_m$ is the message occupying the ith position of queue m, and $1 \leq k \leq N_m$; $c_m = < >$ represents the queue m when it is empty, and $\#c_m$ the number of messages held by queue m. The state of a variable l is denoted by v_l and its initial state is denoted by v_{l_0}; the state of the x machine variables is jointly represented by $w = (v_1, \dots, v_l, \dots, v_x)$, being W the set of all possible w, and $w \in W$. Q is the finite set of state machine control states. The state machine global space state is then given by $G = Q \times C \times W$, and contains states $g_i = (q_i, (c_{1_i}, c_{2_i}, \dots, c_{m_i}), (v_{1_i}, v_{2_i}, \dots, v_{x_i}))$, where $g_i \in G$.

An Extended Finite State Machine is defined by $P = (G_P, g_{0_P}, A_P, T_P, M_P)$. G_P is the finite and non empty set of global states; g_{0_P} is the initial state; A_P is the set of actions of P; $T_P \subseteq G_P \times A_P \times G_P$ is the transition relation of P; M_P is the set of message queues used by P. The P actions are given by $A_P = \mathcal{I}_P \cup \mathcal{O}_P \cup \mathcal{W}_P \cup \{\tau\}$. $\mathcal{I}_P$ is the set of input symbols of P, representing the reception of messages from the queues. $\mathcal{O}_P$ is the set of output symbols, representing the transmission of messages to queues, and $\mathcal{I}_P \cap \mathcal{O}_P = \emptyset$. $\mathcal{W}_P$ is the set of symbols denoting the operations over the machine variables. τ labels the transitions between states with no execution of actions in $\mathcal{I}_P$, $\mathcal{O}_P$, or $\mathcal{W}_P$. The execution of actions in $\mathcal{I}_P$ or $\mathcal{O}_P$ depends on the state of the message queues. A transition $t \in T_P$ results from the execution of an action $a \in A_P$ and, leads the machine from the state g_{i_P} to state g_{i+1_P}. This transition is represented by $t (g_{i_P}, a) = g_{i+1_P}$, or $(g_{i_P}, a, g_{i+1_P}) \in T_P$.

For each action $a \in \mathcal{I}_P \cup \mathcal{O}_P$, a unique $d(a)$ identifies the queue used by the action a; the message transferred through the $d(a)$ queue is represented by $msg(a)$. As N_m represents the number of slots in the message queue m, $N_m > 0$, a transition resulting from the execution of action $a \in \mathcal{I}_P$ is possible or executable when $d(a)$ queue is not empty, i.e. $\#c_{d(a)} \neq 0$, $msg(a) = u_{d(a),1}$. In state g_{i+1_P}, after the execution of a, the state of queue $c_{d(a)_{i+1}}$ is defined by $c_{d(a)_{i+1}} = c_{d(a)_i} \setminus u_{d(a),1}$. A transition resulting from an action $a \in \mathcal{O}_P$ is executable when $d(a)$ queue is not full, i.e. $\#c_{d(a)} < N_{d(a)}$, $msg(a) \in U_{d(a)}$, in this case the new state of queue $d(a)$ is defined by $c_{d(a)_{i+1}} = c_{d(a)_i} \cup u_{d(a),1}$ where $u_{d(a),k} = msg(a)$ and $k = \#c_{d(a)_i} + 1$.

A quiescent state g_δ is a state having only outgoing transitions labelled with input actions. The set of quiescent states of machine P is defined by $\Delta_P = \{ g_\delta \in G_P \mid \forall \ a \in (A_P \setminus \mathcal{I}_P) : t(g_\delta, a) \notin G_P \}$.

A_P^* represents the set of all the ordered combinations of A_P actions. A *trace* is an ordered set of actions executed by P, and it is given by $\sigma \in A_P^*$. The length of the σ trace is represented by $| \sigma |$.

The concatenation of two traces σ_a and σ_b is represented by $\sigma_a.\sigma_b$, while $\sigma_c.a$ denotes the concatenation of trace σ_c with the action a. Moreover, a function $tail(\sigma)$ identifies the last action of σ, such that $tail(\sigma_a.a) = a$. The function $head(\sigma)$ identifies the first action of σ, such that $head(a.\sigma_b) = a$.

Moving from a state by executing a trace leads to extended transitions $\hat{T}_P \subseteq G_P \times A_P^* \times G_P$, represented by $\hat{t}(g,\sigma)=g'$ or $(g, \sigma, g') \in \hat{T}_P$. The set of all the traces defined in P is represented by *traces(P)*.

