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Modeling of Avionics Applications and Performance Evaluation Techniques using the Synchronous Language SIGNAL *

Abdoulaye GAMATIÉ [1], Thierry GAUTIER [2]

IRISA / INRIA - Campus de Beaulieu - 35042 Rennes cedex, France

Loïc BESNARD [3]

IRISA / CNRS - Campus de Beaulieu - 35042 Rennes cedex, France

Abstract

Modeling is widely accepted to be essential to design activity. A major benefit is the use of formal methods for analysis and predictability. In Polychrony, the tool-set of the Signal language, a component-based approach have been defined to model avionics applications. This approach uses Signal models of so-called APEX services based on the avionics standard ARINC 653. This gives access to the formal tools and techniques available within Polychrony for verification and analysis.

In this paper, we illustrate the approach by considering a small example of avionics application. We show how an associated Signal model is obtained for the purpose of temporal validation. This brings out the capability of the Signal to seamlessly address critical issues in real-time system design.

1 Introduction

Today, in the design of embedded systems such as avionics systems, key challenges are typically the correctness of the design with respect to the requirements, the development effort and time to market, and the correctness and reliability of the implementation. This calls for a seamless design process which takes into account these challenges. In such a context, modeling plays a central role. Among advantages [14], we mention the enhanced adaptability

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[1] agamatie@irisa.fr

[2] gautier@irisa.fr

[3] lbesnard@irisa.fr

of models and their parameters; more general descriptions by using genericity, abstraction, behavioral non determinism, and the possibility of applying formal methods for analysis and predictability.

Several model-based approaches have been proposed [15] [9] [2] for the development and verification of embedded systems. They use different kinds of formalisms for the modeling and provide tools for system development and validation. While our approach aims at the same objective, its main particularity relies on the use of a single semantical model, SIGNAL [7], to describe embedded applications from specification to implementation with the possibility of verification and analysis. This facilitates the validation. POLYCHRONY, the tool-set for SIGNAL (`http://www.irisa.fr/espresso/Polychrony`) developed by INRIA [4], offers the required functionalities (high level specifications, modular verification and analysis, automatic code generation, etc.).

The work presented in this paper is part of a more general design methodology for distributed embedded applications, defined during the SACRES project [6] and currently improved. This methodology is based on the iterative application of transformations on a SIGNAL model that preserve semantic properties. During the transformations, "abstract" components can be instantiated in different ways from modules related to actual target architecture features, addressing various purposes (e.g. embedded code generation, temporal validation). In this context, a library of specific components has been defined in SIGNAL. It includes on the one hand elementary communication mechanisms such as FIFOs [5], and on the other hand more complex models such as those presented in [4] for the description of avionics applications based on the ARINC standard. In particular, we illustrate here how the SIGNAL model of an avionics application is specified using these components in order to perform timing analysis within POLYCHRONY.

The remainder of the paper is organized as follows: section 2 first discusses the ARINC 653 specification. Then, section 3 introduces the main features of the SIGNAL language, while section 4 concentrates on the modeling of an avionics application in SIGNAL. In section 5, we address issues on performance evaluation for temporal validation based on the SIGNAL language. Finally, conclusions are given in section 6.

2 The standard ARINC 653

The ARINC specification 653 [3] defines the interface between the application software and the core software (OS, system specific functions), called APEX (APplication EXecutive). This specification is based on the *Integrated Modular Avionics* approach (IMA). In an IMA system, several avionics applications can be grouped into one core module hosted on a single shared computer

[4] There is also an industrial version, SILDEX, implemented and commercialized by TNI-Valiosys (`http://www.tni-valiosys.com`).

system. A critical issue is to ensure that shared computer resources are safely allocated so that no fault propagation occurs from one hosted avionics function to another. This is addressed by *partitioning* the system. Basically, it consists in a functional decomposition of the avionics applications, with respect to available time and memory resources.

A *partition* [3] is an allocation unit resulting from this decomposition. Suitable mechanisms are provided in order to prevent a partition from having "abnormal" access to the memory area of another partition. The processor is allocated to each partition for a fixed time window within a major time frame maintained by the core *module-level* OS. A partition cannot be distributed over multiple processors neither in the same module nor in different modules. Partitions communicate asynchronously via logical *ports* and *channels*.

