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True Concurrency in Models of Asynchronous Circuit Behavior*

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Abstract. In the study of asynchronous designs most authors use the interleaving model of concurrency when describing the behavior of a network; this is usually done for simplicity. The interleaving model assumes the behavior of an asynchronous circuit can be adequately represented by allowing only one signal to change at a time. In contrast to this, true concurrency models allow an arbitrary number of simultaneous signal changes. It seems that little effort has been made to determine what effect the choice of model may have on the analysis of a network. In this paper, we attempt to discover the circumstances under which the assumption of single signal changes can be made without affecting the results of circuit analysis. We prove, in a formal network model, that, in the context of delay-insensitivity and semi-modularity, the single change assumption is valid. We also prove that the same is true for a different definition of delay-insensitivity, restricted to deterministic behaviors. Consequently, in these cases, the more complicated true concurrency analysis is not required.

Keywords: asynchronous, circuit, delay-insensitive, multiple-winner, single-winner, interleaving, semi-modular, true concurrency

1. Introduction

Asynchronous circuits operate without the aid of a global clock. While this gives the potential for high speed and low energy consumption, it also creates concerns similar to those in other concurrent systems, such as deadlock and safety violations. Much of the work on concurrency theory has been applied to asynchronous circuit theory, even though some assumptions made in concurrent models may not be valid in the case of asynchronous circuits. In particular, many models of concurrent behavior assume that a system can be represented adequately by allowing only one action to occur at any given time. Most models of asynchronous circuit behavior also use this assumption, although multiple signal changes sometimes produce different results than single signal changes. It seems that little effort has been made to determine what effect, if any, this assumption might have on the results of the analysis of a circuit. This paper seeks to shed some light on this question. Our main results relate to delay-insensitivity and semi-modularity, but we also briefly mention such concerns as safety and speed-independence.

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Semi-modularity and delay-insensitivity are frequently encountered concepts in asynchronous circuit theory. Semi-modularity was first introduced by Muller [19, 21]. Roughly speaking, it requires that no enabled transition can be disabled until it is fired. Varshavsky et al. [32] proved that if a circuit is semi-modular then any state which is reachable from the initial state using multiple changes can also be reached through a sequence of single changes. It follows from this result that, when checking for semi-modularity, it is sufficient to consider only single changes. Here we study the effects of simultaneous changes on the property of *quasi semi-modularity*, introduced by Brzozowski and Zhang [6].[1] Quasi semi-modularity is a generalization of Muller's semi-modularity to nondeterministic components.

The second property that we study is delay-insensitivity, which has recently received considerable attention. Roughly speaking, a circuit is delay-insensitive if it operates correctly regardless of the delays in the circuit components and wires. Some of the first work on circuit behaviors in the presence of arbitrary delays can also be traced back to Muller [19, 21]. He described the behavior of a circuit by sets of allowed sequences that specify the order in which circuit elements can change. If all the allowed sequences for a given circuit with the same initial state end in the same state or a repeating set of states, then the circuit is said to be *speed-independent*. Later, Molnar et al. [20] introduced the "foam-rubber wrapper" postulate to describe delay-insensitive specifications of circuit components. In this point of view, each component is seen as being surrounded by a "foam-rubber wrapper." Signals travel through this wrapper, which assumes no specific form and may change shape over time. Thus, the time it takes for signals traveling to and from circuit components is unknown. Following this idea, Udding [30] introduced the first formal definition of delay-insensitivity. Here we concentrate on two more recent definitions of delay-insensitivity. The first is *strong delay-insensitivity*, introduced by Brzozowski and Zhang [6], which is based on the notion of observational equivalence or bisimulation. This definition uses a model which allows only single signal changes. We also consider a trace-based definition of delay-insensitivity, called *trace preservation*, which compares the traces of a circuit to those of the same circuit with arbitrary delays added.

In this paper, we explore the effect of multiple signal changes. We show that a circuit may be speed-independent under the single-change model, but not under the multiple-change model. A circuit is said to be *safe* if no component is ever sent a signal it is not ready to receive. We show that a circuit may be safe in the single-change model, but not in the multiple-change model. On a more positive note, our main results are as follows:

- A circuit is quasi semi-modular in the single-change model if and only if it is quasi semi-modular in the multiple-change model.
- A circuit is strongly delay-insensitive in the single-change model if and only if it is strongly delay-insensitive in the multiple-change model.
- For deterministic behaviors, a circuit is trace preserving in the single-change model if and only if it is trace preserving in the multiple-change model. This result does not hold for nondeterministic behaviors.

The paper is structured as follows. In the remainder of this section, we first briefly survey the main types of models of concurrency. Next, we give some examples where multiple signal changes can affect the results of the analysis of a circuit. In Section 2, we describe

the circuit model and the behavioral model used for most of our results. Section 3 deals with semi-modularity. Sections 4 and 5 deal with the two types of delay-insensitivity we consider. Section 6 concludes the paper.

1.1. Models of concurrency

The simplest, and probably most common, way of describing a concurrent process is with an *interleaving model*. In this type of model, concurrency is simulated by a nondeterministic choice of the ordering of actions. An interleaving is thus a total order of event occurrences. Each possible sequence of events is taken into account under the assumption that one (or more) of these interleavings represents reality. The main advantage of this approach is the simplicity of the underlying mathematics. Proponents of this approach argue that concurrency is not observable, and hence, it is not relevant in many circumstances [10]. Critics point out that the interleaving approach does not offer a faithful view of reality, since it does not take into account the possibility that actions may occur simultaneously. Nonetheless, this model is still probably the most popular model of concurrency in the study of asynchronous circuits, as well as in concurrency theory in general. Trace theory [8, 9, 30, 31, 33], often used to describe the behavior of an asynchronous circuit, is a type of interleaving model.

Non-interleaving approaches are usually referred to as *true concurrency* models because they handle concurrency explicitly. One true concurrency approach, which has been quite popular for general concurrency models, is the partial order approach [1, 7, 11, 22, 27]. This model has also been used in asynchronous circuit theory [18, 23–25]. In the case of partial order models, the behavior of a concurrent system is represented by a set of possible actions and a partial order representing the necessary temporal precedences among these actions. The partial order is usually expressed by the causality relation "$\rightarrow$", which states that $a \rightarrow b$ if and only if action a must precede action b [22]. In this model, two actions are concurrent if they are independent, i.e., if there is no causal relation between them. There is no necessary relation between concurrency and simultaneity; if two events are independent then they may occur simultaneously or in either order. One of the main advantages of this approach over interleaving is that the difference between independence and nondeterministic interleaving, where two actions are not concurrent but may occur in either order, is easily expressed in partial order semantics. Also, since this model allows us to reason about sets of observations rather than considering every possible sequence of events, it helps to avoid the state explosion problem usually associated with modelling concurrency. If needed, one can easily retrieve the interleavings from a partial order model. Unfortunately, causal partial orders are not expressive enough to satisfactorily model the invariant properties of certain kinds of concurrent systems [16]. For example, a system might include priority constraints on the ordering of events such as, "if event a has higher priority than event b, then, whenever it is possible to execute both events, b must not be executed." It is not always possible to describe the behavior of such a system using only causality [2, 15]. In the case of asynchronous circuits, there is no way to represent one event disabling another. Consequently, this model does not address the possibility that there may be events, which may occur simultaneously, but cannot occur one after the other.

Some true concurrency models do express concurrency as simultaneity rather than as independence. One such model is *step sequences* or *step traces* [2, 14, 16, 26, 28, 34]. This model is similar to interleaving except that, instead of sequences of actions, it represents an execution as a sequence of *sets* of actions. Each of these sets is called a *step* and represents a concurrent firing of a set of transitions. In this model, simultaneous actions are easily represented, and there is no need to assume that, because two actions occur simultaneously, they must be able to occur in either order. Thus, this model gives a more realistic representation of the execution of an asynchronous circuit. Rozenberg and Verraedt [28] showed that using step sequences, it is possible to discover differences in behaviors of Petri nets, which cannot be observed using a string language approach. Reisig [26] gave similar examples. This model can also adequately represent systems with priorities, which cannot be represented with interleavings or partial orders [2, 15]. One of the major drawbacks of this approach is that it only makes the state explosion problem worse. In the case of asynchronous circuits, unless the circuit is totally sequential, there are many more step sequences to consider than interleaving sequences. Also, allowing sets of actions at each step can complicate the underlying mathematics.

