Hardware Implementation of Communication Protocols modeled by Concurrent EFSMs with Multi-way Synchronization

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ABSTRACT

In this paper, we propose a technique to implement communication protocols as hardware circuits using a model of concurrent EFSMs with multi-way synchronization. Since use of multi-way synchronization enables simple and comprehensible specifications of recent communication protocols which frequently use complicated mechanisms such as mutual exclusion and dynamic job assignment, the proposed model is expected to reduce development cost in designing/developing such protocols. We implement specifications described in the model so that EFSMs work synchronously with the same clock, and that the synchronization mechanism for checking executability of each tuple of synchronizing transitions is implemented as a combinational logic circuit. Through some experiments, we have confirmed that the proposed technique can synthesize hardware circuits with relatively good performances for practical use.

General Terms

high-level synthesis, concurrent EFSMs, multi-way synchronization, LOTOS, communication protocols

1. INTRODUCTION

For high-performance computer networking, hardware implementation of communication protocols has become important in recent years. In general, while developing high performance communication protocols, their internal algorithms and structures are usually modified repeatedly and simulations are applied until reaching expected performance. For reducing development cost, rapid prototyping techniques for automatic synthesis of hardware circuits from high-level specifications are essential in early stages of development.

For the purpose, researchers have begun focusing on the use of formal specification languages (formal description techniques: FDT) for communication protocols as starting points to synthesize hard-

ware circuits for protocols [6, 9, 11, 14]. Using FDTs, message exchanges among concurrent processes such as multi-point/broadcast communication and mutual exclusion for accessing shared resources (e.g., FIFO queue) can be represented in a straightforward way. Since a lot of verification/validation techniques and the corresponding tools for FDTs are now available [2], hardware synthesis from protocol specifications in FDTs is useful to improve reliability of hardware circuits.

Several hardware implementation techniques for SDL and Estelle specifications have been proposed [3, 6, 14]. However, they require complicated operations for mutual exclusion in accessing shared resources among concurrent EFSMs since only one-to-one asynchronous communication between EFSMs is available in SDL and Estelle. On the other hand, LOTOS has a mechanism called multi-way synchronization (which allows multiple concurrent processes to synchronize with each other by exchanging data when some conditions hold among the processes). It provides simplicity and comprehensibility in specifying complicated communication among multiple concurrent processes such as mutual exclusion and dynamic job assignment, which are frequently used in recent communication protocols. In addition, multi-way synchronization enables the constraint oriented specification style [5, 13] where each functional unit of a system is designed as an independent module and then appropriate constraints (described as processes) are specified among those modules so that they work cooperatively. This technique is useful, for example, when we frequently need to modify constraints among modules and/or modify internal structure of each functional unit.

In this paper, we propose a technique and a tool to convert protocol specifications modeled by concurrent EFSMs with multi-way synchronization into the corresponding RT-level VHDL descriptions. The corresponding hardware circuits can be synthesized using usual VHDL synthesis tools on the market. In our model, we suppose general EFSMs where each EFSM executes one of transitions outgoing from its current state. Each transition corresponds to an I/O action at a port (called *gate* in LOTOS literature) where multiple parameters can be transmitted in an I/O action. An execution condition (called *guard*) consisting of some variables and constants can be attached to each transition. In addition, any tuple of transitions with the same gate can be specified to synchronize with each other among a subset of EFSMs in order to exchange some values by multi-way synchronization. We implement specifications de-

scribed in the proposed model so that EFSMs work synchronously with the same clock, and that the synchronization mechanism for checking executability of each tuple of synchronizing transitions is implemented as a combinational logic circuit.

The proposed technique may take some overhead for implementing multi-way synchronization among EFSMs compared to other models without synchronization. Through some experiments in development of example circuits such as network switches and ATM switches, we have confirmed that hardware circuits synthesized with the proposed technique have good performances comparable to actual network products on the market. Since use of multi-way synchronization provides simple and comprehensible design of communication protocols, the proposed technique will be useful to reduce development cost and improve reliability of circuits.

