

**THÈSE POUR OBTENIR LE GRADE DE DOCTEUR
DE L'UNIVERSITÉ DE MONTPELLIER**

En Informatique

École doctorale : Information, Structures, Systèmes

Unité de recherche LIRMM

**Vérification formelle d'une méthodologie pour la conception et
la production de systèmes numériques critiques**

*Formal verification of a methodology for the design and production of
safety-critical digital systems*

Présentée par Vincent IAMPIETRO

Le 16 décembre 2021

**Sous la direction de David Delahaye
et David Andreu**

Devant le jury composé de

Marc Pouzet, Professeur, ENS, Paris

Sandrine Blazy, Professeure, Université de Rennes

Frédéric Boniol, Maître de recherche, ONERA, Toulouse

David Déharbe, Docteur, Ingénieur, Clearsy

David Delahaye, Professeur, Université de Montpellier

David Andreu, MCF, Université de Montpellier

Président du jury

Rapporteuse

Rapporteur

Examineur

Directeur

Co-directeur



**UNIVERSITÉ
DE MONTPELLIER**

Contents

1	Implementation of the HILECOP Petri nets	1
1.1	Informal presentation of Synchronously executed Petri nets	1
1.1.1	Preliminary notions on Petri nets	1
1.1.2	Particularities of SITPNs	7
1.2	Formalization of the SITPN structure and semantics	12
1.2.1	SITPN structure	12
1.2.2	SITPN State	13
1.2.3	Preliminary definitions and fired transitions	14
1.2.4	SITPN Semantics	16
1.2.5	SITPN Execution	19
1.2.6	Well-definition of a SITPN	20
1.2.7	Boundedness of a SITPN	23
1.3	Implementation of the SITPN structure and semantics	23
1.3.1	Implementation of the SITPN and the SITPN state structure	24
1.3.2	Implementation of the SITPN semantics	25
1.4	Conclusion	27
	Bibliography	29

Chapter 1

Implementation of the HILECOP Petri nets

In this chapter, we present the input formalism of our transformation function: Synchronously executed Interpreted Time Petri Nets with priorities (SITPNs). The formalization of the SITPN structure and semantics is mainly the result of two former Ph.D. theses [4, 5]. However, we contributed to the simplification and clarification of both the definition of the SITPN structure and its semantics. Moreover, we added complementary definitions that are required to express the semantic preservation theorem about the HILECOP model-to-text transformation (cf. Chapter ??). Our main contribution in this part lies in the implementation of the SITPN structure and semantics with the Coq proof assistant. This chapter is structured as follows: Section 1.1 is a reminder on the PN formalism and also gives an informal presentation of SITPNs; Section 1.2 provides the formal definitions of the SITPN structure and semantics; Section 1.3 deals with the implementation of SITPNs with the Coq proof assistant.

1.1 Informal presentation of Synchronously executed Petri nets

Here, fundamentals on the Petri net formalism are outlined, and certain classes of Petri nets are described more precisely. Then, the specificities of the Petri nets used to design the behavior of electronic components in the HILECOP methodology are presented. For more information on the topic of Petri nets, the reader can refer to [2], [6], or [3].

1.1.1 Preliminary notions on Petri nets

Petri nets (PNs), invented by C. A. Petri [7], have been designed to model a broad range of *dynamic* systems: resource sharing between concurrent processes [2], behavior of agents in multi-agent systems [1], behavior of digital components [8]. A Petri net is a directed graph composed of two types of node: place nodes (*circles*) and transition nodes (*squares* or *lines*). As shown in Figure 1.1, place nodes usually represent a part of the state of the modelled system, here, the states of two computer processes and a semaphore; transition nodes usually refer to events triggering the system evolution (or state changing). In Figure 1.1, places p_0 , p_3 and sem are marked with tokens, represented by filled black circles. This means that places p_0 , p_3 and sem are currently active. The distribution of tokens over places is called the *marking* of the

net. The marking of a Petri net reflects the overall state of the modelled system at a certain moment in its activity cycle. We will see later that there exists a lot of different classes of PNs. Figure 1.1 presents an example of the most simple form of PN, namely, the *place-transition* PN. In this chapter, when no precision is given on the class of PN considered, a PN refers to a *place-transition* PN.

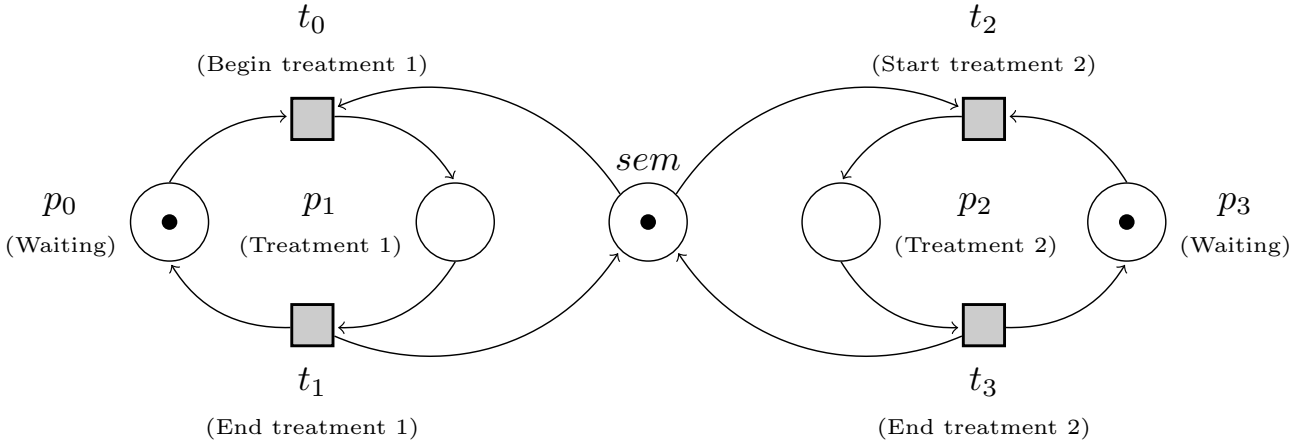


FIGURE 1.1: An example of Petri net. The semaphore place *sem* prevents the parallel execution of *Treatment 1* (place *p1*) and *Treatment 2* (place *p2*).

Edges

In a Petri net, directed edges link together places and transitions. Places cannot be linked to other places, and the same stands for transitions. There are two kinds of edges, *pre* or *incoming* edges, going from a place to a transition, and *post* or *outcoming* edges, going from a transition to a place. Places linked to a transition *t* by incoming (resp. outcoming) edges will be referred to as the *input* places (resp. *output* places) of *t*. The same stands for the transitions linked to a place *p*. For instance, in Figure 1.1, *p0* and *sem* are the input places of *t0*, and *p1* is the output place of *t0*; *t1* and *t3* are the input transitions of place *sem*, and *t0* and *t2* are the output transitions of *sem*. Some weight –a natural number– is associated to the edges of a Petri net. If no label appears on the edge then one is the default weight. Petri nets are said to be *generalized* when the weight of the edges are possibly greater than one.

Transition firing

In a Petri net, the marking evolves based on a token consumption-production system. Transitions consume tokens from their input places, and produce tokens to their output places. This whole process is called *transition firing*. In order to be *firable*, a transition must be *sensitized* (or *enabled*), meaning that the number of tokens in each of its input places must be equal or greater than the weight of the associated incoming edges. For instance, in Figure 1.1, the transition *t0* is sensitized because the weight of the arcs (*p0*, *t0*) and (*sem*, *t0*) is of one (default value), and place *p0* and *sem* are marked with one token. As a counter example, transition *t3* is not

sensitized because its input place p_2 holds no token, where at least one token is expected for t_3 to be sensitized. Depending on the class of PNs that is considered, other parameters affect the *firability* of transitions (see interpreted Petri nets, time Petri nets and Section 1.1.2). When a sensitized transition is fired, tokens are retrieved from its input places (as many tokens as the weight of the input arcs) and produced in its output places (as many tokens as the weight of the output arcs). This process represents the occurrence of an event (denoted by the transition) triggering the evolution of the system from one state to another. Figure 1.2 shows the state of the PN of Figure 1.1 after the firing of the transition t_0 .

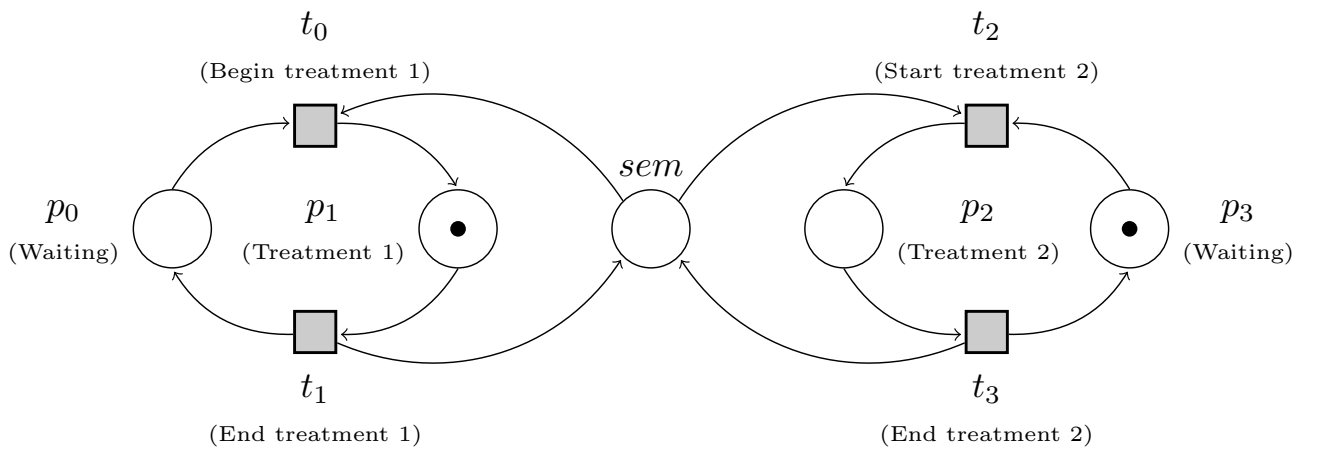


FIGURE 1.2: The PN of Figure 1.1 after the firing of transition t_0 .