The first model designed specifically for asynchronous circuits was introduced by Huffman [13] in 1954. Although this model was introduced before step sequences were formally defined, it can be considered a type of step trace model since it allows for simultaneous changes. Many more asynchronous circuit models have been described since then and these can be divided into interleaving and true concurrency models, depending on whether or not they take simultaneous signal changes into account. We are using the GMW or *general multiple-winner* model to study true concurrency in the analysis of asynchronous circuits. In this model, any number of excited circuit components are allowed to change simultaneously. Such a model was first described by Muller [19, 21], but we use the notation of Brzozowski and Seger [4]. The GMW model is in contrast to the GSW or *general single-winner* model [4], which only allows one component to change at a time. Yakovlev et al. [35] also introduced a model that uses the general single-winner relation (called the *single change model*). As do step sequences, the GMW model provides a more faithful view of reality, but greatly increases the complexity of the analysis. If there are n possible next states to consider from a given state in the GSW model, then there are $2^n - 1$ possible next states to consider when multiple signal changes are taken into account. We use the GSW and GMW models to determine the effect of simultaneous signal changes for the results in Sections 3–5.

1.2. Problems with interleaving

In this section, we discuss some of the problems encountered if multiple changes are not taken into account. Problems arise when multiple changes permit the circuit to enter a state that could not have been entered if only single changes are considered. We first look at this problem in the context of *speed-independence*, introduced by Muller [21]. A circuit is speed-independent if the outcome of each of its transitions does not depend on the speed of the individual circuit elements.

Figure 1(a) shows a circuit C_1 and figure 1(b) shows a state diagram for this circuit using only single changes, with excited elements underlined. We can see that, starting from state

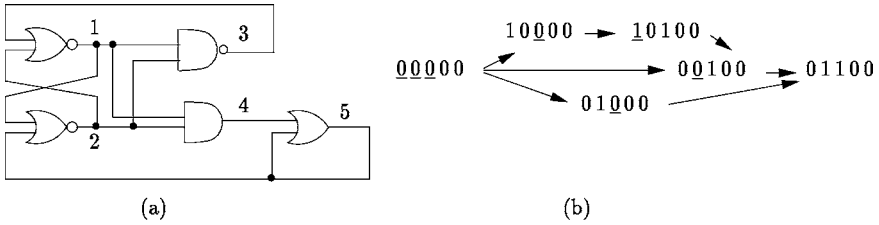

Figure 1. (a) Circuit C_1; (b) state diagram with single changes.

00000, at most one of the two NOR gates has output 1 at any given time. As a result, the AND gate, and hence also the OR gate, remain stable and the circuit always terminates in state 01100, independently of the delays in the individual circuit elements. However, when multiple changes are included, the two NOR gates may temporarily become high, changing the excitation of the AND gate, and causing the OR gate to stabilize in state 1 as shown in the following execution:

$$\underline{0}\,\underline{0}\,\underline{0}\,0\,0 \to \underline{1}\,\underline{1}\,0\,\underline{0}\,0 \to \underline{1}\,\underline{1}\,0\,1\,\underline{0} \to \underline{1}\,\underline{1}\,0\,1\,1 \to 1\,0\,\underline{0}\,\underline{1}\,1 \to \underline{1}\,0\,1\,\underline{1}\,1$$
$$\to \underline{1}\,0\,1\,0\,1 \to 0\,0\,1\,0\,1.$$

This is impossible under the single-change model. Hence, a circuit may be speed-independent under an interleaving model, but not under a multiple-change model.

Another concern in the design of asynchronous circuits is *safety*. Roughly speaking, safety ensures that "something bad does not happen" [17]. This means that a circuit element never receives a signal for which it is not ready.

Figure 2(a) shows a circuit C_2. The first three elements are $\hat{C}$-elements defined by $C = \bar{a}\bar{b} + (\bar{a} + \bar{b})c$, where a and b are the inputs, c is the current output, and C is the current excitation. A MERGE element receives a signal from one of its input ports, produces an output, and then waits for another signal from an input port. It is not prepared to receive a second input before it has produced an output, for this would be a safety violation. Figure 2(b) shows the state diagram of the circuit in figure 2(a) under the single-change model. Only one of the AND gates may change, and hence the MERGE element receives only one input. Figure 2(c) shows an execution of the circuit taking into account simultaneous changes. In this case, both AND gates may change, and the MERGE element may receive a second input before it has time to process the first. This safety violation cannot be found using the single-change model.

2. Networks

We now define a formal model in which we will prove our main results. For a complete description of the model see [6].

A network consists of components, called modules, which are nondeterministic sequential machines of the Moore type. To hide the details of the internal design and keep the model simple, we represent a module by an abstract internal state taking its values from a finite

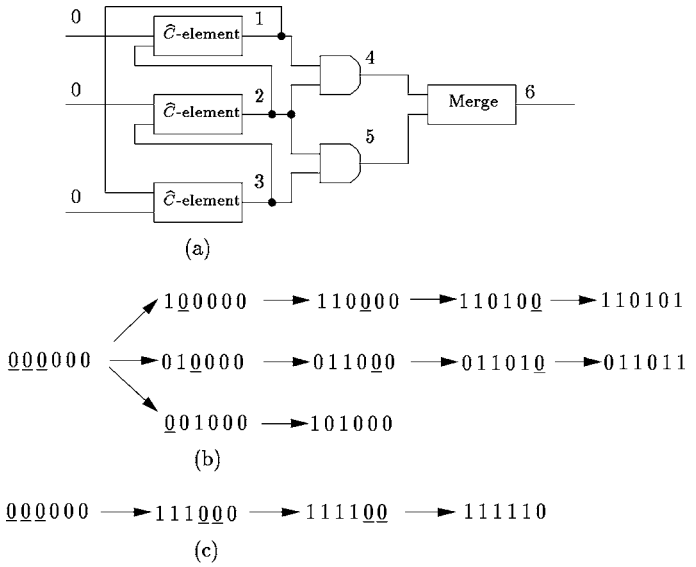

Figure 2. (a) Circuit C_2; (b) single changes; (c) multiple changes.

set; however, the inputs and outputs remain binary. Delays in the input and output wires of a module are not introduced, which allows us to model isochronic forks and similar components.

Definition 2.1. A *module M* is a sequential machine $M = \langle \mathcal{S}, \mathcal{X}, y, \mathcal{Z}, \delta, \lambda \rangle$, where

- $\mathcal{S}$ is a finite set of *internal states* of M;
- $\mathcal{X} = \{x_1, \ldots, x_m\}$ is the set of *binary input variables*;
- y is the *internal state variable*;
- $\mathcal{Z} = \{z_1, \ldots, z_p\}$ is the set of *binary output variables*;
- δ is the *excitation function*, $\delta : \{0, 1\}^m \times \mathcal{S} \to 2^{\mathcal{S}} \setminus \{\emptyset\}$, satisfying the restriction that, for any $a \in \{0, 1\}^m$ and $b \in \mathcal{S}$, either $\delta(a, b) = \{b\}$ or $b \notin \delta(a, b)$;
- $\lambda = (\lambda_1, \ldots, \lambda_p)$ is the *output function*, $\lambda : \mathcal{S} \to \{0, 1\}^p$.

The excitation function δ takes an input vector and an internal state and returns a set of possible next states. If $\delta(a, b) = \{b\}$ then the module is stable; otherwise the module is excited to change to one or more new states.

Example 2.1. Tables 1 and 2 define the functions of a delay module and a simple arbiter respectively. A delay module has $\mathcal{S} = \{0, 1\}$, $m = 1$, and $p = 1$. An arbiter has $\mathcal{S} = \{0, 1, 2\}$, $m = 2$, and $p = 2$.

We now define a network. This definition is restricted to closed, or autonomous, networks. An open network can be transformed into a closed network by modeling the environment as a module.

Table 1. Functions of a delay module.

	x		
y	0	1	$\lambda(y)$
0	{0}	{1}	0
1	{0}	{1}	1
	$\delta(x, y)$		

Table 2. Functions of an arbiter.

	$\mathcal{X} = \{x_1, x_2\}$				
y	00	01	10	11	$\lambda(y)$
0	{0}	{2}	{1}	{1,2}	00
1	{0}	{0}	{1}	{1}	10
2	{0}	{2}	{0}	{2}	01
		$\delta(x, y)$			

Definition 2.2. A *network* is a pair $N = \langle \mathcal{M}, \mathcal{K} \rangle$, where

- $\mathcal{M} = \{M^1, \ldots, M^n\}$, $n \geq 1$, is a set of modules;
- $\mathcal{K}$ is a set of *connections*, each of which is an ordered pair (z_i, x_j), where z_i is the output variable of some module, and x_j is the input variable of some module. Moreover, for each input variable x_j (respectively, for each output variable z_i), there is exactly one output variable z_i (respectively, one input variable x_j) such that $(z_i, x_j) \in \mathcal{K}$.