Each partition is composed of one or more *processes* which represent the executive units [5] . Processes run concurrently to achieve functions associated with the partition. The *partition-level* OS is responsible for the correct execution of processes, and the scheduling policy is priority preemptive. Communications between processes are achieved by three basic mechanisms: the bounded *buffer* is used to send and receive messages, it allows storing messages in FIFO queues; the *event* permits the application to notify some processes in the partition of the occurrence of a condition; and the *blackboard* is used to display and read messages, no message queues are allowed and any message written to a blackboard remains there until the message is either cleared or overwritten by a new instance of the message. Synchronizations are achieved by *semaphores*.

The APEX interface includes services for communication between partitions/processes, synchronization services for processes, partition and process management services, etc.

3 An overview of the SIGNAL language

The underlying theory of the synchronous approach [1] is that of discrete event systems and automata theory. Time is logical: it is handled according to partial order and simultaneity of events. Durations of execution are viewed as constraints to be verified at the implementation level. Typical examples of synchronous languages are Esterel, Lustre, or Signal which is used here.

The Signal language [7] handles unbounded series of typed values $(x_t)_{t\in\mathbb{N}}$, denoted as `x` in the language, implicitly indexed by discrete time (denoted by t in the semantic notation): they are called *signals*. At a given instant, a signal may be present, then it holds a value; or absent, then it is denoted by the special symbol $\perp$ in the semantic notation. There is a particular type of signals called `event`. A signal of this type is always *true* when it is present (otherwise, it is $\perp$). The set of instants where a signal `x` is present is called its

[5] An ARINC partition/process is akin a UNIX process/task.

clock. It is noted as `^x` and is of type `event`. Signals that have the same clock are said to be *synchronous*. A SIGNAL program, also called *process*, is a system of equations over signals. The SIGNAL language relies on a handful of primitive constructs that are combined using a composition operator (also referred to as the *language kernel*). These core constructs are of sufficient expressive power to derive other constructs for comfort and structuring.

To check a SIGNAL program, one can distinguish two kinds of properties: *invariant* properties (e.g. a program exhibits no contradiction between clocks of involved signals), and *dynamical* properties (e.g. reachability, liveness). The SIGNAL compiler itself addresses only invariant properties. For a given program, it checks the consistency of constraints between clocks of signals, and statically proves properties (e.g. the *endochrony* property guarantees determinism). A major part of the compiler task is referred to as the *clock calculus*. Dynamical properties are addressed using other connected tools such as the boolean model checker SIGALI. Performance evaluation is another functionality of POLYCHRONY, section 5 discusses it in a detailed way.

Finally, put together, all these features of SIGNAL programming favor modular and reliable designs.

4 Modeling of an avionics application

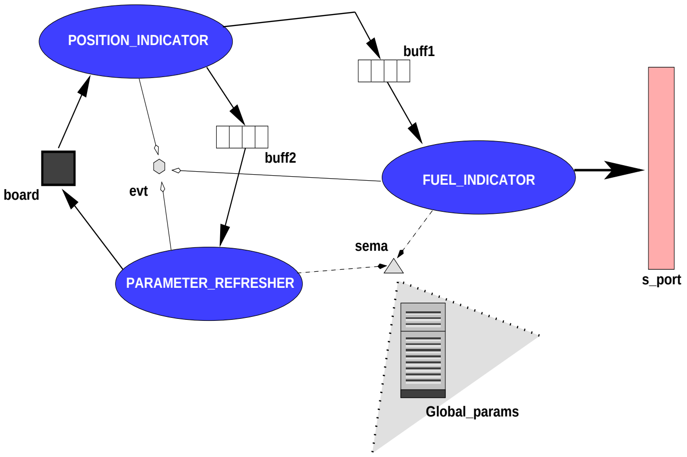


Figure 1. The partition ON_FLIGHT.

A presentation of the basic component models (communication and synchronization services, ARINC processes, etc.) required for the description of avionics applications has been given in [4]. Here, we show how these models are used to describe avionics applications[6]. Then, we illustrate how timing issues are addressed, e.g. to compute worst case execution times on the resulting description.

[6] The example considered in the following takes its inspiration from a real world avionics application which is currently being modeled.

Informal specification of the application. The application is represented by one partition, called *ON_FLIGHT*. Roughly, its function consists in computing the current position and fuel level. A *report message* is produced in the following format:

```
[date_of_the_report::height::latitude::longitude::fuel_level]
```

The partition includes the following objects: a blackboard `board`, two buffers `buff1` and `buff2`, an event `evt`, a semaphore `sema`, a sampling port[7] `s_port`, and a resource `global_params` which contains some parameters.
There are three processes.

