Behavioural and Structural Composition Rules Preserving Liveness by Synchronization for Coloured FIFO Nets

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Abstract. This paper deals with the compositionality of liveness when synchronizing two coloured FIFO nets. The composition operator allows to merge transitions as well as some adjacent places or queues.

A behavioural sufficient condition for liveness compositionality relies on a mutual non constraining relation between component nets. A structural sufficient condition for synchronization preserving liveness is then given in the case of a state machine at the interface of the merged elements with the non merged ones of each component net. It requires that the conflictual coloured transitions of the interface state machines satisfy the structural freeing or blocking relations.

Finally an example shows how these conditions simplify the analysis of a protocol within a layered architecture.

Keywords: blocking relation, coloured FIFO nets, compositionality, equal conflict, freeing relation, liveness, non constraining relation, state machine, synchronization, synchronization medium.

1 Introduction

Compositional specification and validation are fundamental for handling large Petri net models [BC92]. Modular analysis reduces the cost of handling the entire systems. Local properties of each component net can be checked separately and composition rules allow to preserve some global properties.

Communication protocols constitute a privileged field for composition of Petri nets [Dia87] [BWWH88] [BK89]. Protocols which allow to interconnect heterogeneous systems are organized within layered architectures with accurate interface rules between modules. In [BMR83], is proposed a way to construct a live system of sequential machines from smaller ones. [ES91] have studied the synchronization operator which is based on the merging of transitions and of some adjacent places. They have given for this operator a structural characterization preserving liveness within the framework of free choice nets. In [Ber86], the addition of a non constraining net is a P/T net transformation defined in behavioural terms which has been proposed to preserve liveness and/or boundedness of the initial net in the resulting net.

High level Petri nets constitute a natural framework for the liveness compositionality. FIFO nets [MF85] are models defined for systems where processes have asynchronous communications by serialized messages. Their queues contain words of coloured tokens. Colored FIFO nets defined in Section 2, also have coloured transitions and some of their places may contain bags of coloured tokens. These nets are very efficient for specification but there is a lack of validation tools because handling the order of tokens is difficult. [Fan91] has defined a process algebra based on FIFO nets. [Sou91] has proposed a structural sufficient condition for liveness compositionality in FIFO nets, which is expressed in terms of connectivity of the non merged queues with the merged transitions. Our paper extends this approach for coloured FIFO nets and brings new structural conditions for liveness compositionality.

The notion of a non constraining net is adapted in Section 3 to the synchronization of coloured FIFO nets and we show that it constitutes a systematic mean for preserving liveness from component nets to the compound net. We specialize and deepen this behavioural definition to obtain a simpler structural sufficient condition.

In Section 4, we focus on synchronizations where the subnet generated by the merged elements (called the synchronization medium) is a mono-marked state machine. Such a medium is usual in protocol interfaces, because it simplifies the management of messages between communicating entities. We introduce two new asymmetrical behavioural relations involving conflictual coloured transitions of the state machine medium: the freeing and the blocking relations. They allow to express a sufficient condition for a component net to be non constraining w.r.t. a second one given the liveness of the merged transitions in the compound net. It is a useful technical result for the composition theorem of Section 5. Then we propose structural sufficient conditions for these behavioural relations which are well suited to coloured FIFO nets.

The main part of the paper (Section 5) is devoted to a structural sufficient condition for the non constraining relation. We show that it is sufficient to study separately the two interfaces between the synchronization medium and each component net. They must be mono-marked state machines and any couple of their conflictual coloured transitions has to satisfy either the structural blocking relation or the structural freeing relation. The composition theorem states that component nets which are structurally non constraining w.r.t. each other is a sufficient condition for the liveness compositionality. This theorem relaxes the constraints which have limited the use of the result of [Sou91]. At last, this modular specification and validation technique is applied through an example for communication protocols within a layered architecture.

2 Coloured FIFO nets and Synchronization

We first give the basic notions of coloured FIFO nets and recall the definition of a composition operator between coloured FIFO nets, the synchronization.

2.1 Coloured FIFO nets

A coloured FIFO net is based on a finite valuated tripartite graph where each element x (place, queue or transition) has a finite color domain C(x). The main originality of coloured FIFO nets consists in their two types of marking:
– words of $C(q)^*$ for the marking of a queue q,
– multisets on $C(p)$ for the marking of a coloured place p.
Straightforward examples show that suppressing the FIFO behaviour of queues may change liveness or boundedness. The decidable problems in P/T nets (liveness, boundedness and reachability) are undecidable in coloured FIFO nets. Some classes of FIFO nets with decidable properties have been obtained by restrictions on the valuations of arcs [Mem83], [Fin86], [Cho87].

Definition 2.1 *A multiset over X is a function $f : X \rightarrow \mathbb{N}$; the support of f is $Y \subseteq X$ such that $Y = \{x \in X, f(x) \neq 0\}$. The set of multisets over X is denoted by $\mathbb{N}^X$.*

Notations Given a finite set A, $A*$ denotes the free monoid with base A. The empty word is denoted by ϵ. $|x|$ is the length of the word x of A^*. $x \prec y$ means x is a prefix of y i.e. there exists z in A^* such that $y = x.z$ where "." is the concatenation.

Definition 2.2 (A coloured FIFO net) $N =< P, Q, T, C, W >$ *is a coloured FIFO net where:*

- *P, Q and T are disjoint finite sets respectively the set of places (represented by circles) the set of FIFO queues (represented by ellipses) and the set of transitions (represented by rectangles)*

- *C is the color function: $\forall x \in P \cup Q \cup T, C(x)$ is a finite set called the color domain of x. $\forall t \in T$, $\forall ct \in C(t)$, the couple (t, ct) is called a coloured transition. We denote $TC = \{(t, ct) \mid t \in T$ and $ct \in C(t)\}$ the set of all coloured transitions of N*

- *W is the coloured weight function defined for each arc:*
  $W(p,t), W(t,p) \in [C(t) \rightarrow \mathbb{N}^{C(p)}]$, $\forall p \in P$, $\forall t \in T$ *and* $W(q,t)$, $W(t,q)$ $\in [C(t) \rightarrow C(Q)^*]$, $\forall q \in Q$, $\forall t \in T$.
  For convenience, we denote $W(p,t)((ct, cp))$ by $W(p,t,ct,cp)$, $W(p,t,ct)$ is the function $g : C(p) \rightarrow \mathbb{N}$ such that $g(cp)=W(p,t,ct,cp)$ and $W(q,t,ct)$ is a word of $C(q)^*$.

Notations For any set X of nodes of:
– P the preset (resp. postset) of X is given by $^\bullet X = \{y \in T \mid \exists x \in X, W(y,x) \neq 0\}$ (resp. $X^\bullet = \{y \in T \mid \exists x \in X, W(x,y) \neq 0\}$),
– T the preset (resp. postset) of X is given by $^\bullet X = \{y \in P \mid \exists x \in X, W(y,x) \neq 0\} \cup \{y \in Q \mid \exists x \in X, W(y,x) \neq \epsilon\}$ (resp. $X^\bullet = \{y \in P \mid \exists x \in X, W(x,y) \neq 0\} \cup \{y \in Q \mid \exists x \in X, W(x,y) \neq \epsilon\}$),
– Q the preset (resp. postset) of X is given by $^\bullet X = \{y \in T \mid \exists x \in X, W(y,x) \neq \epsilon\}$ (resp. $X^\bullet = \{y \in T \mid \exists x \in X, W(x,y) \neq \epsilon\}$).
$^\bullet X^\bullet$ denotes the union of the preset and the postset of X.