The state variable of module M^i is y^i and its state set is $\mathcal{S}^i$. The set of *state variables* of a network is $\mathcal{Y} = \{y^1, \ldots, y^n\}$. The set of *states* of a network is $\mathcal{S} = \mathcal{S}^1 \times \ldots \times \mathcal{S}^n$. For $y^i \in \mathcal{Y}$ and $s = (s_1, \ldots, s_n) \in \mathcal{S}$, the *excitation* of y^i in state s is denoted S_i. A state is said to be *stable* if $S_i = \{s_i\}$ for all i; otherwise s is unstable. The set of unstable state variables in state s is denoted by $\mathcal{U}(s) = \{y^i \in \mathcal{Y} \mid S_i \neq \{s_i\}\}$.

Example 2.2. Figure 3 shows an example of a network with state variables $\mathcal{Y} = \{y^1, y^2, y^3\}$. Let s be the current state of the network. For the OR gate module M^2, $S_2 = z^1 + z^3$ and $z_1^2 = z_2^2 = y^2$. For the two inverter modules M^1 and M^3, $S_1 = \overline{z_1^2}$, $z^1 = y^1$, $S_3 = \overline{z_2^2}$, and $z^3 = y^3$. After some substitutions we find $S_1 = \overline{y^2}$, $S_2 = y^1 + y^3$, $S_3 = \overline{y^2}$.

We now define the behavior of a network. To allow for simultaneous signal changes, the GSW (general single-winner) relation used in the definition of a behavior in [6] is replaced with the GMW (general multiple-winner) relation [4]. To avoid confusion, throughout this paper we use subscripts s and m to differentiate between GSW and GMW behaviors, respectively.

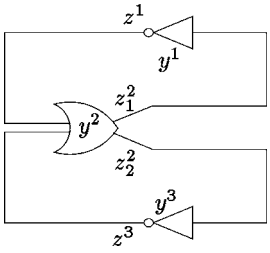

Figure 3. Example network N_1.

Definition 2.3. The *GSW relation* on the set $\mathcal{S}$ of states of a network N is a binary relation $\mathbf{R}_s$, such that $(s, t) \in \mathbf{R}_s$ if and only if s differs from t in exactly one component, say i, (i.e., $s_i \neq t_i$), $y^i \in \mathcal{U}(s)$, and $t_i \in \mathcal{S}_i$.

Definition 2.4. The *GMW relation* on the set $\mathcal{S}$ of states of a network N is a binary relation $\mathbf{R}_m$, such that $(s, t) \in \mathbf{R}_m$ if and only if s differs from t in one or more components, and for each such component i with $s_i \neq t_i$, we have $y^i \in \mathcal{U}(s)$, and $t_i \in \mathcal{S}_i$.

Definition 2.5. A *GMW behavior* of a network N is an initialized directed graph $B_m = \langle q_m, \mathcal{Q}_m, \mathcal{R}_m \rangle$, where

- $q_m \in \mathcal{S}$ is the initial state;
- $\mathcal{Q}_m$, specifying the vertices of B_m, is the set of states reachable via the relation $\mathbf{R}_m$,

$$\mathcal{Q}_m = \{s \in \mathcal{S} \mid (q_m, s) \in \mathbf{R}_m^*\};$$

- $\mathcal{R}_m$, specifying the edges of B_m, is the $\mathbf{R}_m$ relation restricted to $\mathcal{Q}_m$.

If $(s, t) \in \mathcal{R}_m$, we attach to edge (s, t) a *tag* $\tau(s, t) \in 2^{\mathcal{Y}}$, which denotes the set of state variables in which s and t differ.

We define the GSW behavior, $B_s = \langle q_s, \mathcal{Q}_s, \mathcal{R}_s \rangle$, of a network N similarly, by replacing $\mathbf{R}_m$ with $\mathbf{R}_s$. Under the GSW model, $\tau(s, t) \in \mathcal{Y}$. Figure 4(a) shows the GSW behavior of network N_1 of figure 3 with initial state 000. Figure 4(b) shows the additional transitions possible under the GMW model. If state t is reachable from state s under the GSW model ($(s, t) \in \mathcal{R}_s^*$) through a sequence $w \in \mathcal{Y}^*$ of state changes, then we use the notation $t \in sw$; under the GMW model we write $t \in sW$ where $W \in (2^{\mathcal{Y}})^*$. If w consists of only one element y^i, then $t \in sy^i$; if W consists of only one set $\mathcal{T}$, then $t \in s\mathcal{T}$. It is easy to see that $\mathcal{R}_s$ is a subset of $\mathcal{R}_m$, and therefore $\mathcal{Q}_s$ is a subset of $\mathcal{Q}_m$.

A behavior $B = \langle q, \mathcal{Q}, \mathcal{R} \rangle$ of a network can also be represented as a nondeterministic finite automaton $\mathcal{B}$ where every state is an accepting state and the language $L(\mathcal{B})$ accepted by $\mathcal{B}$ is defined in the usual way [6]. A network is deterministic if its behavior automaton is deterministic.

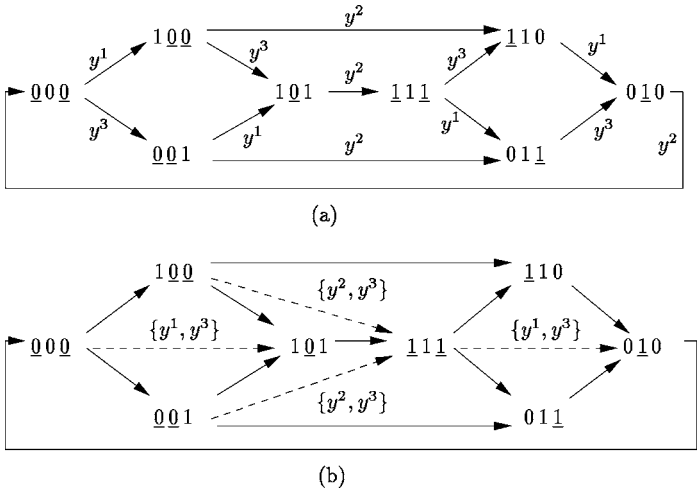

Figure 4. (a) A GSW behavior of N_1; (b) a GMW behavior of N_1.

3. Quasi semi-modularity

Semi-modularity was first defined in [21] for deterministic behaviors, which include multiple signal changes. A generalization, called quasi semi-modularity, was introduced in [6] to allow nondeterminism, although the behaviors considered are restricted to those including only single signal changes. The name semi-modularity comes from the fact that a certain partially ordered set derived from the states of a semi-modular circuit forms a semi-modular lattice [21]. No such correspondence has been found for circuits exhibiting nondeterminism, hence the name quasi semi-modularity. When only deterministic circuits are considered, the two definitions are equivalent. Quasi semi-modularity ensures that, once a variable becomes excited to change to a certain value, that excitation cannot be destroyed until the variable changes. For example, the behavior of the circuit in figure 1 is not semi-modular because, from the initial state, either of the NOR gates may be disabled without changing. We now modify the definition of quasi semi-modularity found in [6] to include simultaneous signal changes.

Definition 3.1. Let $B_m = \langle q_m, \mathcal{Q}_m, \mathcal{R}_m \rangle$ be a (GMW) behavior of a network N. A state $s \in \mathcal{Q}_m$ is said to be *multiple-change quasi semi-modular* if, for all states $t \in \mathcal{Q}_m$ and $\mathcal{T} \in 2^{\mathcal{Y}}$, if $t \in s\mathcal{T}$, then the excitation of a module M^j in state s is a subset of its excitation in state t ($S_j \subseteq T_j$) for all j such that $y^j \notin \mathcal{T}$ and $y^j \in \mathcal{U}(s)$. If s is multiple-change quasi semi-modular for all $s \in \mathcal{Q}_m$, then B_m is *multiple-change quasi semi-modular*.

The type of semi-modularity introduced in [6], which we call *single-change quasi semi-modularity*, is a special case of this definition, where only one element changes in going from state s to state t, i.e., $\mathcal{T}$ is a singleton set.

Let N be a network. Let $B_s = \langle q_s, \mathcal{Q}_s, \mathcal{R}_s \rangle$ be a GSW behavior of N and let $B_m = \langle q_m, \mathcal{Q}_m, \mathcal{R}_m \rangle$ be the corresponding GMW behavior of N such that the initial states are

equal ($q_m = q_s = q$). We show that the single-winner behavior B_s is single-change quasi semi-modular if and only if the multiple-winner behavior B_m is multiple-change quasi semi-modular. It is proven by Varshavsky [32] that, if a circuit is semi-modular, then the set of states reachable from the initial state is the same as the set of states which can be reached from the initial state by single changes. Basically, this is true because any modules which can change simultaneously may also change one at a time, since the excitation cannot be lost. In order to prove the final theorem for this section, we first show that this result also holds for quasi semi-modular networks. This proposition is a simple extension of Varshavsky's result using the new definition of semi-modularity.

