The I^2 C-bus in discrete-time process algebra

Citation for published version (APA):

Document status and date:
Published: 01/01/1996

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
The \( I^2 C \)-bus in Discrete-Time Process Algebra

by

S.H.J. Bos and M.A. Reniers

96/14

ISSN 0926-4515

All rights reserved
editors: prof.dr. R.C. Backhouse
         prof.dr. J.C.M. Baeten

Reports are available at:
http://www.win.tue.nl/win/cs

Computing Science Report 96/14
Eindhoven, June 1996
The $I^2C$-bus in Discrete-Time Process Algebra

S.H.J. Bos and M.A. Reniers
Department of Mathematics and Computing Science,
Eindhoven University of Technology, The Netherlands

Abstract

Using discrete time process algebra with relative timing, a model for the $I^2C$-bus is designed. The model of the $I^2C$-bus is divided in three parts: a model for the bus lines, a model for the master interfaces and a model for the slave interfaces. The model of the bus lines is based on a model for a wired-AND. For the models of the interfaces, the approach is to start from a high level bus protocol and refine it step by step. First, a single master without timing constraints is considered. Then the model is adapted to deal with the timing constraints. Then also the restriction to a single master is relaxed. It turns out that the model for the slave interfaces can be based on the model for the master interfaces. The use of the model obtained is discussed and illustrated.

1 Introduction

The $I^2C$-bus is a bidirectional bus for Inter-IC control [Phi89]. Devices on the $I^2C$-bus can be microprocessors, RAM, LCD-drivers, I/O-ports, etc. All $I^2C$-bus compatible devices incorporate an on-chip interface which allows them to communicate with each other via the $I^2C$-bus without additional external interfacing.

For devices communicating with each other on the bus, a communication protocol is defined which avoids all possibilities of confusion, data loss and blockage of information. The timing aspects form an important part of the communication protocol of the bus.

For the exchange of information between the devices connected to the $I^2C$-bus it has two bidirectional wires, called serial data (SDA) and serial clock (SCL). The devices can be considered as masters or slaves when performing data transfers. During a data transfer there is exactly one master and one slave; a master is the device which initiates a data transfer and generates the clock signals that permit that transfer.

The $I^2C$-bus is widely used in mass electronics products because of several advantages it offers. Firstly, it can be implemented in a very cheap way; the wires can be made by exploiting certain properties of the electronic circuitry, not demanding additional logic. Secondly, it serves as a standard for specification and design of a wide variety of ICs such as microprocessors, RAMs, LCD-drivers, I/O-ports, etc. Moreover, the fact that it is a two-wire bus instead of 8, 16 or 32, makes it very attractive since the layout and routing of such wide busses is much harder. Finally,
there are ongoing developments of new protocols, notably ACCESS.bus [ACC93], which extend \( \text{I}^2\text{C}-\text{bus} \).

The interoperability of the many versions and types of \( \text{I}^2\text{C}-\text{bus} \) components from different vendors is an important issue. Much attention has already been paid to the electrical aspects of the interoperability problem (value of pull-up resistors etc.). But the timing aspects are more difficult to describe rigorously and therefore this paper presents an explicit rigorous model of the \( \text{I}^2\text{C}-\text{bus} \) and its interface with the devices connected to it. The availability of such a model is important for checking conformance of new implementations with respect to the standard. This model can be used for checking properties such as freedom of deadlocks of implementations.

To model the \( \text{I}^2\text{C}-\text{bus} \) and its interfaces, we will discuss a discrete time process algebra [BB95, BB96] with relative timing with some additional features. Since the timing aspects in the protocol for the \( \text{I}^2\text{C}-\text{bus} \) is the main concern within the specification and verification of the processes to be designed, the choice for a timed process algebra is straightforward. We choose for a discrete time version rather than a real time one, because all specified delays imposed by the timing constraints are multiples of a certain unit. Furthermore, the motivation for considering relative timing instead of absolute timing is based on the fact that all timing constraints involve pairs of transitions; each second transition of such a pair is allowed to occur a specified amount of time after the first transition has taken place.

Using discrete time process algebra, we will design processes that model the behaviour of the bus itself, and of its interfaces with the devices connected to the bus. Since the task of the interface is to translate instructions from the device to bus transitions and vice versa, it must communicate with the device on the one hand and with the bus on the other. Communications with the bus are needed to accomplish the clamping, releasing and polling of the bus lines. Communications with the device contain the instructions from the device. We make a distinction between interfaces for master devices and for slave devices, since their behaviour is different. The design of the master and slave devices is considered beyond the scope of this paper, because of the enormous variety of applications that can be implemented by master and slave devices.

The model given in this paper can be used when designing devices to be connected to the \( \text{I}^2\text{C}-\text{bus} \). It is of uttermost importance that the interface between a device and the bus is well-understood. It is our firm belief that a formal specification of such an interface improves this understanding considerably. Also, if a formal specification of the device is provided, there are possibilities to reason formally about the device being connected to the bus, i.e., their interaction can be considered.

Another, minor, reason for this research is that, with the recent appearance of [BV95, BB95, BB96], discrete-time process algebra seems to have reached a decent state of maturity. This application can therefore also be seen as a case study in the practical application of discrete-time process algebra.

**Structure of the paper** The paper is structured as follows. The Sections 2 and 3 give a short introduction to the \( \text{I}^2\text{C}-\text{bus} \) and relative discrete time process algebra respectively. In Section 4, a model for the bus lines is given. Then, in Section 5, an interface is designed for a master device in a single-master environment. The approach is to take a high level bus protocol and refine this
protocol step by step until an interface is obtained. In Section 6, the interface for a single master is extended to function in a multi-master environment. After having designed those master interfaces, we give an interface for a slave device in Section 7. This concludes the construction of a model for the $I^2C$-bus in relative discrete time process algebra. The following section deals with the usage of the model presented in this paper. Some conclusions and suggestions for further research are given in Section 9.

Acknowledgements The first author would like to thank Jos Baeten (Eindhoven University of Technology) and Rudolf Mak (Eindhoven University of Technology) for their valuable remarks on preliminary (and extended) versions of this document. The second author would also like to thank Jos Baeten for setting-up the collaboration between the authors. We also would like to acknowledge Twan Basten (Eindhoven University of Technology), Loe Feijs (Eindhoven University of Technology and Philips Research Laboratory Eindhoven), and the anonymous referees for their valuable comments.

2 The $I^2C$-bus

In this section we will give a concise introduction into the $I^2C$-bus; for a more thorough description and explanation we refer to [Phi89, Han93, Bos95].

The $I^2C$-bus is used to interconnect integrated circuits. Devices communicating with each other on the bus must have some form of protocol which avoids all possibilities of confusion, data loss and blockage of information. Fast devices must be able to communicate with slow devices. The system must not depend on the devices connected to it. A procedure has to be devised to decide which device will be in control of the bus and when.

For the exchange of information between the devices connected to it, the $I^2C$-bus has two wires along which information is carried between the devices connected to the bus: the SDA line, that carries the data signal and the SCL line along which clock pulses are transmitted.

Each device is recognized by a unique address and can operate as either a transmitter or a receiver, depending on the function of the device. Devices can also be considered as masters and slaves when performing data transfers. A master is the device which initiates a data transfer on the bus and generates the clock signals that permit that transfer.

The $I^2C$-bus is a multi-master bus: more than one device capable of controlling the bus can be connected to it. As a consequence more than one master could try to initiate a data transfer at the same time. To avoid the chaos that might ensue from such an event, an arbitration procedure has been developed. For a description of this procedure we refer to Section 6.4.

Both SDA and SCL are bidirectional lines. When the bus is free, both lines are high. Devices are capable of clamping and releasing the wires. If one of the devices connected to the bus clamps a line, this line will become low and only if all devices have released a line, it will become high again. A line behaving in such a way is called a wired-AND. A wired-AND is an electronic building block with $N$ inputs and a single output that computes the logical $N$-ary AND function. The low-to-high and high-to-low transitions of the wire are not instantaneous; they require the passage of a certain rise and fall time respectively. During such a transition the voltage level on the wire
is not stable. Apart from rise and fall times, which are related to the physical properties of the bus wires, the specification for the bus will contain no timing constraints. Indeed all other timing constraints have to do with the protocol that prescribes how the bus wires should be manipulated and are therefore the responsibility of the interfaces that connect the devices to the $PC$-bus. The behaviour of the wires consists solely of alternating high-to-low and low-to-high transitions on both lines. These transitions are always responses to the clamping and releasing actions initiated by the devices connected to the bus. The duration of the high and low level periods of the wires are determined by the devices that clamp and release the bus lines and the timing constraints imposed by the bus protocol.

Within the procedure of the $PC$-bus, unique states arise which are defined as start and stop conditions. A high-to-low transition on the $SDA$ line while the $SCL$ line is high indicates a start condition. A low-to-high transition on the $SDA$ line while the $SCL$ line is high defines a stop condition. Start and stop conditions are always generated by a master. A bus session starts with a start condition and ends with a stop condition. The bus is considered to be free when there is no bus session. In between the start and stop condition the following events take place: a slave is addressed, the addressed slave acknowledges, data bytes are transmitted in both directions and acknowledged byte-wise. The sending (receiving) of a byte is achieved by sending (receiving) eight bits serially. Obviously this complicates the bus protocol considerably. In order to restrict the size of the problem, we will have the device take care of addressing and byte-wise data transfer. Thereby we shift some complexity from the interface to the devices, which are beyond the scope of this paper. With these restrictions a data transfer only consists of sending and receiving bits.