Marking A marking of N is a function M defined on $P \cup Q$ where $M(p) \in \mathbb{N}^{C(p)}, \forall p \in P$ and $M(q)) \in C(q)^*, \forall q \in Q$. $|M'(q)|$ is the length of the word $M'(q)$ and $|M'(p)| = \sum_{x \in C(p)} M'(p)(x)$.
The couple (N, M) is a marked coloured FIFO net.

Enabling and firing of transitions and sequences A transition t is enabled at M for the color $ct \in C(t)$, written $M((t, ct) >$ iff $\forall q \in {}^\bullet t \cap Q$, $W(q, t, ct) \prec M(q)$ and $\forall p \in {}^\bullet t \cap P, \forall cp \in C(p)$, $W(p, t, ct, cp) \leq M(p)(cp)$.
If the coloured transition (t, ct) is enabled at M, it may fire. Its occurrence leads to a reachable marking M' (written $M((t, ct) > M')$. For each coloured place (p, cp), $M'(p)(cp) = M(p)(cp) + W(t, p, ct, cp) - W(p, t, ct, cp)$ and for each queue q, $W(q, t, ct).M'(q) = M(q).W(t, q, ct)$. For the queues of Q, M' is obtained from M by removing from each queue q of ${}^\bullet t$ the word $W(q, t, ct)$ and by appending to each queue q' of $t^\bullet$ the word $W(t, q', ct)$. These notions can be extended in a natural way to sequences of coloured transitions $\sigma \in TC^*$.

Reachability set, Language The reachability set of a marked net (N, M) is denoted by $[N, M >= \{M' \mid \exists \sigma \in TC^*, M(\sigma > M'\}$.
The language of (N, M) is the set $L(N, M) = \{\sigma \in TC^* \mid M(\sigma >\}$.

Boundedness $x \in P \cup Q$ is bounded in (N, M) iff $\exists n \in \mathbb{N}$ such that $\forall M' \in [N, M >, |M'(x)| \leq n$.
(N, M) is bounded iff $\forall x \in P \cup Q$, x is bounded in (N, M).

Liveness $t \in T$ is live in (N, M) iff $\forall M' \in [N, M >, \forall ct \in C(t), \exists \sigma \in TC^*$ such that $M'(\sigma.(t, ct) >$.
(N, M) is live (or that M is live) iff every transition of T is live in (N, M).

Subnet Let P' be a subset of P, Q' be a subset of Q and T' a subset of T. We call subnet of N, generated by (P', Q', T') the coloured FIFO net $N(P', Q', T') =< P', Q', T', W', C' >$ defined by: $\forall x, y \in ((P' \cup Q') \times T') \cup (T' \times (P' \cup Q')), W'(x, y) = W(x, y)$, $C'(x) = C(x)$.
The following operators allow to express the relationships between the behaviours of a net and its subnets. Let M be a marking of N, TC' the set

of coloured transitions of $N(P',Q',T')$, SL a subset of TC^* and σ a sequence of TC^*.
$Proj(\sigma,TC')$ is the sequence obtained by removing from σ the couples (t,ct) which do not belong to TC'.
$Proj(SL,TC') = \{Proj(\sigma,TC') \mid \sigma \in SL\}$.
$M/(P' \cup Q')$ stands for the restriction of M to places of P' and queues of Q'. $M/(P' \cup Q')$ is therefore a marking of $N(P',Q',T')$.
Let N' be a subnet of N, t a transition of N' and $\hat{\Gamma}_{N'}(t) = \{x \in P' \cup Q' \cup T' \mid \exists x_1, ..., x_n : x_n = x \text{ } and \text{ } x_1 = t\}$. It denotes the set of descendant nodes of t in the graph N'.

State machine In a coloured FIFO net, all places that only behave as a P/T net place have a color domain that is only the neutral color e which must not appear in the domain of other places and queues. They are represented using the notations of P/T nets, dropping the neutral color indication on their arcs. A state machine is a P/T net with exactly one place in the preset and in the postset of each transition. A mono-marked state machine has only one place marked by one neutral token.

2.2 Synchronization of coloured FIFO nets

We consider here coloured FIFO nets composed by synchronization. This composition operator has been studied in [ES91] within the framework of P/T nets and in [Sou91] within the framework of FIFO nets.

Synchronization consists of merging distinguished transitions and distinguished adjacent places or queues, so that each one is involved in exactly one merging as shown in Figure 1. A merged transition, place or queue can be interpreted as a communication by respectively rendez-vous, common variables or serialized messages.

A modular view of the synchronization points out two explicit modules, the component nets and an implicit module called the synchronization medium. This medium is a subnet of the compound net generated by all the merged transitions, places and queues and shared by the two component nets. It is thus different from the communication medium [SM89] which is the subnet generated only by the merged transitions.

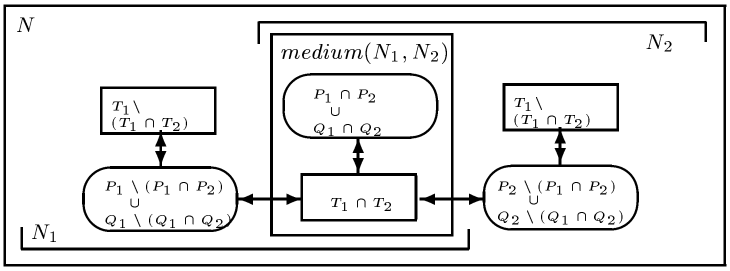

Fig. 1. (N,M) synchronization of (N_1, M_1) and (N_2, M_2)

Definition 2.3 (Synchronization and synchronization medium)

- *Let* (N_1, M_1) *and* (N_2, M_2) *be two marked coloured FIFO nets.* (N_1, M_1) *and* (N_2, M_2) *may be synchronized iff:*

  1. $^\bullet((P_1 \cap P_2) \cup (Q_1 \cap Q_2))^\bullet \subset T_1 \cap T_2$,
  2. $\forall x, y \in (((P_1 \cap P_2) \cup (Q_1 \cap Q_2)) \times (T_1 \cap T_2)) \cup ((T_1 \cap T_2) \times ((P_1 \cap P_2) \cup (Q_1 \cap Q_2))), W_1(x, y) = W_2(x, y)$,
  3. $M_1/(P_1 \cap P_2) = M_2/(P_1 \cap P_2)$,
  4. $M_1/(Q_1 \cap Q_2) = M_2/(Q_1 \cap Q_2)$.

- *The synchronization medium of* N_1 *and* N_2 *denoted by* $medium(N_1, N_2)$ *is the common subnet of* N_1 *and* N_2 *generated by* $((P_1 \cap P_2), (Q_1 \cap Q_2), (T_1 \cap T_2))$.

- *The synchronization* (N, M) *of* (N_1, M_1) *and* (N_2, M_2) *is defined by:*

  1. $P = P_1 \cup P_2, Q = Q_1 \cup Q_2, T = T_1 \cup T_2, W = W_1 \cup W_2, C = C_1 \cup C_2$,
  2. $M/(P_i \cup Q_i) = M_i, \forall i \in \{1, 2\}$.