In Figure 1.2, the tokens in the input places of t_0 , i.e. places p_0 and sem have been consumed, and one token has been produced in the output place p_1 . The current marking indicates that the task “Treatment 1” is being performed (place p_1 is active).

In Figure 1.1, transition t_0 and t_2 are enabled at the same time. However, the *standard* semantics of PNs is such that only one transition can be fired in that case. Either t_0 consumes the token in place sem or t_2 does, but never both. Thus, the transition firing process in the standard PN semantics is a nondeterministic process. From the marking of Figure 1.1, two markings are reachable: the marking resulting of the firing of transition t_0 and the one resulting of the firing of transition t_2 . Also, in standard PNs, the transition firing process is asynchronous; as soon as a transition is enabled, the transition firing process can be triggered.

Extended Petri nets

The class of *extended* Petri nets introduces the inhibitor and test edges. As shown in Figure 1.3, test arcs are represented with a black-filled circle head and inhibitor arcs with a white-filled circle head. Inhibitor and test edges are incoming edges, always coming from a place toward a transition.

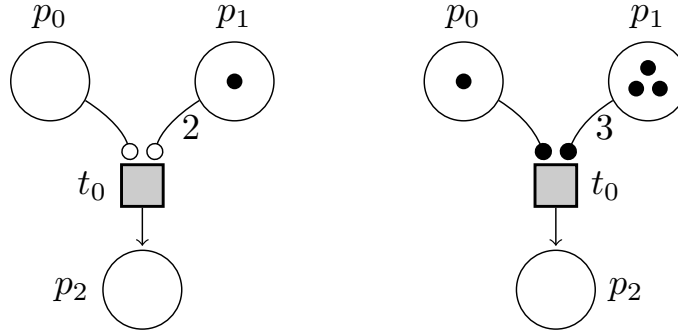


FIGURE 1.3: Two examples of extended Petri nets; on the left side, a PN with inhibitor arcs; on the right side, a PN with test arcs.

The particularity of the inhibitor and test edges is that they are not consuming tokens in input places after the firing of a transition. They are just testing the number of tokens in incoming places to determine if the transition is enabled. Inhibitor arcs ensure that the number of tokens in input places is strictly lower than their weights; test arcs ensure that the number of tokens in incoming places is equal or greater than their weights. Therefore, on the left side of Figure 1.3, transition t_0 is sensitized because there is strictly less than one token in place p_0 and strictly less than two tokens in place p_1 . On the right side of Figure 1.3, transition t_0 is sensitized because there is at least one token in place p_0 and three tokens in place p_1 .

Interpreted Petri nets

As stated in [2], Interpreted Petri Nets (IPN) “can be applied to various interpretations according to the use wished to be made of it”. In its general definition, an IPN is associated with a finite set of variables V , a finite set of operations O , and a finite set of conditions C . Operations of the O set are associated with places and triggered when the places become marked. The execution of operations affects the value of the variables, and the value of conditions depends on Boolean expressions computed upon the variables. Conditions are associated with transitions and become involved in the firing process. Thus, in an IPN, a transition is firable if:

- It is enabled.
- All its associated conditions are true.

Among other applications, IPNs are handy to model the behavior of hardware controllers. Thus, interpretation aspects have been naturally introduced to the HILECOP high-level models, which are models of hardware systems. The HILECOP version of IPNs refines the concepts of the general definition. In this version, the set of variables corresponds to the set of VHDL signals that are handled by the model; a signal can be an input port, an output port or an internal signal of the modeled hardware circuit. The operations are separated in two kinds, namely: actions and functions. Actions (or continuous operations) are associated to the places; all the actions associated to a place p are activated as long as p is marked (i.e. as long as p holds a token). Functions (or discrete operations) are associated to the transitions; when a transition t is fired, all functions associated to t are executed once.

Figure 1.4 illustrates the use of actions, functions and conditions in an interpreted Petri net as applied in the HILECOP high-level models.

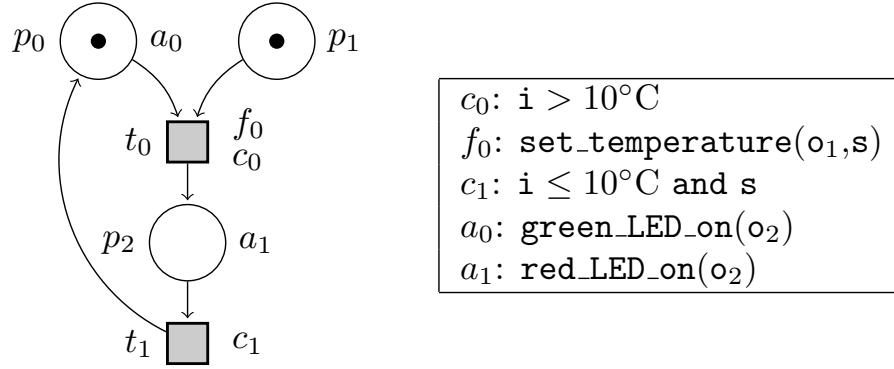


FIGURE 1.4: An example of interpreted Petri net; on the left side, the interpreted Petri net; on the right side, examples of tests associated to conditions and operations associated to actions and functions.

In Figure 1.4, the set of VHDL signals, on which the interpretation elements act upon, is $\{i, s, o_1, o_2\}$. Here, signal i is an input port of the hardware, s is an internal signal, and o_1 and o_2 are two output ports. The action a_0 is activated as place p_0 is marked by one token; thus, the operation `green_LED_on(o2)` is currently executed. Also, function f_0 will be executed (i.e. operation `set_temperature(o1, s)`) at the firing of t_0 , that is if condition c_0 is true and t_0 is sensitized. On the right side of Figure 1.4, we associate Boolean expressions with conditions; these expressions depend on the value of the signals declared by the model. Also, we associate actions and functions with operations that handle the signals of the model which are passed as inputs. Concretely, in the HILECOP high-level models, functions and actions are declared as VHDL procedures. Listing 1.1 gives one possible implementation of the `set_temperature` operation as a VHDL procedure; the `set_temperature` operation is associated with function f_0 in Figure 1.4.

```

1  procedure set_temperature(signal tmp : out integer; signal flag : inout std_logic) is
2  begin
3      if flag = '1' then
4          tmp <= 30;
5          flag <= '0';
6      else
7          tmp <= 10;
8          flag <= '1';
9      endif;
10     return;
11 end set_temperature;
```

LISTING 1.1: An example of VHDL procedure implementing the operation `set_temperature` associated with the function f_0 .

In Listing 1.1, the `set_temperature` procedure declares two parameters: the `tmp` signal which is a write-only signal of type integer, and the `flag` signal which is a both readable and writable signal of the Boolean type (`std_logic` in VHDL). The `set_temperature` procedure checks the value of the `flag` signal and assigns a new value to the `tmp` and `flag` signals accordingly. The \leftarrow operator is the assignment operator for signals in the VHDL syntax (more on that in Chapter ??).

Therefore, to compute the evolution of an IPN, we must be able to interpret the content of operations associated with actions and functions, and also to evaluate the Boolean expressions associated with conditions. This implies the definition of interpretation rules that give an execution semantics to operations and expressions. For now, we consider a simplified version of the interpretation that permits us not to bother with the semantics of operations and Boolean expressions. In fact, we do not consider the set of VHDL signals as a part of the HILECOP PN structure; thus, we are not interested in the representation of the Boolean expressions associated with conditions, nor in the VHDL procedures that implement functions and actions. Regarding conditions, we consider that they directly receive their value from an environment that would have computed in our stead the values of the Boolean expressions. Thus, we no more have to consider the Boolean expressions associated with conditions, and only have to rely on the values given by the environment. Regarding actions and functions, we are only interested in the fact that a given action/function is activated/executed but no more in actually executing the associated operation.

Time Petri nets

In a time Petri net (TPN), time intervals are associated to transitions. The goal is to constrain the firing of a transition to a certain time window. As shown in Figure 1.5, time intervals are of the form $[a, b]$, where $a \in \mathbb{N}^*$ and $b \in \mathbb{N}^* \sqcup \{\infty\}$. Other definitions of time intervals exist for TPNs (e.g. with real numbers), but here we will only consider the latter definition. In Figure 1.5, time counters are represented in red between diamond brackets. The current value of time counters is part of the state of the TPN, along with its current marking, whereas time intervals are part of the static structure of the TPN.

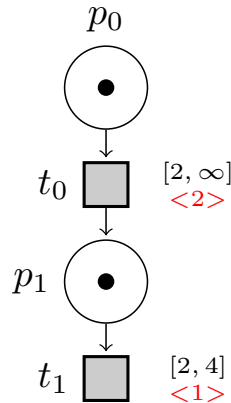


FIGURE 1.5: An example of time Petri net. The value of time counters appears in red.

For each sensitized transition associated with a time interval, time counters are incremented at a certain time step, previously defined by the designer. For instance, in the case of SITPNs, i.e. Petri nets used in the HILECOP methodology, the reference time step for the increment of time counters is the clock cycle.

When a transition associated with a time interval is fired or disabled, a reset order is sent to the transition to set its time counter to zero. In time Petri nets, a transition is firable if:

- It is enabled.
- Its time counter value is within its time interval.

For instance, in Figure 1.5, only transition t_0 is firable. Moreover, there are several possible firing policies for TPNs. Here, we will only consider the *imperative* firing policy: as soon as a time counter reaches the lower bound of a time interval, the associated transition must be fired if all the other firability conditions are verified.