One clock pulse is generated for each data bit transferred. The data on the $SDA$ line must be stable during the high period of this clock pulse. The sending of a bit with value 0 is now achieved by clamping (if necessary) the $SDA$ line and generating a clock pulse. Likewise, a bit with value 1 is sent by releasing (if necessary) the $SDA$ line and then generating a clock pulse. Receiving a bit is achieved by generating a clock pulse and then polling the $SDA$ line to determine whether a 0 or a 1 has been received.

The timing constraints involved in the $PC$-bus are discussed next. There are only two timing constraints dealing with a maximum delay, i.e., they express that an event takes at most a certain amount of time. These are the rise time $tR$ and fall time $tF$ of the $SCL$ line. These express the maximum time needed for the $SCL$ line to perform a low-to-high and a high-to-low transition respectively. All other timing constraints are dealing with minimum delays, i.e., they express that an event takes at least a certain amount of time. There is only one minimum timing constraint which is related solely to the $SDA$ line: $tBUF$ denotes the bus free time, i.e., the minimal time needed for the $SDA$ line to be high between a stop and a start condition. The timing constraints $tLOW$ and $tHIGH$ denote the clock low and clock high period respectively. These are dealing solely with the $SCL$ line. The remaining timing constraints deal with both the $SDA$ and $SCL$ line. There are three timing constraints for set-up times: the data set-up time ($tSU;DAT$), the set-up time for a start condition ($tSU;STA$), and the set-up time for a stop condition ($tSU;STO$). Besides these set-up times there are also two hold times: the data hold time ($tHD;DAT$) and the hold time for a start condition ($tHD;STA$). In Figure 1 the timing constraints are depicted in relation to both the $SDA$ and $SCL$ lines. The names of the timing constraints are taken from [Phi89].
In the previous part of this section the protocol on the I²C-bus is described. In this protocol the communication primitives have been discussed. We described how these primitives are used in relation to each other to build a complete bus session. Apart from this protocol for communications on the bus, there should also exist another protocol between masters and slaves, which we will call the "meta-protocol." This meta-protocol describes the communication behaviour between masters and slaves. The meta-protocol states that arbitration is not allowed between a start condition and a data bit, a stop condition and a data bit, and a start condition and a stop condition [Phi89]. For a more thorough explanation of the meta-protocol we refer to [Bos95]. For our model, it is important that start and stop signals never will be involved in the arbitration procedure.

3 Discrete Time Process Algebra with Relative Timing

In this section, we will introduce the process algebra used for modelling the I²C-bus in this paper. Such an algebraic theory is given by a signature, i.e., a set of constant and function symbols, and a set of equations (often called axioms). The process algebra is parameterized by a set A of constants and a partial, commutative and associative function γ. We will instantiate the set A of constants and the communication function γ later on. Using the constant and function symbols, terms can be constructed. These terms represent processes. The axioms express which processes are to be considered equal. The axioms for this process algebra are given in Appendix A. In the axioms also auxiliary operators ν_red, ⌈⌉, ⌊⌋, and | appear. The axioms can also be found in [BB92, BB95, BB96, Bos95]. Also for other issues concerning discrete time process algebra we refer to these papers.

We only list the operators that play a role in the main text of this paper. The signature consists, among others, of the following constant and function symbols:
1. the special constants $\delta$, $\tau$, $\delta$, and $\tau$;

2. for $a \in A$, the constants $\underline{a}$ and $a$;

3. the binary operators $+,$ and $\|$;

4. the unary operators $\sigma_{rlh}$, $\rho_f$, $\delta_H$, $\tau_I$, $\pi_{\phi}$, and $\Theta_C$ for $f : A \rightarrow A$, and $H, I, C \subseteq A$;

The special constants $\delta$ and $\tau$ denote deadlock and the silent step in the current time slice respectively. The constants $\underline{a}$ and $a$ are the delayable versions thereof; they can occur in any time slice.

For our application, we assume that the set $A$ contains actions $s_{ch}(v)$, $r_{ch}(v)$, and $c_{ch}(v)$ for a channel $ch$ and a datum $v$. These actions denote the sending, reception, and communication of datum $v$ along channel $ch$. For $a \in A$, the action $\underline{a}$ denotes the execution of $a$ in the current time slice, and the action $a$ denotes the execution of $a$ in any time slice. The execution of atomic actions and inaction is considered to be instantaneous.

The binary operators $+$ and $\cdot$ denote alternative and sequential composition respectively. The alternative composition of the processes $x$ and $y$ is the process that executes process $x$ or process $y$, but not both. We have the time factorization assumption, i.e., passage of time as such cannot determine a choice. The sequential composition of the processes $x$ and $y$ is the process that first executes $x$, and upon termination thereof starts with the execution of process $y$.

With the unit delay operator processes can be delayed one time slice: the process $\sigma_{rel}(x)$ denotes the process $x$ starting in the next time slice. In order to express that a process $x$ has to be delayed for $n \geq 0$ time slices, we introduce the shorthand $\sigma_{rel}^n(x)$ for the $n$ times repeated application of $\sigma_{rel}$.

Two processes can be composed in parallel with the parallel composition operator $\parallel$. The process $x \parallel y$ interleaves the behaviours of $x$ and $y$ and tries to communicate send actions with receive actions of the same datum along the same channel, but is forced to synchronize on time steps, i.e., a clock tick is executed by both processes at the same time or, if this is not possible, the process deadlocks. In our application the communication function $\gamma$ is defined as follows $\gamma(s_{ch}(v), r_{ch}(v)) = c_{ch}(v)$ and $\gamma(r_{ch}(v), s_{ch}(v)) = c_{ch}(v)$. For all other cases $\gamma$ is undefined.

The renaming operator $\rho_f$ is used to rename atomic actions into atomic actions according to the mapping $f : A \rightarrow A$. The encapsulation operator is a special renaming operator where all actions given by the set $H$ ($H \subseteq A$) are renamed into $\delta$. This operator is used to block the execution of unwanted actions. The abstraction operator $\tau_I$ is also a special renaming operator; in this case all atomic actions given by the set $I$ ($I \subseteq A$) are renamed into the atomic action $\tau$, while all others remain unchanged. This operator, as may be clear from its name, is used to abstract from actions which are considered to be unobservable. These actions are given by the parameter $I$. The time abstraction operator $\pi_{\phi}$ is used to abstract from timing by embedding processes in the time-free theory, i.e., all atomic actions are made delayable and all time steps are removed. The priority operator $\Theta_C$ is used to achieve minimum delays (or maximal progress) for atomic actions from the set $C$ ($C \subseteq A$).
4 A model for the bus lines

In this section we will design a process that models the behaviour of an individual wire of the \textit{I$^2$C-bus}. This is necessary in order to validate the design for the interface of the next section.

Since the behaviour of one line does not depend on the behaviour of the other and since both lines are copies of the same piece of hardware, viz. a wired-AND, it suffices to design a process that describes a wired-AND. Hence, a model for the \textit{I$^2$C-bus} consists of the parallel composition of the behaviour of two processes describing a wired-AND. Since there is no physical interaction between the two wires, the processes that model the wires will not communicate, with each other, when composed in parallel.

First we consider the communication between the wired-AND and its environment (see Figure 2), the processes connected to it. Suppose the number of devices is \( N \). The actions clamping and releasing by device \( i \) are represented as communications between the wired-AND and the device's interface over a channel \( ch(i) \). Clamping the wire by device \( i \) will be denoted by sending the value \( dn \) along channel \( ch(i) \) and releasing the wire is denoted by sending the value \( up \). We also introduce the channels \( stat(i) \), one for each device connected to the wired-AND. This channel is used to signal the current voltage level of the wire (high or low) to the devices communicating with it. Each process connected to the wire is then able to poll the wire in order to obtain the current voltage level.

Now we are ready to describe the process representing the wired-AND formally. This process is denoted by \( WA \). We will use auxiliary processes \( WA(k) \), for \( 0 \leq k \leq N \), that describe the situation where \( k \) devices clamp the wire. Initially, there is no device that clamps the wire, so \( WA = WA(0) \). The specifications of these processes can be found in Table 1.

Each of the processes \( WA(k) \), \( 0 \leq k < N \), is at any time willing to receive the \( dn \) value from a device. Then the parameter is increased by one in order to keep track of the number of clamping devices. In the situation where no devices are clamping the wire (\( k = 0 \)), and a device clamps the wire, the voltage level of the wired-AND has to be changed to \textit{Low}. This is achieved by the process \( WA(0 \rightarrow 1) \). Process \( WA(N) \) is not capable of receiving a \( dn \) value since all devices are already clamping the wire.

Process \( WA(k) \), \( 0 < k \leq N \), is at any time willing to receive an \( up \) value. In that case, the parameter is decreased by one. If the number of devices clamping the wire changes from 1 to 0,
the voltage level of the wired-AND is changed to High. This is achieved by the process \( WA(1 \rightarrow 0) \). Process \( WA(0) \) is not capable of receiving an up value since no devices are clamping the wire.

The processes \( WA(0 \rightarrow 1) \) and \( WA(1 \rightarrow 0) \) incorporate the maximum delay periods fall time \( t_f \) and rise time \( t_r \) respectively. In order to make the choice of delay time uncontrollable by the environment of the wire, we use the silent action \( \tau \). The \( \tau \) can be considered to hide a delay time determining action which is internal to the bus and hence invisible for the environment.