Because synchronization allows communication by rendez-vous through the merged transitions, by projecting sequences of the compound net on the transitions of a component net, we obtain sequences of the component net. The restriction of a global reachable marking to places and queues of a component net also gives a reachable marking of the component net.

Property 2.4 *Let* (N, M) *be the synchronization of* (N_1, M_1) *and* (N_2, M_2). *We have,* $\forall i \in \{1, 2\}$*:*

1. $Proj(L(N, M), TC_i) \subset L(N_i, M_i)$
2. $\forall \sigma \in TC^*$, $M(\sigma > M' \Longrightarrow M_i(\sigma_i > M'/(P_i \cup Q_i)$ *where* $\sigma_i = Proj(\sigma, TC_i)$

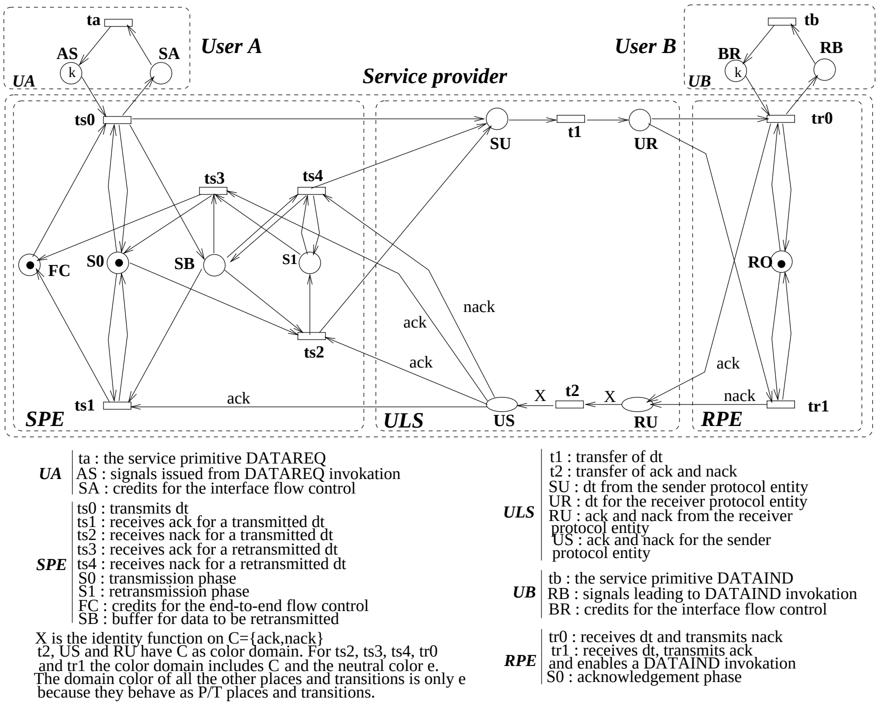

Fig. 2. A coloured FIFO net N for a protocol within a layered architecture

Example The coloured FIFO net N represented in Figure 2 models a simple protocol within a layered architecture. The protocol supports a unidirectional flow of data with an error recovery due to negative acknowledgements and a one-sized sliding window for flow control. It will be generalized in Section 5 to an n-sized sliding window.

A functional view of the model brings out three entities: the service provider, user A and user B. Here these user subnets are only represented by single transitions respectively ta and tb with the interface places AS and SA respectively the places BR and RB but in the general case they may be arbitrarily complex nets.

The service provider gathering the subnets SPE (Sender Protocol Entity), ULS (Underlying Layer Service) and RPE (Receiver Protocol Entity) is a natural medium $N_m = SPE \cup ULS \cup RPE$. The underlying layer may corrupt messages and it is assumed that the corruption of messages is reliably detected by the protocol. We consider a very simple service according to which user A invokes a $DATAREQ$ which will be delivered to user B as a $DATAIND$.

Using the synchronization operator, the global coloured FIFO net N can be decomposed into two component nets $N_1 = UA \cup N_m$ and $N_2 = UB \cup N_m$ composed of each service user together with the service provider.

3 A behavioural sufficient condition for liveness compositionality by synchronization

Liveness is not preserved by synchronization in a general case whereas boundedness is preserved by synchronization with no restriction (if the component nets are bounded then the compound net is bounded).

A natural composition mechanism preserving liveness is based on non constraining component nets w.r.t. each other. For P/T nets, this notion has first appeared in [Ber86] who has proposed a transformation called the addition of a non constraining net. This transformation which is defined in behavioural terms allows to preserve any sequence of the initial net through a sequence of the resulting net. This notion has been also used in [BRG87] to check the conformity of a protocol w.r.t. its service, both modelled by P/T nets.

We first define the non constraining relation for coloured FIFO nets that are synchronized. We then prove that this condition, if verified by each component net w.r.t. the other, is a sufficient condition for the liveness compositionality. This section concludes by a discussion on the conditions for checking the non constraining relation.

Let (N, M) be the synchronization of (N_1, M_1) and (N_2, M_2) with $N_m = medium(N_1, N_2)$.

3.1 The non constraining relation

The non constraining relation net is defined as an asymmetrical relation. A component net is non constraining w.r.t. to a second one if for each reachable marking M' of the compound net N, each transition t which is enabled at the restriction of M' to the second net, is enabled in N after firing at M' a sequence σ of the first net without merged transitions.

Definition 3.1 (Non constraining relation) (N_1, M_1) *is non constraining w.r.t.* (N_2, M_2) *iff:*
$\forall M' \in [N, M >, \forall (t, c) \in TC_2$ *such that* $M'/(P_2 \cup Q_2)((t, c) >, \exists \sigma \in TC^*$ *such that* $M'(\sigma.(t, c) >$ *and* $Proj(\sigma, TC_2) = \epsilon$.

Proposition 3.2 (N_1, M_1) *is non constraining w.r.t.* (N_2, M_2) *iff:*
$\forall M' \in [N, M >, \forall \sigma \in TC_2^*$ *such that* $M'/(P_2 \cup Q_2)(\sigma >, \exists \sigma' \in TC^*$ *such that* $M'(\sigma' >$ *and* $Proj(\sigma', TC_2) = \sigma$.

Proof.

$\Longleftarrow$ Straightforward.

$\Longrightarrow$ Let $M' \in [N, M >$ and $\sigma \in TC_2^*$ such that $M'/(P_2 \cup Q_2)(\sigma >$. We shall prove that there exists $\sigma' \in TC^*$ such that $M'(\sigma' t >$ and $Proj(\sigma', TC_2) = \sigma$. The proof is constructed by induction over the length n of $Proj(\sigma, TC_1 \cap TC_2)$.

