Chapter 6

Properties of Information Transmission

This chapter presents properties of information transmission. First, in Section 6.1, properties of component interfaces, and properties of local component and link traces related to information transmission are presented. In Section 6.2, properties of compatibility relations are defined. Some of these properties are related to properties of component interfaces defined in Section 6.1. Finally, in Section 6.3, a discussion of the notion of a compatibility relation is presented.

6.1 Properties of Interfaces and Traces

In this section, two properties of (component) interfaces and local component and link traces are discussed. The first property is properness of traces. The properness property ensures that for each state in a trace, an immediate successor state can be distinguished. Properness is presented in Section 6.1.1. The second property, input persistence, is a property of the input interface of a component or of a link. This property states that input information can only change as a result of information transmission. The input persistence property is defined in terms of an important notion, transmission octets, which is defined in Section 6.1.2 below. The input persistence property itself is discussed in Section 6.1.3.

6.1.1 Properness and Finite Variability

Some properties of compatibility relations refer to immediate successor states, or *next states*. Time frames as defined in Section 5.2.1 are not necessarily discrete. Therefore, a next state of a state $\nu_{A,i}$ is defined as the first state after $\nu_{A,i}$ that differs from $\nu_{A,i}$. Formally:

Definition 6.1. (Next and previous state). *Let $LT = \langle TF; V \rangle$ be a local component or link trace with time frame $TF = \langle T; < \rangle$.*

- *A* next state *of a state* $V(t)$ *is a state* $V(t')$ *such that* $t<t'$ *and* $V(t')\neq V(t)$ *and for all* t'' *with* $t<t''<t'$ *it holds that* $V(t)=V(t'')$. *The set of all next states of a state* $V(t)$ *is denoted* $next_{LT}(V(t))$.
- *A* previous state *of a state* $V(t)$ *is a state* $V(t')$ *such that* $t'<t$ *and* $V(t')\neq V(t)$ *and for all* t'' *with* $t'<t''<t$ *it holds that* $V(t)=V(t'')$. *The set of all previous states of a state* $V(t)$ *is denoted* $prev_{LT}(V(t))$.

Note that, for a discrete time frame, it is possible that there are two time points t and t' such that there is no t'' with $t<t''<t'$, while $V(t')=V(t)$. For a dense time frame, there are usually intervals of time for which the state remains constant.

Traces in which up to a specific point in time t, each state $V(t')$ with $t'<t$ has a next state and a previous state (unless $t'=\bot$), are called *proper traces*.

Definition 6.2. (Proper trace). *A local component or link trace* $LT=\langle TF;V\rangle$ *with time frame* $TF=\langle T;<\rangle$ *is a* proper trace *iff for all* $t\in T$, $V(t)$ *has a next state and a previous state unless* $t=\bot$, *or there is a* $t'\in T$ *such that for all* $t\in T$ *with* $t'<t$, $V(t)$ *has a next state and a previous state unless* $t=\bot$, *and for all* $t''\geq t'$, $V(t'')=V(t')$.

It is not the case that for a proper trace, the order of the time frame is necessarily discrete. However, the order of the *states* induced by the next state relation, i.e. the order $\{\langle v_{S,i};v_{S,j}\rangle \mid v_{s,j}\in next_{LT}(v_{S,i})\}$, is discrete.

For a proper trace with a dense order, another property can be defined: the *finite variability* or *non-Zenoness* property (Barringer, Kuiper & Pnueli, 1986). This property asserts that in a finite amount of time, only a finite number of next states can be distinguished. This property is not formally defined in this thesis. Instead, a trace that does not have the finite variability property is depicted (Figure 6.1).

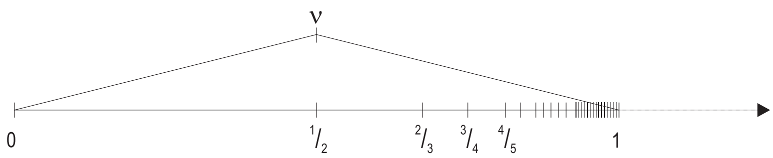

Figure 6.1: A trace that does not have the finite variability property.

In Figure 6.1, the horizontal line represents a dense set of time points of the time frame, i.e. the set of reals. The small vertical lines represent time points at which there is a state change. As can be seen from the figure, on the horizontal line, state changes occur at $t=1/2$, $t=2/3$, $3/4$, $t=4/5$, and so on. There are an infinite number of state changes before $t=1$, but nevertheless, for every $t\in[0,1)$, the state at t has a next state. Thus, the trace depicted in the figure is a trace that does not have the finite variability property. (The trace depicted in Figure 6.1 is a proper trace, because all states except the state at $t=0$ have a previous state. A previous state of the state at $t=1$ is state ν.)

The semantic structure presented in this thesis is not committed to a specific choice with respect to properness and finite variability of traces. However, as indicated in Chapter 1, the semantic structure is based on the assumption that global time does not exist. This assumption is related to the properties presented in this section. First, two different conceptions of the notion of time are presented, which are called *observer time* and *implied time*:

- A local trace describes the behaviour of a component or link. A possible way to interpret such a trace is to view the trace as a record of observations made by a dedicated observer of the component or link. An observer has access to a device that generates a sequence of time points. (E.g., a wall clock, or a stopwatch. Whether these ticks are generated at regular intervals cannot be determined by the observer.) The observer is able to observe the state of the component or link. (As the observer is dedicated to the component or link it observes, the observer does not observe any other component or link.) At each time tick, the observer makes note of the state of the component or link, which results in a local component or link trace. Thus, this trace is based on *observer time*: the (notion of) time of an observer. The observer's time device can be assumed to generate a continuous sequence of time points (this is probably the normal conception of real-world time). This case naturally leads to a dense time frame for the local component trace, although this is not necessary. With observer time, whether dense or discrete, it is frequently the case that for two consecutive time points or an interval of time, the state of the component or link remains the same.

- A second way to interpret a local trace is to view the component or link itself as the source of the time frame of the trace. No observer and no external time device is assumed. Instead, each change of the (externally visible part) of the component or link defines a new point in time. In other words, (a notion of) time is *implied* by the activity of the component or link. If the behaviour of the component or link is continuous, the implied time is dense. If the behaviour of the component or link is discrete, the implied time is discrete. A consequence of this interpretation is that, in a discrete time frame, for any pair of time points t,t' such that there is no t'' with $t<t''<t'$, $V(t)\neq V(t')$. (If this were not the case, then t' would not be distinguished as a new point in time). In a dense time frame, a similar property holds: for any two points in time t and t', no matter how close to one another, there is always a time point t'' such that $t<t''<t'$, $V(t'')\neq V(t)$ and $V(t'')\neq V(t')$.

The semantic structure presented in this thesis does not assume that local traces are interpreted as observer time or as implied time. However, as the semantic structure is based on the assumption that global time does not exist, neither the observer time interpretation nor the implied time interpretation for a specific component or link can be used as a reference time for another component or link. As an example, if the observer time interpretation is adopted, then it is assumed that no two components or link share an observer or its time device. (This is the result of the assumption that observers are dedicated.)