All processes \( WA(k) \) are capable of signalling the current value of the wire. If there are no devices clamping the wire, the current voltage level is High and in all other cases, except when the wire is not stable, the voltage level is Low. The wire is not stable during the transition from high-to-low (\( WA(1 \rightarrow 0) \)) and from low-to-high (\( WA(0 \rightarrow 1) \)); in these cases, the wire cannot signal its current value.

\[
\begin{align*}
WA & = WA(0) \\
WA(0) & = \sum_{1 \leq i \leq N} (r_{ch(i)}(dn) \cdot WA(0 \rightarrow 1) + s_{stat(i)}(High) \cdot WA(0)) \\
WA(1) & = \sum_{1 \leq i \leq N} (r_{ch(i)}(dn) \cdot WA(2) + r_{ch(i)}(up) \cdot WA(1 \rightarrow 0) + s_{stat(i)}(Low) \cdot WA(1)) \\
WA(k) & = \sum_{1 \leq i \leq N} (r_{ch(i)}(dn) \cdot WA(k + 1) + r_{ch(i)}(up) \cdot WA(k - 1) + s_{stat(i)}(Low) \cdot WA(k)) \\
WA(N) & = \sum_{0 \leq m \leq t_f} \tau \cdot \sigma_m^{wa}(WA(1)) \\
WA(0 \rightarrow 1) & = \sum_{0 \leq m \leq t_r} \tau \cdot \sigma_m^{wa}(WA(0)) \\
WA(1 \rightarrow 0) & = \sum_{0 \leq m \leq t_r} \tau \cdot \sigma_m^{wa}(WA(0))
\end{align*}
\]

Table 1: Equations describing a wired-AND: \( 2 \leq k < N \).

The process descriptions for the SDA and SCL lines can now be obtained from process \( WA \) by renaming the channels according to the renaming functions \( fd \) and \( fc \) which are given in Table 2.

\[
\begin{align*}
fd(r_{ch(i)}(v)) & = r_{d(i)}(v) \\
fc(r_{ch(i)}(v)) & = r_{c(i)}(v) \\
fd(s_{stat(i)}(w)) & = s_{t(i)}(w) \\
fc(s_{stat(i)}(w)) & = s_{t(i)}(w)
\end{align*}
\]

Table 2: The renaming functions \( fd \) and \( fc \) (\( 1 \leq i \leq N, v \in \{up, dn\}, w \in \{High, Low\} \)).
Using these renamings, the specifications of the lines are given by $SDA = r_{pj}(WA)$ and $SCL = r_{jc}(WA)$. The bus is then specified as the parallel composition of the two lines: $Bus = SDA \parallel SCL$.

5 Designing an interface for a single master

5.1 Introduction

In this section, we design a process which acts as an interface between the $I^2C$-bus and the devices connected to the bus. This interface translates the bus protocol in terms of the actions $start$, $stop$, $zero$, $one$, and $rebit$ into clamping, releasing and polling the bus wires and vice versa. Furthermore, the interface will see to it that the timing constraints concerning the transitions are being met. In this way the master (slave) does not have to deal with the timing aspects of the protocol. Initially, we reduce the complexity of the design stage by simplifying the problem by imposing the following restrictions:

- we base the design on the behaviour of a pure master, i.e., a device which only acts as a master and not as a slave device;
- we limit the number of masters connected to the bus to one;
- we neglect the timing constraints.

In Section 5.4, an interface for a single master with timing constraints is designed based on the interface for the single master without timing constraints and in Section 6, we extend the interface to function in a multi-master environment. The first restriction will be maintained, we do not consider a device which can act as both a master and a slave. Before we design the interface, we describe the bus protocol in terms of the actions $start$, $stop$, $zero$, $one$, and $rebit$ in Section 5.2.

5.2 The bus protocol

In this section, we will explain the communication protocol on the bus and how this protocol is used in the design of the interface between the bus and a device. The communication on the $I^2C$-bus can be described as the behaviour of the following process, with initial state $I$:

$$I = start \cdot N$$
$$N = send0 \cdot N + send1 \cdot N + rebit \cdot N + stop \cdot I$$

The communication actions $start$ and $stop$ denote bus transitions which stand for the transmissions of $start$ and $stop$ signals and are always initiated by a master device. Communication actions $send0$, $send1$ and $rebit$ indicate the transmission of a single bit with value zero or one, and the reception of a single bit respectively.

Process $IF_i$, which models the interface for device $i$ is connected to the processes $SDA$, $SCL$ and the device as indicated in Figure 3. Channel $c_i$ is used for communications $up$ and $dn$ that cause transitions on the $SCL$ line, channel $s_i$ is used to signal the current state to the interface,
channel $d_i$ is used for communications \textit{up} and \textit{dn} that cause transitions on the SDA line, channel $t_i$ is used to pass on the current state to the interface, channel $m_i$ is used by the device to issue the commands to the process $IF_i$, and channel $a_i$ is used to acknowledge to the device when an action is performed. Since the process specification for the interface is the same for each device, we will omit the subscript $i$ when it is clear from the context which device is meant.

5.3 Interface for a single master

In this section, we construct an interface module for a pure master in a single master environment. In order to achieve this, we extend the bus protocol from the previous section. Since we are designing an interface that does not have to deal with any timing constraints at this point, we consider the rise and fall times to be zero: $t_R = t_F = 0$ or equivalently we consider $\pi_f(Bus)$ instead of $Bus$.

The bus protocol is described in the previous section in terms of the primitives \textit{start}, \textit{stop}, \textit{zero}, \textit{one}, and \textit{recbit}. These are all initiated by the master device. The matching signals that should occur on the bus are generated by $IF$'s subprocesses $T$, $P$, $S_0$, $S_1$, and $R$ respectively. These will also send matching acknowledgements to the device. Equations for process $IF$ and its subprocesses can be found in Table 3.

The initial state is associated with process $I$. This state represents the situation that the master is not involved in a bus session. Since we have assumed that there is only one master connected to the bus, it follows that the bus is free, so both the SDA and SCL line are high. This means that when the interface returns to the initial state after a bus session, i.e., after the occurrence of a stop condition, both lines must be released.

As mentioned before, a session consists of communication actions. In between consecutive actions, the SCL line has to be clamped by the master. This situation is represented by process $N$. Although the $PC$-bus-specification [Phi89] does not restrict the value of the SDA line, while the SCL line is low, we will demand that the master releases the SDA line. With this assumption a slave which is waiting to manipulate the data line is able to do so as soon as possible. We try to realize minimum delays. This decision is also convenient when a slave-transmitter is trying to manipulate the data line.

In Figure 4 the bus transitions associated to the communication primitives are depicted. The
IF = I
I = r_m(start) \cdot T
N = r_m(stop) \cdot P
+ r_m(send_0) \cdot S0
+ r_m(send_1) \cdot S1
+ r_m(recbit) \cdot R
CU = s_c(up)
CD = s_c(dn)

T = DD \cdot CD \cdot (s_a(ready) || DU) \cdot N
P = DD \cdot CU \cdot DU \cdot s_a(ready) \cdot I
S0 = DD \cdot CU \cdot CD \cdot (s_a(ready)) || DU \cdot N
S1 = CU \cdot CD \cdot s_a(success) \cdot N
R = CU \cdot (r_1(High)) \cdot CD \cdot s_a(one)
+ r_1(Low) \cdot CD \cdot s_a(zero)) \cdot N
DU = s_d(up)
DD = s_d(dn)

Table 3: Equations for the single master interface without timing constraints.

<table>
<thead>
<tr>
<th>T (start)</th>
<th>P (stop)</th>
<th>S0 (send_0)</th>
<th>S1 (send_1)</th>
<th>R (recbit)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SDA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SCL</td>
</tr>
</tbody>
</table>

Figure 4: The actions in terms of bus transitions.

equations from Table 3 correspond closely to these diagrams. Additionally, acknowledgements are sent via channel a to the device.

In order to send a one, the SDA line must be high during the clock pulse. Because we restricted the number of masters to one, and the SDA line had been released already, we do not have to check this voltage level. To read a single bit from the bus, the data line value must be checked during the high period of the clock, since only then the value of the SDA line can be considered stable. During the clock high period the voltage level of the SDA line is polled and its value is passed on to the device along channel a. The master must have released the SDA line to enable the slave-transmitter to put data on the bus.

5.4 Timing

From now on, we will no longer demand that the rise and fall times are equal to zero, as we did in Section 5.3. The new process that models the behaviour of the interface, within which timing constraints have to be met, will be called TIF. The connection with the bus and the device remains the same, however. In order to have process TIF deal with rise and fall times correctly, we will add some synchronization statements. Our construction of the bus with the transitional states SCL(0→1) and SCL(1→0) and the signalling of the current state provides a mechanism to solve this rather elegantly: after a releasing or clamping action the process that caused the transition, is simply delayed until the desired value is signalled by the bus lines. We can now describe the up-going and down-going flanks of both the SDA and SCL line quite simply. Process CD (clock
down) describes the clamping of the clock line and the subsequent waiting for the line to become low. Process $CU$ (clock up) describes the releasing of the clock line and the delay that is caused by counting off the rise time. Processes $DD$ (data down) and $DU$ (data up) behave alike with regard to the $SDA$ line. See Table 4 for their specifications. Note that the send actions of these processes are non-delayable because of the following assumption: A device will not delay an action unnecessarily.

\[

cu = \overline{s(c)(up)} \cdot r_s(High) \\
\overline{cd} = \overline{s(c)(dn)} \cdot r_s(Low) \\
\overline{du} = s_d(up) \cdot r_i(High) \\
\overline{dd} = s_d(dn) \cdot r_i(Low)
\]

Table 4: Equations for upgoing and downgoing flanks.

It is assumed that all devices connected to the bus have a local internal clock mechanism. This implies that each device has a local clock high and clock low period. For device $i$ these will be denoted by $T_{High}(i)$ and $T_{Low}(i)$ respectively. If no confusion can arise, we omit the $i$. Furthermore, it is demanded that these local clock high and clock low periods are related to the "global" clock high and clock low period as follows: for all $i$, $T_{High}(i) \geq t_{HIGH}$ and $T_{Low}(i) \geq t_{LOW}$.