1. $|Proj(\sigma, TC_1 \cap TC_2)| = 0$. $\sigma \in (TC_2 \setminus TC_1)^* \Longrightarrow M'(\sigma >$.
2. Let us suppose that the property is true for any $\sigma \in TC_2^*$ such that $|Proj(\sigma, TC_1 \cap TC_2)| \leq n, \forall n \geq 1$.
   Let $\sigma \in L(N_2, M'/(P_2 \cup Q_2))$ of length n+1.
   Let $\sigma = \alpha.(t', c').\beta$ with $(t', c') \in TC_1 \cap TC_2$ and $\alpha \in (TC_2 \setminus TC_1)^*$.
   Let $M'/(P_2 \cup Q_2)(\alpha.(t', c') > M_2'$.
   As $\alpha \in (TC_2 \setminus TC_1)^*$, we have $M'(\alpha >$.
   Let $M'(\alpha > M''$.
   We can apply the definition of (N_1, M_1) non constraining w.r.t. (N_2, M_2) to M'' and (t', c'). Then there exists a sequence $\delta \in TC^*$ such that $M''(\delta.(t', c') >$ and $Proj(\delta, TC_2) = \epsilon$.
   Let $M''(\delta.(t', c') > M'''$, we have $M'''/(P_2 \cup Q_2) = M_2'$.
   We can apply the induction hypothesis to M''' and β. This leads to the existence of $\zeta \in TC^*$ such that $\zeta = Proj(\beta, TC_2)$.
   Let $\sigma' = \alpha.\delta.(t', c').\zeta$.
   We have $M'(\sigma' >$ and $Proj(\sigma', TC_2) = \sigma$. □

3.2 The liveness compositionality

The non constraining relation of a component net w.r.t a second one preserves the liveness of the transitions which belong to the second component net. Moreover if the second net is also non constraining w.r.t. the first one, we obtain a sufficient condition for the liveness of the compound net.

Lemma 3.3 *If (N_2, M_2) is live then:*
(N_1, M_1) is non constraining w.r.t. $(N_2, M_2) \Longrightarrow T_2$ is live in (N,M).

Proof. Let $M' \in [N, M >$ and $(t, c) \in TC_2$
(N_2, M_2) live and $M'/(P_2 \cup Q_2) \in [N_2, M_2 > \Longrightarrow (N_2, M'/(P_2 \cup Q_2))$ live.
So $\exists \sigma \in TC_2^*$ such that $M'/(P_2 \cup Q_2)(\sigma.(t, c) >$.
Because (N_1, M_1) is non constraining w.r.t. (N_2, M_2), Proposition 3.2 gives the existence $\sigma' \in TC^*$ such that $M'(\sigma' >$ and $Proj(\sigma', TC_2) = \sigma.(t, c)$.
Therefore we have the existence of $\alpha, \beta \in TC^*$ such that $\sigma' = \alpha.(t, c).\beta$ and $M'(\alpha.(t, c) >$. □

Theorem 3.4 *If (N_1, M_1) and (N_2, M_2) are non constraining w.r.t. each other then:*
(N_1, M_1) and (N_2, M_2) are live $\Longrightarrow (N, M)$ is live.

Proof. It follows from lemma 3.3. □

3.3 How to check the non constraining relation

Practical use of these compositionality results is limited by the difficulty of checking the non constraining relation. The algorithm deals with the reachability graph of the compound net. The main difficulty is that the finite character is undecidable for a coloured FIFO net as for a FIFO net. Indeed the construction of the reachability graph, if finite, would allow to check the liveness of the compound net but this would not be in the the spirit of liveness compositionality.

Therefore this relation can be more easily checked for component nets having a reduced size or some regularities in their structure. The verification of the non constraining relation of (N_1, M_1) w.r.t. (N_2, M_2) may be simplified if N_1 can be further decomposed by synchronization into the medium N_m and a new subnet N_{1m}.

Proposition 3.5 *Let* (N_1, M_1) *be itself the synchronization of* (N_m, N_m) *and* (N_{1m}, N_{1m})*. We have:*
(N_{1m}, M_{1m}) *is non constraining w.r.t.* $(N_m, M_m) \Longrightarrow (N_1, M_1)$ *is non constraining w.r.t.* (N_2, M_2)

Proof. Let $M' \in [N, M >$ and $(t, c) \in L(N_2, M'/(P_2 \cup Q_2))$.

1. $(t, c) \in TC_2 \setminus TC_{1m}$. We have $M'((t, c) >$.
2. $(t, c) \in TC_{1m}$
   $(t, c) \in L(N_2, M'/P_2 \cup Q_2) \Longrightarrow (t, c) \in L(N_m, M'/P_m \cup Q_m)$.
   As (N_{1m}, M_{1m}) is non constraining w.r.t. (N_m, M_m), $\exists \sigma \in (TC_{1m} \setminus TC_m)^*$ such that $M'/(P_1 \cup Q_1)(\sigma.(t, c) >$.
   We have $\sigma \in TC_1 \setminus TC_m$, let us prove that $M'(\sigma.(t, c) >$.
   As $(t, c) \in TC_{1m} \cap TC_m$, σ allows the preconditions of (t, c) in $P_{1m} \cup Q_{1m}$ to be verified.
   As $M'/(P_2 \cup Q_2)((t, c) >$, the preconditions of (t, c) in $P_m \cup Q_m$ are verified at M'.
   As σ does not affect the marking of $P_m \cup Q_m$, the preconditions of (t, c) in $P_m \cup Q_m$ remain unchanged after firing σ. Then $M'(\sigma.(t, c) >$. $\square$

In Figure 2, $SPE \setminus \{FC\}$ and RPE are mono-marked state machines. Let $N_{a1} = SPE \setminus \{FC\}$ and $N_{a2} = RPE$. The decomposition of (N_1, M_1) by the synchronization with (N_{a1}, M_{a1}) as synchronization medium gives (N_m, M_m) and (N_{1m}, M_{1m}) where $N_{1m} = UA \cup SPE \setminus \{FC\}$ represents user A together with the sender protocol entity. With (N_{a2}, M_{a2}) as synchronization medium, we have the same decomposition for (N_2, M_2) into (N_m, M_m) and (N_{2m}, M_{2m}) where $N_{2m} = UB \cup RPE$ represents user B together with the receiver protocol entity.

The advantage of Proposition 3.5 is that given a subnet N_{1m} of N_1 non constraining w.r.t. the synchronization medium N_m, we also have N_1 non constraining w.r.t. any component N_2 having the same synchronization medium N_m. Thus it is valuable to create libraries of subnets N_{1m} non constraining w.r.t the synchronization medium N_m.

More particularly state machines appear as interfaces in numerous models, among which communication protocols. They lead to a structural sufficient condition for synchronization preserving liveness in [Sou91]. So in the next section, we consider the case where a component net N_1 may be decomposed into $N_m = medium(N_1, N_2)$ and N_{1m} such that $medium(N_{1m}, N_m)$, allowing us to establish structural conditions for an easy verification of the non constraining relation.

4 A state machine as a synchronization medium

We now assume that the synchronization medium is a mono-marked state machine and that its transitions are live in the compound net. This behaviour is wide spread in interface modules of real systems.

We first present a behavioural sufficient condition for a component net to be non constraining w.r.t. a second one, given the liveness of the state machine transitions in the compound net. This sufficient condition is expressed under the form of two behavioural constraints, the freeing and the blocking relations between the conflictual merged transitions. Finally the well known notions of conflicts [TS93] are exploited and extended to coloured FIFO nets to derive structural freeing and blocking relations that imply the behavioural ones. These technical results will be useful for liveness compositionality in Section 5.