1.1 Related work

As related work, several high-level synthesis techniques which treat concurrent processes with their synchronization have been proposed [1, 4].

In [1], a technique to share resources among concurrent processes without conflicts based on the hierarchical scheduling technique is proposed. This technique first generates a communication dependency graph among processes, and then detects synchronization points for avoiding conflicts of shared resources using the graph. In this model, although designers do not have to specify mutual exclusion among processes, it may be costly to find synchronization points and scheduling of processes without conflicts.

In [4], an automatic conversion technique of system-level VHDL specifications into RT-level specifications is proposed. In this model, multi-point communication such as 1 to N and M to N is considered to improve simplicity/comprehensibility in system-level specifications. However, unlike multi-way synchronization of the proposed model, this model does not clearly handle more complicated multi-point communication such as dynamic selection among several exclusive synchronization tuples (i.e., mutual exclusion).

As LOTOS based synthesis techniques, in [10], a technique to convert timed LOTOS specifications to VHDL specifications has been proposed. However, only two-way synchronization between two processes is considered. [11] has also proposed a technique to synthesize hardware circuits from LOTOS specifications, but focuses only on Basic LOTOS [7] (i.e., LOTOS without data values).

Unlike the above techniques, in our model we specify communication protocols as concurrent EFSMs with multi-way synchronization where more complicated communication such as 1 to N data distribution and a random selection of a synchronization tuple among several exclusive ones can be easily specified.

2. CONCURRENT EFSMS WITH MULTI-WAY SYNCHRONIZATION

2.1 multi-way synchronization

In LOTOS [7], with the parallel operator with synchronization gates, we can specify multiple concurrent processes to execute some events and exchange data values in synchronization with each other (called multi-way synchronization).

$P[a, b, c] \parallel [a, b] (Q[a, b, d] \parallel [a] R[a, b])$
($P[a, b, c]$ means P uses three gates a, b and c , and $\parallel [gate_list]$

Table 1: Synchronization condition

P_i	P_j	condition	result
$g!E_i$	$g!E_j$	$val(E_i) = val(E_j)$	—
$g!E_i$	$g?x : t$	$val(E_i) \in domain(t)$	$x \leftarrow val(E_i)$
$g?x : t$	$g?y : u$	$t = u$	$x, y \leftarrow Ext,$ $Ext \in domain(t)$

($val(E)$ is the value of E , Ext is the value input from gate g)

specifies multi-way synchronization among processes)

In the above example, processes P, Q and R must execute events on gate a in synchronization with each other. On the other hand, events on gate b can be executed between either processes P and Q or processes P and R . Events on gates c and d can be executed in each process independently of the others. Value exchange among processes are also possible by multi-way synchronization. In each pair of synchronizing events, when one event is an output action (e.g., $a!3$) and the other is an input action (e.g., $a?x : int[p(x)]$), the output value is substituted to the variable (x), if both the output value and the input variable have the same data type and guard expression $p(x)$ holds. When synchronizing events are all output actions, synchronization can be executed if all of the output values are the same. More formally, a tuple of synchronizing events can be executed by multi-way synchronization if and only if any pair of those events satisfies the conditions in Table 1.

2.2 Definition of S-EFSMs model

In S-EFSMs model, we suppose that each EFSM can have a finite number of registers (variables), that an execution condition called the *guard* expression can be specified to each transition, and that each transition can input/output several values via a gate as an I/O action. Each transition is denoted by $g \ v \ [f]$ where g is a gate, v is a sequence consisting of input variables ($?x : t$) and output expressions ($!E$) on gate g , and f is a guard expression of the transition.

In S-EFSMs model, any subset of concurrent EFSMs can communicate with each other via gates by multi-way synchronization. For the purpose, we borrow the parallel operators used in LOTOS. Finally, S-EFSMs are described by the following notation.

$$S ::= S \parallel [gate_list] S \mid S \parallel S \mid EFSM$$

($EFSM$ denotes an EFSM. $gate_list$ indicates the gates whose events have to be synchronized between its operands. $\parallel$ is an independent parallel operator, and it is defined as the special case of the parallel operator such that $gate_list = \emptyset$.)