(i) The process *POSITION_INDICATOR* first produces the report message which is updated with the current position information (height, latitude and longitude). It works as follows:

```
elaborate the report message and set the current date;
send a request to the process PARAMETER_REFRESHER for a refreshment of global parameters, via buff2 (in order to be able to update the report message with position informations);
wait for notification of end of refreshment, using evt;
read the refreshed position values displayed on board;
update the report message with height, latitude and longitude informations;
send the report message to the process FUEL_INDICATOR, via buff1;
```

(ii) The main task of *FUEL_INDICATOR* is to update the report message (produced by *POSITION_INDICATOR*) with the current fuel level.

```
if a message is contained in the buffer buff1 then
  retrieve this message;
end if
update it with the fuel level information from Global_params, via protected access (using sema);
send the final report message via the sampling port s_port;
re-initialize evt;
```

(iii) Finally, the process *PARAMETER_REFRESHER* refreshes all the global parameters used by the other processes in the partition.

```
if a refresh request arrives in the buffer buff2 then
  retrieve this message;
end if
refresh all the global parameters in Global_params, using protected access;
display refreshed position values on board;
notify the end of the refreshment, using evt;
```

Now, let us describe the associated synchronous model.

The Signal model of the partition. The executable model of a partition

[7] A sampling port allows no message queuing. There are two kinds of ports: *source* and *destination*. A message remains in a source port until it is transmitted by the channel or overwritten by a new occurrence of the message. During transmissions, channels ensure that messages leave source ports and reach destination ports in the same order. A received message remains in the destination port until it is overwritten.

consists of three basic components: first, the executive units represented by ARINC processes; second, the interactions between processes expressed via APEX services; and finally, the partition-level OS which is in charge of resource allocation to processes within the partition.

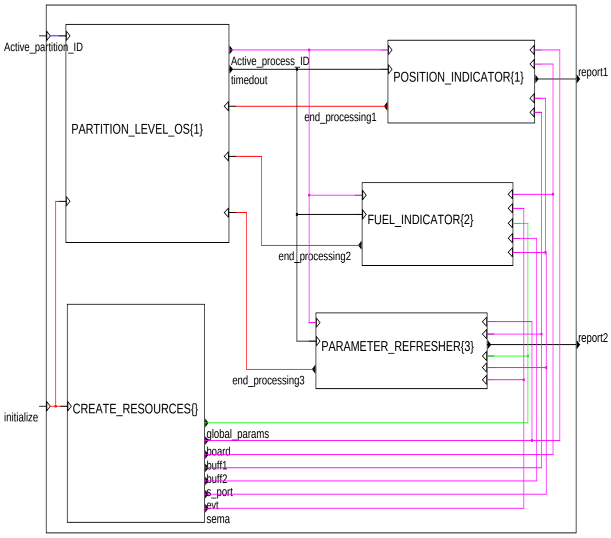


Figure 2. A SIGNAL model of the partition ON_FLIGHT.

The model of the partition *ON_FLIGHT* is shown in Figure 2. We clearly distinguish the partition-level OS as well as the three processes. The box that contains the SIGNAL process `CREATE_RESOURCES` has been added for structuring. It provides the processes with communication and synchronization mechanisms (e.g. `buff1`, `sema`). These mechanisms are created on the occurrence of the input signal `initialize`. The presence of this signal corresponds to the *initialization* phase of the partition. The input `Active_partition_ID` represents the identifier of the running partition selected by the module-level OS[8], and it denotes an execution order when it identifies the current partition. Whenever the partition executes, the partition-level OS designates an active process within the partition. This is represented by its output signal `Active_process_ID`. It is sent to all the processes. Every process that completes notifies the OS through a special signal (e.g. `end_processing1` for the process `POSITION_INDICATOR`), so the OS can take a decision about the next process to execute.

A process can be blocked during its execution, for instance, when it tries to send a message to a full buffer. A time counter may be initiated to wait for the availability of space in the buffer. The signal `timedout` produced by the partition-level OS notifies processes of the expiration of their associated time counters.

[8] The activation of each partition depends on this signal. It is produced by the module-level OS which is in charge of the management of partitions in a module.