The composition of machines $X = (G_X, g_{0_X}, A_X, T_X, M_X)$ and $Y = (G_Y, g_{0_Y}, A_Y, T_Y, M_Y)$ is defined by a machine $Z = (G_Z, g_{0_Z}, A_Z, T_Z, M_Z)$ where: $G_Z = G_X \times G_Y$, (since $G_Z = Q_Z \times C_Z \times W_Z$, now $Q_Z = Q_X \times Q_Y$, $C_Z=C_X \times C_Y$, and $W_Z=W_X \times W_Y$); g_{0_Z} is the initial state, defined by $g_{0_Z}=(g_{0_X}, g_{0_Y})$; $A_Z=A_X \cup A_Y = \mathcal{I}_Z \cup \mathcal{O}_Z \cup \mathcal{W}_Z \cup \{\tau\}$ is the set of actions of Z, in which $\mathcal{I}_Z = \mathcal{I}_X \cup \mathcal{I}_Y$, $\mathcal{O}_Z = \mathcal{O}_X \cup \mathcal{O}_Y$ and $\mathcal{I}_Z \cap \mathcal{O}_Z = \emptyset$. $\mathcal{W}_Z=\mathcal{W}_X \cup \mathcal{W}_Y$ is the set of symbols representing the manipulation of Z variables; $T_Z \subseteq G_Z \times A_Z \times G_Z$ defines the transitions between states of Z; $M_Z = M_X \cup M_Y$ is the set of message queues of Z.

Communication through message queue m can be classified as asynchronous or synchronous. The communication is asynchronous when the queue has a non-null number of message slots, $N_m > 0$. In this case a transition $((g_{i_X}, g_{i_Y}), a, (g_{i+1_X}, g_{i+1_Y}))$ is defined in T_Z if either:

$\forall_{a \in I_X \cup O_X} (g_{i_X}, a, g_{i+1_X}) \in T_X$, $\exists g_{i_Y}, g_{i+1_Y} \in G_Y : (d(a) \in M_Y \wedge (g_{i_Y}, \tau, g_{i+1_Y}) \in T_Y) \vee (d(a) \notin M_Y \wedge g_{i_Y} = g_{i+1_Y})$,

$\forall_{a \in I_Y \cup O_Y} (g_{i_Y}, a, g_{i+1_Y}) \in T_Y$, $\exists g_{i_X}, g_{i+1_X} \in G_X : (d(a) \in M_X \wedge (g_{i_Y}, \tau, g_{i+1_Y}) \in T_X) \vee (d(a) \notin M_X \wedge g_{i_Y} = g_{i+1_Y})$

$\forall\ a \in A_X \setminus (\mathcal{I}_X \cup \mathcal{O}_X) \wedge (g_{i_X}, a, g_{i+1_X}) \in T_X$, $\exists\ g_{i_Y}, g_{i+1_Y} \in G_Y : g_{i_Y} = g_{i+1_Y}$,

$\forall\ a \in A_Y \setminus (\mathcal{I}_Y \cup \mathcal{O}_Y) \wedge (g_{i_Y}, a, g_{i+1_Y}) \in T_Y$, $\exists\ g_{i_X}, g_{i+1_X} \in G_X : g_{i_X} \} = g_{i+1_X}$.

The communication is synchronous when the queue has a zero message capacity ($N_m = 0$) and, therefore, a transmission through this queue requires that the receiver is able to simultaneously accept the message. In this case, the transition $((g_{i_X}, g_{i_Y}), a, (g_{i+1_X}, g_{i+1_Y}))$ is defined in T_Z by replacing the first two conditions mentioned above by

$\forall\ a \in \mathcal{O}_x, b \in \mathcal{I}_Y, \exists (g_{i_X}, a, g_{i+1_X}) \in T_x, (g_{i_Y}, b, g_{i+1_Y}) \in T_Y : d(a) = d(b) \wedge msg(a) = msg(b)$,

$\forall\ a \in \mathcal{I}_x, b \in \mathcal{O}_Y, \exists (g_{i_X}, a, g_{i+1_X}) \in T_x, (g_{i_Y}, b, g_{i+1_Y}) \in T_Y : d(a) = d(b) \wedge msg(a) = msg(b)$

The set of Z states resulting from the composition of quiescent states of X is

$$\Delta_Z^X = \{ g \in G_Z \mid \forall\ g_\delta \in \Delta_x, g_Y \in G_Y : g = (g_\delta, g_Y) \}$$

3. PROGRESSIVE CONFORMANCE TESTING

Let us consider a protocol specified by a set of communicating extended finite state machines. After composition, the specification is assumed to be represented by $S = (G_S, g_{0_S}, A_S, T_S, M_S)$.