Petri nets with priorities

Two transitions are in structural conflict if they have a common input place connected through a *basic* arc (i.e. neither inhibitor nor test arc). When two transitions in structural conflict are firable at the same time and if the firing of one of the transitions disables the other, then, the conflict becomes *effective*. In a Petri net with priorities, it is possible to specify a firing priority in the case where the conflict between two transitions becomes effective. In that case, the transition with the highest firing priority will always be fired first. Figure 1.6 illustrates the application of a priority relation to solve the effective conflict between two transitions.

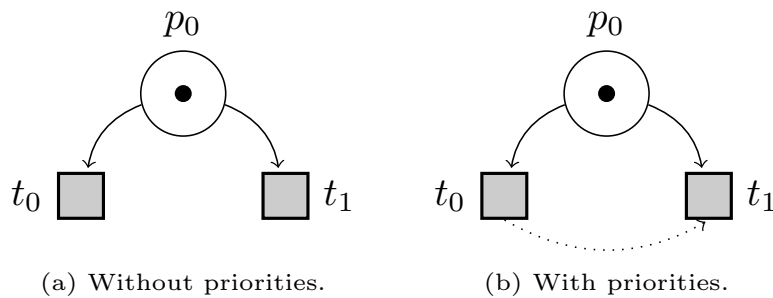


FIGURE 1.6: An example of transitions in structural and effective conflict. In sub-figure (b), the dotted arrow represents the priority relation between t_0 and t_1 . The transition with the highest firing priority is at the source of the arrow; here, transition t_0 .

1.1.2 Particularities of SITPNs

Here, we will informally present the specificities of the Petri nets describing the internal behavior of the HILECOP high-level model components. These Petri nets are called: Synchronously executed, extended, generalized, Interpreted, Time Petri Nets with priorities or SITPNs. SITPNs are a combination of multiple classes of PNs, namely: extended PNs, generalized PNs,

interpreted PNs, time PNs and PNs with priorities. These classes were presented in the above section. We will now talk about another aspect of SITPNs that constitutes the originality of the formalism compared to the standard PN semantics: its synchronous execution.

The class of interpreted Petri nets increases the expressiveness of the HILECOP high-level models. However, to ensure the safe execution of functions after the synthesis of the designed circuit, the whole system must be synchronized with a clock signal [4]. As a consequence, a clock signal also regulates the evolution of SITPNs (i.e. it is a part of their semantics). The evolution of a SITPN is *synchronized* with two clock events: the rising edge and the falling edge of the signal. Figure 1.7 depicts the process of state evolution, following the clock signal.

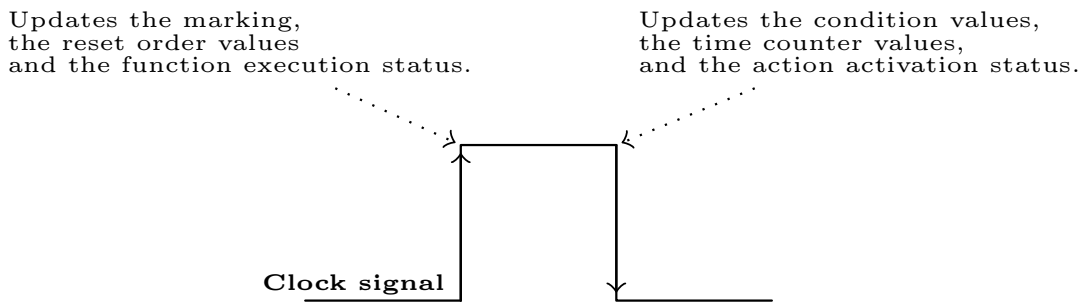


FIGURE 1.7: Evolution of an SITPN synchronized with a clock signal.

Considering the different classes of PNs that define SITPNs, the state of a SITPN is characterized by its marking, the value of time counters, the reset orders assigned to time counters, the execution/activation status of actions/functions (Boolean values), and the value of conditions (also Boolean). As shown in figure 1.7, the state evolution process of a SITPN is divided into two steps. The rising edge of the clock signal triggers the marking update, which is the consequence of transition firing; all transitions that have been fired or disabled by the firing process receive reset orders; all functions associated with fired transitions are executed. Then, on the falling edge of the clock signal, the environment provides a new value to each condition. The falling edge triggers the evolution of the time counter values; values are incremented, reset, or stalling in the case where a time counter has reached the upper bound of its associated time interval (see the following remark on locked time counters). Finally, all actions associated with marked places are activated. Figure 1.8 gives an example of the evolution of the state of a given SITPN through one clock cycle. The aim of this figure and the explanation that follows is to give some hints to the reader about the semantics of SITPNs before giving its formal definition in Section 1.2.4.

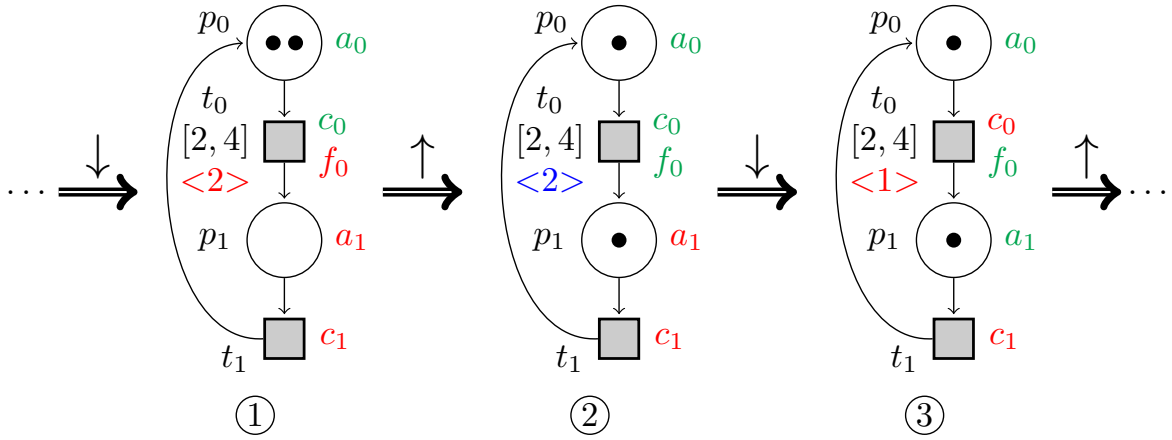


FIGURE 1.8: Evolution of a SITPN over one clock cycle. Conditions appear in **green** when their value is true and in **red** otherwise; actions and functions appear in **green** when they are activated/executed and in **red** otherwise; time counters appear in **red** and between diamond brackets; time counters appear in **blue** when they receive reset orders.

From Step 1 to Step 2, the rising edge of the clock signal triggers the SITPN state evolution. Here, transition t_0 is fired. At Step 1, transition t_0 gathers all the necessary conditions to trigger the firing process, namely:

- t_0 is enabled by the current marking.
- Condition c_0 is true (appears in **green**).
- The value of t_0 's time counter is within the associated time interval ($2 \in [2, 4]$).

As a consequence, one token is consumed in place p_0 and one token is produced in place p_1 . Also, function f_0 is executed at the occurrence of the rising edge of the clock signal, and thus, f_0 appears in **green** at Step 2. Due to the firing of t_0 at the rising edge, a reset order is sent to the time counter of t_0 , and it appears in **blue** at Step 2. From Step 2 to Step 3, the falling edge updates the action activation status: a_0 stays activated as place p_0 is still marked; a_1 becomes newly activated as p_1 is marked. The value of time counters is updated: t_0 's time counter is set to zero as the transition previously received a reset order. However, as t_0 is still enabled by the new marking, its time counter is incremented. Thus, the resulting time counter value at Step 3 is of one (i.e. result of reset plus increment). Also, the environment provides a new value to each condition. As a consequence, condition c_0 takes the value false and condition c_1 keeps the same value.

A remark on priorities

The semantics of synchronous execution is that all transitions are fired at the same time. In Figure 1.9, transitions t_0 and t_1 are both sensitized by place p_0 , and consequently are both fired at the same time. The system acts as if two tokens were available in place p_0 , one for the firing of t_0 and another for the firing of t_1 .

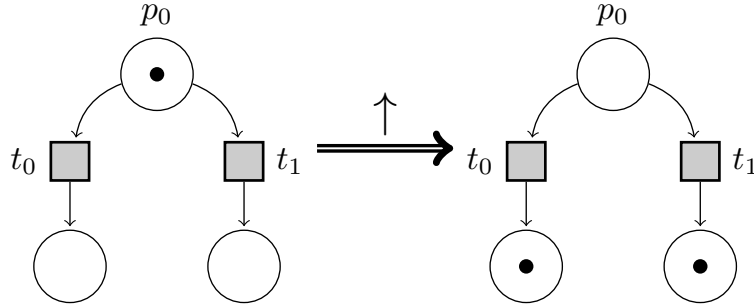


FIGURE 1.9: Double consumption of one token in a SITPN. On the left side, the current marking before the firing of t_0 and t_1 ; on the right side, the marking resulting of the firing of t_0 and t_1 . The arrow indicates the occurrence of a rising edge that triggers the firing process.

In the context of a SITPN, a branching like the one of Figure 1.8, normally interpreted as a disjunctive branching, takes the semantics of a conjunctive branching when no priority are prescribed between the conflicting transitions. To avoid the phenomenon of “double consumption” of tokens, we enforce the resolution of any structural conflict by means of mutual exclusion or through the application of priorities. This policy about the resolution of structural conflicts is part of the definition of a well-defined SITPN presented in Section 1.2.6. The property of well-definition is mandatory to produce safe models of digital systems.

When a structural conflict between transitions is solved with priorities, the firing process follows a slightly different mechanism. As illustrated in Figure 1.10, to determine which transitions of t_0 , t_1 and t_2 must be fired, a *residual marking* is computed by following the priority order. For each transition of the group t_0 , t_1 and t_2 , the residual marking represents the remaining tokens in p_0 after the firing of transitions with a higher firing priority. Thus, in the semantics of SITPNs, we add an extra condition to the firing of a transition: to be fired, a transition must be:

- enabled by the current marking
- must have all its conditions valuated to true
- must have its time counter within its time interval
- *and* must be enabled by the residual marking.

