Single-Link and Time Communicating Finite State Machines

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Abstract

We propose two variants of the classical Communicating Finite State Machines (CFSMs) model – Single-Link Communicating Finite State Machines (SLCFSMs) and Time Communicating Finite State Machines (TCFSMs). For SLCFSMs the notion of well-formedness, which provides a necessary condition for SLCFSMs to be free of some logical errors, is proposed. For TCFSMs, it is argued that they are more suitable for modeling delay-sensitive distributed algorithms/communication protocols. Two practical communication protocols – a token ring and a sliding window protocol – are modeled using TCFSMs.

1 Introduction

A network of communicating finite state machines (CFSM) consists of a set of finite state machines which communicate asynchronously with each other over (potentially) unbounded FIFO channels by sending and receiving typed messages. As a concurrency model, CFSMs has been widely used to specify and validate communications protocols [1, 6, 12, 10, 11].

This paper consists of two parts. In the first part, a new concurrency model – single-link communicating finite state machines (SLCFSMs), which is a variation of the CFSM model, is proposed. In a network of CFSMs, incoming messages from different machines to any individual machine are coming from different and separate FIFO channels. For SLCFSMs, each machine has only one incoming FIFO link and incoming messages from different machines all come from this single link.

This new model is primarily motivated by our perception that the software component of many communication protocols on individual computers (or systems) can be abstracted by a guarded command en-

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for specifying and verifying delay sensitive communication protocols.

We start by introducing SLCSFsMs in Section 2. In Section 3, TCFSMs is proposed. Section 4 discusses some interesting properties of the TCFSMs model. Two example applications of TCFSMs are given in Section 5. Section 6 concludes the paper with some remarks.

2 Single-link communicating finite state machines

We define the SLCSFM model in this section. First we define CFSMs. Let \( I = \{1, 2, \cdots, n\} \), where \( n \geq 2 \) is some constant (denoting the number of processes in a network).

2.1 CFSMs

**Definition 2.1 (Communicating Finite State Machines)** A communicating finite state machine \( P_i \) is a four-tuple \((S_i, \Sigma_i, \delta_i, \rho_i)\), where

- \( S_i \) is the set of local states of machine \( P_i \).
- \( \rho_i \in S_i \) is the start state of machine \( P_i \).
- \( \Sigma_i = \sum_{1 \leq j \leq n} \Sigma_{ij} \cup \sum_{1 \leq j \leq n} \Sigma_{ji} \)

where \( \Sigma_{ij}, 1 \leq j \leq n \) is the alphabet of messages that \( P_i \) can send to \( P_j \), and \( \Sigma_{ji}, 1 \leq j \leq n \) is the alphabet of messages that \( P_i \) can receive from \( P_j \).

- \( \delta_i : S_i \times \Sigma_i \times I \rightarrow 2^{S_i} \) is the transition function. \( \delta_i(p, \epsilon, j) \) is the set of states that process \( P_i \) could move to from state \( p \) after sending a message \( m \) to process \( P_j \). \( \delta_i(p, +m, j) \) is the set of states that process \( P_i \) could move to from state \( p \) after receiving a message \( m \) sent by process \( P_j \).

A network of CFSMs (NCFSMs) is a tuple \((P_1, P_2, \cdots, P_n)\) where each \( P_i \) is a CFSM. Detailed definitions of NCFSMs can be found in [1, 6, 10, 12]. We shall take the freedom of using \( c_0 \) to denote an all-empty channel and \([v_0, c_0]\) the initial global state. A global state \([\bar{v}, \bar{c}]\) in a NCFSMs is reachable from another global state \([\bar{v}', \bar{c}']\) if the former is reachable from the latter in zero or more steps. The reachability set, denoted by \( RS(N) \), is defined as the least set that contains all the global states reachable from \([v_0, c_0]\). We shall use \( \delta \) to denote the the global state transition function [10].

The task of verifying a NCFSMs modeling a communication protocol is to determine if the NCFSMs possesses some undesirable properties that reflects some logic errors in the original protocol. Among the most interested and investigated undesirable properties are Deadlocks, unspecified receptions, and unbounded communications [1, 6, 10, 11].

The topology graph, noted \( TG(N) \) for a NCFSMs \( N \), is a directed graph where the nodes are the CFMSs in the network and an edge from \( P_i \) to \( P_j \) indicates that there is a unidirectional channel from the former to the latter. A global state \([\bar{v}, \bar{c}]\) is said to be stable if \( \bar{c} = c_0 \), i.e. all channels are empty. Apparently, a deadlock state is also a stable state, but the reverse is not true.