2.3 Extraction of rendezvous table

Like LOTOS, multi-way synchronization in S-EFSMs is specified by just giving abstract relationships among concurrent EFSMs by the parallel operators. For the efficient implementation of multi-way synchronization, we should calculate in advance the information about (i) the combinations of synchronizing EFSMs, (ii) the tuples of synchronizing transitions (*synchronization tuples*) and (iii) their execution conditions. If we count up all synchronization tuples among EFSMs, the number may be $O(k^n)$ in the worst case where n and k are the number of EFSMs and the number of transitions in an EFSM, respectively.

We represent all synchronization tuples by a set of *rendezvous indications* where each indication denotes a tuple of transition sets on a gate for a combination of synchronizing EFSMs. Here, every combination of transitions (i.e., every synchronization tuple) in the sets has the possibility to be executed by multi-way synchronization

Figure 1: Network switch.

(i.e., every synchronization tuple satisfies the condition in Table 1). We denote each rendezvous indication r by $\langle (E_1, \dots, E_m), (A_1, \dots, A_m), \text{confset} \rangle$ where $(E_1, \dots, E_m)$ is a tuple of synchronizing EFSMs, each A_i is the *synchronization transition set* which contains transitions executed in E_i for the synchronization, and confset is the set of rendezvous indications which may conflict with r . We represent elements of A_i as the triples (a, p, I) . Here, a is the transition name consisting of a gate name and I/O parameters, p is a guard expression, and I is the set of substitution to input variables.

Using the above technique, the number of rendezvous indications is bound to $O(p \cdot k \cdot n)$ [15] where p is the maximum number of combinations of the synchronizing EFSMs on a gate (usually p can be considered as a constant).

A set of all rendezvous indications is said to be the *rendezvous table* and denoted by $\mathcal{R}$. If several EFSMs with the parallel operators specified among them are given, the corresponding rendezvous table can be calculated automatically [15]. In this paper, due to space restriction, we omit the details of the calculation.

To implement multi-way synchronization efficiently, we convert each rendezvous indication $\langle (E_1, \dots, E_m), (A_1, \dots, A_m), \text{confset} \rangle$ to the following form using the technique in [15]: (1) all transitions in each A_i must be either all input transitions ($g?$) or all output transitions ($g!$); (2) each A_i must not contain transitions with different kind of output values which are executed at the same state (i.e. if two transitions $a!V_1$ and $a!V_2$ are executable at a state, we assign them to different rendezvous indications); and (3) at most one A_i of $(A_1, \dots, A_m)$ can have a set of output transitions.

By the above conversion, we can easily know in each rendezvous indication what EFSM outputs some values and what other EFSMs expect the output values as their inputs. This contributes to implement data paths to transfer the output values among related EFSMs to evaluate the synchronization condition.

2.4 An example specification in S-EFSMs model

For example, let us design a network switch in S-EFSMs model which has the following requirements: The switch has three ports (i.e., gates) a , b and c which are connected to different networks A, B and C, respectively (see Fig. 1). Each data packet arriving at the switch should be forwarded to the appropriate network based on its destination. Here, we route the packets based on the intervals: i.e., if the packet's destination belongs to the interval $[1, N1]$, the packet should be directed towards network A (via port a); if in the interval $[N1, N2]$, towards network B; if in $[N2, \infty)$, towards network C. If the switch receives the packet with the destination 0 (i.e., broadcast), the packet should be broadcasted to all ports

except for its reception port.

It is desirable to design the behavior of each port independently of the others. For a better response time, input and output behaviors for each port should be able to work in parallel. In addition, in order to allow asynchrony among ports we use a FIFO queue shared among them. Here, we introduce three internal ports (gates) qi , qo and m for the access to the queue. We suppose a new packet can be added to the queue via qi and the packet in the queue can be taken via qo in FIFO manner (see Fig. 1). Although m is used in the same way as qo , it is dedicated to the purpose of broadcast.