The architectural and functional characteristics of the tester depend strongly on the specification model. S is said to be an open model in the sense that the behaviour of its environment is not described. In order to generate tests, a "maximum behaviour environment" needs to be created. This environment is described by a machine that can always send and receive all the messages; thus, it can generate every sequence of inputs in S and receive every output sequence generated by S. This environment is represented by the state machine $E = (G_E, g_{0_E}, A_E, T_E, M_E)$. The actions of A_E are either message transmissions or receptions, and are related with the transmissions and receptions of S. The set $\mathcal{O}_E$ is defined by $\mathcal{O}_E = \{ a' \mid a \in \mathcal{I}_S \wedge msg(a)=msg(a') \wedge d(a)=d(a') \wedge a' \notin \mathcal{O}_S \}$ and the set $\mathcal{I}_E$ of reception actions is given by $\mathcal{I}_E = \{ a' \mid a \in \mathcal{O}_S \wedge msg(a)=msg(a') \wedge d(a)=d(a') \wedge a' \notin \mathcal{I}_S \}$. The transitions of E satisfy the condition $\forall\ a \in A_E : (g_{0_E}, a, g_{0_E}) \in T_E$. The set M_E is given by $M_E = \{ m_{d(a)} \mid a \in \mathcal{I}_E \cup \mathcal{O}_E \}$. When S is composed with the specification E, a closed machine is obtained. This machine, named *closed specification* (**C**), represents the composition of state machines S and E, and is described by $\boldsymbol{C} = (G_C, g_{0_C}, A_C, T_C, M_C)$.

The behaviour of our tester is inferred from **C**. The architecture of the tester is imposed by the queues of E. The tester actions are defined by the actions of E. The test transitions are obtained by exploring **C**; the

reception of a message by the tester is possible only if the reception of the message is also possible in **C**. The tester **T** can be described by **T** = *(*G_T*,* g_{0_T} *,* A_T*,* T_T*,* M_T*)* where $G_{\mathbf{T}}$ = *(* $Q_{\mathbf{T}} \times C_{\mathbf{T}} \times W_{\mathbf{T}}$*)* ∪ { **pass**, **fail** } is the set of **T** states; $g_{0_T} = g_{0_C}$ is the initial state of **T**; $A_{\mathbf{T}}$ = *(* $\mathcal{I}_{\mathbf{T}} \cup \mathcal{O}_{\mathbf{T}} \cup \mathcal{W}_{\mathbf{T}} \cup \{ \tau \}$ *)* is the actions set; $T_{\mathbf{T}} \subseteq G_{\mathbf{T}} \times A_{\mathbf{T}} \times G_{\mathbf{T}}$ is the set of **T** transitions; $M_{\mathbf{T}}$ is the set of **T** queues. $\mathcal{O}_{\mathbf{T}}$ represents the actions of $\mathcal{O}_E$. $\mathcal{I}_{\mathbf{T}}$ includes also two additional input actions, $\mathcal{I}_{\mathbf{T}} = \mathcal{I}_{\mathrm{E}} \cup \{\xi, \delta'\}$; ξ represents the reception of unknown messages; δ' represents the detection of an invalid quiescence state on the implementation under test (*iut*). The queues $M_{\mathbf{T}}$ are replicas of the queues M_{E}; however, the vocabulary of $M_{\mathbf{T}}$ queues is larger than the vocabulary of M_{E} queues, in order to accommodate the invalid *iut* messages. The $G_{\mathbf{T}}$ and $T_{\mathbf{T}}$ sets are defined dynamically by executing simultaneously the tester and the *iut*. Let us consider that the *iut* is modelled by the, a priori unknown, model **I** = (G_{I}, g_{0_I} , A_{I}, T_{I}, M_{I}), and assume that $M_{\mathrm{I}} = M_{\mathbf{T}}$, in order to enable the interoperation between **I** and **T**. Initially, we consider that the tester **T** has an empty set of transitions and is in its initial state g_{0_T} . During the test execution, messages are exchanged between **T** and **I** through the $M_{\mathbf{T}}$ queues. Testing is realised by checking the queues $M_{\mathbf{T}}$ for messages sent by **I**. When, according to specification *S*, the *iut* has no messages to send, we say that the *iut* is in a quiescent state. In this case, **T** is required to transmit a message, being each transmission of **T** preceded by a message selection phase on **C**. The transitions of **T** are defined by the routine RunTest( ) illustrated in Figure 1.