To improve the readability of the paper, we present the proofs of all our results in the Appendix.

Proposition 3.1. *If the behavior B_s is single-change quasi semi-modular then $\mathcal{Q}_s = \mathcal{Q}_m$.*

Using this result, we can prove the following theorem.

Theorem 3.1. *A GSW behavior $B_s = \langle q, \mathcal{Q}_s, \mathcal{R}_s \rangle$ of a network N is single-change quasi semi-modular if and only if the GMW behavior $B_m = \langle q, \mathcal{Q}_m, \mathcal{R}_m \rangle$ is multiple-change quasi semi-modular.*

The proof of this theorem relies on the fact that, if a network is single-change quasi semi-modular, then any state which may be reached by a multiple change may also be reached by a series of single changes. Since the excitation of any unchanged components in a single-change quasi semi-modular network cannot be destroyed through the series of single changes, it cannot have been destroyed by the multiple change which reaches the same state. Hence the network must also be multiple-change quasi semi-modular.

4. Strong delay-insensitivity

Roughly speaking, a network is delay-insensitive if it continues to operate correctly even if the delays in its components and wires change arbitrarily [3]. Strong delay-insensitivity [6] compares the behavior of a network N to the behaviors of the networks obtained by adding delay elements to N. Such networks are referred to as a *delay extensions* of N, are denoted $\hat{N}$, and are obtained from N by inserting some delay modules in its connections. Figure 5

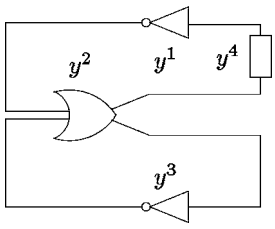

Figure 5. A delay extension of N_1.

shows a possible delay extension of network N_1 from figure 3, with a delay added between modules M^2 and M^1. The set of all delay extensions of N is denoted $\mathcal{D}(N)$.

A network N is defined to be strongly delay-insensitive if the behavior of any delay extension $\hat{N}$, with added delays projected out, is bisimilar (or observationally equivalent) to the original network N. More precisely, N and $\hat{N}$ are bisimilar if every step of N can be simulated in $\hat{N}$, and vice versa. It is shown in [6] that the first condition always holds, i.e., for every step of N there is a matching step of $\hat{N}$. Thus bisimilarity is reduced to proving that for every step of $\hat{N}$ there is a corresponding step of N. This condition is called *safety* and is formally defined in Definition 4.2.

We now introduce some of the terminology of [6], and then redefine strong delay-insensitivity to include behaviors with multiple signal changes. We then show that the class of strongly delay-insensitive networks does not change under this less restrictive definition of behaviors.

A network is said to be delay-dense if, for every pair of connected modules, at least one is a delay. It was proven in [6] that, under the general single-winner model, if a network is delay-dense, then quasi semi-modularity and delay-insensitivity are equivalent. Here we chose not to restrict our discussion to delay-dense networks; hence we prove our result independently of the results of the previous section.

Definition 4.1. Let $\hat{N} \in \mathcal{D}(N)$. The *projection of a state* $\hat{s}$ of $\hat{N}$ with respect to N is the $|\mathcal{Y}|$-tuple $s = \hat{s} \downarrow \mathcal{Y}$ obtained by removing all components corresponding to variables not in $\mathcal{Y}$. The *projection of a word* $\hat{W} \in (2^{\hat{\mathcal{Y}}})^*$ with respect to N is the word $W = \hat{W} \downarrow \mathcal{Y}$ obtained from $\hat{W}$ by erasing all the symbols not in $\mathcal{Y}$. The projection of a word $\hat{w} \in \hat{\mathcal{Y}}^*$ is defined similarly.

A state $\hat{s}$ is said to be an *extension* of s if s is a projection of $\hat{s}$. If $\hat{s}$ is the extension of s where all the inserted delays are stable, then $\hat{s}$ is the *stable-delay extension* of s. We say that a behavior $\hat{B} = \langle \hat{q}, \hat{\mathcal{Q}}, \hat{\mathcal{R}} \rangle$ of $\hat{N}$ is *initial state compatible* with a behavior $B = \langle q, \mathcal{Q}, \mathcal{R} \rangle$ of N if $\hat{q}$ is the stable-delay extension of q.

Example 4.1. Consider networks N_1 and $\hat{N}_1$ of figures 3 and 5 respectively. State $s = 011$ of N_1 is a projection of state $\hat{s} = 0110$ of $\hat{N}_1$. Consequently, state $\hat{s}$ is an extension of state s. State $\hat{s}' = 0111$ is the stable-delay extension of s. The projection of the word $\hat{W} = \{y^2, y^4\}\{y^4\}\{y^1, y^3\}$ with respect to N_1 is the word $W = \{y^2\}\{y^1, y^3\}$.

The definition of strong delay-insensitivity depends on the notion of safety, which guarantees that, for any transition in a delay extension of a network, there is an equivalent transition in the original network. Here we define safety for GMW behaviors. The definition for GSW behaviors can be obtained by substituting $\hat{w} \in \mathcal{Y}^*$ in place of $\hat{W}$, and y^i, for some $y^i \in \mathcal{Y}$, in place of $\mathcal{T}$.

Let $\hat{N} \in \mathcal{D}(N)$. Let $B_m = \langle q_m, \mathcal{Q}_m, \mathcal{R}_m \rangle$ be a behavior of N, and let $\hat{B}_m = \langle \hat{q}_m, \hat{\mathcal{Q}}_m, \hat{\mathcal{R}}_m \rangle$ be the behavior of $\hat{N}$, which is initial-state compatible with B_m.

Definition 4.2. The behavior $\hat{B}_m$ is said to be *safe with respect to* B_m if whenever $\hat{s} \in \hat{\mathcal{Q}}_m$ is an extension of $s \in \mathcal{Q}_m$, then for all $\hat{t} \in \hat{\mathcal{Q}}_m$ and $\hat{W} \in (2^{\hat{\mathcal{Y}}})^*$, if $\hat{t} \in \hat{s}\hat{W}$ and $\hat{W} \downarrow \mathcal{Y} = \mathcal{T}$

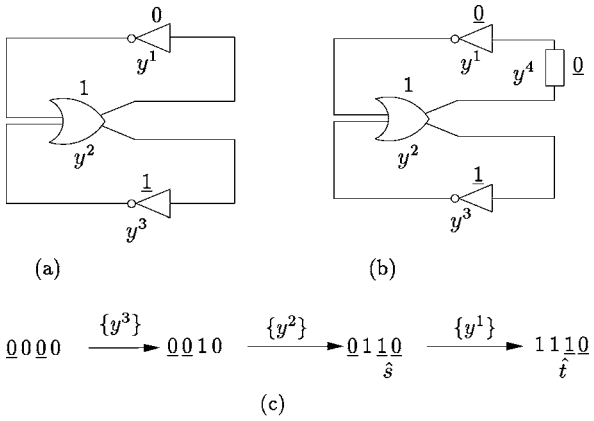

Figure 6. (a) N_1 in state s; (b) $\hat{N}_1$ in state $\hat{s}$; (c) an execution of $\hat{N}_1$.

for some $\mathcal{T} \in 2^{\mathcal{Y}}$, there exists $t \in \mathcal{Q}_m$ such that $t \in s\mathcal{T}$ and t is the projection of $\hat{t}$ with respect to N.

Example 4.2. Consider networks N_1 and $\hat{N}_1$ of figure 6. Let B_m be the GMW behavior of N_1 with initial state 000 and let $\hat{B}_m$ be the GMW behavior of $\hat{N}_1$ with initial state 0000. Let the states of the modules be as shown, with unstable states underlined. Let $s = 011$ be the current state of N_1 and let $\hat{s} = 0110$ be the current state of $\hat{N}_1$. Obviously, $\hat{s}$ is an extension of s. From figure 4, we can see that s is reachable from initial state 000. We can see from the execution in figure 6(c) that $\hat{s}$ is reachable from the initial state 0000, the stable-delay extension of 000. We can also see that $\hat{t} \in \hat{s}\hat{W}$, where $\hat{t} = 1110$ and $\hat{W} = \{y^1\}$, so that $\hat{W} \downarrow \mathcal{Y} = \{y^1\}$. Since y^1 is not excited in state s, there is a violation of safety.

Definition 4.3. A network N is *strongly delay-insensitive with respect to q* if, for any delay extension $\hat{N}$ of N, $\hat{B}$ is safe with respect to B.

In order to prove our main theorem concerning strong delay-insensitivity, we need the following auxiliary results.

In [4] it was shown that, if a sufficient number of delays are included in the network, then the GSW model can simulate the GMW model. A *delay-completion* of a network N, denoted $\tilde{N}$, is a delay extension obtained by inserting one delay module in each connection.