4.1 Freeing and blocking relations

As component nets are coloured FIFO nets, a conflict in the synchronization medium state machine relates two coloured transitions (t, c) and (t', c') where c and c' are respectively colors of transitions t and t' having the same input place with t and t' possibly the same. We introduce two behavioural configurations for the conflicts in the synchronization medium state machine : (t, c) frees (t', c') or (t, c) blocks (t', c') in a given component net N_i. In the last configuration, the non merged part of N_i irreversibly solves the conflict in favour of (t, c) whereas in the former configuration, a resolution of the conflict in favour of (t, c), implies a resolution in favour of (t', c') by the non merged part of N_i. These behavioural conflict relations allow to express a sufficient condition for a component net to be non constraining w.r.t. a second one, provided the state machine transitions are live in the compound net.

Definition 4.1 *(N, M) is a synchronization of (N_1, M_1) and (N_2, M_2) via a mono-marked state machine (N_a, M_a) iff $medium(N_1, N_2) = N_a$ and (N_a, M_a) is a mono-marked state machine.*

Definition 4.2 (Freeness and blocking relations) *Let (N, M) be a synchronization of (N_1, M_1) and (N_2, M_2) via a mono-marked state machine (N_a, M_a). Let $p \in P_a$, $t, t' \in p^\bullet$, $c \in C(t)$, $c' \in C(t')$ and $i \in \{1, 2\}$.*

1. *(t, c) blocks (t', c') in N_i iff:*
   $\forall M'_i \in [M_i >, M'_i((t, c) > \Longrightarrow \nexists \sigma \in (TC_i \setminus \{(t, c)\})^*$ *such that* $M'_i(\sigma.(t', c') >$,
2. *(t, c) frees (t', c') in N_i iff:*
   $\forall M'_i \in [M_i >, \exists \sigma \in (TC_i \setminus \tau_b)^*$ *such that* $M'_i((t, c).\sigma.(t', c') > \Longrightarrow$ $\exists \sigma' \in (TC_i \setminus (\{(t, c)\} \cup \tau_b)^*$ *such that* $M'_i(\sigma'.(t', c') >$ *and* $|Proj(\sigma', \tau)| \leq |Proj(\sigma, \tau)|$

where $\tau = \{(t'', c'') \in TC_a \mid t'' \in p^\bullet$ *and* $c'' \in C(t'')\}$ *and* $\tau_b = \{(t'', c'') \in \tau \mid (t', c')$ *blocks* (t'', c'') *in* $N_j\}$ *with* $j \in \{1, 2\}$ *and* $j \neq i$.

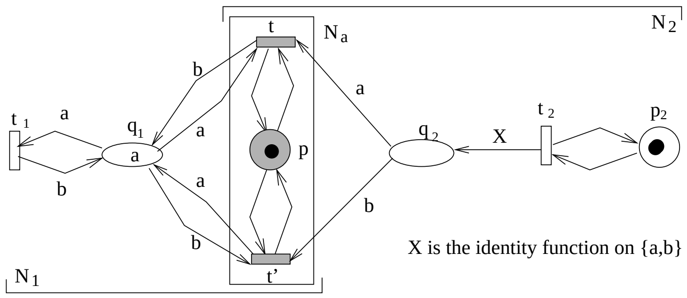

Fig. 3. Example

In the example of Figure 3, the state machine N_a consists only of the transitions t and t' and one place p that contains only a neutral color e. (t, e) and (t', e) are in conflict in N_a.

In N_2, when (t, e) is firable, no sequence without (t, e) allows to fire (t', e). So (t, e) blocks (t', e) in N_2. Similarly, (t', e) also blocks (t, e).

In N_1, for any sequence starting by (t, e) enabling (t', e) without more occurences of (t, e), there exists a sequence which with less conflict transition occurrences which does not include (t, e) and makes (t', e) firable. So (t, e) frees (t', e) in N_1.

The following proposition gives a structural condition for the non constraining relation in the case of a synchronization via a mono-marked state machine provided that the transitions of this state machine are live in the compound net. This rather technical proposition will allow to prove the Lemma 18 of Section 5. The liveness assumption that here appears as limitative, will be a natural requirement for the component nets in order that the composition rules preserve liveness.

Notation Let $im(\sigma) = \{(t, ct) \in TC \mid n(\sigma, (t, ct)) \geq 1\}$ where $n(\sigma, (t, ct))$ stands for the number of occurrences of (t, ct) in σ.

Proposition 4.3 *Let* (N, M) *be a synchronization of* (N_1, M_1) *and* (N_2, M_2) *via a mono-marked state machine* (N_a, M_a) *such that* T_a *is live in* (N, M).
If ($\forall p \in P_a$, $\forall t, t' \in p^\bullet$, $\forall c \in C(t)$, $\forall c' \in C(t')$, (t, c) *blocks* (t', c') *in* N_2 *or* (t', c') *frees* (t, c) *in* N_1*) then* (N_1, M_1) *is non constraining w.r.t.* (N_2, M_2).

Proof. Let $M' \in [M >$ such that $M'/(P_2 \cup Q_2)((t, c) >$.

1. $(t, c) \in TC_2 \setminus TC_1$, $M'/(P_2 \cup Q_2)((t, c) > \Longrightarrow M'((t, c) >$
2. $(t, c) \in TC_2 \cap TC_1$
   Because of the liveness of T_a in (N, M), there exists $\sigma \in TC^*$ such that $M'(\sigma.(t, c) >$.

Let us prove by contradiction that the shortest sequence σ_0 satisfies $Proj(\sigma, TC_2) = \epsilon$.
Let us assume $(t,c) \notin im(\sigma)$.
$\forall (t'', c'') \in im(\sigma) \cap \tau$, let $\sigma = \sigma'.(t'', c'').\sigma''$.
Let us first prove by contradiction that (t,c) does not block (t'', c'') in N_2.
We have $M'/(P_2 \cup Q_2)((t,c) >$ and $M'/(P_2 \cup Q_2)(Proj(\sigma'.(t'', c''), TC_2).(t,c) >$ with $(t,c) \notin im(\sigma')$ which is in contradiction with (t,c) blocks (t'', c'') in N_2.
So we have (t'', c'') frees (t,c) in N_1.
Let (t', c') be the first occurrence transition of τ in σ. Let $\sigma = \sigma_1.(t', c').\sigma_2$ and M'' be the marking reached after firing σ_1 at M'.
We have $M''/(P_1 \cup Q_1)((t', c').Proj(\sigma_2, TC_1).(t,c) >$.
(t', c') frees (t,c) in N_1 gives $\exists \sigma_1' \in (TC_1 \setminus (\{(t,c\} \cup \tau_b))^*$ such that $M''/(P_1 \cup Q_1)(\sigma_1'.(t,c) >$ and $|Proj(\sigma_1', \tau)| \leq |Proj(\sigma_1, \tau)|$.
A straightforward reasoning by induction on the length of $Proj(\sigma_1', \tau)$ gives $\exists \sigma_1'' \in (TC_1 \setminus (\{(t,c\} \cup \tau_b))^*$ such that $M''/(P_1 \cup Q_1)(\sigma_1''.(t,c) >$ and $|Proj(\sigma_1'', \tau)| = 0$ or $|Proj(\sigma_1'', TC_a)| = 0$.
So we have $M'/(P_1 \cup Q_1)(Proj(\sigma_1, T_1).\sigma_1''.(t,c) >$ and $Proj(\sigma_1, T_1).\sigma_1'' \in (TC_1 \setminus TC_a)^*$.
As $M'/(P_2 \cup Q_2)((t,c) >$ and $Proj(\sigma_1, T_1).\sigma_1''$ does not affect the marking of $P_2 \cup Q_2$, we have $M'(Proj(\sigma_1, T_1).\sigma_1''.(t,c) >$.
Then $Proj(\sigma_1, T_1).\sigma_1''$ is in contradiction with the minimality of σ. □

4.2 Structural sufficient conditions for the blocking and freeing relations

To obtain structural sufficient condition for the behavioural notions introduced in the former subsection, we use structural conflict relations and connectivity constraints. These relations have been first defined in [TS93] which studied the relationships between the structure and the behaviour of Equal Conflict Systems. These definitions are here naturally extended to coloured FIFO nets and a new asymmetrical conflict relation relation is defined.