Figure 1. On-the-fly random algorithm

```
T_T = { }                              /* set of T transitions */
t_c ∈ T_C ; t_t ∈ T_T
g_t ∈ G_T ; g_c ∈ G_C
QueuesWithMessages = { }          /* set of queues having messages from the iut */

RunTest( )
{
.   g_t = g0_T ; g_c = g0_C
.   m ∈ QueuesWithMessages
.   GetQueuesWithMessages( )                    /* updates the set QueuesWithMessages*/
.   while g_t ≠ fail
.   {
.   .   if #QueuesWithMessages == 0
.   .   {
.   .   .   if IsQuiescent( g_c )                  /* verifies if quiescence is valid, */
.   .   .   {                                  /* i.e. r ∈ I_E is unreachable from state g_c */
.   .   .   .   if ( SortNextTxMsg( g_c ) )      /* selects randomly the next O_E action reachable*/
.   .   .   .   {                              /* from state g_c, and obtains the σ trace to the action */
.   .   .   .   .   G_T = G_T ∪ { g'_t }     /* creates a new test state g'_t in G_T, and defines */
.   .   .   .   .                              /* a new T_T transition to it on the execution */
.   .   .   .   .   T_T = T_T ∪ { ( g_t, tail( σ ), g'_t)      /* of the action tail(σ) */
.   .   .   .   .   g_t = t_T(g_t, tail( σ ) )
.   .   .   .   .   g_c = t̂_C( g_c, σ )      /* updates the states of T and C */
.   .   .   .   .   SendMsg( tail( σ ) )      /* transmits the msg(tail(σ)) action to iut */
.   .   .   .   .   GetQueuesWithMessages( )
.   .   .   .   }
.   .   .   }
.   .   .   else                    /* if invalid quiescence is detected */
.   .   .   {
.   .   .   .   T_T = T_T ∪ { ( g_t, δ', fail ) }     /* a transition with δ' action is added to */
.   .   .   .   g_t = t_T(g_t, δ' ) = fail             /* T leading it to the fail state*/
.   .   .   }
.   .   }
.   .   else                    /* #QueuesWithMessages ≠ 0 */
.   .   {
.   .   .   if RcvdMsgIsValid ( m, g_c )       /* validates the first message received in the queue m, */
.   .   .   {                                  /* and obtains the σ trace towards an action of */
.   .   .                                      /* I_E labbelling the reception of that message; */
.   .   .   .   G_T = G_T ∪ { g'_t }             /* creates a new test state g'_t in G_T, and defines */
.   .   .   .   .                              /* a new T_T transition to it on the execution */
.   .   .   .   T_T = T_T ∪ (g_t, tail( σ ), g'_t)       /* of the action tail(σ) */
.   .   .   .   g_t = t_T(g_t, tail( σ ) )
.   .   .   .   g_c = t̂_C( g_c, σ )               /* updates the states of T and C */
.   .   .   .   RcvMsg( m )                      /* removes first message from queue m */

.   .   .   .   GetQueuesWithMessages( )
.   .   .   }
.   .   .   else               /* if the received msg is not valid */
.   .   .   {
.   .   .   .   T_T = T_T ∪ { ( g_t, ξ, fail ) }     /* a transition with ξ action is added to */
.   .   .   .   g_t = t_T(g_t, ξ ) = fail            /* T leading it to the fail state*/
.   .   .   }
.   .   }
.   }
}
```

3.1 OPTIMISED TEST MODES

The random algorithm presented enables to test *on-the-fly* an *iut*; the tester and *iut* exchange messages until a message is sent by the *iut* which is not allowed by the specification. The *ioco* conformance relation defined in [Tretmans, 1996a] [Tretmans, 1996b] [Tretmans, 1996c] [Brinksma et al., 1997] is adopted. When a fault is found, the test log enables its characterisation. After the fault is eliminated, a new test session should be initiated, until some pre-defined criteria for ending the test is reached. This approach brings problems, such as (1) the length of test traces and (2) the difficulty in reproducing detected failures. Besides, the lack of test control may conduce to situations in which sever non-conformance cases are undetected, just because the test events selected randomly did not exercise some basic interoperability function.

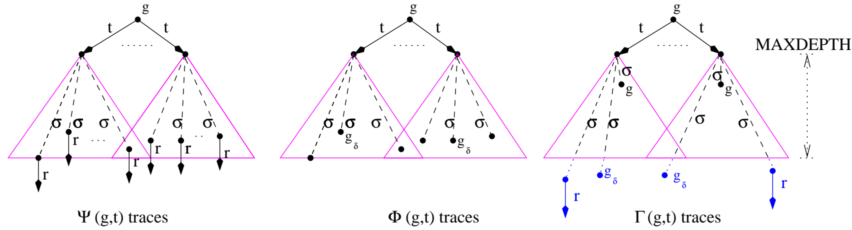
In order to alleviate these problems, three additional testing algorithms are proposed. These algorithms address 3 types of behaviour commonly observed during the test sessions by human operators: **1)** a correct *iut* usually answers immediately to a received message; **2)** a correct *iut* accepts messages leading to quiescent states and does not answer them; and **3)** a correct *iut* usually discards silently messages that are invalid or unexpected. We defined one testing algorithm for each of these commonly observed behaviours; each algorithm is associated to what we called a test mode.