6.1.2 Transmission Octets

Information transmission establishes a relation between two components and a link, or between two links and a component. More specifically, each occurrence of an information transmission establishes a relation between states of the domain and co-domain of a specific link: a state of the domain contains information, which is transmitted to the co-domain, in which a new state results from this transmission. This correspondence is the basis of interaction.

In fact, in the semantic structure presented in this thesis, the relation can be extended to a correspondence between eight states, as explained in this section. Tuples of eight states that correspond as a result of information transmission are called *transmission octets*. The relation between the eight states of a transmission octet is related to an information link mapping: tuples composed of eight states that occur in local component and link traces of a link, its domain and co-domain, form a transmission octet if they comply with the information link mapping of the link. This relation is formally defined in this section.

A transmission octet for a link *I* is an octet consisting of two states from a local component or link trace of the domain of *I*, four states from a local link trace of *I* and two states from a local component or link trace of the co-domain of *I*. A transmission octet thus consists of states taken from the behaviour of a link, its domain and its co-domain as represented by local component and link traces. The connection with the intended information transmission functionality of the link is made as follows: an octet of states is a transmission octet if the states in the octet equal an element of the information link mapping of *I* and have a specific order in the local traces from which they are taken. (The information link mapping of a link consists of substates taken from the set of all possible states of a link, its domain and co-domain—the sets $\mathcal{S}_I$, $\mathcal{S}_{dom(I)}$ and $\mathcal{S}_{cdom(I)}$, respectively.

The definition of a transmission octet only enforces that the two states of the domain have a specific order in the local trace of the domain, and likewise for the four states of the link itself and the two states of the co-domain. The definition of a transmission octet does not enforce any other relation between the two states of the domain of the link, or between the two states of the co-domain of the link, or between the four states of the link itself. Thus, almost any two states of the domain of a link, together with four states of the link itself and two states of the co-domain, can potentially form a transmission octet, regardless of the number of states in-between the states in the domain, link or co-domain,. The definitions of properties of compatibility relations in Section 6.2, however, do enforce relations between the two states of the domain of a link, between the four states of the link, and between the two states of the co-domain. E.g., a specific property holds for a compatibility relation for a link if a state of the domain of the link and its immediate successor state, together with four states of the link in a specific order and a state of the co-domain with its immediate successor, form a transmission octet.

The notion of a transmission octet is close to the notion of an information link mapping. The difference between, on the one hand, a transmission octet, and, on the other hand, an information link mapping is as follows. An information link mapping consists, as indicated by Definition 5.6, of octets of *substates* taken from the sets of possible states of a link, its domain and co-domain. (The exact choice of substates varies for the six types of information links distinguished in the semantic structure.) However, local component and link traces consist of states. For a specific property of a compatibility relation, only specific substates of these states are relevant, depending on the type of the link with which the compatibility relation is associated (see below). Contrary to an information link mapping, a transmission octet consists of *states*. A transmission octets matches *states* from local component or link traces with (input and output) *substates* from an information link mapping.

As stated before, properties of compatibility relations are expressed in terms of transmission octets. The relationship between compatibility relations and transmission octets can be illustrated as follows. Loosely speaking, properties of compatibility relations (which are relations defined on *traces*), require that specific combinations of eight states—two from a local trace of the domain of a link, four from a local trace of the link itself and two of a local trace of the co-domain—form transmission octets. Again loosely speaking, if for all states in a trace of the domain or co-domain of a link, such combinations can be found, then a compatibility relation for that link satisfies a specific property.

To summarise, information link mappings, transmission octets and compatibility relations are compared as follows. An information link mapping relates *eight substates* from the *sets of all states* of two components and a link or a component and two links (Thus, an information link mapping does not refer to traces). A transmission octet relates *eight states* taken from *traces* of two components and a link or one component and two links, such that these eight states constitute an instance of transmission as described by an information link mapping. A *property* of a compatibility relation requires, loosely speaking, that specific octets of states taken from triples of traces in the compatibility relation form transmission octets. (Different properties require different specific octets to form transmission octets.)

For ease of comprehension, the definition of a transmission octet below deliberately uses the names of the link, components and states depicted in Figure 2.7 as the names of the variables in the definition. In the definition, the following notation is used: let $LT_S=\langle T;V\rangle\in\mathcal{LT}_S$ be a local component or link trace. The state $V(t)$ in LT_S at time point $t\in T$ is denoted $v_{S,t}$ or sometimes $LT_S(t)$.

Definition 6.3. (Transmission octet). *Let LT_A, LT_B and LT_L be three local traces of components A and B and an information link L with information link mapping λ_L, such* *that A=dom(L) and B=cdom(L). Let* $\nu_{A,i}$ *and* $\nu_{A,j}$ *be two states in* LT_A*, let* $\nu_{L,i''}$*,* $\nu_{L,j''}$*,* $\nu_{L,k}$ *and* $\nu_{L,l}$ *be four states in* LT_L *and let* $\nu_{B,i'}$ *and* $\nu_{B,j'}$ *be two states in* LT_B*. The octet* $\langle\langle\nu_{A,i};\nu_{A,j}\rangle;\langle\nu_{L,i''};\nu_{L,j''};\nu_{L,k};\nu_{L,l}\rangle;\langle\nu_{B,i'};\nu_{B,j'}\rangle\rangle$ *is a* transmission octet *with respect to* LT_A*,* LT_L *and* LT_B *iff* $i<_A j$*,* $i''<_L j''<_L k<_L l$*,* $i'<_B j'$ *and:*

- *L is a private link and* $\langle\langle out(\nu_{A,i});out(\nu_{A,j})\rangle;\langle\nu_{L,i''};\nu_{L,j''};\nu_{L,k};\nu_{L,l}\rangle;\langle in(\nu_{B,i'});in(\nu_{B,j'})\rangle\rangle\in\lambda_L$*, or*
- *L is an import mediating link and* $\langle\langle in(\nu_{A,i});in(\nu_{A,j})\rangle;\langle\nu_{L,i''};\nu_{L,j''};\nu_{L,k};\nu_{L,l}\rangle;\langle in(\nu_{B,i'});in(\nu_{B,j'})\rangle\rangle\in\lambda_L$*, or*
- *L is an export mediating link and* $\langle\langle out(\nu_{A,i});out(\nu_{A,j})\rangle;\langle\nu_{L,i''};\nu_{L,j''};\nu_{L,k};\nu_{L,l}\rangle;\langle out(\nu_{B,i'});out(\nu_{B,j'})\rangle\rangle\in\lambda_L$*, or*
- *L is a cross-mediating link and* $\langle\langle in(\nu_{A,i});in(\nu_{A,j})\rangle;\langle\nu_{L,i''};\nu_{L,j''};\nu_{L,k};\nu_{L,l}\rangle;\langle out(\nu_{B,i'});out(\nu_{B,j'})\rangle\rangle\in\lambda_L$*, or*
- *L is a link modifier link and* $\langle\langle out(\nu_{A,i});out(\nu_{A,j})\rangle;\langle\nu_{L,i''};\nu_{L,j''};\nu_{L,k};\nu_{L,l}\rangle;\langle\nu_{B,i'};\nu_{B,j'}\rangle\rangle\in\lambda_L$*, or*
- *L is a link monitoring link and* $\langle\langle\nu_{A,i};\nu_{A,j}\rangle;\langle\nu_{L,i''};\nu_{L,j''};\nu_{L,k};\nu_{L,l}\rangle;\langle in(\nu_{B,i'});in(\nu_{B,j'})\rangle\rangle\in\lambda_L$*.*