Let N be a network and let $\tilde{N}$ be the delay-completion of N. Let $B_m = \langle q_m, \mathcal{Q}_m, \mathcal{R}_m \rangle$ be the GMW behavior of N and let $\tilde{B}_s = \langle \tilde{q}_s, \tilde{\mathcal{Q}}_s, \tilde{\mathcal{R}}_s \rangle$ be the GSW behavior of $\tilde{N}$ that is initial-state compatible with B_m. To prove the main result of this section, we first show that, for any transition in B_m, there is a series of transitions in $\tilde{B}_s$ that produce the same result.

Proposition 4.1. *Suppose $s, t \in \mathcal{Q}_m$, $t \in s\mathcal{T}$, $\tilde{s} \in \tilde{\mathcal{Q}}_s$, and $\tilde{s}$ is an extension of s. Then there exists an extension $\tilde{t}$ of t such that $\tilde{t} \in \tilde{s}\tilde{w}$ for some $\tilde{w}$ consisting of all the elements of $\mathcal{T}$ and possibly some elements of $(\tilde{\mathcal{Y}} - \mathcal{Y})$.*

This proposition can be extended easily to the case where $t \in sW$ for some $W \in (2^{\mathcal{Y}})^*$. Using Proposition 4.1, it is also easy to show the following.

Proposition 4.2. *For every $s \in \mathcal{Q}_m$ there exists at least one $\tilde{s} \in \tilde{\mathcal{Q}}_s$ such that $\tilde{s}$ is an extension of s.*

These propositions are used in the proof of our main theorem for this section.

Theorem 4.1. *A network is strongly delay-insensitive with respect to a state under the GSW model if and only if it is strongly delay-insensitive with respect to that state under the GMW model.*

The proof of this theorem relies on the fact that, if a network is strongly delay-insensitive under the GSW model, then the delay-completion must be safe with respect to the original network. Since any multiple change can be mimicked by a series of transitions in the delay-completion, we can show that any delay extension of the network must also be safe under the GMW model.

5. Trace preservation

Trace theory [8, 9, 30, 31, 33] is a commonly used formalism for asynchronous circuit specification. In terms of trace theory, there are two ways of defining delay-insensitivity. The first, introduced by J.T. Udding [30], is a set of rules which each module in the circuit must obey. The JTU rules insure the absence of ordering between certain signals, since there is an unknown delay between the times a signal is sent and received. Another way of checking delay-insensitivity is by adding delays to connections and comparing the traces of the behavior of this network to those of the behavior of the network without these delays. This is the definition used in this paper. We refer to this type of delay-insensitivity as trace preservation. If a network is strongly delay-insensitive, then it must be trace preserving, but the opposite is not always true. Because of this, and the fact that trace preservation does not take the state of the network into account, the results of the previous sections cannot be reused.

A *trace structure* is a pair $T = \langle \mathbf{a}T, \mathbf{t}T \rangle$, where $\mathbf{a}T$ is the *alphabet* of T and $\mathbf{t}T \subseteq (\mathbf{a}T)^*$ is the *trace set* of T. In our application, with the GSW model, the alphabet of a trace structure is the set $\mathcal{Y}$ of internal state variables of a network. In the GMW behavior of a network, multiple state changes are allowed, and so, our traces consist of sequences of sets of symbols. Hence, $\mathbf{a}T$ is the set of all non-empty subsets of $\mathcal{Y}$. This model is similar to step sequences [2, 14, 16, 28, 34]. Note that we do not assume that, if two events occur simultaneously, then they must also occur in sequence. Recall that $L(\mathcal{B})$ is the language defined by the finite automaton derived from a behavior B.

Definition 5.1. Let $B_s = \langle q_s, \mathcal{Q}_s, \mathcal{R}_s \rangle$ be a GSW behavior of network N. The *trace structure induced by* B_s is a pair $T_s = \langle \mathbf{a}T_s, \mathbf{t}T_s \rangle$, where $\mathbf{a}T_s = \mathcal{Y}$ and $\mathbf{t}T_s = L(\mathcal{B}_s)$.

Definition 5.2. Let $B_m = \langle q_m, \mathcal{Q}_m, \mathcal{R}_m \rangle$ be a GMW behavior of network N. The *trace structure induced by* B_m is a pair $T_m = \langle \mathbf{a}T_m, \mathbf{t}T_m \rangle$, where $\mathbf{a}T_m = 2^{\mathcal{Y}} \setminus \{\emptyset\}$ and $\mathbf{t}T_m = L(\mathcal{B}_m)$.

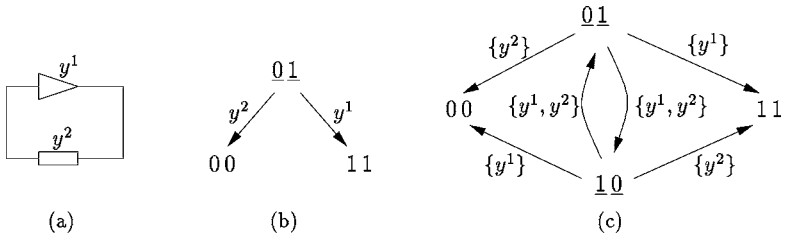

Figure 7. (a) N_2; (b) GSW behavior of N_2; (c) GMW behavior of N_2.

Example 5.1. The trace set of the GSW behavior of figure 7(b) is $\{y^1, y^2\}$, while that of the GMW behavior of figure 7(c) is $\{\{y^1\}, \{y^2\}, \{y^1, y^2\}, \{y^1, y^2\}\{y^1\}, \ldots\}$.

Let N be a network and let $\hat{N}$ be a delay extension of N. Let B_s be the GSW behavior of N with initial state q. Let $\hat{B}_s$ be the GSW behavior of $\hat{N}$ which is initial state compatible with B_s. Let T_s and $\hat{T}_s$ be the trace structures of B_s and $\hat{B}_s$, respectively.

Definition 5.3. Network N is said to be *single-change trace preserving* with respect to state q if, whenever $\hat{w} \in \mathbf{t}\hat{T}_s$ there exists a $w \in \mathbf{t}T_s$ such that $\hat{w} \downarrow \mathbf{a}T = w$.

We define a multiple-change trace preserving network similarly.

Example 5.2. Consider networks N_3 and $\hat{N}_3$ of figure 8. Starting from state 01, network N_3 reaches the current state after trace y^1. Starting from state 010, the stable-delay extension of 01, network $\hat{N}_3$ also reaches its current state after trace y^1. We see that y^1y^2 is also a trace of this GSW behavior of $\hat{N}_3$. This trace is not in the GSW behavior of N_3; hence N_3 with initial state 01 is not single-change trace preserving.

Theorem 5.1. *A deterministic delay-dense network N is single-change trace preserving with respect to state q if and only if it is multiple-change trace preserving with respect to q.*

Basically, this theorem holds because, if a network is deterministic and delay-dense, multiple changes can be simulated by changing elements one at a time without affecting the next non-delay element.

This theorem does not hold for networks which are nondeterministic since the state reached by a particular trace in a nondeterministic network need not be unique. Hence, there may be a trace which may lead to two different states from which two or more modules

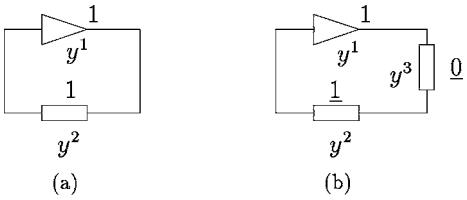

Figure 8. (a) N_3 in state s; (b) $\hat{N}_3$, a delay extension of N_3, in state $\hat{s}$.

can change in either order but not simultaneously. It is possible that, in a delay extension of the network, an extension of that trace may lead to a state in which those modules may change simultaneously. Such a network would not be multiple-change trace preserving but may still be single-change trace preserving. For an example of such a network, see [29].

Similarly, if a network is not delay-dense it may have two excited non-delay elements in a loop which may change in either order and excite a third element or change simultaneously without exciting the third element. If a delay were added to the loop then, under the multiple-change model, both elements in the loop could change simultaneously and excite the third element which could result in a trace which was not possible before the delay was added. Such a network would not be multiple-change trace preserving but may still be single-change trace preserving.

6. Conclusion

We have shown that the multiple-change model produces the same results as the single-change model for three properties: quasi semi-modularity, strong delay-insensitivity, and, for deterministic delay-dense networks, trace preservation. Each of these properties is related to the intuitive concept of delay-insensitivity, which states that the results of an analysis of an asynchronous circuit should be independent of the exact sizes of the delays in its components and wires. From this intuitive definition, it seems logical that simultaneous changes should *not* play a significant role, if delays can be arbitrary. However, an open question remains what constitutes a "delay-insensitive property," since trace preservation does not ensure delay-insensitivity for all types of networks.