3.1.1 Special traces and actions

The definition of these algorithms demands the characterisation of some special behaviour traces. The classification of traces is usually carried out after an *iut* reaches a quiescent state, and by simulating the possible behaviour paths through the reachability graph of *S*. These simulations are initiated at the quiescent state and explore all the inputs until one of the following conditions is detected: *a)* an output action is detected, which corresponds to an input action of *E*; *b)* a quiescent state is detected; and *c)* the maximum simulation depth is reached. The simulation traces are classified according to the termination condition.

Let us consider that the execution of a test **T** leads the machine **C** to a state $g \in \Delta_{\mathbf{C}}^{S}$, and also *t* output actions in $\mathcal{O}_E$ matching all the implementation inputs specified for a state *g*.

Figure 2. Trace classes for *t* actions on state *g*



Each *t* action can initiate the following three classes of traces also illustrated in Figure 2:

i) Ψ traces lead **C** to the input actions $r \in \mathcal{I}_E$; the set $\Psi(g, t)$ contains the Ψ traces initiated with the action t on state g and is defined by:

$$\Psi(g,t) = \{\sigma_\psi \in traces(\mathbf{C}) \mid \exists\, \sigma \in traces(S),\, g' \in G_C,\, r \in \mathcal{I}_E : (g,t.\sigma.r,g') \in \hat{T}_C \wedge \sigma_\psi = t.\sigma.r \wedge |\sigma| < \text{MAXDEPTH}\}$$

The *t* actions initiating the Ψ traces belong to the set A_ψ, defined by $A_\psi(g) = \{t \in \mathcal{O}_E \mid \exists\, g \in G_{\mathbf{C}} : \Psi(g,t) \neq \emptyset\}$.

ii) Φ traces lead **C** to the quiescent states $g_\delta \in \Delta_{\mathbf{C}}^{S}$; the set $\Phi(g,t)$ contains the Φ traces initiated with the action *t* on state *g*

$$\Phi(g,t) = \{\sigma_\phi \in traces(\mathbf{C}) \mid \exists\, g \in G_{\mathbf{C}},\, g_\delta \in \Delta_{\mathbf{C}}^{S},\, \sigma \in traces(S) : (g,t.\sigma,g_\delta) \in \hat{T}_C \wedge \sigma_\phi = t.\sigma \wedge 1 < |\sigma| < \text{MAXDEPTH}\}$$

The actions *t* initiating the Φ traces belong to the set A_ϕ, defined by $A_\phi(g) = \{t \in \mathcal{O}_E \mid \exists\, g \in G_{\mathbf{C}} : \Phi(g,t) \neq \emptyset\}$.

iii) Γ traces have length 1, or lead **C** to quiescent states, for which no judgement is possible. The $\Gamma(g,t)$ set contains the Γ traces initiated with *t* on state *g* that either ignore *t* or that do not belong to $\Psi(g,t)$ nor $\Phi(g,t)$. The Γ(g,t) set is defined by

$$\Gamma(g,t) = \{\sigma_\gamma \in traces(\mathbf{C}) \mid \exists\, g,g' \in G_{\mathbf{C}},\, g_\delta \in \Delta_{\mathbf{C}}^{S},\, r \in \mathcal{I}_E,\, \sigma \in traces(S) : (\sigma_\gamma = t.\sigma.r \wedge (g, t.\sigma.r,g') \in \hat{T}_C \wedge \wedge |\sigma| > \text{MAXDEPTH}) \vee (\sigma_\gamma = t.\sigma \wedge (g, t.\sigma, g_\delta) \in \hat{T}_C \wedge (|\sigma| = 1 \vee |\sigma| > \text{MAXDEPTH}))\}$$

The t actions starting the $\Gamma(g,t)$ traces belong to the set A_γ, defined by $A_\gamma(g)=\{t \in \mathcal{O}_E \mid \exists\, g \in G_\mathbf{C} : \Gamma(g,t) \neq \emptyset\}$

3.2 TEST MODE_1

Test Mode_1 aims at detecting faults related to the first type of behaviour mentioned in Section 3.1. The cases of non-conformance that can be detected using this test mode are invalid answering messages, missing messages and incorrect message coding. The selection of test actions in this test mode is made by the function *SelectTM1TxMsg* of Figure 3, instead of the *SelectNextTxMsg*, presented above.

Figure 3. Mode_1 action selector

```
σ ∈ traces(C)

Boolean SelectTM1TxMsg( g ∈ G_C )
{
.    σ = { }
.    ClassifyActions( g )                 /* build sets Ψ, Φ and Γ using actions in O_E on the state g */
.    if A_ψ(g) ≠ ∅     a ∈ A_ψ(g)                 /* random selection of action a from A_ψ(g) */
.    . else if A_φ(g) ≠ ∅     a ∈ A_φ(g)          /* random selection of action a from A_φ(g) */
.    . . else if A_γ(g) ≠ ∅     a ∈ A_γ(g)        /* random selection of action a from A_γ(g) */
.    . . . else return FALSE
.    FindAction( g, a, O_E )              /* define the trace σ from state g to the action a in O_E */
.    return TRUE
}
```

The *SelectTM1TxMsg* function starts with the classification of the test actions executable from state g, and their distribution by the sets A_ψ, A_ϕ or A_γ, according to the trace they initiate. Then, one test action a is randomly selected from these sets depending on their emptiness. At the end, the *FindAction* function is used to identify the σ trace that will be used to drive the machine **C** toward the selected action a.