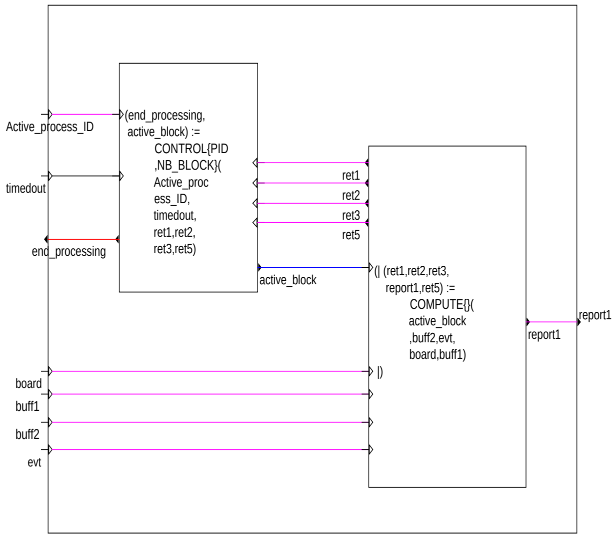
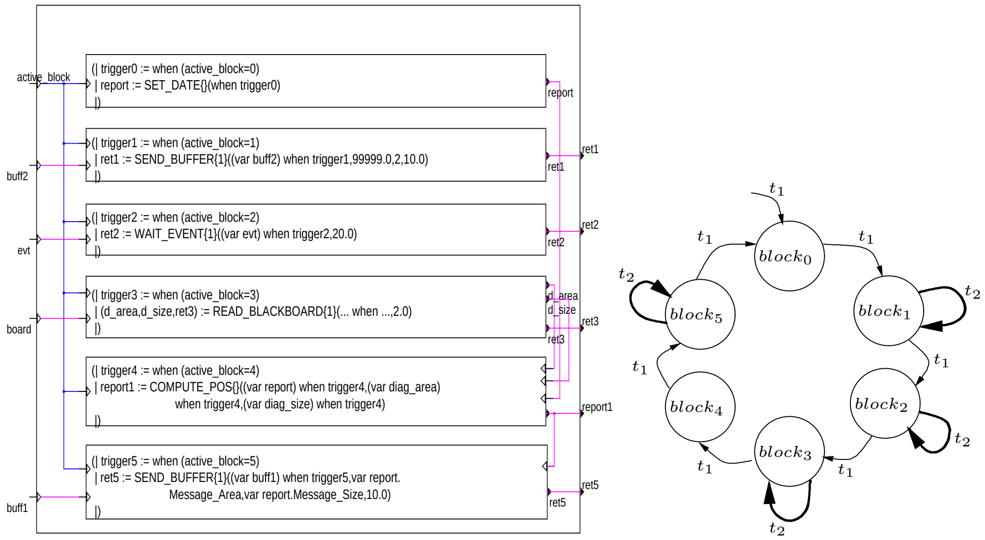


Figure 3. A Signal model of the process POSITION_INDICATOR.

Modeling of processes. To illustrate the description of processes, we mainly focus on the process *POSITION_INDICATOR* (the modeling of the other processes follows the same scheme).

A well-known design principle for getting modularity consists in splitting the considered system into *control* and *computation* parts. Among others, one can note the great popularity gained by this idea in hardware design. The model we propose for *ARINC* processes relies on this principle. So, two basic sub-components are distinguished as shown in Figure 3: *CONTROL* and *COMPUTE*. The former specifies the execution flow of the process. Typically, it is a finite state machine that indicates which statements (or actions) should be executed whenever the process is active. The latter describes these statements grouped into *blocks*. Each block is attached to a state specified in *CONTROL*. The way the two sub-components of the process model interact is similar to what happens in a mode-automaton [11]. On the other hand, a block is assumed to be executed without interruption, within a bounded amount of time.