The computation of the residual marking only involves the consumption phase of the firing process; tokens are withdrawn from places, but none are generated.

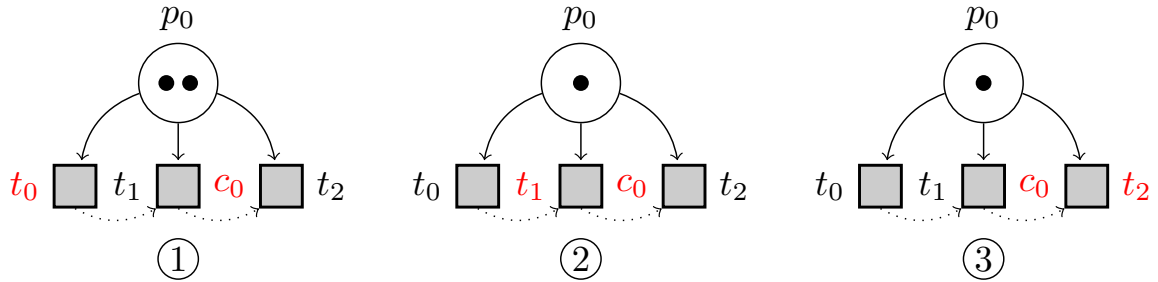


FIGURE 1.10: Computation of the residual marking for a group of conflicting transitions. At ① (resp. ② and ③), place p_0 holds the residual marking for transition t_0 (resp. t_1 and t_2). Condition c_0 is in red to indicate that its current value is false.

In Figure 1.10, the residual marking for t_0 corresponds to the marking obtained after the firing of all transitions with a higher priority. As t_0 is the transition with the highest firing priority, the residual marking for t_0 is equal to the current marking. Transition t_0 gathers all the conditions to be firable and is enabled by the residual marking; thus, t_0 will be fired on the next rising edge. The residual marking for t_1 is the marking obtained after the firing of t_0 , i.e. the only transition with a higher priority. As illustrated at ②, t_1 is enabled by the residual marking. However, t_1 does not gather all the conditions to be firable as the value of condition c_0 is false. Thus, t_1 will not be fired on the new rising edge. The residual marking for t_2 is obtained after the firing of t_0 only. Even though transition t_1 has a higher firing priority than t_2 , t_1 is not a member of the set of fired transitions. Thus, t_1 is not taken into account in the computation of the residual marking for t_2 . The residual marking at ③ enables transition t_2 , and as t_2 gathers all the conditions to be firable, then t_2 will be fired on the next rising edge.

Locked time counters

SITPNs inherit the properties of time PN and interpreted PN. The phenomenon of *locked* time counters is a consequence of this inheritance. As illustrated in Figure 1.11, the value of a time counter can overreach the upper bound of its associated time interval. This situation can only arise if a condition hinders the firing of a given transition while the considered transition is still enabled by the marking. As a consequence, the time counter will be incremented at every clock cycle until the upper bound of the time interval is overreached. Then, at this point, the time counter is said to be *locked* and its value will no more evolve.

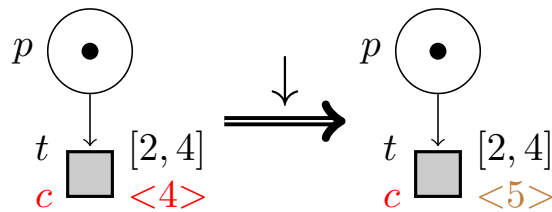


FIGURE 1.11: An example of locked time counter. Condition c is equal to false and thus appears in red.

In Figure 1.11, condition c is valuated to false before the falling edge of the clock signal. Thus, transition t can not be fired but is still enabled by the marking. On the next falling edge, the time counter of transition t is incremented and overreaches the upper bound of interval $[2, 4]$ and thus becomes locked. If the designer of the model has not anticipated the case of a locked time counter, and has not provided an alternative to disable place p in that case, then the transition t will never be firable again.

1.2 Formalization of the SITPN structure and semantics

We hope that the reader has now a fair understanding of the concepts underlying the SITPNs and of the dynamics governing the SITPN state evolution process. In this section, we give the formal definition of the SITPN structure and of its execution semantics. We also introduce the concept of a *well-defined* SITPN at the end of the section.

1.2.1 SITPN structure

The structure of SITPNs is formally defined as follows:

Definition 1 (SITPN). *A synchronously executed, extended, generalized, interpreted, and time Petri net with priorities is a tuple $\langle P, T, pre, post, M_0, \succ, \mathcal{A}, \mathcal{C}, \mathcal{F}, \mathbb{A}, \mathbb{C}, \mathbb{F}, I_s \rangle$, where we have:*

1. $P = \{p_0, \dots, p_n\}$, a finite set of places.
2. $T = \{t_0, \dots, t_m\}$, a finite set of transitions.
3. $pre \in P \rightarrow T \rightarrow (\mathbb{N}^* \times \{\text{basic}, \text{inhib}, \text{test}\})$, the function associating a weight to place-transition edges.
4. $post \in T \rightarrow P \rightarrow \mathbb{N}^*$, the function associating a weight and a type to transition-place edges.
5. $M_0 \in P \rightarrow \mathbb{N}$, the initial marking of the SITPN.
6. $\succ \subseteq (T \times T)$, the priority relation, which is a partial order over the set of transitions.
7. $\mathcal{A} = \{a_0, \dots, a_i\}$, a finite set of continuous actions.
8. $\mathcal{F} = \{f_0, \dots, f_k\}$, a finite set of functions (instantaneous actions).
9. $\mathcal{C} = \{c_0, \dots, c_j\}$, a finite set of conditions.
10. $\mathbb{A} \in P \rightarrow \mathcal{A} \rightarrow \mathbb{B}$, the function associating actions to places. $\forall p \in P, \forall a \in \mathcal{A}, \mathbb{A}(p, a) = \text{true}$, if a is associated to p , $\mathbb{A}(p, a) = \text{false}$ otherwise.
11. $\mathbb{F} \in T \rightarrow \mathcal{F} \rightarrow \mathbb{B}$, the function associating functions to transitions. $\forall t \in T, \forall f \in \mathcal{F}, \mathbb{F}(t, f) = \text{true}$, if f is associated to t , $\mathbb{F}(t, f) = \text{false}$ otherwise.

12. $\mathbb{C} \in T \rightarrow \mathcal{C} \rightarrow \{-1, 0, 1\}$, the function associating conditions to transitions. $\forall t \in T, \forall c \in \mathcal{C}, \mathbb{C}(t, c) = 1$, if c is associated to t , $\mathbb{C}(t, c) = -1$, if \bar{c} is associated to t , $\mathbb{C}(t, c) = 0$ otherwise.
13. $I_s \in T \rightarrow \mathbb{I}^+$, the partial function associating static time intervals to transitions, where $\mathbb{I}^+ \subseteq (\mathbb{N}^* \times (\mathbb{N}^* \sqcup \{\infty\}))$.

In Definition 1, the structure holds the *static* elements of a SITPN model, i.e. all the elements which value does not evolve with the execution of the model. Therefore, the value of time counters associated with transitions does not appear in the SITPN structure. As the value of time counters is *dynamic*, i.e. it evolves with the execution of an SITPN model, it is a part of the SITPN state.

Notation 1 (Time transitions). For a given $sitpn \in SITPN$, T_i denotes the definition domain of I_s , i.e. the set of transitions associated with a time interval, referred to as time transitions.

In the current formal definition of the SITPN structure, and as discussed in Section 1.1.1, we do not consider the set of VHDL signals manipulated by a SITPN model. As a consequence, the structure holds neither the association between conditions and boolean expressions, and nor the association between actions/functions and operations (i.e. VHDL procedures that act upon signal values) that would be necessary in the presence of the set of VHDL signals. In this simplified version of the SITPN structure, conditions, actions and functions are only considered as finite sets of indexed elements associated with the places and transitions of an SITPN.

1.2.2 SITPN State

The SITPN semantics describes the evolution of the state of an SITPN through a given number of clock cycles; thus, we must first define the SITPN state structure:

Definition 2 (SITPN State). For a given $sitpn \in SITPN$, let $S(sitpn)$ be the set of possible states of $sitpn$. An SITPN state $s \in S(sitpn)$ is a tuple $\langle M, I, reset_t, ex, cond \rangle$, where:

1. $M \in P \rightarrow \mathbb{N}$ is the current marking of $sitpn$.
2. $I \in T_i \rightarrow \mathbb{N}$ is the function mapping time transitions to their current time counter value.
3. $reset_t \in T_i \rightarrow \mathbb{B}$ is the function mapping time transitions to time counter reset orders (defined as Booleans).
4. $ex \in \mathcal{A} \sqcup \mathcal{F} \rightarrow \mathbb{B}$ is the function representing the current activation (resp. execution) state of actions (resp. functions).
5. $cond \in \mathcal{C} \rightarrow \mathbb{B}$ is the function representing the current value of conditions (defined as Booleans).

Notation 2 (SITPN state and fields). In the rest of memoir, we refer to a specific field of a SITPN state s with the infix pointed notation, e.g. $s.M$ refers to the marking of state s , and $s.M(p)$ denotes the marking of a given place p at state s ; $s.I$ refers the function yielding the value of time counters at state s , and $s.I(t)$ denotes the value of the time counter associated with the transtion t at state s .

At the beginning of its execution, a SITPN model is associated with an initial state defined as follows:

Definition 3 (Initial state). For a given $sitpn \in SITPN$, $s_0 \in S(sitpn)$ is the initial state of $sitpn$, such that $s_0 = \langle M_0, O_N, O_B, O_B, O_B \rangle$, where M_0 is the initial marking of the SITPN, O_N is a function that always returns 0, O_B is a function that always returns *false*.

1.2.3 Preliminary definitions and fired transitions

Before formalizing the full SITPN semantics, we must introduce some definitions and notations, especially the definition of a *firable* and a *fired* transition. We use the two following notations to simplify the formalization of the SITPN semantics.