2.2 SLCSFsMs

Syntactically, a SLCSFM is the same as a CFSM. However, the semantics of a network of SLCSFsMs is quite different from a NCFSMs. Formally, we define:

**Definition 2.2 (Networks of Single-Link Communicating Finite State Machines)** A network of single-link communicating finite state machines (NSLCSFsMs) is a tuple \((P_1, P_2, \cdots, P_n)\) where each \( P_i \) is a SLCSFM. Let \( c_i \) denote the (potentially) unbounded FIFO buffer that holds messages that process \( P_i \) can receive from other machines (It is also assumed that any machine \( P_i \), cannot send to and/or receive messages from itself). The semantics of a NSLCSFsMs can be captured by the concepts of global states and global state transitions. A global state is a tuple \([\bar{v}, \bar{c}]\), where \( \bar{v} = (p_i)_{i \in I} \) and \( \bar{c} = (c_i)_{i \in I} \) are the \( n \) FIFO links, one per machine. The initial global state is \([p_0, c_0]\), where \( c_i = \epsilon \). A global state \([p_k, c_k]\) is one-step reachable from a global state \([p_e, c_e]\) if \( \exists i, j \in I \) such that:

- either \( p_i \xleftarrow{(-m,j)} p_i' \) in \( P_i \), \( \forall k \in I(k \neq i \rightarrow p_k = p_k') \); and \( c_j' = c_j + m, \forall k \in I(k \neq j \rightarrow c_k' = c_k) \); or
- \( p_i \xrightarrow{(+m,j)} p_i', \forall k \in I(k \neq i \rightarrow p_k = p_k') \); and \( m, c_j' = c_j, \forall k \in I(k \neq i \rightarrow c_k' = c_k) \).

Fig. 1 illustrates the semantic difference between NCFSMs and NSLCSFsMs. In a NCFSMs, incoming messages from a CFSM \( P_i \) to a CFSM \( P_j \) will go through the FIFO channel \( c_{ij} \) and messages from different machines go through different FIFO channels. In a NSLCSFsMs, on the other hand, there is only a single FIFO link leading to any SLCSFM \( P_i \). Messages from different machines will be mixed up in the
order of arrival in that single link. Notice that messages from different machines sent at the same time to any individual machine $P_i$ will be mixed up nondeterministically in the link for $P_i$.

From the definition, it can be seen that for any NCFSMs $N$, if there is at most one incoming channel for any NCFSM in $N$, then $N$ is also a NSLCFSMs. In particular, every cyclic NCFSMs is also a NSLCFSMs (a NCFSMs is cyclic if its topology graph is a simple cycle. Cf. [11]). We summarize this fact in the following proposition.

**Proposition 2.1** If there is at most one incoming channel for any NCFSM in a NCFSMs $N$, then $N$ is also a NSLCFSMs.

Most definitions in NCFSMs, such as deadlocks, unboundedness, reachability, reachability sets, and stable global states, carry over to NSLCFSMs with no need for or with obvious modifications. Therefore we do not repeat them here.

### 2.3 Well-formed NSLCFSMs

In this section we propose the notion of well-formedness of NSLCFSMs, which provides a necessary condition for NSLCFSMs to be free of some potential errors.

In CFSMs send actions from different machines that send messages to a specific machine will be queued in different FIFO channels. In NSLCFSMs, however, these messages will be queued in a single FIFO channel. Consider the case shown in Fig. 2. If the send action $0^*(-m_1,3)$ in machine $P_1$ is delayed until $P_3$ reaches state 3, there is no unspecified reception. However, since send actions are non-blocking, the send action $0^*(-m_1,3)$ can occur at any time. This motivates the notion of well-formedness. We first present several supporting definitions.

Let $s_{i,j}$ denote the event of machine $P_i$ sending a message to $P_j$ and $r_{i,j}$ the event of machine $P_i$ receiving a message sent by machine $P_j$. Let $\Sigma^-$ be the set of send events in machine $P_i$, i.e. $\Sigma^- = \{s_{i,j} | j \in I & P_j \rightarrow P_i \in TG(N)\}$. Let $\Sigma^+$ be the set of receive events in machine $P_i$, i.e. $\Sigma^+ = \{r_{i,j} | j \in I & P_j \rightarrow P_i \in TG(N)\}$. Use the abbreviation $\Sigma^\pm = \Sigma^- \cup \Sigma^+$ to denote the set of all events of machine $P_i$ and $\Sigma^\pm = \bigcup_{i \in I} \Sigma^\pm_i$ to denote the set of all events of the network.