According to the above discussion, the input and output behaviors for port a are described as two EFSMs: EFSM1 and EFSM2 in Fig. 2, respectively. For the other ports, the same EFSMs are used (i.e., EFSM3 and EFSM4 for port b and EFSM5 and EFSM6 for port c). In Fig. 2, we suppose that functions $\text{dst}(\text{data})$ and $\text{src}(\text{data})$ are used for obtaining the destination and source of the packet data , and that they are available as primitive hardware components.

Next, we need a coordinator for the FIFO queue. We suppose that the corresponding primitives for the queue and its operations are prepared in advance. The coordinator stores a new packet coming to qi to the queue, or outputs the last entry in the queue to either qo or m based on its destination. The behavior of the coordinator can be described as EFSM7 in Fig. 2 (here, $\text{size}()$, $\text{append}()$, $\text{head}()$ and $\text{tail}()$ are the primitives for the queue operations. MAX is the maximum number of entries in the queue).

Finally, we specify interaction among the above EFSMs. In general, we have to design the mutual exclusion mechanism for the queue since multiple concurrent EFSMs may access it at the same time. However, in S-EFSMs model, we can simply describe such a mechanism with multi-way synchronization as follows.

$$((\text{EFSM1} \parallel \text{EFSM2}) \parallel [m]) (\text{EFSM3} \parallel \text{EFSM4}) \parallel [m] \\ (\text{EFSM5} \parallel \text{EFSM6}) \parallel [qi, qo, m] \text{EFSM7}$$

In the above S-EFSMs, one of EFSM1/EFSM2, EFSM3/EFSM4 or EFSM5/EFSM6 synchronizes with EFSM7 to store/extract a packet to/from the queue via internal ports qi/qo . When the packet's destination is 0, all of EFSM2, EFSM4 and EFSM6 get the packet at the same time by multi-way synchronization on m . From the above S-EFSMs, we can obtain the rendezvous table in Table 2.

2.5 Behavior of S-EFSMs

Here, we explain how EFSMs with its rendezvous table work in cooperation, using an example in Fig. 2 and Table 2. In Fig. 2, the dotted line shows that one of EFSM1, EFSM3 and EFSM5 can synchronize with EFSM7 on gate qi at the same time (one of EFSM2, EFSM4 and EFSM6 on gate qo); the solid line shows that EFSM2, EFSM4, EFSM6 and EFSM7 can synchronize with each other simultaneously on gate m . In the initial state (s_1, s_1, s_1) of EFSM1, EFSM5 and EFSM7, they have the outgoing transitions $a?idt, c?idt$ and $qi?data[\text{size}(\text{queue}) < \text{MAX}]$, respectively. The first two transitions are not included in any rendezvous indications of Table 2, so they are executed independently of the other EFSMs when the input data come to the gates. When $a?idt$ is executed in EFSM1, the current state is changed to (s_2, s_1, s_1) . In the state, EFSM1 and EFSM7 have the outgoing edges $qi!idt$ and $qi?data[\text{size}(\text{queue}) < \text{MAX}]$, respectively. Since queue contains nothing initially, the execution condition $\text{size}(\text{queue}) < \text{MAX}$

Figure 2: S-EFSMs for the network switch.