Notation 3 (Relations between markings). For all relation \mathcal{R} existing between two marking functions M and M' , the expression $\mathcal{R}(M, M')$ is a notation for $\forall p \in P, \mathcal{R}(M(p), M'(p))$. For instance, $M' = M - \sum_{t_i \in T'} pre(t_i)$ is a notation for $\forall p \in P, M'(p) = M(p) - \sum_{t_i \in T'} pre(p, t_i)$ where $T' \subseteq T$.

Notation 4 (Sum expressions and arc types). Many times in this document, we need to express the number of tokens coming to or from places, after the firing of a certain subset of transitions. To do so, we use two kinds of sum expression:

1. The first kind of expression computes a number of output tokens. For instance, for a given place p , $\sum_{t \in T'} pre(p, t)$ where $T' \subseteq T$.

The expression $\sum_{t \in T'} pre(p, t)$ is a notation for $\sum_{t \in T'} \begin{cases} \omega & \text{if } pre(p, t) = (\omega, \text{basic}) \\ 0 & \text{otherwise} \end{cases}$

When computing a sum of output tokens (i.e. resulting of a firing process), we want to add to the sum the weight of the arc between place p and a transition $t \in T'$ only if there exists an arc of type *basic* from p to t (remember that the test and inhibitor never lead to the withdrawal of tokens during the firing process). Otherwise, we add 0 to the sum as it is a neutral element of the addition operator over natural numbers.

2. The second kind of expression computes a number of input tokens. For instance, for a given place p , $\sum_{t \in T'} post(p, t)$ where $T' \subseteq T$.

The expression $\sum_{t \in T'} post(p, t)$ is a notation for $\sum_{t \in T'} \begin{cases} \omega & \text{if } post(t, p) = \omega \\ 0 & \text{otherwise} \end{cases}$

Here, we add the weight of the arc from t to p only if there exists such an arc; we add 0 to the sum otherwise.

Therefore, in the rest of the document, we will use the conciser notations $\sum_{t \in T'} pre(p, t)$ to denote an output token sum, and $\sum_{t \in T'} post(t, p)$ to denote an input token sum.

We give the formal definition of the sensitization of a transition by a given marking as follows:

Definition 4 (Sensitization). A transition $t \in T$ is said to be sensitized, or enabled, by a marking M , which is noted $t \in Sens(M)$, if $\forall p \in P, \forall \omega \in \mathbb{N}^*, (pre(p, t) = (\omega, \text{basic}) \vee pre(p, t) = (\omega, \text{test})) \Rightarrow M(p) \geq \omega$, and $pre(p, t) = (\omega, \text{inhib}) \Rightarrow M(p) < \omega$.

We give the formal definition of a *firable* transition at a given SITPN state as follows:

Definition 5 (Firability). A transition $t \in T$ is said to be firable at a state $s = \langle M, I, reset_t, ex, cond \rangle$, which is noted $t \in Firable(s)$, if $t \in Sens(M)$, and $t \notin T_i$ or $I(t) \in I_s(t)$, and $\forall c \in C, C(t, c) = 1 \Rightarrow cond(c) = 1$ and $C(t, c) = -1 \Rightarrow cond(c) = 0$.

As explained in Section 1.1.2, the firability conditions are not sufficient for a transition to be fired. A transition must also be enabled by the residual marking to go through the firing process. Definition 6 gives the formal definition of a fired transition at a given SITPN state:

Definition 6 (Fired). A transition $t \in T$ is said to be fired at the SITPN state $s = \langle M, I, reset_t, ex, cond \rangle$, which is noted $t \in Fired(s)$, if $t \in Firable(s)$ and $t \in Sens(M - \sum_{t_i \in Pr(t)} pre(t_i))$, where $Pr(t) = \{t_i \mid t_i \succ t \wedge t_i \in Fired(s)\}$.

One can notice that the definition of the set of fired transitions is recursive. To compute the residual marking necessary to the definition of a fired transition, the Pr set must be defined. For a given transition t , the Pr set represents all the transitions with a higher firing priority than t that are also fired transitions; hence the recursive definition. As the priority relation is a partial order over the finite set of transitions, all transitions have a finite set of transitions with a higher firing priority. Thus, the computation of the set of fired transitions always terminates.

In Definition 6, the marking $M - \sum_{t_i \in Pr(t)} pre(t_i)$ formally qualifies the residual marking for a given transition t and at a given SITPN state s .

1.2.4 SITPN Semantics

We formalize the semantics of a given SITPN as a transition system. The SITPN state transition relation defined in the SITPN semantics has two cases of definition, one for each clock event. The SITPN state transition relation describes the evolution of the state of a SITPN.

Definition 7 (SITPN Semantics). *The semantics of a given $sitpn \in SITPN$ is the transition system $\langle L, E_c, \rightarrow \rangle$ where:*

- $L \subseteq \{\uparrow, \downarrow\} \times \mathbb{N}$ is the set of transition labels. A label is a couple (clk, τ) composed of a clock event $clk \in \{\uparrow, \downarrow\}$, and a time value $\tau \in \mathbb{N}$ expressing the current count of clock cycles.
- $E_c \in \mathbb{N} \rightarrow \mathcal{C} \rightarrow \mathbb{B}$ is the environment function, which gives (Boolean) values to conditions (\mathcal{C}) depending on the count of clock cycles (\mathbb{N}).
- $\rightarrow \subseteq S(sitpn) \times L \times S(sitpn)$ is the SITPN state transition relation, which is noted $E_c, \tau \vdash s \xrightarrow{clk} s'$ where $s, s' \in S(sitpn)$ and $(clk, \tau) \in L$, and which is defined as follows:

* $\forall \tau \in \mathbb{N}, \forall s, s' \in S(sitpn)$, we have $E_c, \tau \vdash s \xrightarrow{\downarrow} s'$, where $s = \langle M, I, reset_t, ex, cond \rangle$ and $s' = \langle M, I', reset_t, ex', cond' \rangle$, if:

(1) $cond'$ is the function giving the (Boolean) values of conditions that are extracted from the environment E_c at the clock count τ , i.e.:

$$\forall c \in \mathcal{C}, cond'(c) = E_c(\tau, c).$$

(2) All the actions associated with at least one marked place in the marking M are activated, i.e.:

$$\forall a \in \mathcal{A}, ex'(a) = \sum_{p \in \text{marked}(M)} \mathbb{A}(p, a) \text{ where } \text{marked}(M) = \{p' \in P \mid M(p') > 0\}.$$

(3) All the time transitions that are sensitized by the marking M and received the order to reset their time intervals, have their time counter reset and incremented, i.e.:

$$\forall t \in T_i, t \in \text{Sens}(M) \wedge reset_t(t) = \text{true} \Rightarrow I'(t) = 1.$$

(4) All the time transitions that are sensitized by the marking M , and did not receive a reset order, increment their time counters if time counters are still active, i.e.:

$$\begin{aligned} \forall t \in T_i, t \in \text{Sens}(M) \wedge reset_t(t) = \text{false} \wedge [I(t) \leq u(I_s(t)) \vee u(I_s(t)) = \infty] \\ \Rightarrow I'(t) = I(t) + 1. \end{aligned}$$

(5) All the time transitions verifying the same conditions as above, but with locked counters, keep having locked counters (values are stalling), i.e.:

$$\forall t \in T_i, t \in \text{Sens}(M) \wedge \text{reset}_t(t) = \text{false} \wedge I(t) > u(I_s(t)) \wedge u(I_s(t)) \neq \infty \\ \Rightarrow I'(t) = I(t).$$

(6) All the time transitions disabled by the marking M have their time counters set to zero, i.e.:

$$\forall t \in T_i, t \notin \text{Sens}(M) \Rightarrow I'(t) = 0.$$

* $\forall \tau \in \mathbb{N}, \forall s, s' \in S(\text{sitpn})$, we have $E_c, \tau \vdash s \xrightarrow{\uparrow} s'$, where $s = \langle M, I, \text{reset}_t, \text{ex}, \text{cond} \rangle$ and $s' = \langle M', I, \text{reset}'_t, \text{ex}', \text{cond} \rangle$, if:

(7) M' is the new marking resulting from the firing of all the transitions contained in $\text{Fired}(s)$, i.e.:

$$\forall p \in P, M'(p) = M(p) - \sum_{t \in \text{Fired}(s)} \text{pre}(p, t) + \sum_{t \in \text{Fired}(s)} \text{post}(t, p).$$

(8) A time transition receives a reset order if it is fired at state s , or, if there exists a place p connected to t by a *basic* or *test* arc and at least one output transition of p is fired and the transient marking of p disables t ; no reset order is sent otherwise:

$$\begin{aligned} & \forall t \in T_i, t \in \text{Fired}(s) \\ & \vee (\exists p \in P, \omega \in \mathbb{N}^*, \\ & [\text{pre}(p, t) = (\omega, \text{basic}) \vee \text{pre}(p, t) = (\omega, \text{test})] \\ & \wedge \sum_{t_i \in \text{Fired}(s)} \text{pre}(p, t_i) > 0 \\ & \wedge M(p) - \sum_{t_i \in \text{Fired}(s)} \text{pre}(p, t_i) < \omega) \\ & \Rightarrow \text{reset}'_t(t) = \text{true} \text{ and } \text{reset}'_t(t) = \text{false} \text{ otherwise.} \end{aligned}$$

(9) All functions associated with at least one fired transition are executed, i.e:

$$\forall f \in \mathcal{F}, \text{ex}'(f) = \sum_{t \in \text{Fired}(s)} \mathbb{F}(t, f).$$

We inherit from [4] and [5], the form of Definition 7. In this thesis, we prefer to use rule instances to define execution relations, or relations that are involved in an operational semantics. Thus, Definition 7 can be equivalently represented with the following rule instances, where the premises of the rules refer to the items of Definition 7:

FALLINGEDGE						RISINGEDGE		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$E_c, \tau \vdash s \xrightarrow{\downarrow} s'$						$E_c, \tau \vdash s \xrightarrow{\uparrow} s'$		

Premises (1) to (6) describe the SITPN state evolution at the falling edge of the clock signal. Premises (1) and (2) deal with the update of condition values and the activation status of actions. Note that in Premise (2) (and also in Premise (9)), the sum expression corresponds to the Boolean sum expression, i.e. the application of the or operator over the elements of the iterated set. Premises (3), (4), (5) and (6) focus on the update of time counter values. In Premise (4) of the SITPN semantics, the *active* time counters refer to the time counters that have not yet overreached the upper bound of their associated time interval. Of course, a time counter is always active when the upper bound is infinite. In Premise (5), the *locked* time counters refer to the time counters that have overreached the upper bound of their associated time interval. Of course, time counters can never be locked in the presence of an infinite upper bound. In Premises (4) and (5), for a given time interval i , $u(i)$ denotes the upper bound of the time interval, and $l(i)$ denotes the lower bound of the time interval.