- For any word $e \in (\Sigma^\pm)^*$, the notation $\text{prefix}(e)$ denotes the set of prefixes of $e$, i.e. $\text{prefix}(e) = \{e' | \exists e'' \in (\Sigma^\pm)^* : e'e'' = e\}$.
- A word $e$ in $(\Sigma^\pm)^*$ is called an event sequence.
- An event sequence $e \in (\Sigma^\pm)^*$ is feasible, if $\forall e' \in \text{prefix}(e) \forall i, j \in I | e'|_{r_{i,j}} \subseteq e'|_{s_{i,j}}$.
- An event sequence $e$ is executable, if $\delta(e)$ is defined, i.e., $\delta(e) \neq \emptyset$.
- An event sequence is stable if (a) it is feasible and (b) it contains the same number of send and receive events of all types.
- For any event sequence $e$ and $i \in I$, $e_i$ denotes the projection of $e$ over machine $P_i$, i.e. the sequence of actions from machine $P_i$.

**Definition 2.3** Two event sequences $e_1$ and $e_2$ are equivalent, denoted as $e_1 \simeq e_2$, iff for every $i \in I$, $e_1|_i = e_2|_i$.

**Definition 2.4** (Well-formed NSLCFSMs) A NSLCFSMs $N$ is well-formed if for every executable event sequence $e$, every feasible event sequence $e'$ equivalent to $e$ is also executable.
The importance of the concept of well-formed SLCFSMs is that it provides a necessary condition for SLCFSMs to be free from deadlocks and unspecified reception errors.

**Theorem 2.1** If a NSLCFSMs \( N \) is not well-formed, it has deadlocks or unspecified receptions.

**Proof:** Let \( N \) be a non-well-formed NSLCFSMs. Let \( e \) be an executable event sequence in \( N \) and \( e_i = e|_i \) be the projection of \( e \) over \( P_i \). It is easy to show that:

The set of event sequences resulted from all possible concurrent executions of these \( e_i \)'s is equal to the set of all feasible event sequences equivalent to \( e \).

Because \( N \) is not well-formed, one of these concurrent execution is actually not executable. Hence a deadlock or unspecified reception will occur.

From the definition, it is not difficult to see that every two-machine NSLCFSMs is well-formed.

### 3 Time communicating finite state machines

In this section the new TCFSMs model is defined. As for CFSMs, TCSFsMs assume asynchronous semantics of nonblocking sending and blocking receiving, except that both now have to conform to the additional time constraints.

Let \( N \) denote the set of natural numbers, including \( \infty \), and let \( \mathcal{N}_+ = N \cup \{ \bot \} \).

**Definition 3.1 (Time Communicating Finite State Machines)** A time communicating finite state machine \( P_i \) is a four-tuple \((S_i, \Sigma_i^+, \delta_i, p_{0i})\), where

- \( S_i \) is the set of local states of machine \( P_i \).
- \( p_{0i} \in S_i \) is the start state of machine \( P_i \).
- \( \Sigma_i^+ = \bigoplus_{1 \leq j \leq n} \Sigma_{i,j} \bigcup \bigoplus_{1 \leq j \leq n} \Sigma_{j,i} \)

where \( \Sigma_{i,j}, 1 \leq j \leq n \) is the alphabet of messages that \( P_i \) can send to \( P_j \), and \( \Sigma_{j,i}, 1 \leq j \leq n \) is the alphabet of messages that \( P_i \) can receive from \( P_j \).

- \( \delta_i : S_i \times (\pm \Sigma_i \times I \times N_+ \times N) \to 2^{S_i} \) is the transition function defined as:

- \( \delta_i(p, a, j, t, \sigma), \) where \( a \) is either of the form \(-m \) or \(+m \) for some message type \( m \), and \( t \neq \bot \), is the set of states that process \( P_i \) could move to from state \( p \) after sending a message \( m \) to (or receiving a message \( m \) from) process \( P_j \). However, this action is allowed only when \( P_i \) has been in the local state \( p \) for at least \( t \) amount of time, and can only be performed before (including) the time \( t + \sigma \).