As a consequence of our theorems, we have shown that the results of [6] proved in the single-change model also hold in the multiple-change model. In particular the following more general versions of theorems from [6] hold:

Theorem (6.1 *of* [6])**.** *If a network is strongly delay-insensitive with respect to a state under the GMW model, then its GMW behavior originating from that state is multiple-change quasi semi-modular.*

Theorem (6.2 *of* [6])**.** *If a GMW behavior of a delay-dense network is multiple-change quasi semi-modular, then the network is strongly delay-insensitive under the GMW model with respect to the initial state of that behavior.*

Our results are limited to certain properties of asynchronous circuits. They show that true concurrency may or may not be equivalent to interleaving. More work needs to be done on this topic; however, it seems clear that great care must be taken in any theory of concurrency before deciding which model is appropriate.

Appendix

A.1. Quasi semi-modularity

Proof of Proposition 3.1: Since we already know that $\mathcal{Q}_s \subseteq \mathcal{Q}_m$, it remains to be shown that if $s \in \mathcal{Q}_m$, then $s \in \mathcal{Q}_s$. The proof is by induction on the length l of the shortest

path from q to s in B_m. If $l = 0$, then $s = q$, and the result holds trivially. Now suppose that $l = n$. There must be some state r in the path from q to s such that the length of the path from q to r is $n - 1$ and $s \in r\mathcal{T}$ for some $\mathcal{T} \in 2^{\mathcal{Y}}$. Assume that $r \in \mathcal{Q}_s$. Clearly, if $y^i \in \mathcal{T}$, then y^i is excited in r to change to its value in s ($s_i \in R_i$). Since B_s is single-change quasi semi-modular starting from state r, each $y^i \in \mathcal{T}$ can change to its value in s, one at a time, without destroying the excitations of the other variables of $\mathcal{T}$, which have not yet changed. Hence, $s \in rw$, where w consists of all the elements of $\mathcal{T}$ in any order, and $s \in \mathcal{Q}_s$. Therefore, every state reachable from q in B_m is also reachable from q in B_s, and hence $\mathcal{Q}_s = \mathcal{Q}_m$. □

Proof of Theorem 3.1: First we prove by contradiction that, if behavior B_s is single-change quasi semi-modular, then B_m must be multiple-change quasi semi-modular. Assume that B_s is single-change quasi semi-modular. Suppose that B_m is not multiple-change quasi semi-modular. There must be some state $s \in \mathcal{Q}_m$ that is not multiple-change quasi semi-modular. Then there exists a state $t \in \mathcal{Q}_m$ such that $t \in s\mathcal{T}$ and there exists a j such that $y^j \notin \mathcal{T}$, $y^j \in \mathcal{U}(s)$, and $S_j \not\subseteq T_j$. By Proposition 3.1, $s \in \mathcal{Q}_s$. Since B_s is single-change quasi semi-modular, starting from s, the values of the $y^i \in \mathcal{T}$ can change, one at a time, without destroying the excitations of the other elements of $\mathcal{T}$ that have not yet changed. Therefore, $t \in sw$, where w consists of all the elements of $\mathcal{T}$ in any order. Since $y^j \notin \mathcal{T}$, y^j does not appear in w. Since B_s is single-change quasi semi-modular and $y^j \in \mathcal{U}(s)$, we know that $S_j \subseteq T_j$, which is a contradiction. Hence, B_m must be multiple-change quasi semi-modular.

To prove the second part of the theorem, we show that, if B_m is multiple-change quasi semi-modular, then B_s is single-change quasi semi-modular. Assume that B_m is multiple-change quasi semi-modular. Let s be any state in $\mathcal{Q}_s$. Since $\mathcal{Q}_s \subseteq \mathcal{Q}_m$, we know that $s \in \mathcal{Q}_m$. For all $t \in \mathcal{Q}_s$, if $t \in sy^i$, then $t \in s\mathcal{T}$ with $\mathcal{T} = \{y^i\}$. Since s is multiple-change quasi semi-modular with respect to B_m, $S_j \subseteq T_j$ for all $j \neq i$ such that $y^j \in \mathcal{U}(s)$; hence, s is also single-change quasi semi-modular. Since s could have been any state, B_s is single-change quasi semi-modular. □

A.2. Strong delay-insensitivity

Proof of Proposition 4.1: By allowing the unstable inserted delays to change one at a time, starting with those closest to an original module, as suggested in Proposition 4.2 of [6], we get $\tilde{w}_1 \in (\tilde{\mathcal{Y}} - \mathcal{Y})^*$ such that $\tilde{s}\tilde{w}_1 = \tilde{s}'$, where $\tilde{s}'$ is the stable-delay extension of s. It follows that the excitations of all the original modules of N are the same in s and $\tilde{s}'$. This result is proven in Proposition 4.1 in [6]. Hence, $S_i = \tilde{S}_i'$ for all i such that $y^i \in \mathcal{T}$. The inputs of every M^i in $\tilde{N}$ such that $y^i \in \mathcal{T}$ are inserted delays; hence, starting from state $\tilde{s}'$, the elements of $\mathcal{T}$ can change to their values in t one at a time without affecting the excitation of the other elements of $\mathcal{T}$ that have not yet changed. Let $\tilde{t}$ be the state reached from $\tilde{s}$ by applying the changes in $\tilde{w} = \tilde{w}_1\tilde{w}_2$, where $\tilde{w}_2$ consists of all the elements of $\mathcal{T}$. Since $\tilde{t} \in \tilde{s}\tilde{w}$, and $\tilde{t}$ is an extension of t, our claim holds. □

Proof of Proposition 4.2: The proof is by induction on the length l of the shortest path from q_m to s in B_m. If $l = 0$, then $s = q_m$, then the result is trivial since $\tilde{q}_s$ is an extension of

q_m with respect to N. Now suppose $l = n$. There must be some state r in the path from q_m to s where the length of the path from q_m to r is $n-1$ and $s \in r\mathcal{T}$ for some $\mathcal{T} \in 2^{\mathcal{Y}}$. Assume that there is an $\tilde{r} \in \tilde{\mathcal{Q}}_s$, which is an extension of r with respect to N. By Proposition 4.1, there exists an $\tilde{s} \in \tilde{\mathcal{Q}}_s$ such that $\tilde{s}$ is an extension of s with respect to N. □

Proof of Theorem 4.1: Let N be a network and let $B_s = \langle q_s, \mathcal{Q}_s, \mathcal{R}_s \rangle$ be a GSW behavior of N. Let $B_m = \langle q_m, \mathcal{Q}_m, \mathcal{R}_m \rangle$ be the GMW behavior of N with $q_m = q_s$. Let $\hat{N} \in \mathcal{D}(N)$ and let $\hat{B}_m = \langle \hat{q}_m, \hat{\mathcal{Q}}_m, \hat{\mathcal{R}}_m \rangle$ be the GMW behavior of $\hat{N}$ which is initial state compatible with B_m. First, suppose that N is strongly delay-insensitive with respect to q_s under the GSW model. We shall prove that N is also strongly delay-insensitive, with respect to the same state, under the GMW model, by showing that $\hat{B}_m$ is safe with respect to B_m as shown in the following diagram.

$\hat{B}_m$: if $\hat{s} \xrightarrow{\hat{W}} \hat{t}$, with $\hat{W} \downarrow \mathcal{Y} = \mathcal{T}$ and $\hat{s} \downarrow \mathcal{Y} = s$, then
B_m: $s \xrightarrow{\mathcal{T}} t$, where $\hat{t} \downarrow \mathcal{Y} = t$.

Let $\tilde{\hat{N}}$ be the delay-completion of $\hat{N}$. Since $\hat{N}$ is a delay extension of N and $\tilde{\hat{N}}$ is a delay extension of $\hat{N}$, $\tilde{\hat{N}} \in \mathcal{D}(N)$. Let $\tilde{\hat{B}}_s = \langle \tilde{\hat{q}}_s, \tilde{\hat{\mathcal{Q}}}_s, \tilde{\hat{\mathcal{R}}}_s \rangle$ be the GSW behavior of $\tilde{\hat{N}}$ which is initial state compatible with $\hat{B}_m$. Behavior $\tilde{\hat{B}}_s$ must also be initial state compatible with B_s, since $\hat{B}_m$ is initial state compatible with B_m, which has the same initial state as B_s.