Premises (7) to (9) describe the SITPN state evolution at the rising edge of the clock signal. Premise (7) corresponds to the marking update. The computation of the new marking uses the set of fired transitions at state s , i.e. $Fired(s)$. Premise (9) deals with the update of the function execution status. Premise (8) computes the reset orders for time transitions. There are two cases where a time transition receives the order to reset its time counter. First, if the transition is one of the fired transitions at state s , then its time counter must be reset on the next falling edge. Second, if the transition is disabled in a *transient* manner, then its time counter must also be reset. Figure 1.12 illustrates the case of a transition disabled by the *transient* marking, i.e. the marking obtained after the token consumption phase of the firing process.

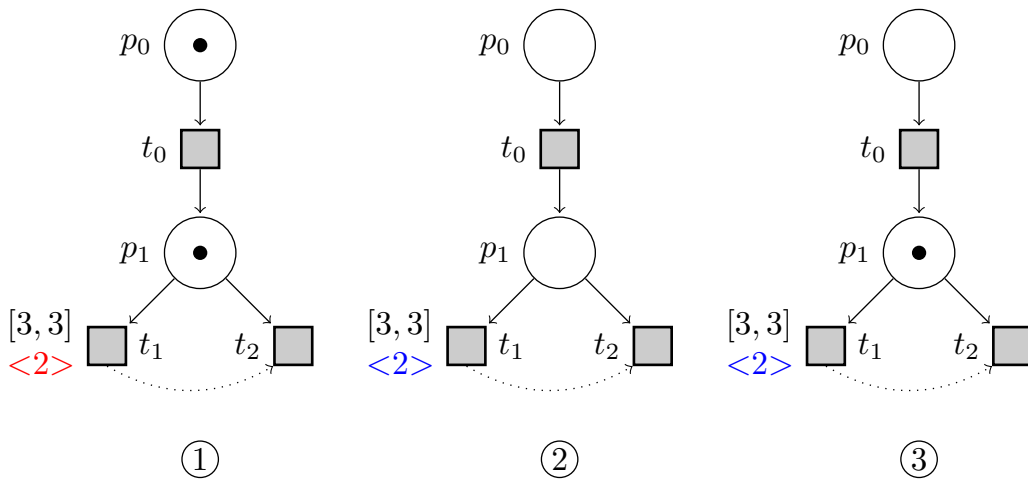


FIGURE 1.12: An example of transition that receives a reset order after being disabled by the transient marking. At ①, the marking before the firing of transitions t_0 and t_2 ; at ②, the transient marking; at ③, the marking at the end of the firing process.

In Figure 1.12, the situation at ① describes the state of the SITPN before a rising edge. Given the current SITPN state at ①, transition t_0 and t_2 will be fired on the next rising edge event. Situation ② depicts the marking obtained after the consumption phase of the firing process (once the rising edge occurred), i.e. the so-called *transient* marking. Situation ③ corresponds to the marking at the end of the firing process, where t_0 and t_2 have been fired. At ③, transition t_1 is enabled by the marking. However, at ②, the transient marking disables t_1 and thus t_1 must receive a reset order (represented by a blue time counter). This reset order will be taken into account at the next falling edge event, and the time counter associated with transition t_1 will then be reset.

Contributions to the SITPN semantics

We brought the following changes to the SITPN semantics that was defined in [4] and [5]:

- We clarified the definition of the set of fired transitions. In the former SITPN semantics, four premises were dedicated to the computation of the set of fired transitions in the definition of the SITPN state transition relation on falling edge. We removed these premises from the definition, and made a *standalone* definition of the set of fired transitions that only depends on a given SITPN state (cf. Definition 6).
- We completed Premise (8) with the condition $\sum_{t_i \in \text{Fired}(s)} \text{pre}(p, t_i) > 0$. This condition is mandatory to perform the proof of semantic preservation.
- We added Premise (6) to the definition of the SITPN state relation on falling edge. This premise is also mandatory to perform the proof of semantic preservation.

1.2.5 SITPN Execution

As a part of the SITPN semantics, we define here the SITPN execution and SITPN full execution relations. These relations bind a given SITPN to an execution trace, i.e. a time-ordered list of states. This execution trace represents the successive states of the SITPN during its execution for a given number of clock cycles. These definitions are additional elements corresponding to our own contribution to the formalization of the SITPN semantics. These two relations provide a small-step semantics to the SITPNs, given that we are interested in keeping the intermediary states in an execution trace.

Definition 8 (SITPN execution). *For a given $\text{sitpn} \in \text{SITPN}$, a starting state $s \in S(\text{sitpn})$, a clock cycle count $\tau \in \mathbb{N}$, and an environment $E_c \in \mathbb{N} \rightarrow \mathcal{C} \rightarrow \mathbb{B}$, sitpn yields the execution trace θ from starting state s , written $E_c, \tau \vdash \text{sitpn}, s \rightarrow \theta$, by following the two rules below:*

EXECUTIONEND

$\frac{}{E_c, 0 \vdash \text{sitpn}, s \rightarrow []}$

EXECUTIONLOOP

$$\frac{E_c, \tau \vdash \text{sitpn}, s \xrightarrow{\uparrow} s' \quad E_c, \tau \vdash \text{sitpn}, s' \xrightarrow{\downarrow} s'' \quad E_c, \tau - 1 \vdash \text{sitpn}, s'' \rightarrow \theta}{E_c, \tau \vdash \text{sitpn}, s \rightarrow (s' :: s'' :: \theta)} \quad \tau > 0$$

The EXECUTIONEND rule states that the execution of a $\text{sitpn} \in \text{SITPN}$, starting from a state $s \in S(\text{sitpn})$ in the environment $E_c \in \mathbb{N} \rightarrow \mathcal{C} \rightarrow \mathbb{B}$, yields an empty execution trace if the clock count comes down to 0.

The EXECUTELOOP rule describes how the execution trace related to the execution of a $\text{sitpn} \in \text{SITPN}$ is built in the case where the clock count τ is greater than zero. The final execution trace is composed of a head state s' , followed by state s'' and the tail trace θ . The $::$ operator builds a new trace by adding a new element at the head of an existing trace. Starting from state s , sitpn reaches state s' after a rising edge event; then from state s' , it reaches state s'' after a falling edge event. Finally, the execution trace θ is obtained through the recursive call to the SITPN execution relation where sitpn is executed during $\tau - 1$ cycles starting from state s'' .

Definition 9 (SITPN full execution). *For a given $\text{sitpn} \in \text{SITPN}$, a clock cycle count $\tau \in \mathbb{N}$, and an environment $E_c \in \mathbb{N} \rightarrow \mathcal{C} \rightarrow \mathbb{B}$, sitpn yields the execution trace θ starting from its initial state $s_0 \in S(\text{sitpn})$ (as defined in Definition 3), written $E_c, \tau \vdash \text{sitpn} \rightarrow \theta$, by following the two rules below:*

$$\frac{\text{FULLEXEC0}}{E_c, 0 \vdash \text{sitpn} \xrightarrow{\text{full}} [s_0]} \quad \frac{\text{FULLEXECCONS} \quad E_c, \tau \vdash s_0 \xrightarrow{\downarrow} s \quad E_c, \tau - 1 \vdash \text{sitpn}, s \rightarrow \theta_s}{E_c, \tau \vdash \text{sitpn} \xrightarrow{\text{full}} (s_0 :: s_0 :: s :: \theta_s)} \quad \tau > 0$$

The FULLEXECCONS rule of the SITPN full execution relation (Definition 9) appeals to the SITPN execution relation (Definition 8). However, the definition of the SITPN full execution relation is necessary because the first cycle of execution, starting from the initial state s_0 , is particular. As a matter of fact, no transitions are fired during the first rising edge. Thus, the first rising edge does not change the initial state s_0 . This is why the execution trace of Rule FULLEXECCONS begins with two states s_0 , thus representing the idle first rising edge.

1.2.6 Well-definition of a SITPN

To be able to transform a given SITPN into a VHDL design and also to perform the proof of semantic preservation, a SITPN must verify some properties ensuring its *well-definition*. Here, we formalize the predicate stating that a given SITPN is well-defined.

The main interest of the well-definition predicate is to prevent the phenomenon of the “double consumption” of tokens at the execution of a SITPN. In a well-defined SITPN, a conflict resolution strategy must be applied to every group of transitions in structural conflict. We must be able to decide which transition in a conflicting pair will be fired when the conflict becomes effective. Thus, we give the formal definition of a conflicting pair of transitions and of a conflict group.

Definition 10 (Conflict). For a given $sitpn \in SITPN$, two transitions $t, t' \in T$ are in conflict if there exist a place $p \in P$ and two weights $\omega, \omega' \in \mathbb{N}^*$ such that $pre(p, t) = (\omega, \text{basic})$ and $pre(p, t') = (\omega', \text{basic})$.

A conflict group qualifies a finite set of transitions that are all in conflict with each other through at least a common input place. In Figure 1.13, the set $\{t_0, t_1\}$ is a conflict group. The formal definition of a conflict group is as follows:

Definition 11 (Conflict Group). For a given $sitpn \in SITPN$, $T_c \subseteq T$ is a conflict group if there exists a place p such that $\forall t \in T, (\exists \omega \in \mathbb{N}^*, pre(p, t) = (\omega, \text{basic})) \Leftrightarrow t \in T_c$.