- \( \delta_i(p, +m, j, \bot, \sigma) \) is the set of states that process \( P_i \) could move to from state \( p \) after receiving message \( m \) sent by process \( P_j \). However, this action is allowed only when \( P_i \) has been in state \( p \) for less than or equal to \( \sigma \) amount of time, and must be executed immediately once the desired message \( m \) is available in the channel during the time interval between \( 0 \) and \( \sigma \).

For any local state \( p \) in a TCFSMs, the two time quantities \( t \) and \( \sigma \) associated with each transition originated from \( p \) regulate a time span during which the transition can execute. The collection of all these pairs of values define a time span during which some of these transitions can execute. To better understand the above definition, one can imagine that whenever a TCFSMs enter a local state \( p \), it will start a clock initialized to zero. A transition \( \delta_i(p, a, j, t, \sigma) \) can only execute during the time interval \([t, t + \sigma]\). We say that this transition is valid in the interval \([t, t + \sigma]\). Because send transition is nonblocking, the only constraint to a send transition is that it can only execute within the regulated time interval. For a receive transition, besides the time restriction, the desired message must be in the channel during that time interval before it can execute.

The special receive transition \( \delta_i(p, +m, j, \bot, \sigma) \) must be executed once the message \( m \) appears in the channel during the interval \([0, \sigma]\). This type of transitions can be very useful for modeling signal interuptions that should be handled immediately. A network of time communicating finite state machines (NTCFSMs) is defined similarly as for a network of communicating finite state machines (NCFSMs). The notions of global states and reachability in NTCFSMs are defined similarly as in NCFSMs.

### 4 Some properties of TCFSMs

From any given NTCFSMs \( N \), a NCFSMs \( N' \) can be constructed by ignoring the time constraint enforced on each transition (or equivalent by replacing
each transition \((p, a, j, t, \sigma)\) in every machine \(P_i\) in \(N\) with a new transition \((p, a, j, 0, 0)\). Let us call this \(N'\) the NCFSMs underlying the NTCFSMs \(N\).

### 4.1 Deadlocks and dead at a local state

The definition of deadlocks for CFSMs is not directly applicable to TCFSMs. There are many subtle communication scenarios that have to be carefully defined and clarified.

#### 4.1.1 Late arriving or early arrived messages

Consider portion of a NTCFSMs \(N_i\) depicted in Fig. 3. Assume that machine \(P_1\) and \(Q_1\) arrive in local states \(p\) and \(q\) respectively at the same time. There are three possible interactions between \(P_1\) and \(P_2\):

(a) \(t_1 + \sigma_1 < t_2\). In this case, message \(m\) will arrive too early to be received by \(Q_1\).

(b) \(t_2 + \sigma_2 < t_1\). In this case, message \(m\) will arrive too late to be received by \(Q_1\).

(c) The intervals \([t_1, t_1 + \sigma_1]\) and \([t_2, t_2 + \sigma_2]\) overlap.

Both cases (a) and (b) indicate communication errors. Machine \(Q_1\) is said dead at state \(q\) in both cases. The validity of case (c) depends upon the semantics used, which will be discussed in the next subsection. It is interesting to note that in TCFSMs a single machine can be dead at a local state, while a deadlock in CFSMs always involve more than one machine.

Transitions of the form \(\delta(p, -m, j, t, \infty)\), where \(t \neq \infty\), present another problem. The corresponding receiving events must be able to wait for arbitrarily long for communications to take place. This could be a communication problem in many cases. On the other hand, this type of transitions are useful to model situations such as sending a shutdown message by an operating system.

#### 4.1.2 Forced execution vs. unforced execution

Consider a local state \(p\) with only two receive transitions \((p, +m_1, j_1, t_1, \sigma_1)\) and \((p, +m_2, j_2, t_2, \sigma_2)\) in a TCFSM. There are at least three ways that these two transitions can interact with the rest of the network:

(a) At least one of the two messages \(m_1/m_2\) is available in the time interval \([t_1, t_1 + \sigma_1]\), and the corresponding receive transition is executed.

(b) None of the two messages \(m_1/m_2\) is available in the time interval \([t_1, t_1 + \sigma_1]\), and hence the TCFSM is dead in state \(p\).

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Figure 3: A possible communication problem: (a) Machine \(P_1\); (b) Machine \(Q_1\).

(c) At least one of the two messages \(m_1/m_2\) is available in the time interval \([t_1, t_1 + \sigma_1]\), but none of the two corresponding receive transitions is being elected to execute during its valid interval. The TCFSM is again dead in state \(p\).

We call the semantics stated in case (c) above unforced semantics:

- No transitions from any local state can be forced to be executed.