We have to keep in mind that the timing of some actions does not depend on the execution of the previous action, as is usual with relative timing, but on the execution of some earlier action. We cannot express this naturally using the given algebraic operators.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{timer_connection.png}
\caption{Connecting process $Timer$.}
\end{figure}

This problem can be solved by introducing a timer process $Timer$ (see Table 5), which is placed in parallel with process $TI$, i.e., $TI || {\overline{TIF}}$, that counts time slices that passed since a clock low period has started. As soon as $T_{Low}$ time slices have passed, $s_c(up)$ is allowed to be executed. In a similar way the timer process is used to count off the clock high period as well. Of course this timer process has to be instructed when it has to start counting and it must be able to signal to its environment when the counting has been completed. We need channels $v$ and $w$ along which there is communication between the timer and the interface process $TIF$ (see Figure 5). Along channel $v$ the value finished is sent by the timer if the counting is completed and along channel $w$ process $TIF$ can send the number of time slices that have to be counted off.

In parameter $n$ we store the number of time slices that still have to be counted off. Initially, the value of $n$ equals zero. Process $Timer(0)$ represents the state in which any previous counting process is completed and therefore it is willing to signal this to process $TI$ along channel $v$ by means of the communication action $s_v(finished)$. This action must be delayable due to the fact
Table 5: Equations for process Timer: $1 \leq n$.

That process $TI$ will not always be ready to receive this value. Therefore, process Timer realizes only minimum delays. During execution of any process $\text{Timer}(n)$, $n > 0$, $n$ is decreased by one after each $\sigma$-step. All processes $\text{Timer}(n)$, for $0 \leq n$, have the possibility to restart the counting at any time.

With the assumption that the beginning of the counting off of the clock high and low periods should be based on transitions of the SCL line, we can redefine the processes $\text{CU}$ and $\text{CD}$ (see Table 6). Process $\text{CU}$ now first checks if process Timer has finished counting and hence if the clock line is allowed to become high, by $r_v(\text{finished})$. When this is the case, the clock line is released followed by the delay caused by counting off the rise time by process $SCL$. Finally, process Timer is started to count off the clock high period. Process $\text{CD}$ behaves similarly to start the counting off of the clock low period. Note that a single-master situation is still being regarded and consequently, the clock high period cannot be ended prematurely by another device with a shorter clock high period.

\[
\begin{align*}
\text{CU} &= r_v(\text{finished}) \cdot \text{s}_v(\text{up}) \cdot r_s(\text{High}) \cdot \text{s}_w(\text{THigh}) \\
\text{CD} &= r_v(\text{finished}) \cdot \text{s}_v(\text{dn}) \cdot r_s(\text{Low}) \cdot \text{s}_w(\text{TLow})
\end{align*}
\]

Table 6: Equation for upgoing and downgoing clock flanks.

Now we are equipped with the building blocks to add the timing constraints to our interface. Under the assumption that actions will not be delayed unnecessarily, set-up and hold times will not be increased unnecessarily. In Figure 1 the bus transitions associated to the communication primitives are depicted together with the setup and hold times. The equations from Table 7 correspond closely to those diagrams.

The bus free time between a stop and a start condition is guaranteed by process $\text{TP}$. The rise and fall times and the clock high and low periods are maintained by the processes $\text{CU}$, $\text{CD}$, $\text{DU}$, and $\text{DD}$. When receiving a bit, the setup and hold time for data are enforced by the device transmitting the data bit (see Section 7).
\[ TIF = TI \parallel \text{Timer} \]
\[ TI = r_m(\text{start}) \cdot TT \]
\[ TN = r_m(\text{stop}) \cdot TP + r_m(\text{send}0) \cdot TS0 + r_m(\text{send}1) \cdot TS1 + r_m(\text{rechit}) \cdot TR \]
\[ TT = DD \cdot \sigma_{\text{rel}}^{\text{SDA}(CD)} \cdot \sigma_{\text{rel}}^{\text{SDA}(DU)} (s_u(\text{ready}) \parallel s_u(\text{up})) \cdot TN \]
\[ TP = DD \cdot \sigma_{\text{rel}}^{\text{SDA}(CU)} \cdot \sigma_{\text{rel}}^{\text{SDA}(DU)} (s_u(\text{ready}) \parallel s_u(\text{up})) \cdot TI \]
\[ TS0 = DD \cdot \sigma_{\text{rel}}^{\text{SDA}(CU)} \cdot CD \cdot \sigma_{\text{rel}}^{\text{SDA}(DU)} (s_u(\text{ready}) \parallel s_u(\text{up})) \cdot TN \]
\[ TS1 = r_r(\text{High}) \cdot \sigma_{\text{rel}}^{\text{SDA}(CU)} \cdot CD \cdot \sigma_{\text{rel}}^{\text{SDA}(DU)} (s_u(\text{success})) \cdot TN \]
\[ TR = CU \cdot (r_r(\text{High}) \cdot CD \cdot s_u(\text{one}) + r_r(\text{Low}) \cdot CD \cdot s_u(\text{zero})) \cdot TN \]

Table 7: Equations for a single master interface with timing constraints.

6 Designing an interface for a multi-master environment

6.1 Introduction

When we allow more than one master to control the bus, we will encounter four kinds of difficulties:

- Since a session may only be started when the bus is free, it is not allowed, as in the single master model, to start a session by simply commanding the interface to transmit a start signal. Another master could be using the bus. So, first a check has to be made whether the bus is free. One way to handle this is to detect and keep track of the start and stop signals on the bus. This is the issue of Section 6.3.

- When two or more masters try to put data onto the bus, an arbitration procedure is needed to avoid the chaos that might ensue from such an event. In Section 6.4 we will design a process specification for this arbitration procedure.

- Another aspect of the multi-master control is that of synchronizing the clock signals generated by the various master devices. In Section 6.4, we will explain how clock synchronization can be described.

- Since processes SDA and SCL are deaf during their transitional states, all clamping actions of the SDA line and the SCL line have to become delayable in the multi-master case to prevent the presence of deadlock. Note that all releasing actions can remain non-delayable since only the last interface to release a line will start the low-to-high transition. The altered versions of the processes describing the downgoing flanks of both the SDA and SCL line will be given in Section 6.2.
6.2 The interface in the multi-master environment

The process which models the interface between bus and master device in the multi-master case will be called \( MIF \). The connecting channels between \( MIF \) and the bus and the device are as defined before. The names of the subprocesses of \( MIF \) will start with \( M \).

As we have mentioned earlier all clamping actions of the interface have to become delayable due to the deaf state of the processes modelling the bus lines. This restriction simply means that the processes \( CD \) and \( DD \) from the previous section have to be altered in this respect that the actions \( s_c(dn) \) and \( s_d(dn) \) become delayable. In Table 8 the specifications for \( MCD \) and \( MDD \) are given.

\[
\begin{align*}
MCD &= r_s(\text{finished}) \cdot s_c(dn) \cdot r_s(\text{Low}) \cdot s_w(\text{TLow}) \\
MDD &= s_d(dn) \cdot r_s(\text{Low})
\end{align*}
\]

Table 8: Equations for the processes \( MCD \) and \( MDD \).

6.3 Session recording

We introduce a separate process \( MStatus \), composed in parallel with the processes \( MI \) and \( Timer \), connected to processes \( SCL \) and \( SDA \) by the channels \( s \) and \( t \) respectively and to the device by the new channel \( ms \). Communication between process \( MStatus \) and process \( MI \) takes place along the new channel \( b \) (see also Figure 6).

![Figure 6: Connecting process \( MStatus \).](image)

Process \( MStatus \) is introduced in order to describe a mechanism to monitor the bus lines. During monitoring the transmissions of \( \text{start} \) and \( \text{stop} \) signals can be recognized and from the order of
their occurrence process \textit{MStatus} is able to determine whether the bus is busy or free. Also, process \textit{MStatus} is used to signal the outcome to either the master device or the interface component \textit{MI}.

Initially, the bus is free. Both the \textit{SDA} line and the \textit{SCL} line are high. This state is described by process \textit{MStatus(\text{free})}. \textit{MStatus(\text{free})} is capable of detecting a \textit{start} signal that occurs on the bus (see Table 9). Recall that a \textit{start} is a high-to-low transition on the \textit{SDA} line, while the \textit{SCL} line is high. Such transitions are detected by “polling” the bus lines at well chosen moments in time. In our construction of the bus model, where the \textit{SDA} and \textit{SCL} components are able to signal their status to process \textit{MIF} in every time slice, if the status can be defined, polling can be accomplished by checking whether a communication is possible on the “status” channels \textit{s} of the \textit{SCL} line and \textit{t} of the \textit{SDA} line. Process \textit{MStatus(\text{free})} initiates the communication on channel \textit{t}, connected to process \textit{SDA} by the delayable atomic action \(r,(\text{Low})\). Because of the delayability of this receive action, the process keeps checking whether the \textit{SDA} line is low until it is. The other value, \textit{High}, will be ignored when it is sent by process \textit{SDA}. As soon as the low value on the data line is received, the process waits until the clock line has been pulled down in a similar manner, viz., by \(r,(\text{Low})\). Only then, we can be certain that a \textit{start} has occurred and the bus is now busy. We assume that each device sticks to the protocol, so no undefined transitions are to be expected such as releasing the \textit{SDA} line before the clock line is pulled down.

\begin{align*}
\textit{MStatus} & = \textit{MStatus(\text{free})} \\
\textit{MStatus(\text{free})} & = r,(\text{Low}) \cdot r,(\text{Low}) \cdot \textit{MStatus(\text{busy})} + r_{ms}(\text{start}) \cdot s_{s}(\text{starts}) \cdot \textit{MStatus(\text{free})} \\
\textit{MStatus(\text{busy})} & = r,(\text{High}) \cdot (r,(\text{Low}) \cdot (r,(\text{High}) \cdot a_{rel}^{\text{stop}}(\textit{MStatus(\text{free})}) + r,(\text{Low}) \cdot \textit{MStatus(\text{busy})}) + r,(\text{High}) \cdot r,(\text{Low}) \cdot \textit{MStatus(\text{busy})}) \nonumber \\
& + r_{ms}(\text{start}) \cdot s_{ms}(\text{busy}) \cdot r,(\text{Low}) \cdot \textit{MStatus(\text{busy})} 
\end{align*}

Table 9: Equations for process \textit{MStatus}.