Example 6.4. In Example 5.19 a compatibility relation for the traces $lt_{\text{broker},1}$, $lt_{\text{broker\_to\_user\_1}}$ and $lt_{\text{user\_1},1}$ is presented. The current example presents two transmission octets for these traces, to provide a more detailed view on the compatibility relation. The transmission octets presented in the current example are used in another example in Section 6.2.1 to illustrate the definition of a property of a compatibility relation in terms of transmission octets. For ease of reference, the information link mapping for broker_to_user_1, given in Example 5.7, is repeated here:

$\lambda_{\text{broker\_to\_user\_1}}$ =*{*⟨⟨to_be_communicated_to(*t*,user_1)*;*just_communicated_to(*t*,user_1)⟩*;*
⟨awake_and_empty*;*active_and_contents*(t);*active_and_contents*(t);*
awake_and_empty⟩*;*⟨ready_for_information*;*
communicated_by(*t'*,broker)⟩⟩ | $t\in OT_2$, $t'\in OT_1$ *and t'=trans(t)}.*

In this example, assume that *trans(*res_1*)*=res_3. First, consider the following octet of states, taken from the traces $lt_{\text{broker},1}$ and $lt_{\text{user\_1},1}$ given in Example 5.14, and $lt_{\text{broker\_to\_user\_1}}$, given in Example 5.17:

⟨⟨∅ | belief(match(res_1,query_1)) | to_be_communicated_to(res_1,user_1);	*(4th state in* $lt_{\text{broker},1}$*)*
∅ | belief(match(res_1,query_1)) | just_communicated_to(res_1,user_1)⟩*;*	*(5th state in* $lt_{\text{broker},1}$*)*
⟨awake_and_empty*;*	*(1st state in* $lt_{\text{broker\_to\_user\_1}}$*)*
active_and_contents(res_1)*;*	*(2nd state in* $lt_{\text{broker\_to\_user\_1}}$*)*
active_and_contents(res_1)*;*	*(2nd state in* $lt_{\text{broker\_to\_user\_1}}$*)*
awake_and_empty⟩*;*	*(3rd state in* $lt_{\text{broker\_to\_user\_1}}$*)*

⟨ready_for_information | ∅ | ∅; *(2nd state in* $lt_{\text{user\_1},1}$*)*
communicated_by(res_3,broker) | ∅ | ∅⟩⟩ *(3rd state in* $lt_{\text{user\_1},1}$*)*

The first element in this octet is referred to as $v_{\text{broker\_1},4}$, the second as $v_{\text{broker\_1},5}$ the third to the sixth as $v_{\text{broker\_to\_user\_1},i}$ for $i=1,\ldots 4$, respectively, the seventh as $v_{\text{user\_1},2}$ and the eight as $v_{\text{user\_1},3}$. This octet is a transmission octet for the following reason: broker_to_user_1 is a private link, $out(v_{\text{broker\_1},4})$= to_be_communicated_to(res_1,user_1), $out(v_{\text{broker\_1},5})$=just_communicated_to(res_1,user_1), $in(v_{\text{user\_1},2})$=ready_for_information, and $in(v_{\text{user\_1},3})$=communicated_by(res_3,broker). Thus:

⟨⟨$out(v_{\text{broker\_1},4})$;$out(v_{\text{broker\_1},5})$⟩;
⟨$v_{\text{broker\_to\_user\_1},1}$; $v_{\text{broker\_to\_user\_1},2}$; $v_{\text{broker\_to\_user\_1},2}$; $v_{\text{broker\_to\_user\_1},3}$⟩;
⟨$in(v_{\text{user\_1},2})$;$in(v_{\text{user\_1},3})$⟩⟩
= ⟨⟨to_be_communicated_to(res_1,user_1);just_communicated_to(res_1,user_1)⟩;
⟨awake_and_empty; active_and_contents(res_1);active_and_contents(res_1)
awake_and_empty⟩;⟨ready_for_information;
communicated_by(res_3,broker)⟩⟩
$\in\lambda_{\text{broker\_to\_user\_1}}$

This is exactly as required for a private link by Definition 6.3.

Second, consider an octet of states similar to the octet given in the first part of this example, but with the first element replaced by ∅|belief(match(res_1,query_1))|∅, named $v_{\text{broker\_1},1}$, which is the first state in $lt_{\text{broker\_1},1}$. The octet with $v_{\text{broker\_1},1}$ is *not* a transmission octet for broker_to_user_1, for the following reason: $out(v_{\text{broker\_1},1})$=∅[7], thus ⟨⟨$out(v_{\text{broker\_1},4})$;$out(v_{\text{broker\_1},5})$⟩;⟨$v_{\text{broker\_to\_user\_1},1}$; $v_{\text{broker\_to\_user\_1},2}$; $v_{\text{broker\_to\_user\_1},2}$; $v_{\text{broker\_to\_user\_1},3}$⟩;⟨$in(v_{\text{user\_1},2})$;$in(v_{\text{user\_1},3})$⟩⟩$\notin\lambda_{\text{broker\_to\_user\_1}}$, which is contrary to the requirement for a private link as given by Definition 6.3. ■

6.1.3 Input Persistence

The first property of a component defined in this section, the input persistence property, specifies that information that is input to the component cannot change spontaneously:

Definition 6.5. (Input persistence property). *Let* $SH=\langle Comp;Lnk;\prec;dom;cdom\rangle$ *be a structure hierarchy, let* μ *be a multitrace for SH and let* $C\in Comp$ *be a component with* $\mu_C=\langle\langle T_C;<_C\rangle;V_C\rangle$. *Component C has the* input persistence property *if for each* $j'\in T_C\setminus\{\perp\}$, *either:*

- *There is an* $I\in Lnk$ *with* $cdom(I)=C$, $\mu_I=\langle\langle T_I;<_I\rangle;V_I\rangle$ *and* $\mu_{dom(I)}=\langle\langle T_{dom(I)};<_{dom(I)}\rangle;V_{dom(I)}\rangle$ *such that there exist* $i'\in T_C$, $i''<_I j''<_I k<_I l\in T_I$ *and* $i<_{dom(I)} j\in T_{dom(I)}$ *such that* $\langle\langle v_{dom(I),i};v_{dom(I),j}\rangle;\langle v_{I,i''};v_{I,j''};v_{I,k};v_{I,l}\rangle;\langle v_{C,i'};v_{C,j'}\rangle\rangle$ *is a transmission octet for* $LT_{dom(I)}$, LT_I *and* LT_C,

[7] ∅ is the name of a state (see Example 5.2), not the empty set.