An alternative is forced semantics:

- When execution reaches any given local state \(p\), if there ever exists at least one valid transition out of \(p\), then one valid transition will be executed.

The forced semantics seems more reasonably and is adopted in this paper. With this semantics, case (c) described above is never possible, and case (b) is the same as case (a) and (b) in last subsection (the machine is dead at a local state).

### 4.2 Relationships between TCFSMs and CFSMs

With the force execution semantics and from the definition, it can be easily seen that any NCFSMs \(N'\) is equivalent to a NTCFSMs \(N\) that is obtained by replacing each transition in every machine \(\delta_i(p, a, j)\) in \(N\) by a transition \(\delta_i(p, a, j, 0, 0)\).

It is easy to see that, due to the time constraints, a reachable global state in its underlying NCFSMs may no longer be reachable in the NTCFSMs itself. In addition, it is also apparent that any reachable global state in \(N\) is also a reachable global state in \(N'\). This is because each transition \((p, a, j, 0, 0)\) in \(N'\) can simulate all possible timings of the corresponding transition \((p, a, j, t, \sigma)\). Hence we have the following theorem.
Theorem 4.1  Let $N$ be a NTCSMs, and $N'$ be the NCFSMs underlying $N$. Then

\[ \text{RS}(N) \subseteq \text{RS}(N') \]

The concept of unspecified receptions in TCFSMs is similar to that in CFSMs with obvious modifications. The following theorem can be directly obtained from the relevant definitions and the above theorem.

Theorem 4.2  Let $N$ be a NTCSMs, and $N'$ be the NCFSMs underlying $N$. The following statements are true with respect to $N$ and $N'$.

(1) If $N$ has unspecified receptions or unbounded communications, then $N'$ also has unspecified receptions or unbounded communications. The reverse, however, is not true.

(2) $N'$ can be free of deadlocks while $N$ has dead states, and vice versa.

5  Modeling with TCFSMs

In this section we show through two practical examples how to specify and verify communication protocols using TCFSMs. The concept of self-stabilization used here is based on reachability sets [3]. The notation $LRS(N)$ denotes the set of all legal global states. Informally, a system $N$ self-stabilizes if it either stays in the set $LRS(N)$ if there is no perturbation, or returns to one of states in $LRS(N)$ within a finite number of steps if it strays from $LRS(N)$.

5.1  Example 1: a token ring

Fig. 4 shows a simplified token ring modeled by CFSMs. It is simplified because neither the case of loss of the token nor the case of multiple tokens are handled. In any practical token ring, these two problems can disrupt the entire operation.

The NTCSMs $N_3$ shown in Fig. 5 models a more realistic version of the token ring shown in Fig. 4. Here it is assumed that tokens can get lost or duplicated during communications. To model loss or duplication of tokens, following the practices in CFSMs, n TCFSMs $C_i$ modeling the unreliable communication media are created. In that figure, $\alpha = (n-1)\sigma$, $t'_1 = \sum_{i=2}^{n} t_i$, $t''_1 = t'_1 + \alpha + c_1$, and $t''_1 = t'_1 - c_2$, where $c_1, c_2 > 0$ are two constants. $t_1$ represents the transmission and propagation delay from station $P_i$ to $P_{i+1}$.

The network $N_3$ implements a token ring together with a simple ring management algorithm described as follows. Station $P_1$ is chosen as the ring coordinator. It is assumed that the minimum and maximum delays between two neighbor stations are constants (the value $t_i$). The algorithm also assumes that $P_i$ knows the total delay from station $P_2$ to station $P_i$ (through stations $P_3, P_4, \ldots, P_n$). In addition, $P_i$ also knows the maximum time interval for which each station can keep the token (the value $T$). After sending out the token to its successor station, station $P_1$ will set two timers. The first timer is intended to detect loss of the token and is set to a value slightly larger than the worst case token circulation time. The second timer is intended to check for existence of multiple tokens and is set to a value slightly smaller than the shortest token circulation time.

We now show that $N_3$ correctly implements the above ring management algorithm and is in fact self-stabilizing.

Theorem 5.1  The token ring depicted in Fig. 5 is self-stabilizing.

Proof: The set of legal states $LRS(N_3)$ contains all the global states satisfying one of the following two conditions:

- Every machine is in its local state 0, there is a message $m$ in a channel $P_i \rightarrow C_i$ or $C_i \rightarrow P_{i+1}$, and every other channel is empty;
- There is a machine $P_i$ or $C_i$ that is in its local state 1, every other machine is in its local state 0, and every channel is empty.