Process \textit{MStatus(\text{busy})} (see Table 9) behaves similarly to detect a \textit{stop} condition. After a \textit{stop} signal has been recognized the bus status is free. A \textit{stop} is generated by producing a low-to-high transition on the \textit{SDA} line while the \textit{SCL} line is high. Since the data on the \textit{SDA} line can only be considered valid during a clock high period, inspections of the \textit{SDA} line are only useful after the clock line has been found high. Note that the clock line is always low when process \textit{MStatus(\text{busy})} is started. Since we are only interested in the case in which the clock line is high, the process is delayed until a low-to-high transition on the clock line takes place \(r,(\text{High})\). Then, in the same time slice, the value of the \textit{SDA} line is checked. The non-delayability of this receive action will not cause deadlock since both the set-up stop \(tSU;STO\) and the set-up start \(tSU;STA\) timing constraints see to it, that the value of the data line is at least stable during the first time slice after the high clock period has started.

16
If the value of the SDA line is found to be high in the beginning of the clock high period, the only signal that can occur is the transmission of a one. Hence, a stop did not occur and the status remains busy. A new attempt to detect a stop is made, starting in the next clock low period. This is expressed by the alternative \( r_s (\text{High}) \cdot r_s (\text{Low}) \cdot M\text{Status(busy)}. \)

If, on the other hand, the value of the SDA line is low, two events may occur: the actual stop signal or a high-to-low transition on the clock line, resulting in the transmission of a zero. The latter event can be detected by \( r_s (\text{Low}). \) Also in this case the status remains to be busy.

The first event, in which the actual transmission of the stop signal is completed, indicates that the low-to-high transition of the SDA line will occur before the high period of the clock is ended. Since the end of the clock high period will be noticed immediately by the above alternative, we do not have to add an explicit time bound to the action that detects the transition on the data line \((r_s (\text{High})). \) After the high value is received and subsequently the bus free time is counted off, the status of the bus will be free. Summarizing, the both events, that may happen when the data line was found low immediately after the clock high period started, can be detected by \( r_s (\text{Low}) \cdot (r_s (\text{High}) \cdot \tau_{\text{rel}} (\text{MStatus(free)}) + r_s (\text{Low}) \cdot \text{MStatus(busy)}). \)

After explaining the detection of start and stop conditions on the bus, the one matter left to discuss is which process \( MI, \) or the master, will communicate directly with \( M\text{Status}. \) We choose to let the master signal to process \( M\text{Status} \) that it wants to start a session. Process \( M\text{Status} \) responds by sending the current state, either to the master, when the bus is busy, or to \( MI, \) when the bus is free and so a start condition can be generated. When the bus is busy, the master itself should decide if a new attempt will be made.

In order to accomplish the communication between processes \( M\text{Status} \) and \( MI \) a channel \( b \) has been introduced. The only value that will be sent and received along this channel is startsession, which indicates to process \( MI \) that a session can be started. To handle the communication with the master we introduced a channel \( ms \) between \( M\text{Status} \) and the master device. The process descriptions for process \( M\text{Status} \) can be found in Table 9. As a consequence, process \( MI \) needs some adjustment as well (see Table 10): \( MI = r_b (\text{startsession}) \cdot MT. \) After receiving the startsession signal, now being generated by process \( M\text{Status} \), subprocess \( MT \) is started to produce a start condition on the bus.

### 6.4 Clock synchronization and arbitration

All masters generate their own clock on the SCL line to transfer data on the SPI-bus. Data is only valid during the high period of the clock. A defined clock is therefore needed for the bit-by-bit arbitration procedure to take place.

Clock synchronization is performed using the wired-AND connection of the interfaces to the SCL line. A high-to-low transition on the SCL line will cause all devices concerned to start counting off their low period. When all devices have counted off their low period, the SCL line will be released and go high. Next, all the devices will start counting their high periods. The first device to complete its high period will pull the SCL line down again. In this way, a synchronized clock is generated with its low period determined by the device with the longest clock low period, and its high period determined by the one with the shortest clock high period.
\begin{align*}
MIF &= \text{MI} \parallel \text{Timer} \parallel \text{MStatus} \\
\text{MI} &= r_b(\text{startsession}) \cdot \text{MT} \\
\text{MN} &= r_m(\text{stop}) \cdot \text{MP} + r_m(\text{send0}) \cdot \text{MS0} + r_m(\text{send1}) \cdot \text{MS1} + r_m(\text{recbit}) \cdot \text{MR} \\
\text{MT} &= \text{MDD} \cdot \sigma_{\text{rel}}^{\text{HD,STA}}(\text{ECD}) \cdot \underbrace{\sigma_{\text{rel}}^{\text{HD,DAT}}(s_d(\text{ready}) \parallel s_d(\text{up}))}_{\text{MN}} \\
\text{MP} &= \text{MDD} \cdot \sigma_{\text{rel}}^{\text{SU,DAT}}(\text{CU}) \cdot \sigma_{\text{rel}}^{\text{SU,STO}}(\text{DU}) \cdot \sigma_{\text{rel}}^{\text{HUF}}(s_a(\text{ready})) \cdot \text{MI} \\
\text{MS0} &= \text{MDD} \cdot \sigma_{\text{rel}}^{\text{SU,DAT}}(\text{CU}) \cdot \text{ECD} \cdot \sigma_{\text{rel}}^{\text{HD,DAT}}(s_a(\text{ready}) \parallel s_d(\text{up})) \cdot \text{MN} \\
\text{MS1} &= \sigma_{\text{rel}}^{\text{SU,DAT}}(\text{CU}) \cdot \begin{cases} 
\frac{r_i(\text{High})}{\text{ECD}} \cdot \sigma_{\text{rel}}^{\text{HD,DAT}}(s_a(\text{success})) \cdot \text{MN} \\
+ \frac{r_i(\text{Low})}{\text{ECD}} \cdot s_a(\text{fail}) \cdot \text{MI}
\end{cases} \\
\text{MR} &= \text{CU} \cdot \frac{r_i(\text{High})}{\text{ECD}} \cdot s_a(\text{one}) + \frac{r_i(\text{Low})}{\text{ECD}} \cdot s_a(\text{zero}) \cdot \text{MN} \\
\text{ECD} &= \text{MCD} + r_s(\text{Low}) \cdot s_c(\text{dn}) \cdot s_u(\text{TLow})
\end{align*}

Table 10: Equations for the interface of a pure master in a multi-master environment.

In the single master case, we have used processes CD and CU to model the counting off of the clock low period and clock high period respectively. Since only the counting off of the clock high period can be interrupted and hence shortened by another device, we can leave process CU unchanged and restrict ourselves to extending our description of MCD to ECD (see Table 10). The process ECD (extended clock down) must not only be able to detect whether its own local clock high period is finished, it also has to detect a high-to-low transition on the SCL line caused by another master. In that case the protocol describes that the clock line must be clamped immediately and the clock low period must be counted off. All subprocesses during which a clock releasing action (i.e. MCD occurs) have to be adapted (see Table 10).

Another difficulty that arises in the multi-master case is the arbitration procedure. Two or more masters may generate a start condition within the hold time for a start condition. Arbitration takes place on the SDA line while the SCL line is high, in such a way that the master which transmits a high level on the SDA line while another master is transmitting a low level will lose arbitration. This procedure will not affect the data transfer initiated by the winning master. So, a master can only lose arbitration when it is transmitting a one, while another master is transmitting a zero. Whenever a master loses arbitration it must wait for the bus to become free.

The arbitration procedure can be modelled by polling the value of the SDA line during the high clock period when a one is being sent. If the value of the SDA line is high the session is continued, if the value is low arbitration is lost. In that case the master is notified that the transmission failed (see process MS1 in Table 10).
7 The slave interface

So far, the interface only incorporates the functionality of a master device. In this section we will design an interface for a slave device based on the design of the interface for a master device from the previous section. A slave incorporates functions to detect a start signal on the bus and must be able to send and receive bits on clock pulses generated by a master. Furthermore, the slave interface must be able to mute when the slave device instructs it to do so. This suggests that the interface for a slave can be realized by a part of the interface for a master.

The slave interface, from now on denoted by SIF (see Table 11), will be connected to process SDA via channels d and t and to SCL via channels c and s. It communicates with the slave device along channels m and a. These connections are similar to those used to connect a master interface to its environment (see Figure 3).

The slave interface is a parallel composition of two components SI and SStatus. Process SStatus behaves similar to process MStatus from the master variant. SStatus is connected to process SCL via a channel s and to process SDA via t. Furthermore, SStatus is connected to the slave device via channel ms. Unlike the situation concerning process MStatus, there is no connection necessary between SStatus and SI.

Detecting start and stop signals on the one hand and sending and receiving bits on the other can take place completely independent. We will first construct the part of SIF which takes care of sending and receiving bits. Afterwards, we will use process MStatus to specify a process which will have the same functionality as we want SStatus to have.