In the model in Figure 3, the signal `active_block` identifies a block selected in *CONTROL*. This block is executed *instantaneously*. Therefore, one must take care of what kinds of statements can be put together in a block. Two sorts of statements can be distinguished: those which may cause an interruption of the running process (e.g. a *SEND_BUFFER* request on a full buffer), termed *system calls* (in reference to the fact that they involve the partition-level OS); and statements that never interrupt a running process (typically data computation functions), referred to as *functions*. Since a block is supposed to be non-interruptible, we impose that it contains either one system call or one or more functions. This way, the instantaneousness of the block execution is guaranteed to be coherent with its non-interruptibility.



```
(| trigger0 := when (active_block=0)
 | report := SET_DATE{}(when trigger0)
 |)

(| trigger1 := when (active_block=1)
 | ret1 := SEND_BUFFER{1}((var buff2) when trigger1,99999.0,2,10.0)
 |)

(| trigger2 := when (active_block=2)
 | ret2 := WAIT_EVENT{1}((var evt) when trigger2,20.0)
 |)

(| trigger3 := when (active_block=3)
 | (d_area,d_size,ret3) := READ_BLACKBOARD{1}(... when ...,2.0)
 |)

(| trigger4 := when (active_block=4)
 | report1 := COMPUTE_POS{}((var report) when trigger4,(var diag_area)
                  when trigger4,(var diag_size) when trigger4)
 |)

(| trigger5 := when (active_block=5)
 | ret5 := SEND_BUFFER{1}((var buff1) when trigger5,var report.
                  Message_Area,var report.Message_Size,10.0)
 |)
```

Figure 4. The COMPUTE sub-component and the automaton associated with the CONTROL for the process POSITION_INDICATOR.

Figure 4 shows statements contained in *COMPUTE*. Blocks are represented by inner boxes. The statements associated with a block k are executed whenever the current state of the automaton specified in *CONTROL* is $block_k$, i.e. whenever the event `triggerk` is present. For instance, from top to bottom, the first block contains a function `SET_DATE` which produces an instance of the report message, where only the field `date_of_the_report` is updated. The other fields will be completed later. The second block contains the system call `SEND_BUFFER`, which is used to send a message in `buff2`. Input parameters are the message address and size (respectively, denoted by 99999.0 and 2), and a time-out value (10.0 time units) to wait for space when the buffer is full. A return code `ret1` is sent for diagnostic. Blocks are computed sequentially from top to bottom as represented by transitions labeled by t_1 in the automaton depicted by Figure 4. However, there could be consecutive executions of a same block. This happens when a system call is executed and the required resource is not yet available. For example, consider the `READ_BLACKBOARD` request (used to get a message from `board`), if no message is currently displayed in the blackboard, the calling process will get suspended on this block. After a message is available, the process is switched to the “ready” state. As soon as it becomes active, it should re-execute the same block (which induced its suspension) to read the latest message available in the blackboard. These situations are expressed by transition t_2 in the automaton.

Modeling of the partition-level OS. The main task of the partition-level OS is to ensure a correct concurrent execution of processes within the partition. Its modeling requires on the one hand, APEX services (e.g. in Figure 5, `CREATE_PROCESS` and `START` are used respectively to create and start processes), and implementation-dependent functions on the other hand, for instance to define a scheduling policy (e.g. `PROCESS_SCHEDULINGREQUEST` in Figure 5).

```
(| (att1,att2,att3) := GET_PROCESSES_ATTRIBUTES{}(when initialize)       (a)
 | (pid1,return_code1) := CREATE_PROCESS{}(att1 when initialize)         (b)
 | (pid2,return_code2) := CREATE_PROCESS{}(att2 when initialize)
 | (pid3,return_code3) := CREATE_PROCESS{}(att3 when initialize)
 | return_code4 := SET_PARTITION_MODE{}(#NORMAL when (^return_code3))    (c)
 | return_code5 := START{}(pid1)                                         (d)
 | return_code6 := START{}(pid2)
 | return_code7 := START{}(pid3)
 | partition_is_running := (Active_partition_ID = Partition_ID)          (e)
 | diagnostic := PROCESS_SCHEDULINGREQUEST{}(
                          when partition_is_running)                     (f)
 | (Active_process_ID,status) := PROCESS_GETACTIVESTATUS{}()             (g)
 | timedout := UPDATE_COUNTERS{}()                                       (h)
 | Active_process_ID ^= timedout ^= when partition_is_running
 | return_code8 := SUSPEND{}(Active_process_ID when (end_processing1
                        ^+ end_processing2 ^+ end_processing3))          (i)
 | return_code9 := SET_PARTITION_MODE{}(#IDLE when (^end_processing2))   (j)
 |)
```

Figure 5. The partition-level OS model.