Definition 4.4 (Structural conflicts) *Let $N = < P, Q, T, C, W >$ be a coloured FIFO net, P' a subset of P, Q' a subset of Q and T' a subset of T. Two coloured transitions (t,c) and (t', c') of $N(P', Q', T')$ are in:*

1. *conflict w.r.t. a place or a queue h of $N(P', Q', T')$ iff $h \in {}^\bullet t \cap {}^\bullet t'$,*
2. *conflict in $N(P', Q', T')$ iff $\exists h \in P' \cup Q'$ such that (t,c) and (t', c') are in conflict w.r.t. h,*
3. *equal conflict in $N(P', Q', T')$ iff (t,c) and (t', c') are in conflict in $N(P', Q', T')$ and $\forall h \in P' \cup Q'$, $W(h,t,c) = W(h,t',c')$,*
4. *asymmetrical conflict in $N(P', Q', T')$ iff (t,c) and (t', c') are in conflict in $N(P', Q', T')$ and $(P \cup Q) \cap {}^\bullet t \subset (P' \cup Q') \cap {}^\bullet t'$ and $\forall h \in (P' \cup Q') \cap {}^\bullet t'$, $W(h,t,c) = W(h,t',c')$.*

We first define a structural blocking relation that relies on the order with which words are removed from a FIFO queue. It can be simply expressed by the presence of a common input queue to t and t' such that the words removed by the couples (t, c) and (t', c') are not the prefix of each other. This structural sufficient condition for the blocking relation is easy to check thanks to the specificity of FIFO queues.

Definition 4.5 (Structural blocking relation) *Let $N =< P, Q, T, C, W >$ be a coloured FIFO net, P' a subset of P, Q' a subset of Q and T' a subset of T. Let (t, c) and (t', c') be two coloured transitions of $N(P', Q', T')$. (t, c) structurally blocks (t', c') in $N(P', Q', T')$ iff $\exists h \in Q'$ such that:*

1. *(t, c) and (t', c') are in conflict w.r.t. h,*
2. *$W(h, t, c) \not\prec W(h, t', c')$ and $W(h, t', c') \not\prec W(h, t, c)$,*
3. *$W(h, t, c) \not\prec W(h, t'', c''), \forall t'' \in h^\bullet \setminus \{t, t'\}$.*

Proposition 4.6 *Let (N, M) be a synchronization of (N_1, M_1) and (N_2, M_2) via a mono-marked state machine (N_a, M_a). Let $p \in P_a$, $t, t' \in p^\bullet$, $c \in C(t), c' \in C(t')$ and $i \in \{1, 2\}$. We have:*
(t, c) structurally blocks (t', c') in $N_i \Longrightarrow (t, c)$ blocks (t', c') in N_i.

Proof. Let $M'_i \in [M_i >$ such that $M'_i((t, c) >$.
Let us prove by contradiction that $\nexists \sigma' \in (TC_i \backslash \{(t, c)\})^*$ such that $M'_i(\sigma'.(t', c') >$.
Let $\sigma' \in (TC_i \setminus TC_a)^*$ such that $M'_i(\sigma'.(t', c') >$.
$M'_i((t, c) > \Longrightarrow W(h, t, c) \prec M'_i(h)$.
As h is a FIFO queue, σ' has to remove $W(h, t, c)$ from h. But the only transition which allows it, is (t, c) which is in contradiction with $\sigma' \in (TC_i \setminus \{(t, c)\})^*$.
$\square$

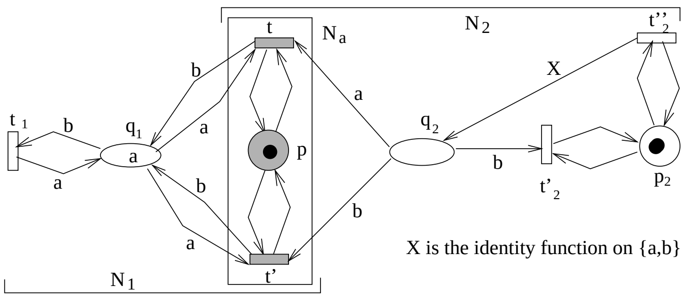

Fig. 4 Example

In Figure 4, (t, e) and (t', e) are in conflict in N_a and q_2 is the common input queue of (t, e) and (t', e). Firing (t, e) removes a from q_2 whereas firing (t', e) removes b from q_2. But a cannot be removed from q_2 by another transition whereas b can also be removed from q_2 by (t'_2, e). So (t, e) structurally blocks (t', e) in N_2. N_2 can fire (t, e) only when q_2 admits the message a as a prefix of its marking but it cannot fire (t', e) without firing (t, e). So (t, e) blocks (t', e) in N_2.

A threefold structural sufficient condition for the freeing relation is proposed. One feature can be simply expressed by means of the equal conflict relation whereas the other features consist for all the descendant transitions of t' not to be connected to non merged places or queues of N_i.

Definition 4.7 (Structural freeing relation) *Let (N, M) be a synchronization of (N_1, M_1) and (N_2, M_2) via a mono-marked state machine (N_a, M_a). Let $p \in P_a$, $t, t' \in T'$, $c, c' \in C(t) \times C(t')$ and $i \in \{1, 2\}$.*
(t', c') structurally frees (t, c) in N_i iff:

- *(t, c) and (t', c') are in asymmetrical conflict in N_i or*
- *no transition of $\{t'\} \cup \hat{\Gamma}_{N_a \setminus \{p\}}(t')$ has an adjacent queue or place in $(P_i \setminus P_a) \cup Q_i$ or*
- *t has no input queue or place in $(P_i \setminus P_a) \cup Q_i$.*

Proposition 4.8 *Let (N, M) be a synchronization of (N_1, M_1) and (N_2, M_2) via a mono-marked state machine (N_a, M_a). Let $p \in P_a$, $t, t' \in T_a$, $c \in C(t)$, $c' \in C(t')$ and $i \in \{1, 2\}$. We have:*
(t', c') structurally frees (t, c) in $N_i \Longrightarrow (t', c')$ frees (t, c) in N_i.