Table 2: The rendezvous table of the network switch

No.	tuple of EFSMs	tuple of synchronization transition sets	confset
(1)	(1, 7)	$\{(q!idt, true, -), \{(qi?data, size(queue) < MAX, data \leftarrow idt)\}\}$	$\{(2),(3),(4),(5),(6),(7)\}$
(2)	(3, 7)	$\{(q!idt, true, -), \{(qi?data, size(queue) < MAX, data \leftarrow idt)\}\}$	$\{(1),(3),(4),(5),(6),(7)\}$
(3)	(5, 7)	$\{(q!idt, true, -), \{(qi?data, size(queue) < MAX, data \leftarrow idt)\}\}$	$\{(1),(2),(4),(5),(6),(7)\}$
(4)	(2, 7)	$\{(qo?odt, dst(odt) < N1, odt \leftarrow head(queue)), \{qo!head(queue), dst(head(queue)) \neq 0, -\}\}$	$\{(1),(2),(3),(5),(6),(7)\}$
(5)	(4, 7)	$\{(qo?odt, N1 \leq dst(odt) < N2, odt \leftarrow head(queue)), \{qo!head(queue), dst(head(queue)) \neq 0, -\}\}$	$\{(1),(2),(3),(4),(6),(7)\}$
(6)	(6, 7)	$\{(qo?odt, N2 \leq dst(odt), odt \leftarrow head(queue)), \{qo!head(queue), dst(head(queue)) \neq 0, -\}\}$	$\{(1),(2),(3),(4),(5),(7)\}$
(7)	(2, 4, 6, 7)	$\{(m?odt, src(odt) < N1, odt \leftarrow head(queue)), (m?odt, not(src(odt) < N1), odt \leftarrow head(queue)), \{(m?odt, N1 \leq src(odt) \leq N2, odt \leftarrow head(queue)), (m?odt, not(N1 \leq src(odt) \leq N2), odt \leftarrow head(queue)), \{(m?odt, N2 \leq src(odt), odt \leftarrow head(queue)), (m?odt, not(N2 \leq src(odt)), odt \leftarrow head(queue)), \{(m!head(queue), dst(head(queue)) == 0, -\}\}$	$\{(1),(2),(3),(4),(5),(6)\}$

holds. Therefore, the tuple $(q!idt, qi?data[size(queue) < MAX])$ can be executed by the rendezvous indication (1) in Table 2. When the tuple is executed, the value of idt is assigned to the undefined variable $data$, and the current state is changed to (s_1, s_1, s_2) in EFSM1, EFSM5 and EFSM7.

In some state, there may be several synchronization tuples to be executable simultaneously. For example, in Fig. 2, when the current state is (s_1, s_1, s_1) for EFSM2, EFSM6 and EFSM7, a synchronization tuple $(qo?odt [dst(odt) < N1], qo!head(queue) [dst(head(queue)) \neq 0])$ could be executed between EFSM2 and EFSM7 by the rendezvous indication (4) as well as $(qo?odt [N2 \leq dst(odt)], qo!head(queue) [dst(head(queue)) \neq 0])$ between EFSM6 and EFSM7 by the rendezvous indication (6). In that case, one of them must be selected in a certain policy.

3. HARDWARE CIRCUIT CONSTRUCTION

In this section, we give the technique to convert given concurrent EFSMs with a rendezvous table into a synchronous sequential circuit. Hereafter, we suppose the modules corresponding to EFSMs work synchronously with the same clock. In each clock cycle, each EFSM can execute one transition as long as its execution condition holds. We assume that primitive hardware components such as arithmetic and boolean functions are provided as combinational logic circuits in advance and they can output the resulting values within one clock cycle. The circuit for each EFSM can be implemented easily as an FSM and datapath. So, here we concentrate on the implementation of multi-way synchronization mechanism among EFSMs.

Given EFSMs and a rendezvous table, we implement multi-way synchronization among EFSMs as the *multi-way synchronization circuit* consisting of the following three sub-parts: (1) *executability check part* checking whether there exist executable synchronization tuples for each rendezvous indication at each state; (2) *data transfer part* transferring the required data from a certain EFSM to the other EFSMs so that each EFSM can calculate the execution condition (guard) of its transition; (3) *conflict avoidance part* selecting a synchronization tuple among some mutually exclusive ones.

Constructing executability checking and data transfer parts

For the executability checking part, every EFSM E_i in each rendezvous indication must check whether some transitions in its synchronization transition set are executable at the current state. So in each E_i , for every $r \in \mathcal{R}$, we provide a circuit generating an output signal $r_i \text{ ok}$ which becomes *true* (i.e., 1) only when a transition in A_i becomes executable. Consequently, for the rendezvous indication r there exist some executable synchronization tuples if and only if all of $r_1 \text{ ok}, \dots, r_m \text{ ok}$ (denoted by $r_* \text{ ok}$) are *true*.