Figure 5 shows a partial view of the SIGNAL description of the partition-level OS. On the presence of the signal `initialize` (which corresponds to the initialization phase of the partition), process attributes are first defined in equation `(a)`, example of attributes are *priority*, *periodicity*. Just after that, processes are created [9] and started [10]. For instance, the lines `(b)` and `(d)` correspond to the creation and starting of the process identified by `pid1` (in fact `POSITION_INDICATOR`). In equation `(c)`, the partition is set to the *NORMAL* mode [11]. The signal `Active_partition_ID` represents the identifier of the running partition selected by the module-level OS. It denotes an execution order when it identifies the current partition, this is the meaning of the boolean `partition_is_running` definition `(e)`. So, process rescheduling is performed whenever the partition is active (see `(f)`), and the process with the highest priority in the ready state is designated to execute (`Active_process_ID` in equation `(g)`). On the other hand, all time counters used in the partition are updated whenever it executes (equation `(h)`). The signal `timedout` is sent to processes to notify them a possible expiration of their associated time counters. A running process gets suspended as soon as it completes (one of the signals `end_processing1`, `end_processing2`, or `end_processing3` is received from processes in the partition). This is expressed in equation `(i)`. Finally,

[9] Creation [3] does not imply dynamic memory allocation, it only creates a link between the given name and a statically allocated process (this is done via a service called *PROCESS_RECORD* in our library) with a suitable stack area having the same name.

[10] The *START* service only puts the specified process in the "ready" state, the process does not execute yet.

[11] There are four operating modes [3]: in the *IDLE* mode, the partition is not executing any process within its allocated windows; in the *COLD_START* mode, the partition is executing a cold start initialization; in the *WARM_START* mode, the partition is executing a warm start initialization; and in the *NORMAL* mode, the scheduler is activated. All the required resources in the partition must have been created before.

the partition is set to *IDLE* mode when no process executes while the partition is still active (line (j)). Here, the process FUEL_INDICATOR completes the last, and notifies the partition-level OS by sending the signal end_processing2.

The above small example aimed to show the feasibility of describing avionics applications using the synchronous language Signal. Modularity and abstraction are key features of the Signal programming. They allow for the scalability of our approach. The description of a large application is achieved with respect to a well-defined design methodology which consists in specifying either completely or partially (by using abstractions) sub-parts of the application. After that, the resulting components can be composed to obtain new components. These components can be also composed and so on, until application is complete.
A great advantage of Signal-based modeling is the possibility to formally analyze specifications. In particular, timing issues such as worst case execution times, can be addressed using the performance evaluation technique implemented in Polychrony .

5 Performance evaluation

A Signal process that models an application is recursively composed of subprocesses, where elementary sub-processes belong to the language kernel and called *atomic nodes*. A profiling of such a process substitutes each signal with a new signal representing availability dates *date_x* and automatically replaces atomic nodes with their timing model counter-part ("timing" morphism). The resulting time model is composed (by standard synchronous composition) with the original functional description of the application, and for each signal x, a synchronization with the signal *date_x* is added. The resulting process is close to (or even represents exactly) the model of the temporal behavior of the application running on its actual architecture. One can obviously design less strict modeling to get faster simulation (or formal verification); it is sufficient to consider more abstract representations either of the architecture or of the program.

5.1 Temporal interpretation of Signal *processes*

An interpretation of a Signal process is a process that exposes a different view of the initial one. The structure of the interpretation process is essentially the same but its computations exhibit another aspect of its behavior. The temporal interpretation exposes the time aspect and allows to see how an implementation of a specified function will behave over time [10].

For each process independent of its complexity level, another process can be automatically derived to model its temporal behavior on a given implementation. These processes are called temporal interpretations. For a Signal process P, its temporal interpretation for an implementation I will be denoted by $T(P_I)$, where P_I is the SIGNAL process that models implementation I of P. Thus, if a system specified by a process P has a variety of possible implementations $I(1)$ to $I(k)$, then each implementation can be modeled by $P_{I(i)}, i \in [1, k]$, and for each $P_{I(i)}$ a temporal interpretation $T(P_{I(i)})$ can be derived. This way, a comparative performance evaluation of the different implementations can be performed and the design space of possible implementations can be effectively explored before committing the design to one particular implementation. Such an approach permits to concentrate the design effort to a set of candidate implementations.