Proof. Let $\tau = \{(t'', c'') \in TC_a \mid t'' \in p^\bullet$ and $c'' \in C(t'')\}$, $\tau_b = \{(t'', c'') \in \tau \mid (t, c)\ blocks\ (t'', c'')\ in\ N_j\}$ with $j \in \{1, 2\}$ and $j \neq i$. Let us prove that $\forall M'_i \in [M_i >$ such that $\exists \sigma \in (TC_i \setminus \tau)^*$, $M'_i((t', c').\sigma.(t, c) > \Longrightarrow \exists \sigma' \in (TC_i \setminus (\{(t', c')\} \cup \tau_b))^*$ such that $M'_i(\sigma'.(t, c) >$. and $|Proj(\sigma', \tau)| \leq |Proj(\sigma, \tau)|$.

1. (t, c) and (t', c') are in asymmetrical conflict in N_i.
   The preconditions of (t, c) are included in those of (t', c'). Then $M'_i((t, c) >$.
   We have $\sigma' = \epsilon$.

2. No transition of $\{t'\} \cup \hat{\Gamma}_{N_a \setminus \{p\}}(t')$ has an adjacent place or queue in $(P_i \setminus P_a) \cup Q_i$.
   Let $\tau' = \{(t, c) \in TC_a \mid t \in \{t'\} \cup \hat{\Gamma}_{N_a \setminus \{p\}}(t'))$ and $c \in C(t)\}$.
   As $Proj(\sigma, \tau')$ does not affect the marking of places or queues of $(P_i \setminus P_a) \cup Q_i$, let $\sigma' = Proj(\sigma', TC_i \setminus \tau')$.
   We have $M'_i(\sigma'.(t, c) >$ with $|Proj(\sigma', \tau)| < |Proj(\sigma, \tau)|$.

3. t has no adjacent place or queue in $(P_i \setminus P_a) \cup Q_i$.
   The preconditions of (t, c) in N_i are then reduced to p. Moreover at M'_i, the only token of N_a is in p. Then $M'_i((t, c) >$. We have $\sigma' = \epsilon$. □

In Figure 4, (t, e) and (t', e) are in equal conflict in N_1. So (t, e) and (t', e) are in asymmetrical conflict and then (t, e) structurally frees (t', e) in N_1. Let M_1 be the marking of N_1. From M_1, N_1 can fire either (t, e) or (t', e) then (t_1, b) to yield M_1. Therefore at any reachable marking M'_1 and for any firable sequence $(t, e).\sigma.(t', e)$ without occurrences of (t, e) in σ, there exists a firable sequence $\sigma'.(t', e)$ such that $(t, e) \notin im(\sigma')$ and $|Proj(\sigma', \tau)| \leq |Proj(\sigma, \tau)|$. So (t, e) frees (t', e) in N_1. Symmetrically (t', e) and (t, e) are in asymmetrical conflict in N_1 so (t', e) frees (t, e) in N_1.

5 A structural sufficient condition for the liveness compositionality

We give in this section a structural sufficient condition for the non constraining relation. This condition relies on the structural freeing and blocking relations which take into account the particularity of FIFO queues. The main result of the paper is a structural sufficient condition for the liveness compositionality which is based on the structurally non constraining relation. This theorem generalizes the one in [Sou91] where the existence of a state machine is required at the interface of the merged transitions with the non merged elements within each component net. Our extension relaxes the constraints concerning the conflicts in this state machine.

5.1 A structural sufficient condition for the non constraining relation

Our structural sufficient condition for the non constraining relation of N_1 w.r.t N_2 requires an adequate decomposition of N_1. It consists in the existence of a mono-marked state machine N_{a1} ensuring the interface with the non merged elements of N_1 (cf. Figure 5). This decomposition may also be expressed by means of a synchronization where N_{a1} is the synchronization medium. The results of the former section which take into account the structural freeing and blocking relations, are applied to express a structural sufficient condition for the non constraining relation.

Let (N, M) be the synchronization of (N_1, M_1) and (N_2, M_2) with $N_m = medium(N_1, N_2)$. Let N_{1m} be a subnet of N_1 such that (N_1, M_1) is the synchronization of (N_{1m}, M_{1m}) and (N_m, M_m) via a mono-marked state machine (N_{a1}, M_{a1}).

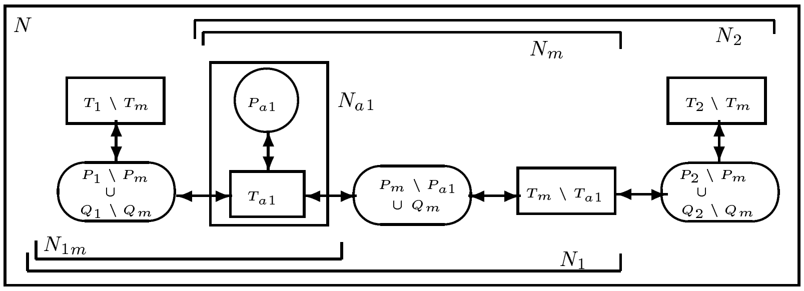

Fig. 5. N_1 structurally non constraining w.r.t. N_2

Definition 5.1 (Structural non constraining relation) N_1 *is structurally non constraining w.r.t.* N_2 *iff:*

1. $^\bullet T_{a1}^\bullet \cap ((P_2 \setminus P_m) \cup (Q_2 \setminus Q_m)) = \emptyset$,
2. $^\bullet((P_1 \setminus P_m) \cup (Q_1 \setminus Q_m))^\bullet \cap (T_m \setminus T_{a1}) = \emptyset$,

3. $\forall p \in P_{a1}$, $\forall t, t' \in p^\bullet$, $\forall c \in C(t)$, $\forall c' \in C(t')$, (t, c) *structurally blocks* (t', c') *in* N_m *or* (t', c') *structurally frees* (t, c) *in* N_{1m}.

All the conditions to hold for the structural non constraining relation are easy to check and especially the structural freeing and blocking relations as seen in Section 4.

In the coloured FIFO net of Figure 2, N_1 and N_2 are structurally non constraining w.r.t. each other.

Lemma 5.2 *Let* T_{a1} *be live in* (N_1, M_1). *We have:*
N_1 *is structurally non constraining w.r.t.* $N_2 \Longrightarrow (N_1, M_1)$ *is non constraining w.r.t.* (N_2, M_2).

Proof. Item 3 of definition 5.1 allows by applying Propositions 4.3, 4.8 and 4.6 to the decomposition of N_1 into N_{1m} and N_m, to conclude that (N_{1m}, M_{1m}) is non constraining w.r.t. (N_m, M_m). Proposition 3.5 then gives (N_1, M_1) non constraining w.r.t. (N_2, M_2). $\square$

5.2 Liveness compositionality theorem

As seen in Section 3, the satisfaction of the mutual non constraining relation by both the component nets is a sufficient condition for liveness compositionality. A structural sufficient condition for the liveness compositionality then follows from the structural non constraining relation. This condition deals with coloured FIFO nets and exploits the specificity of FIFO queues through the basic features of the structural freeing and blocking relations.

Let (N, M) be a synchronization of (N_1, M_1) and (N_2, M_2) with $N_m = medium(N_1, N_2)$. Let N_{1m} be a subnet of N_1 such that (N_1, M_1) is the synchronization of (N_{1m}, M_{1m}) and (N_m, M_m) via a mono-marked state machine (N_{a1}, M_{a1}). Let N_{2m} be a subnet of N_2 such that (N_2, M_2) is the synchronization of (N_{2m}, M_{2m}) and (N_m, M_m) via a mono-marked state machine (N_{a2}, M_{a2}).