3.3 TEST MODE_2

The Test Mode_2 aims at detecting faults related to the second type of behaviour mentioned in Sec. 3.1. This test mode detects the same errors detected with the Test Mode_1 plus the faults associated to unexpected messages. The *SelectTM2TxMsg* function presented in Figure 4 is used, and it replaces the *SortNextTxMsg* used in the random algorithm.

Figure 4. Mode_2 action selector

```
σ ∈ traces(C)
SendAReplyMsg ∈ W_T
SendAReplyMsg = TRUE     /* controlling flag that switches between actions in A_ψ(g) and A_φ(g) */

SelectTM2TxMsg( g ∈ G_C )
{
.    σ = { }
.    ClassifyActions( g )                 /* build sets Ψ, Φ and Γ using actions in O_E on the state g */
.    if A_φ(g) ≠ ∅ and ( not SendAReplyMsg or A_ψ(g) = ∅ )
.    . . a ∈ A_φ(g)                        /* random selection of action a from A_φ(g) */
.    . else if A_ψ(g) ≠ ∅ and SendAReplyMsg and A_φ(g) = ∅
.    . . . a ∈ A_ψ(g)                      /* random selection of action a from A_ψ(g) */
.    . . else if A_γ(g) ≠ ∅ and A_ψ(g) = ∅ and A_φ(g) = ∅
.    . . . . a ∈ A_γ(g)                    /* random selection of action a from A_γ(g) */
.    . . . else return FALSE
.    SendAReplyMsg = not SendAReplyMsg              /* switch the flag state */
.    FindAction( g, a, O_E )              /* define the trace σ from state g to the action a in O_E */
.    return TRUE
}
```

In order to enable implementation evaluation, tests have to make the implementation behaviour observable. The *SelectTM2TxMsg* does this task by alternating the selection of A_ψ and A_ϕ actions, when they exist. For that purpose, the variable *SendAReplyMsg* $\in W_\mathbf{T}$ is used and it controls the selection criteria.

3.4 TEST MODE_3

Test Mode_3 aims at detecting faults related to the third type of behaviour mentioned in Sec. 3.1. This test mode enables the evaluation of implementation behaviours when they are submitted to invalid or unexpected messages. The *SortNextTxMsg* in the random algorithm is replaced in this test mode by the function

SelectTM3TxMsg presented in Figure 5. The *SelectTM3TxMsg* behaviour is similar to the previous one, since the variable *SendAReplyMsg* $\in W_{\mathbf{T}}$ also controls the selection of A_γ and A_ψ actions, when they exist.

Figure 5. Mode_3 action selector

```
σ ∈ traces(C)
SendAReplyMsg ∈ W_T
SendAReplyMsg = FALSE      /* controlling flag that switches between actions of A_ψ(g) and A_γ(g) */

SelectTM3TxMsg( g ∈ G_C )
{
.    σ = { }
.    ClassifyActions( g )              /* build sets Ψ, Φ and Γ using actions in O_E on the state g */
.    if SendAReplyMsg
.    .  if A_ψ(g) ≠ ∅  or A_φ(g) ≠ ∅
.    .  .  a ∈ A_ψ(g) ∪ A_φ(g)         /* random selection of action a from A_ψ(g) or A_φ(g) */
.    .  else a ∈ A_γ(g)                /* random selection of action a from A_γ(g) */
.    else
.    .  if A_γ(g) ≠ ∅
.    .  .  a ∈ A_γ(g)                  /* random selection of action a from A_γ(g) */
.    .  else A_ψ(g) ≠ ∅  or A_φ(g) ≠ ∅
.    .  .  a ∈ A_ψ(g) ∪ A_φ(g)         /* random selection of action a from A_ψ(g) or A_φ(g) */
.    SendAReplyMsg  =  not  SendAReplyMsg              /* switch the flag state */
.    FindAction( g, a, O_E )           /* define the trace σ from state g to the action a of O_E */
.    return TRUE
}
```

4. PROFYT

The test methodology presented in this paper led to the development of a test tool based on the Spin [Holzmann, 2003] verifier: the PRogressive On-the-FlY Tester (PROFYT). This tool requires a closed specification model described in the Promela language [Holzmann, 2003]. In order to close the model, the environment processes must be specified. Based on this model an executable tester is built that operates using the algorithms described above. The tester also includes driver and interface capabilities, which enable the interoperation with the *iut*.