For the data transfer part, EFSMs with input transitions and an EFSM with output transitions can be determined statically for each rendezvous indication as described briefly in Sect. 2.3. Hence, we provide a path D_r among EFSMs for each r so that an EFSM outputs an appropriate value to the path and the others obtain the value.

Constructing conflict avoidance part

Figure 3: An example of EFSMs.

Figure 4: An example of derived circuit.

The conflict avoidance part generates the signal r_en which becomes *true* when r has permission to execute its synchronization tuple, avoiding conflicts between r and other exclusive rendezvous indications specified in *confset*.

There can be some policies for avoiding conflicts. For example, we can select a rendezvous indication by a random number generator, or use modulo of an incremental counter to select alternatives sequentially. Also, we can simply adopt a policy that gives a priority (or total order) among rendezvous indications and selects a rendezvous indication by the priority.

Here, we show hardware construction if we use a priority-based policy. Any synchronization tuples of r cannot be executed when another conflicting rendezvous indication with priority higher than r is ready to execute a synchronization tuple. Consequently, we construct r_en as follows:

$$r_en = r_1_ok \wedge \dots \wedge r_m_ok \wedge pri_r$$

where $pri_r = \neg r^1_en \wedge \dots \wedge \neg r^h_en$

(Here, $\{r^1, \dots, r^h\}$ are the rendezvous indications with higher priorities than r which conflict with r . pri_r means whether r has the right to execute its synchronization tuple or not).

An example of derived circuit

In this section, we explain how we can derive the circuit in Fig. 4 from the concurrent EFSMs in Fig. 3 and the rendezvous table in Table 3.

Hereafter, we denote the output signal from $EFSM_j$ for the rendezvous indication r_i as r_{ij_ok} . At the initial state (s_1, s_1), EFSM1 first calculates the output value r_{11_ok} for the rendezvous indication r_1 as follows. As EFSM1's current state is s_1 , EFSM1 calculates the execution condition $p(x_1) \vee q(x_2)$ for the transitions $a?x_1[p(x_1)]$ and $a?x_2[q(x_2)]$ which are transitions in its transi-

tion set and that of r_1 respectively. Furthermore, since $p(x_1)$ and $q(x_2)$ need external values to calculate the conditions, EFSM1 uses the value from the data path D_{r_1} (the data path for the rendezvous indication r_1) for the values of x_1 and x_2 . So, it outputs the value of $p(D_{r_1}) \vee q(D_{r_1})$ to r_{11_ok} . On the other hand, as EFSM2's current state is s_1 , EFSM2 can execute the transition $a!1$ in its transition set for the rendezvous indication r_1 . So it outputs *true* to r_{12_ok} . In addition, since $a!1$ is an output transition, it outputs the value 1 to the data path D_{r_1} . For other rendezvous indications, EFSMs do the same operation. If r_{11_ok} and r_{21_ok} are both *true*, r_1 and r_2 are conflict with each other because both r_{12_ok} and r_{22_ok} are also *true*. In this case, the conflict avoidance part selects r_1 and outputs *true* only to r_{1_en} (since we assume that the priority $r_1 > r_2 > r_3$ holds).

Finally, if r_{1_en} is *true*, EFSM1 executes either $a?x_1$ or $a?x_2$ depending on which condition in $p(x_1)$ and $q(x_2)$ holds (when the both conditions are *true*, EFSM1 selects one of them by itself). If $a?x_2$ is executed, the value from D_{r_1} is assigned to x_2 .

4. EXPERIMENTAL RESULTS

We have developed a tool for converting S-EFSMs to concurrent EFSMs with its rendezvous table based on the technique in [15] and another tool for converting the EFSMs with the table into the corresponding RT-level VHDL specification based on the technique in Sect. 3.

Here, we have applied the proposed technique to specifications of a switching fabric of an ATM switch described in S-EFSMs model to evaluate our technique. In the experiment, we have used Design Compiler of SYNOPSYS Corp. as a synthesis tool with a CMOS $0.5 \mu m$ library.