Subprocesses SS0, SS1, and SR differ only from MS0, MS1, and MR in this respect that no clock pulse has to be generated during execution and that initially the clock line has to be polled to sense the high and low periods of the clock pulse generated by the master. Exchanging the value mute enables the slave device to instruct the interface to enter the initial state. For example, when the slave, after decoding the address sent by a master, discovers that it is not addressed and therefore no longer has to be part of the current session, the mute value will be sent to the slave’s interface.

Transmitting a zero now consists of waiting for the clock line to become low, clamping the clock line so the master cannot end the low period before the data line is put to the low level and clamping the SDA line. After the value of the SDA line has become low, the set-up data time has to be counted off and afterwards the process releases the clock line, enabling the master to start counting off the clock high period. As soon as the low value is detected on the clock line, the data hold time is counted off, the data line is released, and the slave device is notified that the transmission is completed.

Process SS1 is less complex, since the SDA line was already released. Furthermore, a slave cannot lose arbitration. Receipt of a bit can be expressed in a way similar to the master variant. Only the actions related to the clock line are absent. Note that, at the beginning of the execution of process SI, nothing can be said about the state of the wires, this in contrast with process N from the master’s interface.

As mentioned earlier, process MStatus will be used to express the desired functionality of process SStatus. The only feature we want process SStatus to have is notifying the master that a start signal has been detected. When the high value on the SDA line is detected, we know from Sec-
Table II: Equations for the slave interface.

In order to inform the slave that a start is detected, we simply add the send action \( s_{ms}(\text{start}) \), immediately before the status turns busy. The slave will initially wait for the communication of the value \( \text{start} \) along channel \( ms \) and then it will send its instructions to the interface along channel \( m \).

8 Usefulness of the model

In this section, we will show how a system consisting of the \( I^2C \)-bus with \( M \) master devices and \( S \) slave devices connected to it can be described in the model. Then we indicate for what purposes the model can be used.

Suppose that \( M \) master devices and \( S \) slave devices are connected to the \( I^2C \)-bus and that process algebra specifications \( \text{Master}_i \) and \( \text{Slave}_j \) are given for those. So, \( M + S \) devices are connected to the bus. In Figure 7 this system is depicted.

In Section 4, a model for the bus with \( N \) devices connected is given. Hence, the model for the bus is parameterized with the number of devices connected to it. We will simply write \( \text{Bus} \) instead of \( \text{Bus}_{M+S} \) or \( \text{Bus}(M + S) \). Then the complete system can be described by the process

\[
\Theta_C \odot \partial_H \left( \left( \left| \left| \text{Master}_i \| \text{MIF}_i \right| \right| \right| \right| \left( \left| \left| \text{Slave}_j \| \text{SIF}_j \right| \right| \right| \right| \| \text{Bus} \right)
\]

where the set \( H \) consists of all send and receive actions, and the set \( C \) consists of all successful
communication actions. The application of the encapsulation operator $\partial_H$ removes all send and receive actions which, due to the interleaving, do not result in successful communications. The priority operator $\Theta_C$ ensures that successful communications are not delayed unnecessarily.

Next, we discuss some ways in which this model can be used. Firstly, since we explicitly modelled the timing constraints, it is possible to reason formally about the timing aspects involved in the $\hat{P}C$-bus. Secondly, the model can be used when designing devices to be connected to the $\hat{P}C$-bus. It is of utmost importance that the interface between a device and the bus is well-understood. It is our firm belief that a formal specification of such an interface improves this understanding considerably. Also, if a formal specification of the device is provided, there are possibilities to reason formally about the device being connected to the bus, i.e., their interaction can be considered. Thirdly, in situations where a number of devices have to communicate via the $\hat{P}C$-bus it is useful to establish that there is absence of deadlock. Given specifications of those devices (in process algebra), one can easily check whether the complete system has absence of deadlock (see [Bos95] for some examples). The main technique involved is that of "normalizing" a process term. Such a normal form only contains atomic actions, the constant deadlock and the operators $\cdot$ and $\cdot$. For more information about normalization and related issues we refer to [BW90, BV95]. From a normal form one also easily inspects the actual transitions on the bus lines, which might be useful to compare with the bus transitions that were expected. Fourthly, another important use of the model is that of testing conformance of new implementations of the $\hat{P}C$-bus with the standard. Finally, the model of the $\hat{P}C$-bus allows for abstraction, i.e., it can be looked at from different levels of abstraction. For example, if one is only interested to observe the order in which the communication primitives and the acknowledgements can be executed this can be achieved by applying the abstraction operators $\tau_I$ and $\pi_I$ to the full description ($S$), e.g., $\pi_I \circ \tau_I (S)$, where $I$ consists of the atomic actions from which we want to abstract. In this example we would abstract from successful communications along the channels $b, c, d, ms, s, t, v, w$.

With the abstraction operators, encapsulation and renaming we can also reason formally about the models that are obtained in the various design phases. For example, we can establish that the bus protocol from Section 5.2 and the system consisting of a time-free bus and a single master
interface are in accordance as follows: $I = \rho_f \circ \tau_t \circ \partial_H(\pi_\sigma(Bus) \parallel IF)$, where $f(r_m(p)) = p$, $I$ consists of all successful communications along the channels $c, d, s, t$, and the sending of the acknowledgements to the device, and $H$ consists of the unsuccessful communication actions along $c, d, s, t$.

9 Conclusions

We introduced a special module which provided us with an interface between the bus and the devices. Such an interface simplifies the modelling of the problem considerably, since it is able to translate transitions on the bus into $P$C-bus primitives and vice versa. Regarding the first module, the behaviour of both SDA and SCL line relies on the behaviour of a wired-AND and hence, it sufficed to specify a process which behaves as a wired-AND in order to specify a model for the bus. As for the latter module, we made a distinction between an interface for a master device on the one hand and an interface for a slave device on the other. Starting from a high level specification of the data sessions that take place on the bus, we were able to derive a specification for the interface for a master device in a systematic and incremental manner. Specifications for the interface of a slave device could be derived from the interface for a master device quite easily, since the behaviour of a slave differs only slightly from the behaviour of a master device. We tried to keep the interface for both master and slave devices as simple as possible by shifting some tasks to the devices using the interface. For instance, the conversion of bits to bytes and vice versa and the decoding of the address byte have become tasks of the device.

Because of the large interest of the timing aspects imposed by the bus protocol, a discrete time process algebra with relative timing appeared to be the most suitable algebra to express the system of bus and devices connected to the bus. We can conclude that the discrete time process algebra with relative timing is expressive enough for the specification of a communication protocol which is restricted by timing constraints. We only needed one separate timer process to meet some of the timing constraints. However, due to the relative character of the algebra, most of the timing constraints could be met by simply defining the correct order in which the bus transitions should occur. Some steps in the design path were very straightforward or were the logical consequence of previous steps. Others were more complicated.

With the model for the bus lines and the interfaces with slave and master device as presented in this paper it is possible to

- reason formally about the timing aspects involved in the $P$C-bus;
- check freedom of deadlocks for a given description (in process algebra) of a device;
- test conformance of new implementations of the $P$C-bus with the standard.

In our design, the interface monitors the bus lines in addition to generating the transitions on the lines. Subject of further research could be the uncoupling of these two functions. In this case, the interface must be split into two modules, one for the monitor function and one for the generation of the transitions. We expect that the synchronization of such two modules will be very complex. Still, it would be an interesting starting point. Another option for further research would
be to design an interface, which is solely engaged in transmitting the several bus signals, without having to deal with the timing constraints at all. Timing would be the full responsibility of the device. We chose that the translation performed by the interface occurs on the level of the bus primitives. It would be interesting to investigate other possibilities for the level in which the translation occurs. One could think of a shift towards the \textit{PC-bus}.

**References**


A Axioms

In this appendix the axioms of the discrete time process algebra with relative timing are given, for
x, y, and z variables, a ∈ A ∪ {τ, δ}, H, I, C ⊆ A, f : A → A, and n ≥ 0. The set A of atomic
actions and the partial, commutative and associative communication function γ : A × A → A
are considered parameters of the process algebra.

\[
\begin{align*}
  x + y &= y + x \\
  (x + y) + z &= x + (y + z) \\
  x + x &= x \\
  (x + y) ∗ z &= x ∗ z + y ∗ z \\
  (x ∗ y) ∗ z &= x ∗ (y ∗ z) \\
  ν_{rel}(a) &= a \\
  ν_{rel}(x + y) &= ν_{rel}(x) + ν_{rel}(y) \\
  ν_{rel}(x ∗ y) &= ν_{rel}(x) ∗ y \\
  ν_{rel}(σ_{rel}(x)) &= δ \\
  \sigma_{rel}(x) + \sigma_{rel}(y) &= \sigma_{rel}(x + y) \\
  \sigma_{rel}(x) ∗ y &= \sigma_{rel}(x ∗ y) \\
  x + δ &= x \\
  δ ∗ x &= δ \\
  \sigma_{rel}^{n+1}(x) &= \sigma_{rel}(\sigma_{rel}^n(x)) \\
  [x]_ω &= ν_{rel}(x) + \sigma_{rel}([x]_ω) \\
  a &= \begin{cases} a & \text{if } y \text{ defined} \\
  δ & \text{otherwise} \end{cases} \\
  y &= ν_{rel}(x) + \sigma_{rel}(y) \implies y = [x]_ω
\end{align*}
\]