- *Or, there is an* $i' \in T_C$ *with* $i' <_C j'$ *such that for all* $m \in T_C$ *with* $i' <_C m \leq_C j'$, $in(v_{C,m}) = in(v_{C,j'})$.

This property specifies that for each state $v_{S,j'}$, one of the following requirements holds:

- There is another component or link in *SH* that provides new input to *C*. Formally, it is required that there is a link in *SH* with *C* as co-domain, such that a state $v_{C,i'}$ exists that is a predecessor (not necessarily immediate) of $v_{C,j'}$, four states $v_{I,i''}$, $v_{I,j''}$, $v_{I,k}$, and $v_{I,l}$ and two states $v_{dom(I),i}$ and $v_{dom(I),j}$ such that all eight states together form a transmission octet. This implies that the input substate of state $v_{C,j'}$ contains information obtained from the domain of link *I*, where it was available in state $v_{dom(I),i}$. Moreover, the transmission is carried out in conformance with the information link mapping. Two enabling conditions (represented by the states $v_{I,i''}$ and $v_{C,i'}$, respectively) are also fulfilled.
- Or, the input substate of state $v_{C,j'}$ has not changed, i.e., a time point *i'* can be found such that for all time points *m* between *i'* and *j'*, the input substate of *m* equals the input substate of $v_{C,j'}$.

This property models input persistence in the sense that if the input substate changes, then the change is caused by information transmission. Otherwise, the input substate is persistent: it is the same as in the previous state.

6.2 Properties of Compatibility Relations

Section 5.2.2 defined a compatibility relation for a link *I* as a ternary relation on the set of local component or link traces of the domain of *I*, the set of link traces of *I* and the set of local component or link traces of the co-domain of *I*. The formal definition is repeated here for ease of reference:

Definition 5.18. (Compatibility relation). *A* compatibility relation *for a link I is a relation* $\mathcal{CR}_I \subseteq \mathcal{LT}_{dom(I)} \times \mathcal{LT}_I \times \mathcal{LT}_{cdom(I)}$.

As stated in Section 5.2.2, compatibility relations are used to model constraints imposed by information transmission. However, Section 5.2.2 does not define how compatibility relations model different properties of information transmission, such as reliability (whether information can be lost). This chapter defines such properties of compatibility relations. Applications of the semantic structure may or may not choose to adopt these properties.

As stated earlier, a compatibility relation for a link relates states that occur in the actual behaviour of the link, its domain and co-domain, in conformance with the information link mapping given for the link. In fact, the connection between, on the one hand, an information link mapping and, on the other hand, states that actually occur in local component and link traces is formalised by the notion of *transmission octets*, introduced in Section 6.1.1. The various properties of information transmission are defined in this section in terms of transmission octets. In sections 6.2.1 to 6.2.4, four properties are presented.

6.2.1 Lossless Transmission Property

The first possible property of a compatibility relation defined in this section, the lossless transmission property, specifies that no data is lost during information transmission. Formally:

Definition 6.6. (Lossless transmission property). *Let $\mathcal{CR}_I$ be a compatibility relation for a link I. For this compatibility relation the* lossless transmission property *holds iff for each* $\langle LT_{dom(I)};LT_I;LT_{cdom(I)}\rangle\in\mathcal{CR}_I$: *with* $LT_I=\langle\langle T_I;<_I\rangle;V_I\rangle$, $LT_{dom(I)}=\langle\langle T_{dom(I)};<_{dom(I)}\rangle;V_{dom(I)}\rangle$, *and* $LT_{cdom(I)}=\langle\langle T_{cdom(I)};<_{cdom(I)}\rangle;V_{cdom(I)}\rangle$: *for all* $i\in T_{dom(I)}$ *it holds that either:*

- *There exist* $j\in T_{dom(I)}$, $i''<_I j''<_I k<_I l\in T_I$ *and* $i'<_{cdom(I)} j'\in T_{cdom(I)}$ *such that* $\langle\langle v_{dom(I),i};v_{dom(I),j}\rangle;\langle v_{I,i''};v_{I,j''};v_{I,k};v_{I,l}\rangle;\langle v_{cdom(I),i'};v_{cdom(I),j'}\rangle\rangle$ *is a transmission octet,*
- *Or, one of the following holds:*
  - *There is no* $\langle\langle out(v_{dom(I),i});\sigma_2\rangle;\langle\sigma_3;\sigma_4;\sigma_5;\sigma_6\rangle;\langle\sigma_7;\sigma_8\rangle\rangle\in\lambda_I$ *for any* $\sigma_2,\ldots,\sigma_8$, *if I is a private link, an export mediating link or a link modifier link, and*
  - *There is no* $\langle\langle in(v_{dom(I),i});\sigma_2\rangle;\langle\sigma_3;\sigma_4;\sigma_5;\sigma_6\rangle;\langle\sigma_7;\sigma_8\rangle\rangle\in\lambda_I$ *for any* $\sigma_2,\ldots,\sigma_8$, *if I is an import mediating link or a cross-mediating link, and*
  - *There is no* $\langle\langle v_{dom(I),i};\sigma_2\rangle;\langle\sigma_3;\sigma_4;\sigma_5;\sigma_6\rangle;\langle\sigma_7;\sigma_8\rangle\rangle\in\lambda_I$ *for any* $\sigma_2,\ldots,\sigma_8$, *if I is a link monitoring link.*

This property specifies that for each state $v_{dom(I),i}$, one of the following requirements must hold:

- There exists a state $v_{dom(I),j}$ that is a successor (not necessarily immediate) of $v_{dom(I),i}$, four states $v_{I,i''}$, $v_{I,j''}$, $v_{I,k}$, and $v_{I,l}$, two states $v_{cdom(I),i'}$ and $v_{cdom(I),j'}$ such that all eight states together form a transmission octet. For a private link, this implies that for each state $v_{dom(I),i}$, if the output substate of $v_{dom(I),i}$ should, according to the information link mapping of *I*, be transmitted, and two enabling conditions (represented by the states $v_{I,i''}$ and $v_{cdom(I),i'}$, respectively) are fulfilled, then there should be a state $v_{cdom(I),j'}$ in which the effect of the transmission as specified by the information link mapping is present.
- Or, state $v_{dom(I),j}$ is not applicable for transmission via link *I*, which is indicated by the absence of an octet of states in the information link mapping of *I* in which (a substate of) $v_{dom(I),j}$ is the first element.

This property models lossless transmission in the sense that if, according to the information link mapping, transmission is required, then there is a state in the trace of the co-domain in which the effect of the transmission is present. Thus, the information is not lost in transit.

From the definition of the lossless transmission property, a number of interesting characteristics of compatibility relations can be observed:

- Like an information link mapping, a compatibility relation does not refer to the actual behaviour of components: a compatibility relation only refers to arbitrary local component and link traces. Instead, a compatibility relation in a sense lifts intended information transmission as defined by information link mappings, from possible states to states that occur in local component and link traces. These local component and link traces are possible behaviours and not necessarily actual traces of a component. However, as explained in Section 5.2.2, compatibility relations are used to define actual behaviour of composed components. In this case, compatibility relations impose a structure on multitraces consisting of actual component behaviour.