It is interesting to notice that the initial global state, where every machine is in its local state 0 and every channel is empty, is not in $LRS(N_3)$. This is where the power of self-stabilization shows up. After $t''_1$ amount of time, the transition $0^{(-m, t', 0)}$ in machine $P_1$ will execute and a message $m$ is sent to machine $C_1$, leaving $N$ in a legal state. It is easy to show (by induction) that as long as every transition $0^{(-m, 0, 0)}$ or $0^{(+m, \rightarrow, \infty)}$ in every machine $C_i$ does not execute, $N_3$ will remain in the set of legal states.

Now assume that the transition $0^{(+m, \rightarrow, \infty)}$ in some machine $C_i$ executes at some point, which generates one more message $m$. When $P_1$ sent out the message $m$ last time, it returned to its local state 0. There are now two messages $m$ circulating around the ring. These two messages have to be received by $P_1$ one by one. As a result, when the second message is received, it must arrive in less than $t''_1$ time. The transition $0^{(+m, \rightarrow, t''_1)}$ in machine $P_1$ will then take away the second message $m$, bringing $N_3$ back to a legal global state.
The case where the transition $0 \rightarrow (m, 0, 0)$ in some $C_i$ executes can be proved similarly as for the initial global state. This completes the proof. \hfill \blacksquare

The ring net in Fig. 5 is asymmetric. This is in agreement with the conclusions in [4]. In particular, it is not difficult to see that there is no symmetric version of self-stabilizing extension of the ring net (it is impossible to construct the transition from state 0 to state 1 in each machine $P_i$, $1 \leq i \leq n$ because they are interdependent).

5.2 Example 2: a sliding window protocol

Fig. 6 shows a NCFSMs $N_4$ modeling a sliding window protocol with both send and receive windows equal to 1. The communication media are modeled by the two machines $C_1$ and $C_2$. For simplicity of presentation, it is assumed that messages can get lost, but cannot get duplicated during communications. It is easy to see that $N_4$ is actually self-stabilizing. The only problem is the that existence of the two self-loop send transitions $1 \rightarrow 1$ and $3 \rightarrow 3$ (which model timeout) causes the communication unbounded.

In Fig. 7, the same sliding window protocol is modeled by a NTCFSMs, where $t_1$ and $t_2$ are the (transmission and propagation) delays between the two TCFSMs respectively. Only machines $P_3$ and $Q_3$ are redrawn. Assume that the four self-loop transitions in both $C_1$ and $C_2$ can only execute a predefined number of times during a given unit of time (say one second), $N_5$ is both self-stabilizing and bounded in communications. The proof is simple and hence omitted.

6 Concluding remarks

We have proposed two variants of the classical CF-SMs model. To the author's best knowledge, both the SLCFSMs and TCFSMs models are innovative. As variants of the classical CFSM model, we believe that they can be used to formally specify many practical communication protocols.

The relative modeling power of the CFMS model and the SLCFSM model is interesting. As it is known that the class of two-machine NCFSM has the full power of a Turing machine [1], and any two-machine NCFSM is also a NSLCFSM, we conjecture that these two models have the equal modeling power.

Whether the well-formedness property of SLCFSMs is decidable is still an open problem, although we conjecture that it is undecidable.

The proposed TCFSMs model retains all the advantages of the classical CFMS model. Its added ability of expressing time constraints makes it a very promising candidate for modeling delay-sensitive systems, as demonstrated by its clean and concise modeling of the two example protocols to be presented later. In fact, the TCFSMs model can be viewed as an advanced form of the classical CFMS model. Existing specification and verification methods for CFMS can be used at initial stages of modeling using TCFSMs. New methodologies for specifying and verifying TCFSMs are needed. The crucial problem is timing analysis, which should reveal the inter- and intra-dependencies of time constraints of transitions.

As a new alternative design tool, many questions
Figure 6: A NCFSMs $N_4$ modeling a sliding window protocol with both send and receive window equal 1: (a) Topology graph; (b) Machine $P_4$, the sender; (c) Machine $Q_4$, the receiver; (d) Machine $C_1$; (e) Machine $C_2$

about TCFSMs still remain to be investigated. The semantics still need to be polished. Even the current method of associating time constraints to CFSMs is debatable. However, we feel our proposal is one step further toward a right direction.

Finally it should be noted here that the notion of associating time constraints to transitions is from Merlin's paper about Time Petri nets [8].

References