\[
\begin{align*}
  x ∗ (τ ∗ (ν_{rel}(y) + z) + ν_{rel}(y)) &= x ∗ (ν_{rel}(y) + z) \\
  x ∗ (τ ∗ (y + ν_{rel}(z)) + y) &= x ∗ (y + ν_{rel}(z)) \\
  a ∗ x &= a ∗ y \implies a ∗ (σ_{rel}(x) + ν_{rel}(z)) = a ∗ (σ_{rel}(y) + ν_{rel}(z)) \\
  x ∗ (τ ∗ [y + z]_ω + [y]_ω) &= x ∗ [y + z]_ω \\
  \pi_{γ}(a) &= a \\
  \pi_{γ}(σ_{rel}(x)) &= \pi_{γ}(x) \\
  \pi_{γ}(x ∗ y) &= \pi_{γ}(x) ∗ \pi_{γ}(y) \\
  \pi_{γ}(x + y) &= \pi_{γ}(x) + \pi_{γ}(y) \\
  \pi_{γ}([x]_ω) &= \pi_{γ}(x)
\end{align*}
\]

\[
\begin{align*}
  a ∣ x &= a ∣ y + y ∣ x + x ∣ y \\
  a ∣ x &= a ∣ x \\
  a ∣ x ∣ y &= a ∣ (x ∣ y) \\
  (x + y) ∙ z &= x ∙ z + y ∙ z \\
  σ_{rel}(x) ∙ ν_{rel}(y) &= δ \\
  σ_{rel}(x) ∙ (ν_{rel}(y) + σ_{rel}(z)) &= σ_{rel}(x ∙ z) \\
  a ∙ b &= γ(a, b) \quad \text{if } y \text{ defined} \\
  a ∙ b &= δ \quad \text{otherwise}
\end{align*}
\]
\( p_f(a) = f(a) \) if \( a \in A \)
\( p_f(\delta) = \delta \)
\( p_f(\tau) = \tau \)
\( p_H(a) = a \) if \( a \not\in H \)
\( p_H(\delta) = \delta \) if \( a \in H \)
\( \partial_H(x + y) = \partial_H(x) + \partial_H(y) \)
\( \partial_H(x \cdot y) = \partial_H(x) \cdot \partial_H(y) \)
\( \partial_H(\sigma_{\text{rel}}(x)) = \sigma_{\text{rel}}(\partial_H(x)) \)
\( \Theta_C(a) = a \)
\( \Theta_C(\sigma_{\text{rel}}(x)) = \sigma_{\text{rel}}(\Theta_C(x)) \)
\( \Theta_C(x \cdot y) = \Theta_C(x) \cdot \Theta_C(y) \)
\( \Theta_C(a + x) = a + \Theta_C(x) \) if \( a \not\in C \)
\( \Theta_C(a \cdot x + y) = a \cdot \Theta_C(x) + \Theta_C(y) \) if \( a \not\in C \)
\( \Theta_C(a + \nu_{\text{rel}}(y) + \sigma_{\text{rel}}(z)) = a + \Theta_C(\nu_{\text{rel}}(y)) + \Theta_C(\nu_{\text{rel}}(y)) \) if \( a \in C \)
\( \rho_f(x \cdot y) = \rho_f(x) \cdot \rho_f(y) \)
\( \rho_f(x + y) = \rho_f(x) + \rho_f(y) \)
\( \rho_f(\sigma_{\text{rel}}(x)) = \sigma_{\text{rel}}(\rho_f(x)) \)
\( \tau_f(a) = a \) if \( a \not\in I \)
\( \tau_f(\delta) = \delta \) if \( a \in I \)
\( \tau_f(x \cdot y) = \tau_f(x) \cdot \tau_f(y) \)
\( \tau_f(x + y) = \tau_f(x) + \tau_f(y) \)
\( \tau_f(\sigma_{\text{rel}}(x)) = \sigma_{\text{rel}}(\tau_f(x)) \)
<table>
<thead>
<tr>
<th>Number</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>93/01</td>
<td>R. van Geldrop</td>
<td>Deriving the Aho-Corasick algorithms: a case study into the synergy of programming methods, p. 36.</td>
</tr>
<tr>
<td>93/02</td>
<td>T. Verhoeff</td>
<td>A continuous version of the Prisoner's Dilemma, p. 17.</td>
</tr>
<tr>
<td>93/03</td>
<td>T. Verhoeff</td>
<td>Quicksort for linked lists, p. 8.</td>
</tr>
<tr>
<td>93/04</td>
<td>E.H.L. Aarts, J.H.M. Korst, P.J. Zwiietering</td>
<td>Deterministic and randomized local search, p. 78.</td>
</tr>
<tr>
<td>93/05</td>
<td>J.C.M. Baeten, C. Verhoef</td>
<td>A congruence theorem for structured operational semantics with predicates, p. 18.</td>
</tr>
<tr>
<td>93/06</td>
<td>J.P. Veltkamp</td>
<td>On the unavoidability of metastable behaviour, p. 29.</td>
</tr>
<tr>
<td>93/07</td>
<td>P.D. Moerland</td>
<td>Exercises in Multiprogramming, p. 97.</td>
</tr>
<tr>
<td>93/08</td>
<td>J. Verhoosel</td>
<td>A Formal Deterministic Scheduling Model for Hard Real-Time Executions in DEDOS, p. 32.</td>
</tr>
<tr>
<td>93/10</td>
<td>K.M. van Hee</td>
<td>Systems Engineering: a Formal Approach Part II: Frameworks, p. 44.</td>
</tr>
<tr>
<td>93/16</td>
<td>H. Schepers, J. Hoosman</td>
<td>A Trace-Based Compositional Proof Theory for Fault Tolerant Distributed Systems, p. 27.</td>
</tr>
<tr>
<td>93/17</td>
<td>D. Alstein, P. van der Stok</td>
<td>Hard Real-Time Reliable Multicast in the DEDOS system, p. 19.</td>
</tr>
<tr>
<td>93/18</td>
<td>C. Verhoeff</td>
<td>A congruence theorem for structured operational semantics with predicates and negative premises, p. 22.</td>
</tr>
<tr>
<td>93/19</td>
<td>G.J. Houben</td>
<td>The Design of an Online Help Facility for ExSpect, p. 21.</td>
</tr>
<tr>
<td>93/22</td>
<td>E. Poll</td>
<td>A Typechecker for Bijective Pure Type Systems, p. 28.</td>
</tr>
<tr>
<td>93/23</td>
<td>E. de Kogel</td>
<td>Relational Algebra and Equational Proofs, p. 23.</td>
</tr>
<tr>
<td>93/24</td>
<td>E. Poll and Paula Severi</td>
<td>Pure Type Systems with Definitions, p. 38.</td>
</tr>
<tr>
<td>93/26</td>
<td>W.M.P. van der Aalst</td>
<td>Multi-dimensional Petri nets, p. 25.</td>
</tr>
<tr>
<td>93/27</td>
<td>T. Kloks and D. Kratsch</td>
<td>Finding all minimal separators of a graph, p. 11.</td>
</tr>
<tr>
<td>93/28</td>
<td>F. Kamareddine and R. Nederpelt</td>
<td>A Semantics for a fine λ-calculus with de Bruijn indices, p. 49.</td>
</tr>
<tr>
<td>93/30</td>
<td>J. Deogun, T. Kloks, D. Kratsch, H. Müller</td>
<td>On Vertex Ranking for Permutation and Other Graphs, p. 11.</td>
</tr>
</tbody>
</table>
93/31 W. Körver
93/32 H. ten Eikelder and H. van Geldrop
93/33 L. Loyens and J. Moonen
93/34 J.C.M. Baeten and J.A. Bergstra
93/35 W. Ferrer and P. Severi
93/36 J.C.M. Baeten and J.A. Bergstra
93/37 J. Bruneel and J.-P. Katoen
93/38 C. Verheoef
93/39 W.P.M. Nuijten
93/40 P.D.V. van der Stok
93/41 A. Bijisima
93/42 P.M.P. Rambags
93/43 B.W. Watson
93/44 B.W. Watson
93/45 E.J. Luit
93/46 T. Klok
93/47 W. van der Aalst
93/48 R. Gerth
94/01 P. America
94/02 F. Kamareddine
94/03 L.B. Hartman
94/04 J.C.M. Baeten
94/05 P. Zhou
94/06 T. Baeten
94/07 K.R. Apt
94/08 O.S. van Roosmalen
94/09 J.C.M. Baeten
94/40 Derivation of delay insensitive and speed independent CMOS circuits, using directed commands and production rule sets, p. 40.
93/33 IIAS, a sequential language for parallel matrix computations, p. 20.
93/34 Real Time Process Algebra with Infinitesimals, p. 39.
93/35 Abstract Reduction and Topology, p. 28.
93/36 Non Interleaving Process Algebra, p. 17.
93/37 Design and Analysis of Dynamic Leader Election Protocols in Broadcast Networks, p. 73.
93/38 A general conservative extension theorem in process algebra, p. 17.
93/39 Job Shop Scheduling by Constraint Satisfaction, p. 22.
93/40 A Hierarchical Membership Protocol for Synchronous Distributed Systems, p. 43.
93/41 Temporal operators viewed as predicate transformers, p. 11.
93/42 Automatic Verification of Regular Protocols in P/T Nets, p. 23.
93/43 A taxonomy of finite automata construction algorithms, p. 87.
93/44 A taxonomy of finite automata minimization algorithms, p. 23.
93/45 A precise clock synchronization protocol, p.
93/48 Verifying Sequentially Consistent Memory using Interface Refinement, p. 20.
94/01 The object-oriented paradigm, p. 28.
94/02 Canonical typing and IT-conversion, p. 51.
94/03 Application of Markov Decision Processes to Search Problems, p. 21.
94/04 Graph Isomorphism Models for Non Interleaving Process Algebra, p. 18.
94/06 Time and the Order of Abstract Events in Distributed Computations, p. 29.
94/08 A Hierarchical Diagrammatical Representation of Class Structure, p. 22.
94/09 Process Algebra with Partial Choice, p. 16.
94/10 T. Verhoeff
The testing Paradigm Applied to Network Structure, p. 31.

94/11 J. Peleska
A Comparison of Ward & Mellor's Transformation
Schetsen with State- & Activitycharts, p. 30.