Let $\hat{s} \in \hat{\mathcal{Q}}_m$ be an extension of $s \in \mathcal{Q}_m$. Let $\hat{t} \in \hat{\mathcal{Q}}_m$ and $\hat{W} \in (2^{\hat{\mathcal{Y}}})^*$ such that $\hat{t} \in \hat{s}\hat{W}$ and $\hat{W} \downarrow \mathcal{Y} = \mathcal{T}$ for some $\mathcal{T} \in 2^{\mathcal{Y}}$. Let y^i be an arbitrary element of $\mathcal{T}$. To prove that $\hat{B}_m$ is safe with respect to B_m, it is sufficient to show that $\hat{t}_i \in S_i$, i.e., that module M^i is excited in state s to change to its value in state $\hat{t}_i$. Let $\hat{W} = U_1\hat{\mathcal{T}}U_3$ where $U_1, U_3 \in (2^{\hat{\mathcal{Y}}-\mathcal{Y}})^*$ and $\hat{\mathcal{T}} \downarrow \mathcal{Y} = \mathcal{T}$ and let $\hat{W}' = U_1\{y^i\}$. There must be some state $\hat{r} \in \hat{\mathcal{Q}}_m$ such that $\hat{r} \in \hat{s}\hat{W}'$ and, since y^i does not appear in U_3, $\hat{r}_i = \hat{t}_i$. Note that y^i is the only original module of N included in $\hat{W}'$.

By Proposition 4.2 we know that there exists an $\tilde{\hat{s}} \in \tilde{\hat{\mathcal{Q}}}_s$, where $\tilde{\hat{s}}$ is an extension of $\hat{s}$ with respect to $\hat{N}$. Hence, by Proposition 4.1, there exists an $\tilde{\hat{r}} \in \tilde{\hat{\mathcal{Q}}}_s$ such that $\tilde{\hat{r}} \in \tilde{\hat{s}}\tilde{\hat{w}}$, where $\hat{r}$ is the projection of $\tilde{\hat{r}}$ with respect to $\hat{N}$ and $\tilde{\hat{w}}$ consists of y^i and possibly some elements of $(\tilde{\hat{\mathcal{Y}}} - \mathcal{Y})$. See the diagram below.

$\hat{B}_m$: if $\hat{s} \xrightarrow{\hat{W}} \hat{t}$ and
$\hat{s} \xrightarrow{U_1} \hat{s}' \xrightarrow{y^i} \hat{r}$, where $y^i \in \mathcal{T}$ and $\hat{r}_i = \hat{t}_i$, then
$\tilde{\hat{B}}_s$: $\tilde{\hat{s}} \xrightarrow{\tilde{\hat{w}}} \tilde{\hat{r}}$, where $\tilde{\hat{w}} \downarrow \mathcal{Y} = y^i$.

Since N is strongly delay-insensitive under the GSW model and $\tilde{\hat{N}} \in \mathcal{D}(N)$, $\tilde{\hat{B}}_s$ is safe with respect to B_s. Hence, there must exist an $r \in \mathcal{Q}_s$ such that $r \in sy^i$, where r is the projection of $\tilde{\hat{r}}$ with respect to N and $y^i = \tilde{\hat{w}} \downarrow \mathcal{Y}$. Therefore, $y^i \in \mathcal{U}(s)$ and $r_i \in S_i$. Since $\hat{r}_i = \hat{t}_i$ and r is a projection of $\hat{r}$, $r_i = \hat{r}_i = \hat{t}_i$ and hence, $\hat{t}_i \in S_i$. Since y^i could have been any element of $\mathcal{T}$, $\hat{t}_j \in S_j$ for all j such that $y^j \in \mathcal{T}$. If t is the projection of $\hat{t}$ with respect

to N, then $t \in s\mathcal{T}$. Therefore, $\hat{B}_m$ is safe with respect to B_m. This argument is illustrated below.

$\tilde{\hat{B}}_s$: if $\tilde{\hat{s}} \xrightarrow{\tilde{\hat{w}}} \tilde{\hat{r}}$, where $\tilde{\hat{w}} \downarrow \mathcal{Y} = y^i$, then

B_s: $s \xrightarrow{y^i} r$ and therefore

B_m: $s \xrightarrow{\mathcal{T}} t$.

To prove the second half of the theorem, we show that, if $\hat{B}_m$ is safe with respect to B_m, then $\hat{B}_s$ is safe with respect to B_s. Let $s \in \mathcal{Q}_s$ be a projection of $\hat{s} \in \hat{\mathcal{Q}}_s$. Since $\mathcal{Q}_s \subseteq \mathcal{Q}_m$ and $\hat{\mathcal{Q}}_s \subseteq \hat{\mathcal{Q}}_m$, $s \in \mathcal{Q}_m$ and $\hat{s} \in \hat{\mathcal{Q}}_m$. It is not hard to see that for any $\hat{t} \in \hat{\mathcal{Q}}_s$ and $\hat{w} \in \hat{\mathcal{Y}}^*$ such that $\hat{t} \in \hat{s}\hat{w}$ and $\hat{w} \downarrow \mathcal{Y} = y^i$, $\hat{t} \in \hat{s}\hat{W}$ where $\hat{W}$ consists of all the elements of $\hat{w}$ in singleton sets. Hence, $\hat{W} \downarrow \mathcal{Y} = \{y^i\}$. Since $\hat{B}_m$ is safe with respect to B_m, $t \in s\{y^i\}$, where t is the projection of $\hat{t}$ with respect to N. Hence, y^i is excited in state s and $t \in sy^i$. Therefore, $\hat{B}_s$ is safe with respect to B_s. □

A.3. Trace preservation

We denote traces of a GMW behavior by uppercase letters U, V, W, and those of a GSW behavior, by lowercase letters u, v, w. We say that state s is *reached by* trace w (W) if, starting from the initial state, the network could be in state s after trace w (W) has occurred. If the network is deterministic, then the state reached by w (W) is unique.

Let N be a delay-dense network whose behavior is deterministic, and let $\hat{N}$ be a delay extension of N. Let B_s and B_m be the GSW and GMW behaviors, respectively, of N with initial state q. Let $\hat{B}_s$ and $\hat{B}_m$ be GSW and GMW behaviors of $\hat{N}$ which are initial state compatible with B_s and B_m. Let T_s, T_m, $\hat{T}_s$, and $\hat{T}_m$ be the trace structures of B_s, B_m, $\hat{B}_s$, and $\hat{B}_m$ respectively.

Proposition A.1. *Let $\hat{w} \in \mathbf{t}\hat{T}_s$ and let $\hat{s}$ be the state reached by $\hat{w}$. Let $s \in \mathcal{Q}_s$ be the projection of $\hat{s}$. Then there exists $u \in (\mathbf{a}\hat{T}_s - \mathbf{a}T_s)^*$ such that $\hat{w}u \in \mathbf{t}\hat{T}_s$ and the state reached by $\hat{w}u$ is a stable-delay extension of s.*

Proof: Create u by stabilizing the inserted delays, which are unstable in state $\hat{s}$, one at a time, starting with those delays closest to the original modules, as suggested in Proposition 4.2 of [6]. □

The next proposition is similar to Proposition 4.1. Let $\tilde{N}$ be the delay-completion of N. Let $\tilde{B}_s$ be the GSW behavior of $\tilde{N}$, which is initial state compatible with B_m, and let $\tilde{T}_s$ be the trace structure of $\tilde{B}_s$.

Let $\mathcal{T} \in 2^{\mathcal{Y}}$ and let $\Pi(\mathcal{T})$ be any string in $\mathcal{T}^*$ in which each element of $\mathcal{T}$ appears exactly once. We call $\Pi(\mathcal{T})$ a *permutation string* of $\mathcal{T}$.