Contrary to the statement made in [4, p. 67], we no more consider the notion of conflict as being transitive. To illustrate this, Figure 1.13 shows two conflict groups: $\{t_0, t_1\}$ and $\{t_1, t_2\}$. In a well-defined $SITPN$ (see Section 1.2.6), all conflicts in a conflict group must be dealt with, i.e. for all pair of transitions in the group the conflict must be solved. However, we no more consider transitions t_0 and t_2 as in conflict. We argue that even when no conflict resolution technique is applied between transitions in the same situation as t_0 and t_2 , the execution of the $SITPN$ can neither result in the double-consumption of a token, nor in the case where a transition is not elected to be fired even though it ought to be. Therefore, we no more consider the construction of merged conflict group (i.e, conflict groups must be merged into one if their intersection is not empty; e.g, $\{t_0, t_1, t_2\}$ in Figure 1.13) as being necessary.

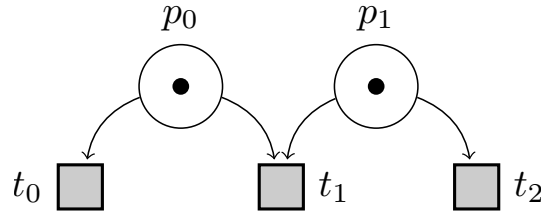


FIGURE 1.13: An example of two separate conflict groups, namely: $\{t_0, t_1\}$ and $\{t_1, t_2\}$.

When the conflict between a pair of transitions becomes effective, there are two ways to be sure that only one transition will be fired. The first way is to define a firing order through a priority relation. The second way is to use a mean of mutual exclusion. A mean of mutual exclusion ensures that the two transitions of a conflicting pair will never be firable at the same time. For now, we only consider two ways of mutual exclusion, namely: mutual exclusion with complementary conditions and mutual exclusion with inhibitor arcs. Here, we give the formal definition of these two means of mutual exclusion.

Definition 12 (Mutual exclusion with complementary conditions). Given two conflicting transitions t_0 and t_1 , t_0 and t_1 are in mutual exclusion with complementary conditions if there exists $c \in \mathcal{C}$ such that $(\mathbb{C}(t_0, c) = 1 \wedge \mathbb{C}(t_1, c) = -1)$ or $(\mathbb{C}(t_0, c) = -1 \wedge \mathbb{C}(t_1, c) = 1)$.

Definition 13 (Mutual exclusion with an inhibitor arc). *Given two conflicting transitions t_0 and t_1 , t_0 and t_1 are in mutual exclusion with an inhibitor arc if there exists $p \in P$ and $\omega \in \mathbb{N}^*$ such that $(pre(p, t_0) = (\omega, \text{basic}) \vee pre(p, t_0) = (\omega, \text{test})) \wedge pre(p, t_1) = (\omega, \text{inhib})$ or $(pre(p, t_1) = (\omega, \text{basic}) \vee pre(p, t_1) = (\omega, \text{test})) \wedge pre(p, t_0) = (\omega, \text{inhib})$.*

Figure 1.14 illustrates the two means of mutual exclusion that can be applied to solve a conflict between two transitions.

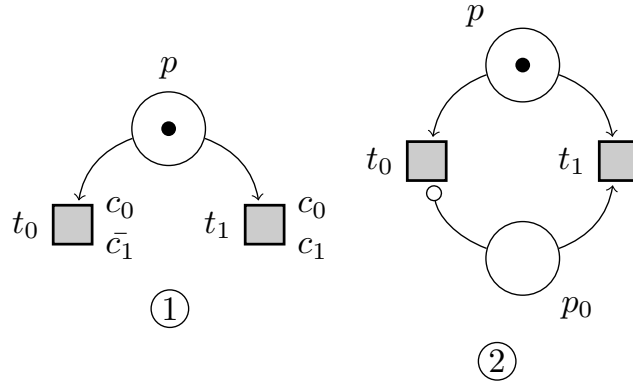


FIGURE 1.14: Examples of conflicting transitions in mutual exclusion. At ①, an example of mutual exclusion with complementary conditions; at ②, an example of mutual exclusion with an inhibitor arc.

In Figure 1.14, in situation ①, condition c_1 is associated to t_1 and the complementary condition is associated to t_0 thus creating the mutual exclusion. In situation ②, the arcs (p_0, t_0) and (p_0, t_1) ensure the mutual exclusion between transitions t_0 and t_1 . Note that in the structure of mutual exclusion with an inhibitor arc, the weight of the inhibitor arc and of the basic or test arc must be the same; otherwise, the mutual exclusion is not effective.

A given $sitpn \in SITPN$ is well-defined if it enforces some properties needed on the HILECOP source models before the transformation into VHDL. If the properties, laid out in Definition 14, are not ensured, they will lead to compile-time errors during the transformation of the SITPN into a VHDL design.

Definition 14 (Well-defined SITPN). *A given $sitpn \in SITPN$ is well-defined if:*

- $T \neq \emptyset$, the set of transitions must not be empty.
- $P \neq \emptyset$, the set of places must not be empty.
- There is no isolated place, i.e, a place that has neither input nor output transitions:
 $\nexists p \in P, input(p) = \emptyset \wedge output(p) = \emptyset$, where $input(p)$ (resp. $output(p)$) denotes the set of input (resp. output) transitions of p .

- There is no isolated transition, i.e., a transition that has neither input nor output places:
 $\nexists t \in T, \text{input}(t) = \emptyset \wedge \text{output}(t) = \emptyset$, where $\text{input}(t)$ (resp. $\text{output}(t)$) denotes the set of input (resp. output) places of t .
- For all conflict group as defined in Definition 11, either all conflicts (i.e. for all pair of transitions in the conflict group) are solved by one of the mean of mutual exclusion, or, the priority relation is a strict total order over the transitions of the conflict group.

1.2.7 Boundedness of a SITPN

We conclude the formalization of the SITPN structure and semantics by the expression of the boundedness of a SITPN model with respect to its execution trace. In the manner of the well-definition property, the boundedness of a SITPN model is a mandatory condition to apply the semantic preservation theorem (cf. Remark ?? in Chapter ??). A SITPN model is bounded if there exists a *bound* for the number of tokens that the places can hold in the course of the execution of the model; formally:

Definition 15 (Bounded SITPN). A given $\text{sitpn} \in \text{SITPN}$ is said to be bounded if for all execution environment $E_c \in \mathbb{N} \rightarrow \mathcal{C} \rightarrow \mathbb{B}$, clock cycle count $\tau \in \mathbb{N}$, execution trace $\theta \in \text{list}(S(\text{sitpn}))$ such that $E_c, \tau \vdash \text{sitpn} \xrightarrow{\text{full}} \theta$, then there exists a bound $k \in \mathbb{N}$ such that for all $p \in P$ and $s \in \theta$, $s.M(p) \leq k$.

We extend the definition of a bounded SITPN model to a version where the bound denoting the maximal marking of each place of the model is passed through a function $b \in P \rightarrow \mathbb{N}$.

Definition 16 (Bounded SITPN through a maximal marking function). A given $\text{sitpn} \in \text{SITPN}$ is said to be bounded through the maximal marking function $b \in P \rightarrow \mathbb{N}$, written $[\text{sitpn}]^b$, if for all execution environment $E_c \in \mathbb{N} \rightarrow \mathcal{C} \rightarrow \mathbb{B}$, clock cycle count $\tau \in \mathbb{N}$, execution trace $\theta \in \text{list}(S(\text{sitpn}))$ such that $E_c, \tau \vdash \text{sitpn} \xrightarrow{\text{full}} \theta$, then for all $p \in P$ and $s \in \theta$, $s.M(p) \leq b(p)$.

1.3 Implementation of the SITPN structure and semantics

In this section, we present our mechanization of the SITPN structure and semantics with the Coq proof assistant. The source code is available to the reader at the address <https://github.com/viampietro/ver-hilecop>. More precisely, the implementation of the SITPN structure and semantics is to be found under the `sitpn/dp` directory. We have made a first implementation of SITPNs without the use of dependent types. For this first version, we have also implemented a SITPN interpreter (a so-called *token player*) and proved that the interpreter was sound and complete w.r.t the SITPN semantics. This first implementation of the SITPNs and the formal proof of soundness and completeness are available at <https://github.com/viampietro/sitpns>.

1.3.1 Implementation of the SITPN and the SITPN state structure

Listing 1.2 presents the implementation of the SITPN structure as a Coq record type. The implementation is almost similar to the formal definition of the SITPN structure given in Definition 1.

```

1  Record Sitpn := BuildSitpn {
2
3    places : list nat;
4    transitions : list nat;
5    P := { p | (fun p0 => In p0 places) p };
6    T := { t | (fun t0 => In t0 transitions) t };
7
8    pre : P -> T -> option (ArcT * N*);
9    post : T -> P -> option N*;
10   M0 : P -> nat;
11   Is : T -> option TimeInterval;
12
13   conditions : list nat;
14   actions : list nat;
15   functions : list nat;
16   C := { c | (fun c0 => In c0 conditions) c };
17   A := { a | (fun a0 => In a0 actions) a };
18   F := { f | (fun f0 => In f0 functions) f };
19
20   C : T -> C -> MOneZeroOne;
21   A : P -> A -> bool;
22   F : T -> F -> bool;
23
24   pr : T -> T -> Prop;
25
26 }.

```

LISTING 1.2: Implementation of the SITPN structure in Coq.