94/12 T. Kloks
C. Huizing
D. Kratsch
H. Müller

94/13 R. Seljée
A New Method for Integrity Constraint checking in Deductive Databases, p. 34.

94/14 W. Peremans
Ups and Downs of Type Theory, p. 9.

94/15 R.J.M. Vaessens
E.H.L. Aarts
J.K. Lenstra
Job Shop Scheduling by Local Search, p. 21.

94/16 R.C. Backhouse
H. Doornbos
Mathematical Induction Made Calculational, p. 36.

94/17 S. Mauw
An Algebraic Semantics of Basic Message
M.A. Reniers
Sequence Charts, p. 9.

94/18 F. Kamareddine
R. Nederpelt
Refining Reduction in the Lambda Calculus, p. 15.

94/19 B.W. Watson
The performance of single-keyword and multiple-keyword pattern matching
algorithms, p. 46.

94/20 R. Bloo
F. Kamareddine
R. Nederpelt
Beyond β-Reduction in Church's λ→, p. 22.

94/21 B.W. Watson
An introduction to the Fire engine: A C++ toolkit for Finite automata and Regular
Expressions.

94/22 B.W. Watson
The design and implementation of the FIRE engine:
A C++ toolkit for Finite automata and regular Expressions.

94/23 S. Mauw and M.A. Reniers
An algebraic semantics of Message Sequence Charts, p. 43.

94/24 D. Dans
O. Grumberg
R. Gerth
Abstract Interpretation of Reactive Systems:
Abstractions Preserving VCTL*, 3CTL* and CTL*, p. 28.

94/25 T. Kloks
K1,3-free and W4-free graphs, p. 10.

94/26 R.R. Hoogerwoord
On the foundations of functional programming: a programmer's point of view, p. 54.

94/27 S. Mauw and H. Mulder

94/28 C.W.A.M. van Overveld
M. Verhoeven

94/29 J. Hooman
Correctness of Real Time Systems by Construction, p. 22.

94/30 J.C.M. Baeten
J.A. Bergstra
Gh. Ştefănescu
Process Algebra with Feedback, p. 22.

94/31 B.W. Watson
R.E. Watson
A Boyer-Moore type algorithm for regular expression pattern matching, p. 22.

94/32 J.J. Vereijken

94/33 T. Laan
A formalization of the Ramified Type Theory, p.40.

94/34 R. Bloo
F. Kamareddine
R. Nederpelt
The Barendregt Cube with Definitions and Generalised Reduction, p. 37.

94/35 J.C.M. Baeten
S. Mauw
Delayed choice: an operator for joining Message
S. Mauw
Sequence Charts, p. 15.

94/36 F. Kamareddine
R. Nederpelt
Canonical typing and II-conversion in the Barendregt Cube, p. 19.

94/37 T. Basten
R. Bol
M. Voorhoeve
Simulating and Analyzing Railway Interlockings in ExSpect, p. 30.

94/38 A. Bijlsma
C.S. Scholten
Point-free substitution, p. 10.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>94/39</td>
<td>A. Blokhuis, T. Klokş</td>
<td>On the equivalence covering number of splitgraphs, p. 4.</td>
</tr>
<tr>
<td>94/40</td>
<td>D. Aistein</td>
<td>Distributed Consensus and Hard Real-Time Systems, p. 34.</td>
</tr>
<tr>
<td>94/41</td>
<td>T. Klokş, D. Kratsch</td>
<td>Computing a perfect edge without vertex elimination ordering of a chordal bipartite graph, p. 6.</td>
</tr>
<tr>
<td>94/43</td>
<td>R.C. Backhouse, M. Bijsterfeld</td>
<td>Category Theory as Coherently Constructive Lattice Theory: An Illustration, p. 35.</td>
</tr>
<tr>
<td>94/45</td>
<td>G.J. Hauben</td>
<td>Tutorial voor de ExSpect-bibliotheek voor &quot;Administratieve Logistiek&quot;, p. 43.</td>
</tr>
<tr>
<td>94/46</td>
<td>R. Bloo, F. Kamareddine, R. Nederpelt</td>
<td>The λ-cube with classes of terms modulo conversion, p. 16.</td>
</tr>
<tr>
<td>94/47</td>
<td>R. Bloo, F. Kamareddine, R. Nederpelt</td>
<td>On Π-conversion in Type Theory, p. 12.</td>
</tr>
<tr>
<td>94/48</td>
<td>Mathematics of Program Construction Group</td>
<td>Fixed-Point Calculus, p. 11.</td>
</tr>
<tr>
<td>94/50</td>
<td>H. Geuvers</td>
<td>A short and flexible proof of Strong Normalization for the Calculus of Constructions, p. 27.</td>
</tr>
<tr>
<td>94/52</td>
<td>W. Penczek, R. Kuiper</td>
<td>Traces and Logic, p. 81</td>
</tr>
<tr>
<td>95/01</td>
<td>J.J. Lukkien</td>
<td>The Construction of a small Communication Library, p. 16.</td>
</tr>
<tr>
<td>95/02</td>
<td>M. Bezem, R. Bol, J.F. Groote</td>
<td>Formalizing Process Algebraic Verifications in the Calculus of Constructions, p. 49.</td>
</tr>
<tr>
<td>95/03</td>
<td>J.C.M. Baeten, C. Verhoef</td>
<td>Concrete process algebra, p. 134.</td>
</tr>
<tr>
<td>95/04</td>
<td>J. Hidders</td>
<td>An Isotopic Invariant for Planar Drawings of Connected Planar Graphs, p. 9.</td>
</tr>
<tr>
<td>95/05</td>
<td>P. Severi</td>
<td>A Type Inference Algorithm for Pure Type Systems, p. 20.</td>
</tr>
<tr>
<td>95/07</td>
<td>G.A.M. de Bruyn, O.S. van Roosmalen</td>
<td>Drawing Execution Graphs by Parsing, p. 10.</td>
</tr>
<tr>
<td>95/08</td>
<td>R. Bloo</td>
<td>Preservation of Strong Normalisation for Explicit Substitution, p. 12.</td>
</tr>
<tr>
<td>95/09</td>
<td>J.C.M. Baeten, J.A. Bergstra</td>
<td>Discrete Time Process Algebra, p. 20</td>
</tr>
<tr>
<td>95/10</td>
<td>R.C. Backhouse, R. Verhoeven, O. Weber</td>
<td>MathJax: A System for On-Line Preparation of Mathematical Documents, p. 15</td>
</tr>
</tbody>
</table>
R. Seljée

S. Mauw and M. Reniers

B.W. Watson and G. Zwaan

A. Ponse, C. Verhoef, S.P.M. Vlijmen (eds.)

P. Niebert and W. Penczek

D. Dams, O. Grumberg, R. Gerth

S. Mauw and E.A. van der Meulen

F. Kamareddine and T. Laan

J.C.M. Baeten and J.A. Bergstra

F. van Raamsdonk and P. Severi

A. van Deursen

W.M.P. van den Aalst

F.P.M. Dignum, W.P.M. Nuijten, L.M.A. Janssen

L. Feijs

W.M.P. van der Aalst

P.D.V. van der Stok, J. van der Wal

W. Fokkink, C. Verhoef

H. Jurjus

J. Hidders, C. Hoskens, J. Paredaens

P. Kelb, D. Dams and R. Gerth

W.M.P. van der Aalst

J. Engelfriet and J.J. Vereijken

J. Zwanenburg

T. Basten and M. Voorhoeve

M. Voorhoeve and T. Basten

P. de Bra and A. Aerts

W.M.P. van der Aalst

J. van Zandvoort

A. van der Meulen

J. Terpstra

T. Basten and W.M.P. van der Aalst

W.M.P. van der Aalst and T. Basten

M. Voorhoeve

A.T.M. Aerts, P.M.E. De Bra, J.T. de Munk

F. Dignum, H. Weigand, E. Verharen

R. Bloo, H. Geuvers

T. Laan

F. Kamareddine and T. Laan

T. Borgschi

Deductive Database Systems and integrity constraint checking, p. 36.

Empty Interworkings and Refinement Semantics of Interworkings Revised, p. 19.


De proceedings: ACP'95, p. 15.

On the Connection of Partial Order Logics and Partial Order Reduction Methods, p. 12.

Abstract Interpretation of Reactive Systems: Preservation of CTL*, p. 27.

Specification of tools for Message Sequence Charts, p. 36.


Discrete Time Process Algebra with Abstraction, p. 15.

On Normalisation, p. 33.

Axiomatizing Early and Late Input by Variable Elimination, p. 44.


Petri net based scheduling, p. 20.


Synchronous Sequence Charts In Action, p. 36.

A Class of Petri nets for modeling and analyzing business processes, p. 24.


A Conservative Look at term Deduction Systems with Variable Binding, p. 29.

On Nesting of a Nonmonotonic Conditional, p. 14

The Formal Model of a Pattern Browsing Technique, p. 24

Practical Symbolic Model Checking of the full μ-calculus using Compositional Abstractions, p. 17.


Context-Free Graph Grammars and Concatenation of Graphs, p. 35.

Record concatenation with intersection types, p. 46.

An algebraic semantics for hierarchical PfT Nets, p. 32.

Process Algebra with Autonomous Actions, p. 12.

Multi-User Publishing in the Web: DreSS, A Document Repository Service Station, p. 12


Example specifications in phi-SDL.


A Petri-Net-Based Approach, p. 18.

Structural Petri Net Equivalence, p. 16.


AUTOMATH and Pure Type Systems, p. 30.

A Correspondence between Nuprl and the Ramified Theory of Types, p. 12.

Polorean Tense Logics in Modal Pure Type Systems, p. 61.