Hereafter, we suppose an ATM switch with 8 incoming and 8 outgoing lines. When each cell is input via one of incoming lines, it is transferred to an appropriate output line by the internal switching fabric.

In a switching fabric, each cell must be forwarded to the appropriate output port by looking up its routing information (e.g., port number). In our S-EFSMs model, for example, we describe several concurrent EFSMs corresponding to behaviors of input and output ports, and specify multi-way synchronization to each pair of any two EFSMs so that they exchange the cell data if a certain condition (i.e., cell's destination port number matches) holds. When we do not specify the internal algorithm of how each cell is switched, our tool generates a circuit with bus architecture where each input port broadcasts cells to all output ports. For each output port, a conflict avoidance mechanism is implemented unless multiple cells received at several input ports pour into the same output port at the same time. This architecture called *multi-bus* needs n^2 cross points for n lines, and thus costly when n becomes large.

In S-EFSMs model, we can also specify the internal algorithm for routing of cells to improve performance. For example, we adopt the Banyan switch [12] as self-routing algorithm. The Banyan switch consists of several switching elements with two input lines and two output lines which are placed in several layers (Fig. 5). When a cell arrives at each switching element, it checks the corresponding bit of header in the cell and forwards the cell to its upper or lower output port. Conflict occurs if two cells are forwarded to the same output port of a switching element simultaneously. In such a case, one of conflicting cells has to be delayed until the next clock cycle,

Table 3: An example of rendezvous table

Info. #	EFSMs	synchronization transition sets	confset
r_1	(EFSM1, EFSM2)	$\{(a?x_1, p(x_1), x_1 \leftarrow 1), (a?x_2, q(x_2), x_2 \leftarrow 1), (a?x_3), \{a!1, true, -\})\}$	$\{r_2\}$
r_2	(EFSM1, EFSM2)	$\{(a?x_1, p(x_1), x_1 \leftarrow g(y)), (a?x_2, q(x_2), x_2 \leftarrow g(y)), (a?x_3), \{a!g(y), true, -\})\}$	$\{r_1\}$
r_3	(EFSM1, EFSM2)	$\{(b!f(x_1), true, -), \{b?y, true, y \leftarrow f(x_1)\})\}$	$\emptyset$

Figure 5: The Banyan switch.

Table 4: The number of logic gates and minimum clock period of various switching fabrics

switching fabric	# of gates	min. clock period (ns)
multi-bus fabric	299,000	8.4
banyan fabric	202,000	7.4
(batcher switch)	401,000	6.6

for example, in a buffer prepared at each input port. By placing a special device such as the Batcher switch [12] to re-order cells in front of the Banyan switch, cell conflict in switching elements can be avoided. The Batcher switch can also be composed of several switching elements with two lines.

In the experiment, we have described three types of switching fabric explained above: multi-bus; the Banyan switch; and the Batcher switch. The specifications could be described in S-EFSMs simply by describing each switching element as an EFSM and by specifying multi-way synchronization among those elements. The size and minimum clock cycles of the synthesized circuits are shown in Table 4 (here, we treated each cell as 53 byte parallel bits).

Usual bandwidth of a general ATM switch is about 150 Mbps. Thus, the maximum number of cell arrivals at each port is about 371,000, and the time for processing each cell is about 2.8 μ s. In 622 Mbps ATM switches, the time will be about 700 ns. From the result in Table 4, we can say that the circuits synthesized with our technique have good performances.

5. CONCLUDED REMARKS

In this paper, we have proposed a hardware implementation technique for communication protocols using a model of concurrent EFSMs with multi-way synchronization.

We have also developed tools to convert specifications in this model to the corresponding RT-level VHDL descriptions. We have confirmed that our technique and tools with usual synthesis tools on the market could synthesize hardware circuits with relatively good

performances.

In the proposed technique, we suppose that each transition as well as each synchronization of transitions is executed in one clock cycle. To improve performance, it is adequate to implement each transition with relatively complicated functions as several transitions. Integrating such features to the proposed technique and treating timing constraints attached to events in E-LOTOS [8] are part of our future work.

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