- The lossless transmission property does *not* specify that the *moment in time* at which state $v_{dom(I),i}$ in $LT_{dom(I)}$ or state $v_{I,k}$ in LT_I occurs must precede the moment in time at which state $v_{cdom(I),j}$ in $LT_{cdom(I)}$ occurs. However, it *does* specify that the input substate of the co-domain of I depends on output substate of the domain of I and the state of I. With the definition presented, it is not even possible to express that moments in time for the domain of I have any relation with moments in time of the co-domain of I, because no relationship between time in the domain and co-domain (represented by their traces) is given. In the next chapter, the relationship between dependence and global temporal precedence is explored in more detail.

- The lossless transmission property is related to the commitments put forward in Chapter 2. In particular, the commitment to non-blocking send and receive operations presented in Section 2.2.5 and Section 2.2.6, respectively, are represented in the definition of the lossless transmission property. These commitments are represented by the (relatively weak) requirements that state $v_{dom(I),j}$ is a successor, but not an immediate successor, of $v_{dom(I),i}$ (non-blocking send) and that state $v_{cdom(I),j'}$ is a successor, but not an immediate successor, of $v_{cdom(I),i'}$ (non-blocking receive).

Example 6.7. Example 5.20 in Chapter 5 presents a compatibility relation for the link broker_to_user_1. Example 5.20 claims that one of the elements of this compatibility relation is the triple $\langle lt_{\text{broker},1};lt_{\text{broker\_to\_user\_1}};lt_{\text{user\_1},1}\rangle$, with the local component traces $lt_{\text{broker},1}$ and $lt_{\text{user\_1},1}$ as presented in Example 5.14 and the local link trace $lt_{\text{broker\_to\_user\_1}}$ as presented in Example 5.17. Example 6.4 presented two transmission octets for these traces.

The current example shows that the triple $\langle lt_{\text{broker},1};lt_{\text{broker\_to\_user\_1}};lt_{\text{user\_1},1}\rangle$ satisfies the lossless transmission property. Thus, for each state $v_{\text{broker},i}$ it has to be shown that either there are states in $lt_{\text{broker\_to\_user\_1}}$ and $lt_{\text{user\_1},1}$ such that these states form a transmission octet, or $v_{\text{broker},i}$ is not applicable to transmission via the (private) link broker_to_user_1:

- $v_{\text{broker},i}$ for $i=1,2,3$: $out(v_{\text{broker},i})=\varnothing$, and there is no element $\langle\langle\varnothing;\sigma_2\rangle;\langle\sigma_3;\sigma_4;\sigma_5;\sigma_6\rangle;\langle\sigma_7;\sigma_8\rangle\rangle\in\lambda_{\text{broker\_to\_user\_1}}$ for any $\sigma_2,\ldots,\sigma_8$, so the second clause of Definition 6.6 holds.
- $v_{\text{broker},4}$: According to Example 6.4, the following octet is a transmission octet for the traces $lt_{\text{broker},1}$, $lt_{\text{broker\_to\_user\_1}}$ and $lt_{\text{user\_1},1}$:

  ⟨⟨∅ | belief(match(res_1,query_1)) | to_be_communicated_to(res_1,user_1);
  ∅ | belief(match(res_1,query_1)) | just_communicated_to(res_1,user_1)⟩;
  ⟨awake_and_empty;
  active_and_contents(res_1);
  active_and_contents(res_1);
  awake_and_empty⟩;
  ⟨ready_for_information | ∅ | ∅;
  communicated_by(res_3,broker) | ∅ | ∅⟩⟩
  $=\langle\langle v_{\text{broker},4};v_{\text{broker},5}\rangle;$
  $\langle v_{\text{broker\_to\_user\_1},1};v_{\text{broker\_to\_user\_1},2};v_{\text{broker\_to\_user\_1},2};v_{\text{broker\_to\_user\_1},3}\rangle;$
  $\langle v_{\text{user\_1},2};v_{\text{user\_1},2}\rangle\rangle.$

  Thus, there exist a j in T_{broker}, an i'', j'', k and l in $T_{\text{broker\_to\_user\_1}}$, and an i' and j' in $T_{\text{user\_1}}$ such that $\langle\langle v_{dom(I),i};v_{dom(I),j}\rangle;\langle v_{I,i''};v_{I,j''};v_{I,k};v_{I,l}\rangle;\langle v_{cdom(I),i'};v_{cdom(I),j'}\rangle\rangle$ is a transmission octet (take $j=5$, $i''=1$, $j''=2$, $k=2$, $l=3$, $i'=2$ and $j'=3$). It also holds that $v_{I,2}\in next_{LT_I}(v_{I,1})$ and $v_{I,3}\in next_{LT_I}(v_{I,3})$, for I=broker_to_user_1. Thus, for $v_{\text{broker},4}$, the first clause of Definition 6.6 holds.

- $v_{\text{broker},5}$: $out(v_{\text{broker},i})$=just_communicated_to(res_1,user_1), and there is no element $\langle\langle$just_communicated_to(res_1,user_1)$;\sigma_2\rangle;\langle\sigma_3;\sigma_4;\sigma_5;\sigma_6\rangle;\langle\sigma_7;\sigma_8\rangle\rangle\in\lambda_{\text{broker\_to\_user\_1}}$ for any $\sigma_2,\ldots,\sigma_8$, so the second clause of Definition 6.6 holds.

Thus, for each state in $lt_{\text{broker},1}$, the requirements of Definition 6.6 hold. ■

Example 6.8. The lossless transmission property only requires that for each state in the domain of a link that contains information that has to be transmitted, there is a state in the co-domain in which this information is present. It does not require that this state is unique. This is illustrated as follows. Suppose that there is a trace $lt_{\text{broker},3}$, which is a copy of $lt_{\text{broker},1}$ extended with two new states, $v_{\text{broker},6}$ and $v_{\text{broker},7}$, with $v_{\text{broker},6}=v_{\text{broker},4}$ and $v_{\text{broker},7}=v_{\text{broker},5}$. The triple $\langle lt_{\text{broker},3};lt_{\text{broker\_to\_user\_1}};lt_{\text{user\_1},1}\rangle$ also satisfies the lossless transmission property: for each state $v_{\text{broker},i}$, either there are states in $lt_{\text{broker\_to\_user\_1}}$ and $lt_{\text{user\_1},1}$ such that these states form a transmission octet, or $v_{\text{broker},i}$ is not applicable to transmission via the (private) link broker_to_user_1:

- $v_{broker,i}$ for $i=1,\ldots,5$: same reason as in the previous example.
- $v_{\text{broker},6}$: According to Example 6.4, the following octet is a transmission octet for the traces $lt_{\text{broker},3}$, $lt_{\text{broker\_to\_user\_1}}$ and $lt_{\text{user\_1},1}$:

  ⟨⟨∅ | belief(match(res_1,query_1)) | to_be_communicated_to(res_1,user_1);
  ∅ | belief(match(res_1,query_1)) | just_communicated_to(res_1,user_1)⟩;
  ⟨awake_and_empty;
  active_and_contents(res_1);
  active_and_contents(res_1);
  awake_and_empty⟩;
  ⟨ready_for_information | ∅ | ∅;
  communicated_by(res_3,broker) | ∅ | ∅⟩⟩
  $=\langle\langle v_{\text{broker},6}; v_{\text{broker},7}\rangle;$
  $\langle v_{\text{broker\_to\_user\_1},1}; v_{\text{broker\_to\_user\_1},2}; v_{\text{broker\_to\_user\_1},2}; v_{\text{broker\_to\_user\_1},3}\rangle;$
  $\langle v_{\text{user\_1},2}; v_{\text{user\_1},2}\rangle\rangle.$

  Thus, there exist a j in T_{broker}, an i'', j'', k and l in $T_{\text{broker\_to\_user\_1}}$, and an i' and j' in $T_{\text{user\_1}}$ such that $\langle\langle v_{dom(I),i}; v_{dom(I),j}\rangle;\langle v_{I,i''}; v_{I,j''}; v_{I,k}; v_{I,l}\rangle;\langle v_{cdom(I),i'}; v_{cdom(I),j'}\rangle\rangle$ is a transmission octet (take $j=7$, $i''=1$, $j''=2$, $k=2$, $l=3$, $i'=2$ and $j'=3$). It also holds that $v_{I,2}\in next_{LT_I}(v_{I,1})$ and $v_{I,3}\in next_{LT_I}(v_{I,3})$, for I=broker_to_user_1. Thus, for $v_{\text{broker},4}$, the first clause of Definition 6.6 holds.

- $v_{\text{broker},7}$: $out(v_{\text{broker},i})$=just_communicated_to(res_1,user_1), and there is no element ⟨⟨just_communicated_to(res_1,user_1)$;\sigma_2\rangle;\langle\sigma_3;\sigma_4;\sigma_5;\sigma_6\rangle;\langle\sigma_7;\sigma_8\rangle\rangle\in\lambda_{\text{broker\_to\_user\_1}}$ for any $\sigma_2,\ldots,\sigma_8$, so the second clause of Definition 6.6 holds.

Thus, for each state in $lt_{\text{broker},1}$, the requirements of Definition 6.6 hold. This example shows that the same pair of states in the co-domain of a link may take part in more than one transmission octet. ■

6.2.2 Order-Preserving Transmission Property

The second property of a compatibility relation defined in this chapter, the order-preserving transmission property, requires that the results of two transmissions from a specific component to a specific other component by the same link occur in the same order as the initiations of the transmissions. As the property is a requirement on the occurrence of two transmissions, the formal definition is stated in terms of two transmission octets. Altogether, the formal definition refers to sixteen states.

Definition 6.9. (Order-preserving transmission property). *Let* $\mathcal{CR}_I$ *be a compatibility relation for a link I. For this compatibility relation the* order-preserving transmission property *holds iff for each* $\langle LT_{dom(I)};LT_I;LT_{cdom(I)}\rangle\in\mathcal{CR}_I$: *with* $LT_I=\langle\langle T_I;<_I\rangle;V_I\rangle,$

$LT_{dom(I)}=\langle\langle T_{dom(I)};<_{dom(I)}\rangle;V_{dom(I)}\rangle$, *and* $LT_{cdom(I)}=\langle\langle T_{cdom(I)};<_{cdom(I)}\rangle;V_{cdom(I)}\rangle$: *for all* $i,j,m,n\in T_{dom(I)}$, $i'',j'',k,l\in T_I$, $m'',n'',o,p\in T_I$, $i',j',m',n'\in T_{cdom(I)}$:

- *if*
  - $\langle\langle v_{dom(I),i};v_{dom(I),j}\rangle;\langle v_{I,i''};v_{I,j''};v_{I,k};v_{I,l}\rangle;\langle v_{cdom(I),i'};v_{cdom(I),j'}\rangle\rangle$ *is a transmission octet,*
  - *and* $\langle\langle v_{dom(I),m};v_{dom(I),n}\rangle;\langle v_{I,m''};v_{I,n''};v_{I,o};v_{I,p}\rangle;\langle v_{cdom(I),m'};v_{cdom(I),n'}\rangle\rangle$ *is a transmission octet,*
  - *and* $i<_{dom(I)}m$,
- *then* $j'<_{cdom(I)}n'$.

The definition states that, for the order-preserving transmission property to hold, for each state $v_{A,i}$ in a trace of the domain of the link, if this state is involved in a transmission that results in a state $v_{B,j'}$, and there is a later state $v_{A,m}$ that is involved in another transmission that results in $v_{B,n'}$, then $v_{B,n'}$ must occur later than $v_{B,j'}$. To illustrate the definition of the order-preserving transmission property, a triple of traces for which the property does *not* hold is depicted. The negation of the property is as follows: there is a triple $\langle LT_{dom(I)};LT_I;LT_{cdom(I)}\rangle\in\mathcal{CR}_I$ with $LT_I=\langle\langle T_I;<_I\rangle;V_I\rangle$, $LT_{dom(I)}=\langle\langle T_{dom(I)};<_{dom(I)}\rangle;V_{dom(I)}\rangle$, and $LT_{cdom(I)}=\langle\langle T_{cdom(I)};<_{cdom(I)}\rangle;V_{cdom(I)}\rangle$ for which there exist $i,j,m,n\in T_{dom(I)}$, $i'',j'',k,l\in T_I$, $m'',n'',o,p\in T_I$, $i',j',m',n'\in T_{cdom(I)}$ such that:

- $\langle\langle v_{dom(I),i};v_{dom(I),j}\rangle;\langle v_{I,i''};v_{I,j''};v_{I,k};v_{I,l}\rangle;\langle v_{cdom(I),i'};v_{cdom(I),j'}\rangle\rangle$ is a transmission octet,
- and $\langle\langle v_{dom(I),m};v_{dom(I),n}\rangle;\langle v_{I,m''};v_{I,n''};v_{I,o};v_{I,p}\rangle;\langle v_{cdom(I),m'};v_{cdom(I),n'}\rangle\rangle$ is a transmission octet,
- and $i<_{dom(I)}m$,
- and $n'<_{cdom(I)}j'$.

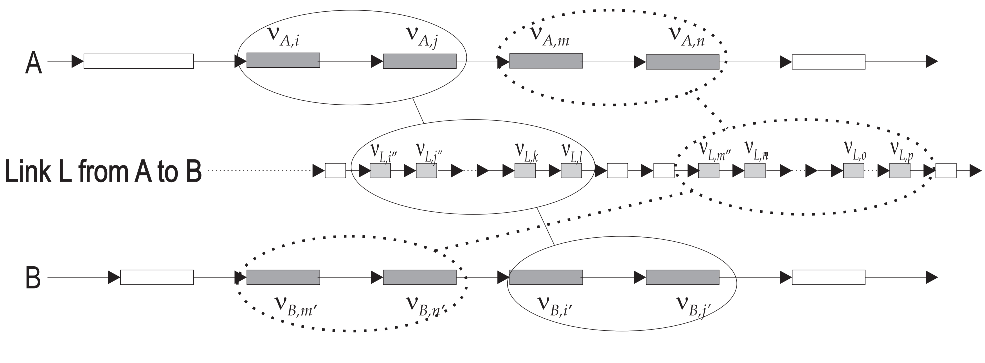

Figure 6.2: Traces that do not satisfy the order-preserving transmission property.