Proposition A.2. *Let $W \in \mathbf{t}T_m$ where $W = \mathcal{T}_1 \ldots \mathcal{T}_n$. There is a trace $\tilde{w} \in \mathbf{t}\tilde{T}_s$ such that $\tilde{w} = d_1\Pi(\mathcal{T}_1)\ldots d_n\Pi(\mathcal{T}_n)$, where $d_i \in (\tilde{\mathcal{Y}} - \mathcal{Y})^*$. Furthermore, the state $\tilde{s}$ reached by $\tilde{w}$ is an extension of the state s reached by W.*

Proof: We will prove this by induction on the length of the trace W. If $W = \epsilon$, then obviously $\tilde{w} = \epsilon \in \mathbf{t}\tilde{T}_s$ is equal to W and the states reached by W and $\tilde{w}$ are the initial states of the respective networks. Now suppose that $W = U\mathcal{T}_l$, where $U = \mathcal{T}_1 \ldots \mathcal{T}_{l-1} \in \mathbf{t}T_m$ and $\mathcal{T}_l \in \mathbf{a}T_m$. Let r be the state reached by U and s be the state reached by $U\mathcal{T}_l$. Suppose there exists a trace $\tilde{u} \in \mathbf{t}\tilde{T}_s$ such that $\tilde{u} = d_1\Pi(\mathcal{T}_1)\ldots d_{l-1}\Pi(\mathcal{T}_{l-1})$ and state $\tilde{r}$ reached by $\tilde{u}$ is an extension of r. From Proposition A.1, we know that there exists a $\tilde{v} \in (\mathbf{a}\tilde{T}_s - \mathbf{a}T_s)^*$ such that the state $\tilde{r}'$ reached by $\tilde{u}\tilde{v}$ is a stable-delay extension of r. Let $d_l = \tilde{v}$. The excitation of each module in N, and therefore each module whose internal state variable appears in $\mathcal{T}$, is the same in states $\tilde{r}'$ and r. This result was proven in Proposition 4.1 of [6]. Since the inputs of every module M^i in $\tilde{N}$ such that $y^i \in \mathcal{T}$ are attached to inserted delays, from $\tilde{r}'$, the module variables of $\mathcal{T}$ can change to the same value as in state s, one at a time, in any order, without affecting the excitation of the other elements of $\mathcal{T}$ which have not yet changed. Thus, $\tilde{w} = \tilde{u}d_l\Pi(\mathcal{T}) = d_1\Pi(\mathcal{T}_1)\ldots d_{l-1}\Pi(\mathcal{T}_{l-1})d_l\Pi(\mathcal{T}) \in \mathbf{t}\tilde{T}_s$ for any permutation string $\Pi(\mathcal{T}_l)$ of $\mathcal{T}_l$. Furthermore, since $\tilde{r}$ is an extension of r and each element of $\mathcal{T}_l$ changed to its value in s, state $\tilde{s}$, reached after $\tilde{w}$, is an extension of s. □

In the following proposition we show that, if we have a number of singleton sets which may appear together in any order in a GMW trace, then including all these elements in one set, i.e., allowing them to change simultaneously, has no effect on the rest of that trace. Let $\Sigma = \{\{y^i\} \mid y^i \in \mathcal{Y}\}$ be the subset of $\mathbf{a}T_m$ consisting of only singleton sets. Let Γ be any subset of Σ, and let V be any string in Γ^* in which each element of Γ appears exactly once. We call V a *permutation string* of Γ. For example, if $\mathcal{Y} = \{y^1, \ldots, y^5\}$ and $\Gamma = \{\{y^1\}, \{y^3\}, \{y^4\}\}$, then $V = \{y^3\}\{y^4\}\{y^1\}$ is a permutation string of Γ.

Proposition A.3. *If there exist $U_1, U_2 \in (\mathbf{a}T_m)^*$ such that $U_1VU_2 \in \mathbf{t}T_m$ for each permutation string V of Γ, then $U_1\mathcal{T}U_2 \in \mathbf{t}T_m$ where $\mathcal{T} = \bigcup_{\{y^i\}\in\Gamma}\{y^i\}$.*

Proof: Let s be the state reached by U_1. Since V can be any permutation string of Γ, all the elements of Γ must be excited in s and hence $U_1\mathcal{T} \in \mathbf{t}T_m$. To show that $U_1\mathcal{T}U_2 \in \mathbf{t}T_m$, it is sufficient to show that the state reached by $U_1\mathcal{T}$ must be the same as the state reached by U_1V for some permutation string V. Let V be one of the permutation strings in which all the non-delay elements come before any delay elements. Let r be the state reached by UV. Since the network is delay-dense, the input to each non-delay element is a delay, and hence, the excitation of each of these elements must stay the same as in s until it changes. The same is true of all the delay elements in Γ since they are all excited in s, and so, if the excitation changed before the element changed, it would be disabled and V would not be possible from state s. Thus, $r_i = S_i$ for each $\{y^i\} \in \Gamma$ and $r_j = s_j$ for each $\{y^j\} \notin \Gamma$. Obviously, the same is true for the state reached by $U_1\mathcal{T}$, and hence, $U_1\mathcal{T}U_2 \in \mathbf{t}T_m$. □

Proof of Theorem 5.1: Let $\tilde{\hat{N}}$ be the delay-completion of $\hat{N}$. Let $\tilde{\hat{B}}_s$ be the GSW behavior of $\tilde{\hat{N}}$ which is initial state compatible with B_m (and hence with $\hat{B}_s$ as well). Let $\tilde{\hat{T}}_s$ be the trace structure of $\tilde{\hat{B}}_s$.

First, suppose that N is single-change trace preserving with respect to state q. To prove that N is multiple-change trace preserving, it must be shown that for any trace $\hat{W} \in \mathbf{t}\hat{T}_m$ there

is a trace $W \in \mathbf{t}T_m$, where $\hat{W} \downarrow \mathbf{a}T_m = W$. Let $\hat{W} = \hat{\mathcal{T}}_1 \ldots \hat{\mathcal{T}}_n$ and let $\hat{\mathcal{T}}_i \downarrow \mathcal{Y} = \mathcal{T}_i$ for each i. Then, $W = \mathcal{T}_1 \ldots \mathcal{T}_n$. From Proposition A.2, we know that for any trace $\hat{W} \in \mathbf{t}\hat{T}_m$ there is a trace $\tilde{\hat{w}} \in \mathbf{t}\tilde{\hat{T}}_s$, where $\tilde{\hat{w}} = d_1\Pi(\hat{\mathcal{T}}_1)\ldots d_n\Pi(\hat{\mathcal{T}}_n)$ and $\Pi(\hat{\mathcal{T}}_i)$ is any permutation string of $\hat{\mathcal{T}}_i$. Since N is single-change trace preserving with respect to state q and $\tilde{\hat{B}}_s$ is initial state compatible with B_s, there must exist a trace $w \in \mathbf{t}T_s$ such that $\tilde{\hat{w}} \downarrow \mathbf{a}T_s = w$. Hence, $w = \Pi(\mathcal{T}_1)\ldots\Pi(\mathcal{T}_n)$. Since each $\Pi(\hat{\mathcal{T}}_i)$ could be any permutation string of $\hat{\mathcal{T}}_i$, each $\Pi(\mathcal{T}_i)$ could be any permutation string of $\mathcal{T}_i$. It is easy to see that for every trace in $w \in \mathbf{t}T_s$ there is a trace $W' \in \mathbf{t}T_m$ with all the elements of w in singleton sets and in the same order as they appear in w. Thus, $W' = \Phi_1 \ldots \Phi_n$, where Φ_i is a string of singleton sets consisting of all the elements of $\Pi(\mathcal{T}_i)$. Since $\Pi(\mathcal{T}_i)$ could be any permutation string of $\mathcal{T}_i$, the singleton sets in Φ_i could appear in any order. It remains to be shown that the elements of each $\mathcal{T}_i$ may occur simultaneously in B_m so that $W \in \mathbf{t}T_m$. Let $U_1 = \epsilon$, $\Gamma = \{\{y^i\} \mid y^i \in \Pi(\mathcal{T}_1)\}$, and $U_3 = \Phi_2 \ldots \Phi_n$. Each permutation string of Γ is equal to some ordering of Φ_1, and since $\Phi_1 \ldots \Phi_n \in \mathbf{t}T_m$ for any ordering of Φ_1, $U_1 V U_3 \in \mathbf{t}T_m$ for any permutation string V of Γ. Since $\mathcal{T}_1 = \bigcup_{\{y^i\}\in\Gamma}\{y^i\}$, from Proposition A.3, $U_1\mathcal{T}_1U_3 = \mathcal{T}_1\Phi_2\ldots\Phi_n \in \mathbf{t}T_m$. We can repeat this procedure by substituting $\mathcal{T}_1$ for Φ_1 in W' and letting $U_1 = \mathcal{T}_1$, $\Gamma = \{\{y^i\} \mid y^i \in \Pi(\mathcal{T}_2)\}$, and $U_3 = \Phi_3 \ldots \Phi_n$. This procedure can be repeated until $W' = \mathcal{T}_1 \ldots \mathcal{T}_n = W$. Thus, $W \in \mathbf{t}T_m$ such that $\hat{W} \downarrow \mathbf{a}T_m = W$ and N is multiple-change trace equivalent with respect to q.

Now suppose that T_m is trace preserving. Let $\hat{w} \in \mathbf{t}\hat{T}_s$ be a trace. Let $\hat{W} \in \mathbf{t}\hat{T}_m$ consist of all the elements of $\hat{w}$ in singleton sets. Since T_m is trace preserving, there is a trace $W \in \mathbf{t}T_m$ such that $\hat{W} \downarrow \mathbf{a}T = W$. Trace W must also consist of singleton sets, and so we also have a trace $w \in \mathbf{t}T_s$ such that $\hat{w} \downarrow \mathbf{a}T = w$. Therefore, N is also single-change trace preserving with respect to q. □

Note

1. Most of the material in [6] appeared earlier in [5, 36].

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