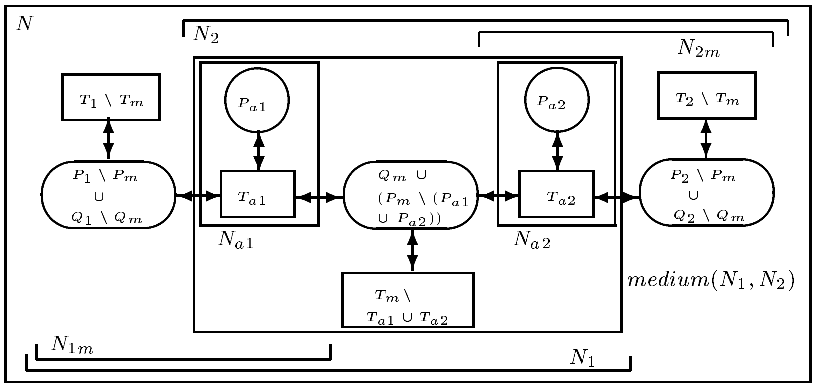

Fig. 6. N_1 and N_2 structurally non constraining w.r.t. each other

Lemma 5.3 *Let T_{a1} and T_{a2} respectively be live in (N_1, M_1) and (N_2, M_2). If the following conditions hold:*

- *N_1 and N_2 are structurally non constraining w.r.t. each other,*
- *$Q_m \cup (P_m \setminus (P_{a1} \cup P_{a2})) \neq \emptyset$,*
- *${}^\bullet(T_m \setminus (T_{a1} \cup T_{a2}))^\bullet \subset Q_m \cup (P_m \setminus (P_{a1} \cup P_{a2}))$*

then (N_1, M_1) and (N_2, M_2) are non constraining w.r.t. each other.

Proof. It follows from lemma 5.2. □

Theorem 5.4 (Composition theorem) *If the following conditions hold:*

- *N_1 and N_2 are structurally non constraining w.r.t. each other*
- *$Q_m \cup (P_m \setminus (P_{a1} \cup P_{a2})) \neq \emptyset$,*
- *${}^\bullet(T_m \setminus (T_{a1} \cup T_{a2}))^\bullet \subset Q_m \cup (P_m \setminus (P_{a1} \cup P_{a2}))$*

then (N_1, M_1) and (N_2, M_2) are live $\Longrightarrow (N, M)$ is live.

Proof. It follows from lemma 5.3 and theorem 3.4. □

5.3 Example

5.3.1 Protocol specification

The coloured FIFO net represented in Figure 7 is a generalization of the service provider modelled in Figure 2. The sliding window of the sender protocol entity has now a size of n and all the frames are numbered. The receiver protocol entity always acknowledges *dt* frames one by one. Functions I, J are used for modelling the management of frames sequence numbers on the arcs.

Within the sender protocol entity, the new features are:
– Two coloured places are now necessary for retransmitting *dt* frames within the sender protocol entity, SB'' shelters the current *dt* frame to retransmit and SB' shelters all the transmitted but not yet positively acknowledged *dt* frames.
– A state variable ruling the sequence number of the next *dt* frame to transmit is modelled by the coloured place SN.
– The first *dt* frame negatively acknowledged is retransmitted until it is positively acknowledged and then each *dt* frame inside the window is retransmitted until it positively is acknowledged.
Within the receiver protocol entity, the new features are:
– The sequence number of a received *dt* frame is compared with a state variable ruling the expected sequence number modelled by the coloured place RN.
– If the received *dt* frame has not the expected sequence number, it is ignored.

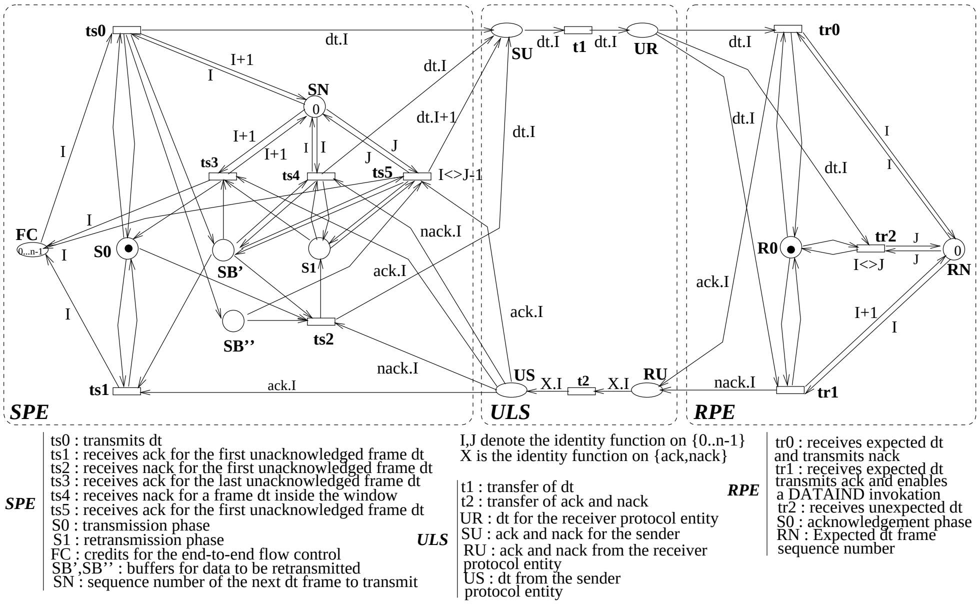

Fig. 7. Service provider model

5.3.2 Protocol verification

Let N_1 and N_2 be composed of the service users of Figure 2, each together with the service provider of Figure 7. The service provider is the synchronization medium associated with the synchronization of N_1 and N_2. It has two interface state machines $N_{a1} = SPE \setminus \{FC, SN\}$ and $N_{a2} = RPE \setminus \{RN\}$.

By checking all the couples of conflictual coloured transitions of N_{a1} and N_{a2}, we can verify that N_1 and N_2 are structurally non constraining w.r.t. each other. Theorem 5.4 can then be used to validate the liveness and boundedness of the global coloured FIFO net. Indeed, it is sufficient to prove the liveness of each component net in order to conclude that the global coloured FIFO net is live. The component nets are bounded by Max(n,k) and live because their marking graphs are strongly connected. We can then conclude that the compound net is bounded and live.

6 Conclusion

In this paper, we have presented a structural sufficient condition for synchronization preserving liveness in coloured FIFO nets. This structural condition is a sufficient condition for mutually non constraining component nets which is itself a behavioural sufficient condition for the liveness compositionality. The structural condition requires for each component net the existence of a mono-marked state machine at the interface of the synchronization medium with its non merged places or queues. Within an interface state machine, conflicts are also submitted to two structural relations. These relations which capture the specificity of FIFO queues, are easy to check and may be applied to protocols models. More general behavioural conflict relations have also been defined which, if combined with the component net requirement decomposition, allow a more general sufficient condition so that the synchronization preserves liveness.

This study may be extended in three directions. The first one is to continue relaxing the constraints of our structural sufficient condition for synchronization to preserve liveness. The second direction consists in facing synchronization to the preservation of other properties such as home state. The third direction is to define some classes of coloured FIFO nets for which liveness can be checked by polynomial algorithms.

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