This situation is depicted in Figure 6.2. The two transmission octets are indicated by solid and dashed ovals. (The lines connecting the ovals indicate which states together form a transmission octet.) It is clear that the traces depicted in Figure 6.2 do not satisfy the order-preserving transmission property.

6.2.3 Asynchronous Transmission Property

The third property presented in this chapter is the asynchronous transmission property, which coincides with the commitment to asynchronous transmission presented in Section 2.2.7. This property is defined in terms of another notion, *dependence*, which is itself defined in terms of transmission octets. Dependence is a binary relation on the union of the sets of states that occur in the traces of a link, its domain and co-domain. As it is not assumed that all $\mathcal{S}_S$ are pairwise disjoint, the relation is defined using coloured versions of the states in each $\mathcal{S}_S$. This makes it possible to define notions that uniquely reference states of specific components. Moreover, it is not assumed that for a specific component or link, states in a local component or link trace are unique. Therefore, for reasons explained shortly, states are also coloured with the point in time at which they occur.

Definition 6.10. (Disjoint union of states). *Let $SH=\langle Comp;Lnk;\prec;dom;cdom\rangle$ be a structure hierarchy and let μ be a multitrace for SH. The* disjoint union *of all local component and link states of the components and links in SH is the set $\mathcal{S}_{SH}=\{\langle v_S;S;i\rangle \mid S\in Comp\cup Lnk,\ v_S\in\mathcal{S}_S$ and $\mu_S(i)=v_S\}$.*

For notational convenience, in the rest of this thesis, coloured versions $\langle v_S;S;i\rangle$ are identified with the uncoloured versions, i.e., a coloured state $\langle v;S;i\rangle$ is denoted $v_{S,i}$..

A state $v_{B,j'}$ depends on a state $v_{A,i}$ if either $A=B$ and $i<j'$ for A's local time ordering, or if there is a state $v_{C,m}$ such that $v_{B,j'}$ depends on $v_{C,m}$, and $v_{C,m}$ depends on $v_{A,i}$, or if $A=dom(L)$ for a link L and $B=cdom(L)$ and $v_{B,j'}$ contains the result of information transmission from $v_{A,i}$. The latter requirement can be expressed formally in terms of transmission octets, as shown in the following definition.

Definition 6.11. (Dependence). *Let $SH=\langle Comp;Lnk;\prec;dom;cdom\rangle$ be a structure hierarchy and let $LT_A=\langle\langle T_A;<_A\rangle;V_A\rangle$, $LT_B=\langle\langle T_B;<_B\rangle;V_B\rangle$ and $LT_L=\langle\langle T_L;<_L\rangle;V_L\rangle$ be three traces of components or links $A,B\in Comp\cup Lnk$ and a link $L\in Lnk$ such that $A=dom(L)$ and $B=cdom(L)$. Let $v_{A,i}$ and $v_{A,j}$ be two states in LT_A, let $v_{L,i''}$, $v_{L,j''}$, $v_{L,k}$ and $v_{L,l}$ be four states in LT_L, and let $v_{B,i'}$ and $v_{B,j'}$ be two states in LT_B. The* dependence *relation $\rightarrow_d\subseteq\mathcal{S}_{SH}\times\mathcal{S}_{SH}$ for LT_A, LT_L and LT_B is defined as the smallest relation $\rightarrow_d$ such that $v_{A,i}\rightarrow_d v_{B,j'}$ iff either*

1. *$A=B$ and $i <_A j'$, or*
2. *$\langle\langle v_{A,i};v_{A,j}\rangle;\langle v_{L,i''};v_{L,j''};v_{L,k};v_{L,l}\rangle;\langle v_{B,i'};v_{B,j'}\rangle\rangle$ is a transmission octet for LT_A, LT_L and LT_B, or*

3. *There is a state* $v_{C,m}$ *of a component or link* $C \in Comp \cup Lnk$ *such that* $v_{A,i} \rightarrow_d v_{C,m}$ *and* $v_{C,m} \rightarrow_d v_{B,j'}$.

Definition 6.12. (Asynchronous transmission property). *Let* $\mathcal{CR}_I$ *be a compatibility relation for a link I. For this compatibility relation the* asynchronous transmission property *holds iff for each* $\langle LT_{dom(I)};LT_I;LT_{cdom(I)}\rangle \in \mathcal{CR}_I$, *the dependence relation* $\rightarrow_d$ *for* $LT_{dom(I)}$, LT_I *and* $LT_{cdom(I)}$ *is a partial order.*

The dependence relation $\rightarrow_d$ is similar to Lamport's (1986) "happens before" relation that defines a temporal order without assuming the existence of global time. (However, Lamport's notion is defined in terms of events and does not support locality.) If $\rightarrow_d$ is a partial order, it cannot contain cycles, so there is no chain of states that all have to occur before their predecessor. This characterisation of asynchronous information transmission is also presented in (Charron-Bost, Mattern & Tel, 1996) in terms of events. Chapter 7 further discusses such partial orders.

Definition 6.12 requires that all states in a local component or link trace of a specific component or link are unique. If states are not unique, $\rightarrow_d$ is naturally symmetric and therefore not a partial order. This is the reason why states are coloured with the point in time at which they occur.

6.2.4 Logically Instantaneous Transmission Property

In Section 2.2.7, a commitment is made to asynchronous transmission. However, in some circumstances, synchronous information transmission is favoured over asynchronous information transmission. From the point of view of the initiator, synchronous information transmission appears to be instantaneous: there are no activities between the initiation of the information transmission and the receipt of the information by another component. Therefore, synchronous communication is more accurately referred to as the logically instantaneous transmission property.

Definition 6.13. (Logically instantaneous transmission property). *Let* $SH=\langle Comp;Lnk;\prec;dom;cdom\rangle$ *be a structure hierarchy and let* LT_A, LT_B *and* LT_L *be three traces of components or links* $A,B \in Comp \cup Lnk$ *and a link* $L \in Lnk$ *such that* $A=dom(L)$ *and* $B=cdom(L)$. *Let* $v_{A,i}$ *and* $v_{A,j}$ *be two states in* LT_A, *let* $v_{L,i''}$, $v_{L,j''}$, $v_{L,k}$ *and* $v_{L,l}$ *be four states in* LT_L, *and let* $v_{B,i'}$ *and* $v_{B,j'}$ *be two states in* LT_B.