5. EVALUATION AND RESULTS

In order to evaluate our methodology, we tested some Conference Protocol implementations [Vries et al., 2000]. The conference protocol entities (CPEs) are the entities responsible for providing the conference service.

5.1 CPE Implementation Under Test

The conference protocol entities (CPEs) under test were implemented in the C programming language. The CPE has two interfaces: the CPE Service Access Point (CSAP), enabling the communication between an user and the CPE processes, and the UDP Service Access Point (USAP), enabling the communication between the CPE processes and the UDP service layer. Different CPEs were tested; each one is a mutant constructed by adding errors to a correct implementation. The conference protocol distribution provides multiple implementation mutants containing faults, from which a total of 29 mutants were tested with PROFYT. For each one, 200 tests with different seeds were executed.

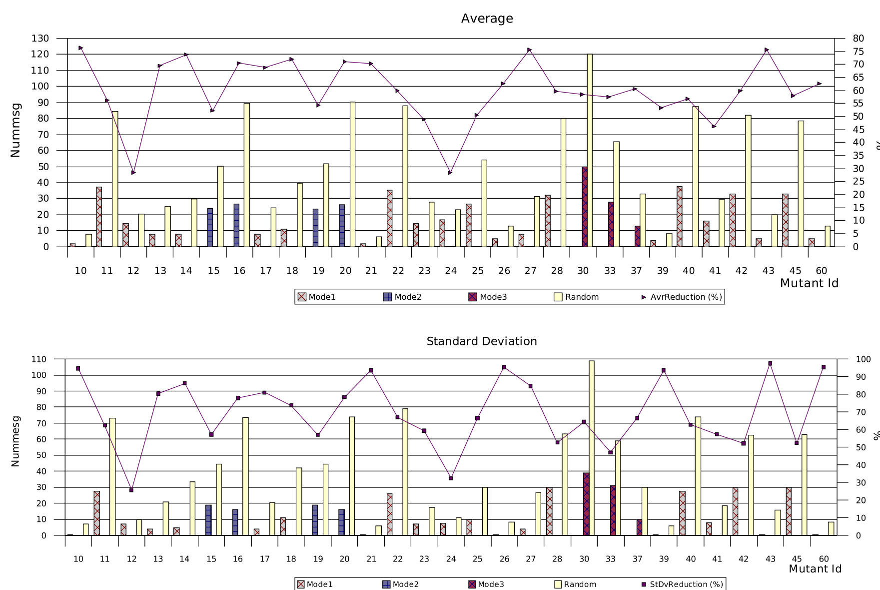
5.2 CPE testing using PROFYT

Testing with the PROFYT tool demands the use of the four test modes: Test Mode_1, Test Mode_2, Test Mode_3, and random. According to the test methodology presented, the test of a faulty implementation (mutant, in this case) starts with the application of the Test Mode_1; this test mode enabled the detection of faults in 22 mutants. The Test Mode_2 is initiated when the operator assumes that most of the faults detectable with the Test Mode_1 were detected and removed; the execution of Test Mode_2 enabled the detection of 4 mutants. The Test Mode_3 enabled the detection of the remaining 3 mutants. In this example, all the mutants were detected using our 3 test modes. Nevertheless, and in order to improve the operator confidence on the *iut*, the random test mode should also be executed at the end.

In order to characterise the value of test modes 1 to 3, the random test mode was also executed and applied to every mutant. The mutants are identified by the numbers defined in the conference protocol distribution. In order to compare de test modes, each mutant was tested 200 times for each test mode, using 200 different seeds. The comparison of the test modes is made based on the number of messages exchanged between the *iut* and the tester before the fault is detected; the number of message exchanged are given as mean and standard deviation values.

The results obtained enable us to conclude that test modes 1, 2, and 3 exhibit shorter traces than the pure random test mode. These results are summarised in the graphics of Figure 5.

Figure 5. Test results average and standard deviation



In order to simplify the graphic, only two columns were represented for each mutant: the right column (with no pattern) refers to the random test mode; the left column refers to the test mode which has exchanged fewer messages with the mutants. Each test mode is represented in a different fill pattern. The first graphic of Figure 5 illustrates the average number of messages exchanged for each mutant. The line presented in this graphic show the reduction on the number of messages exchanged when using test modes 1 to 3; the values marked over this line are obtained by comparing the average value of the best test mode with the random test mode using the formula $AvrReduction = \left(1 - Avr(Test_Mode)/Avr(Random)\right) \times 100$. This reduction is represented as a percentage value, and its scale can be read at the right side of the graphic. The adoption of the test modes 1 to 3, instead of a pure the random test mode, enables the reduction of the number of messages exchanged between the tester and *iut* in about 60%. The second graphic of Figure 5 compares the 4 test modes with respect to the standard deviation of the number of messages exchanged. In this case, the overall reduction is about the 70\%.