We use lists of natural numbers, i.e. `list nat` in Coq, to define the finite sets of places (Line 3), transitions (Line 4), actions (Line 14), conditions (Line 13) and functions (Line 15) in the `Sitpn` record. We want to use these finite sets in the signature of functions appearing in the structure (e.g. use the finite set of places P in the signature of the initial marking $M_0 \in P \rightarrow \mathbb{N}$). To do so, we leverage the Coq `sig` type to define subsets of elements verifying a certain property. Thus, we define the finite set P as the subset of natural numbers that are members of the places list (Line 5). We use the `In` relation defined in the Coq standard library to express the membership of a natural number regarding the elements of the places list. Also, the `ArcT` type (Line 8) implements the set $\{\text{inhib}, \text{test}, \text{basic}\}$; the `TimeInterval` type (Line 11) implements the set \mathbb{I}^+ of time intervals, and the `MOneZeroOne` type (Line 20) implements the set $\{0, 1, -1\}$. The priority relation is implemented by the `pr` function (Line 24) taking two transitions in parameter and projecting to the type of logical propositions, i.e. the `Prop` type.

Listing 1.3 presents the implementation of the SITPN state structure as a Coq record type.

```

1  Record SitpnState (sitpn : Sitpn) := BuildSitpnState {
2
3    M : P sitpn → nat;
4    I : Ti sitpn → nat;
5    reset : Ti sitpn → bool;
6    cond : C sitpn → bool;
7    ex : A sitpn + F sitpn → bool;
8
9  }.

```

LISTING 1.3: Implementation of the SITPN state structure in Coq.

The `SitpnState` type definition depends on a given SITPN passed as a parameter; it is an example of dependent type. Projection functions are automatically generated to access the attributes of a record at the declaration of a type with the `Record` keyword. Thus, in Listing 1.3, we can refer to the set of places of `sitpn` with the term `P sitpn`. The term `Ti sitpn` denotes the set of time transitions of `sitpn`. The set of time transitions for a given SITPN is declared as a sig type qualifying to the subset of transitions with an associated time interval.

1.3.2 Implementation of the SITPN semantics

Here, we present our implementation of the SITPN semantics. In Listing 1.4, we give an excerpt of the implementation of the SITPN state transition relation, i.e. the core of the SITPN semantics.

```

1  Inductive SitpnStateTransition
2    (sitpn : Sitpn) (Ec : nat → C sitpn → bool) (τ : nat) (s s' : SitpnState sitpn) :
3    Clk → Prop :=
4  | SitpnStateTransition_falling :
5
6    (* Rule (2) *)
7    (forall a marked sum,
8      Sig_in_List (P sitpn) (fun p ⇒ M s p > 0) marked →
9      BSum (fun p ⇒ A p a) marked sum →
10     ex s' (inl a) = sum) →
11
12    (* Rules (3), (4), (5) and (6) *)
13    (forall (t : Ti sitpn), ~Sens (M s) t → I s' t = 0) →
14    (forall (t : Ti sitpn), Sens (M s) t → reset s t = true → I s' t = 1) →
15    (forall (t : Ti sitpn),
16      Sens (M s) t →
17      reset s t = false →
18      (TcLeUpper s t ∨ upper t = i+) → I s' t = S (I s t)) →
19    (forall (t : Ti sitpn),
20      Sens (M s) t →
21      reset s t = false →
22      (upper t <> i+ ∧ TcGtUpper s t) → I s' t = S (I s t)) →
23

```

```

24  (** Conclusion *)
25  SitpnStateTransition  $E_c \tau s s' \downarrow$ 
26
27 | SitpnStateTransition_rising:
28
29  (** Rule (7) *)
30  (forall fired, IsNewMarking s fired (M s')) →
31
32  (* Rule (9) *)
33  (forall f fired sum,
34    IsFiredList s fired →
35    BSum (fun t ⇒  $\mathbb{F} t f$ ) fired sum →
36    ex s' (inr f) = sum) →
37
38  (** Conclusion *)
39  SitpnStateTransition  $E_c \tau s s' \uparrow$ .

```

LISTING 1.4: Excerpt of the implementation of the SITPN state transition relation in Coq.

The SITPN state transition relation is implemented in Coq as an inductive type with two constructors, i.e. one for each clock event. The relation has 6 parameters: an SITPN, an environment E_c , a clock count τ , two SITPN states s and s' and a clock event. Note that the two states s and s' are bound to the SITPN parameter through their type, i.e. `SitpnState sitpn`.

In the construction case `SitpnStateTransition_falling`, we give the implementation of Rules (2), (3), (4), (5) and (6) defined in the SITPN semantics. The sum term of Rule (2), i.e.

$\sum_{p \in \text{marked}(M)} \mathbb{A}(p, a)$, is implemented by Lines 8 and 9. At Line 8, the `Sig_in_List` predicate states that all the inhabitant of the `P sitpn` type (i.e. the places of `sitpn`) that verifies the property $(\text{fun } p \Rightarrow M \ s \ p > 0)$ (i.e. the marking of a place is greater than zero at state s) are members of the marked list. Because we can not iterate over the elements of a given `sig` type, we use the `Sig_in_List` relation to convert a `sig` type into a list. Lists are iterable by definition. At Line 9, the `BSum` relation states that `sum` is the Boolean sum obtained by applying the function $(\text{fun } p \Rightarrow \mathbb{A} \ p \ a)$ to the elements of the marked list. Rules (3), (4), (5) and (6) are almost similar in their implementation to the description of Definition 7. The Coq term `Sens (M s) t` implements the term $t \in \text{Sens}(M)$. Due to the particular nature of the upper bound of a time interval, i.e. defined over the set $\mathbb{N}^* \sqcup \{\infty\}$, the test that the current time counter of a given transition t is less than or equal to the upper bound is implemented by a separate predicate `TcLeUpper`. Similarly, the `TcGtUpper` predicate implements the inverse test.

In the construction case `SitpnStateTransition_rising`, we give the implementation of Rules (7) and (9) defined in the SITPN semantics. In the implementation of Rule (7), the `IsNewMarking` predicate hides away the expression:

$$\forall p \in P, M'(p) = M(p) - \sum_{t \in \text{Fired}(s)} \text{pre}(p, t) + \sum_{t \in \text{Fired}(s)} \text{post}(t, p).$$

In its definition, the `IsNewMarking` predicate first checks that the `fired` list implements the set of fired transitions at state s . Then, it builds the marking at state s' for each place p , i.e. $(M \ s')$, by consuming and producing a number of tokens starting from the marking of p at

state s . The fired list is helpful to qualify the input token sum and the output token sum for a given place. Similarly to the implementation of Rule (2), the implementation of Rule (9) at Line 33 leverages the BSum predicate to compute the Boolean sum $\sum_{t \in \text{Fired}(s)} \mathbb{F}(t, f)$. The term

`IsFiredList s fired` states that the fired list implements the set of fired transitions at state s , so we can use the fired list to compute the above sum.

1.4 Conclusion

The class of SITPNs is a particular class of PNs used to model the behavior of components in the HILECOP high-level models. The synchronous evolution of SITPNs constitutes the originality of the model compared to the standard PNs semantics. In this chapter, we gave an informal and formal presentation of SITPNs and their execution semantics. Two previous Ph.D. theses contributed, for the most part, to the formalization of the SITPN structure and semantics. However, we helped to simplify the semantics of SITPNs. We passed from 14 rules in the definition of the SITPN semantics given in [4] to 9 rules in our current definition of semantics. Also, we completed some rules when they happened to be insufficient to prove the theorem of behavior preservation. Finally, we defined the execution relations for the SITPN semantics and formalized the well-definition property for the SITPN structure.

Our other contribution was to implement the SITPN structure and semantics with the Coq proof assistant. There are two implementations: one with and one without dependent types. For the version without dependent types, we implemented a SITPN interpreter or token player. We also proved a soundness and completeness theorem between the interpreter and the formalized SITPN semantics. The first implementation of the SITPNs in Coq represents 5000 lines of specification and 7000 lines of proof. The second implementation leverages dependent types. This implementation is more concise and closer to the formal definition given within the set theory. We chose this implementation to mechanize the proof of the behavior preservation theorem (see Chapter ??).

Bibliography

- [1] Jose R. Celaya, Alan A. Desrochers, and Robert J. Graves. “Modeling and Analysis of Multi-Agent Systems Using Petri Nets”. In: *2007 IEEE International Conference on Systems, Man and Cybernetics*. 2007 IEEE International Conference on Systems, Man and Cybernetics. Oct. 2007, pp. 1439–1444. DOI: [10.1109/ICSMC.2007.4413960](https://doi.org/10.1109/ICSMC.2007.4413960).
- [2] René David and Hassane Alla. “Petri Nets for Modeling of Dynamic Systems: A Survey”. In: *Automatica* 30.2 (Feb. 1, 1994), pp. 175–202. ISSN: 0005-1098. DOI: [10.1016/0005-1098\(94\)90024-8](https://doi.org/10.1016/0005-1098(94)90024-8).
- [3] Michel Diaz. *Les Réseaux de Petri: Modèles Fondamentaux*. Hermès science publications, 2001.
- [4] Hélène Leroux. “Méthodologie de conception d’architectures numériques complexes : du formalisme à l’implémentation en passant par l’analyse, préservation de la conformité. Application aux neuroprothèses”. PhD thesis. Université Montpellier II - Sciences et Techniques du Languedoc, Oct. 28, 2014.
- [5] Ibrahim Merzoug. “Validation formelle des systèmes numériques critiques : génération de l’espace d’états de réseaux de Petri exécutés en synchrone”. PhD thesis. Université Montpellier, Jan. 15, 2018.
- [6] T. Murata. “Petri Nets: Properties, Analysis and Applications”. In: *Proceedings of the IEEE* 77.4 (Apr. 1989), pp. 541–580. ISSN: 1558-2256. DOI: [10.1109/5.24143](https://doi.org/10.1109/5.24143).
- [7] Carl Adam Petri. “Kommunikation mit Automaten”. PhD thesis. Technical University Darmstadt, Germany, 1962.
- [8] Alex Yakovlev and Albert Koelmans. “Petri Nets and Digital Hardware Design”. In: *Lecture Notes in Computer Science - LNCS*. Apr. 11, 2006, pp. 154–236. DOI: [10.1007/3-540-65307-4_49](https://doi.org/10.1007/3-540-65307-4_49).