- *The relation* $K \subseteq \mathcal{S}_{SH} \times \mathcal{S}_{SH}$ *for* LT_A, LT_L *and* LT_B *is defined as follows:* $K=\{\langle v_{A,i}; v_{B,j'}\rangle \mid \langle\langle v_{A,i}; v_{A,j}\rangle;\langle v_{L,i''}; v_{L,j''}; v_{L,k}; v_{L,l}\rangle;\langle v_{B,i'}; v_{B,j'}\rangle\rangle$ *is a transmission octet for* LT_A, LT_L *and* $LT_B\}$;
- *The relation R is defined as* $R=\{\langle v_{S,i}; v_{S,j}\rangle \mid (S=A \text{ or } S=B) \text{ and } i<j\} \cup K$;
- *Let* K^{-1} *be the set* $\{\langle v_{B,j'}; v_{A,i}\rangle \mid \langle\langle v_{A,i}; v_{A,j}\rangle;\langle v_{L,i''}; v_{L,j''}; v_{L,k}; v_{L,l}\rangle;\langle v_{B,i'}; v_{B,j'}\rangle\rangle$ *is a transmission octet for* LT_A, LT_L *and* LT_B *and* $i<j$, $i'<j'\}$;

- *Let $R'=(R\cup K^{-1})^{*}\setminus(K\cup K^{-1})$, where R^{*} denotes the transitive closure of R;*
- *Let $\mathcal{CR}_I$ be a compatibility relation for a link I. For this compatibility relation the* logically instantaneous transmission property *holds iff for each $\langle LT_{dom(I)};LT_I;LT_{cdom(I)}\rangle\in\mathcal{CR}_I$, the relation R' for $LT_{dom(I)}$, LT_I and $LT_{cdom(I)}$ is a partial order.*

The construction $R'=(R\cup K^{-1})^{*}\setminus(K\cup K^{-1})$ is adapted from a proof in (Charron-Bost *et al.*, 1996) in which an equivalent characterisation of logically instantaneous information transmission in terms of events is given. From the logically instantaneous transmission property, it can be proven that an arbitrary state ν of the domain *D* of a link or the co-domain *C* of a link happens before (in Lamport's sense) a state in which information is made available in *D* if and only if it happens before a state in which this information is received by *C*. Likewise, an arbitrary state ν of *D* or *C* happens after (in Lamport's sense) a state in which information is made available in *D* if and only if it happens after a state in which this information is received by *C*. Thus, at the moment of logically instantaneous information transmission, components *C* and *D* have the same past and future. (See (Charron-Bost *et al.*, 1996) for the proof.)

6.3 Discussion

The reader may be surprised to find that non-local phenomena and properties of information transmission can be defined without any relation to the clocks of the components involved. The following observations may further clarify this issue. In the first place, the definition of compatibility given above amounts to a theory of dependence and nothing more. In particular, the three views on the behaviour of a component abstract from (i) the actual time spent by components between two states according to some observer and (ii) synchronisation characteristics and buffering of information transmission between components. In the second place, a non-local view in terms of dependence is, on the one hand, sufficient for many purposes, while, on the other hand, it is the best possibility if one does not want to assume a global clock. A view in terms of dependence is sufficient for the following reasons. If a global clock is assumed, then a dependence ordering implies a temporal ordering, in the real physical reality as well as in any conceivable computer implementation (Lamport, 1986). However, a real temporal ordering is only required if state transitions have side effects not modelled as communication with other components in the system. Thus, a view in terms of dependence is sufficient, if such side effects are modelled explicitly (which is the case for the semantic structure presented in this thesis). If no global clock is assumed (which is the only possibility in relativistic systems and which is often beneficial when modelling widely distributed systems, see (Pratt, 1986)), then no temporal order can be defined whatsoever, so a view in terms of dependence is the best possibility.

An interesting question is whether there are objective criteria to verify the claim that e.g. the logically instantaneous transmission property does indeed characterise instantaneous transmission. This question can be approached as follows. In the context of models of the dynamics of distributed systems, characterisations of various properties of information transmission have been published (Soneoka & Ibaraki, 1994; Charron-Bost *et al.*, 1996). These properties induce a proper hierarchy of classes of computations that (exclusively) use a specific information transmission property. I.e., Charron-Bost and her co-authors identify the following classes of computations: synchronous computations, causally ordered computations, FIFO-computations and asynchronous computations. A FIFO-computation is a computation in which all information exchange is order-preserving in the terminology used in this thesis. A causally ordered computation is a computation in which the order-preserving property not only holds for each individual information link, but also between all links to a specific component. Charron-Bost and her co-authors show that the class of synchronous computations is a proper subclass of the class of causally ordered computations. The class of causally ordered computations is a proper subclass of the class of FIFO-computations, which is itself a proper subclass of the class of asynchronous computations.

The properties formulated in (Soneoka & Ibaraki, 1994; Charron-Bost *et al.*, 1996) are expressed in terms of a global, event based model of a distributed system. In Chapter 7, a comparable global perspective is developed for the semantic structure developed in this thesis. The characterisations published in (Soneoka & Ibaraki, 1994; Charron-Bost *et al.*, 1996) may serve as formal criteria to verify the properties expressed above by considering those properties from the global perspective developed in the next chapter.

For the logically instantaneous information transmission property, this approach provides the following criteria:

- If for all compatibility relations in a structure hierarchy the logically instantaneous transmission property holds, the behaviour of that structure hierarchy is in the class of synchronous computations. If, for all compatibility relations in a structure hierarchy, the order-preserving transmission property holds, then the behaviour of that structure hierarchy is the class of FIFO-computations. As the class of synchronous computations is a subclass of the classes of FIFO computations, the order-preserving transmission property should by implication hold for a compatibility relation for which the logically instantaneous transmission property holds. Note that this criterion does not rely on a global perspective;
- In (Charron-Bost *et al.*, 1996), a refinement of the causality relation for synchronous computations is given. This relation essentially expresses the requirement that two components involved in synchronous information exchange share the same past and future at their (local) time points at which

this information exchange happens. One way to evaluate the definition of Section 6.2.4 consists of defining a requirement similar to the requirement of Charron-Bost *et al.* and to prove that this requirement is equivalent with the definition of the logically instantaneous information transmission property;

- In (Charron-Bost *et al.*, 1996), an equivalent characterisation of synchronous computations is given by a requirement on the common 'happens before' relation as defined by Lamport. (This requirement states that there should exist at least one linear extension of the 'happens before' relation such that for all pairs of corresponding send and receive events, the interval between two corresponding events is empty. Similar to the previous point, a possible way to evaluate the definition of Section 6.2.4 consists of defining a requirement similar to the requirement of Charron-Bost *et al.* and to prove that this requirement is equivalent with the definition of the logically instantaneous information transmission property;
- In (Soneoka & Ibaraki, 1994), yet another characterisation of synchronous computations is given. Soneoka and Ibaraki develop a formal notion that precisely determines whether messages cross each other. They then prove that a communication is synchronous iff no messages can cross. Thus, yet another way to evaluate the definition of Section 6.2.4 consists of defining a requirement similar to the requirement of Soneoke and Ibaraki and to prove that this requirement is equivalent with the definition of the logically instantaneous information exchange property. As an aside, in (Charron-Bost *et al.*, 1996), the no-message-crossing property is also mentioned.