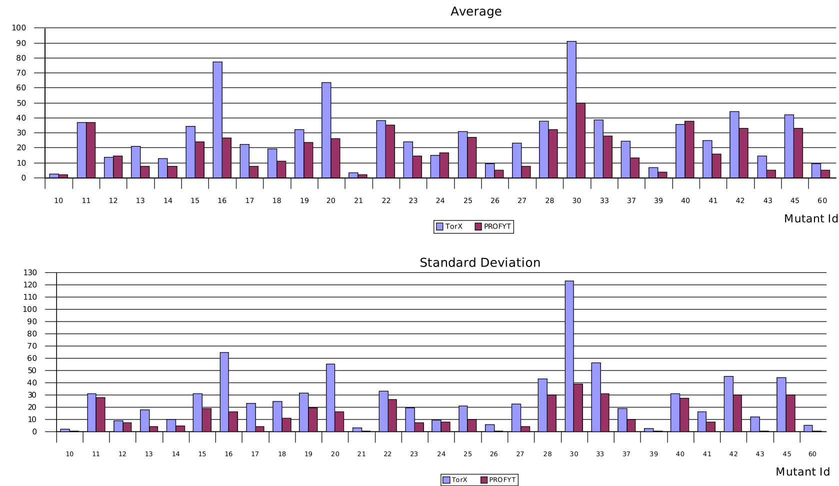
These values enable us to conclude that, by using the test modes 1 to 3, we can keep some of the random nature of testing and, at the same time, we introduce also some control on the test execution, which enables a significant reduction on the number of messages required to find a fault.

5.1 PROFYT vs TorX testing

In order to evaluate the PROFYT performance, we compared it with a similar tool. The TorX tool was chosen for this comparison. The default settings of the conference protocol example (torx-examples-3.3) were assumed. Since both PROFYT and TorX use random test approaches, the comparison of their performance was made based on multiple test runs. For each mutant, 200 tests with different seeds were executed. The mean number of messages exchanged between the tester and the implementation were considered as the comparison metric.

The Figure 6 shows the results obtained. In the first graphic, the average number of exchanged messages is compared for each mutant. We can observe that, for most of these mutant implementations, the PROFYT requires fewer messages than the TorX to detect the faults. However, for the mutants 12 and 24, the values obtained with TorX are better than those obtained with PROFYT. We believe that, in these cases, the algorithm of TorX takes the advantage of selecting the test messages based on their types in a first stage, and then on the messages parameter values; although random selections are made, the probabilities associated to each test message is not uniform.

Figure 6. TorX vs PROFYT



In PROFYT, the selection of test messages is random, i.e., all the test messages, whatever their parameters are, have the same probability of being transmitted. The standard deviations obtained are also favourable to PROFYT. A comparison of these values can be found in the second graphic of Figure 6.

Table 1 summarises the test results by comparing the average number of messages exchanged with the mutants and their standard deviations, in a test mode basis. It also provides the mean ratios of averages and standard deviations, by test modes. The average value represents the relation between the mean values of test sequence lengths obtained with the PROFYT and TorX tools and expresses a reduction of 35% (100%-65%) on test lengths by testing with PROFYT. The standard deviation of the message sequences length is reduced in 55% (100%-45%) by using the PROFYT.

Table 1. TorX vs PROFYT comparison summary

	PROFYT/TorX			
	Avr(Avr/Avr)	Average	Avr(Std/Std)	Std. Dev.
Test Mode_1	69%	**65%**	44%	**45%**
Test Mode_2	54%		44%	
Test Mode_3	60%		47%	

6. CONCLUSION

This paper addresses the problem of testing implementations on-the-fly using random model searches. This test approach is sometimes referred as uncontrolled since there is no human interference on its execution. Although this test approach can exercise the complete reachability graph, it has limitations such as the large number of messages exchanged for detecting the faults and the difficulty in reproducing the faults.

In this paper, we presented a test method that minimises these drawbacks, while maintaining the essential of random model exploration. The method defines 3 modes which enable to focus the testing in 3 types of behaviours commonly observed by the operators. Although random, the selection of the tester messages is constrained by the test type. In this way, the tester messages that are more relevant for each test type are selected first, minimising the number of messages exchanged.

The *iut* conformance testing process is carried out progressively, by executing all the test modes. The progressive approach enables the addressing of fault domains but, simultaneously, it avoids the exploitation of individual test purposes. The method is particularly interesting in the development phases, where it enables an incremental confidence on the implementation. Besides, by keeping the random component of the algorithms, it enables enlarging of test coverage.

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