Signal availability dates. For each signal in the initial SIGNAL specification a date signal is defined in its temporal interpretation: $x \in P \rightarrow T(x) \in T(P)$. For any signal x in P we have a *date_x* in $T(P)$ with x synchronous to *date_x*:

$$P \rightarrow T(P),\ x \rightarrow T(x) = date\_x,\ x\ \hat{=}\ date\_x.$$

These date signals are some sort of time-stamps providing the availability times for the values of the corresponding signals in the functional specification, in respect to a global time reference. Depending on the implementation context, time can be measured using either physical time units or full clock cycles. In the first case the date signals are positive real numbers and in the second positive integers. From a cycle count integer measurement we can go on to physical time measurement by multiplying the cycle count to the cycle period.

Each operation in a SIGNAL specification is represented by a node in the Hierarchical Conditional Dependency Graph, which is the internal representation of a SIGNAL program. To each node in the graph, a delay is associated. This delay is represented by the same data type as the data type used to represent dates and is a function of several parameters. The actual node delay is obtained by giving values to these parameters. The delay depends on parameters like: the operation performed by the node, data types involved, the chosen implementation, etc. Furthermore, a delay can be represented by a pair of numbers corresponding to the worst and best case delays. Since delays are represented by intervals, dates will be represented as intervals too. Computing these dates takes into account the processing delays. It is important to note that this date mechanism allows us to go from logical to physical time.

Non-functional interpretations. The temporal interpretation of a SIGNAL specification is just a special case of a general non-functional interpretation. The non-functional interpretations are SIGNAL processes and as such they can be decomposed into a control and a data part. The control computations are identical to those in the initial processes from which the interpretations are derived. What changes are the data computations since they extract the information related to the particular interpretation.

For a SIGNAL process P we know that $P = C_P | D_P$, with C_P and D_P representing respectively the control and data parts of P. Similarly for an interpretation of P, we have: $T(P) = C_{T(P)} | D_{T(P)}$. Since the interpretation of a complex process can be defined as the recursive composition of the interpre-

tations of the constituent processes for $T(P)$ we have: $T(P) = T(C_P)|T(D_P)$, with $T(C_P) = C_{T(C_P)}|D_{T(C_P)}$ and $T(D_P) = C_{T(D_P)}|D_{T(D_P)}$.
For the control part, we have $C_{T(P)} = C_P$.

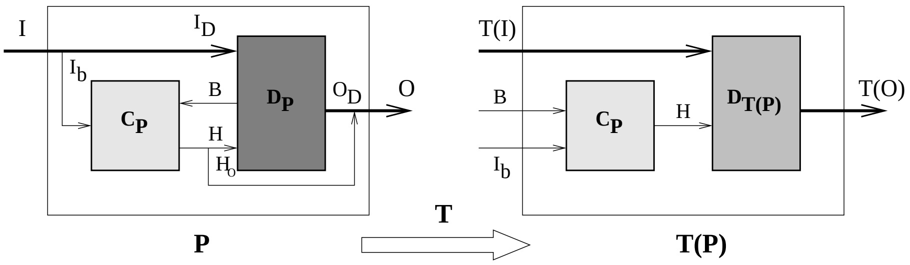


Figure 6. Temporal interpretation of a SIGNAL process P.

The process of obtaining an interpretation $T(P)$ of a process P is graphically depicted in Figure 6. This process gives a general form of *morphism* of SIGNAL programs, which is available in POLYCHRONY. The data part (D_P) of the process P computes output values (O_D) from input values (I). The computations are conditioned by activation events (H) computed in the control part (C_P). To compute the activation conditions H, C_P uses Boolean input signals (I_b) and intermediate Boolean signals B computed by D_P. Finally, certain outputs are output events (H_O) computed by C_P. The control parts of the initial process and its interpretation are identical, but the data computations differ. The data computations in $T(P)$ extract the information of interest, implicit in the initial specification P.
The date computation model. The SIGNAL kernel operators are the simplest processes that can be used to build more complex ones. Similarly, the interpretation of a process can be viewed as the composition of the interpretations of the primitive processes making up the initial process.

The interpretations of the kernel processes perform the appropriate computations relating to a particular interpretation. These interpretations are organized in a collection which represents the *library of cost functions*, defined in SIGNAL. For each interpreted process, this library is extended with the interpretations of external function calls and other separately compiled processes, used in the initial process. For example, the "timing" morphism available in POLYCHRONY associates with the monochronous addition operator `z := x + y`, the following cost function:

```
process CostPlus{type_x, type_y}
   ( ? date_type date_x, date_y, date_clk_z, wait_i;
     ! date_type date_z, done_i )
 (| date_z := MAX2( MAX3( date_x, date_y, date_clk_z), wait_i when ^date_z)
              + getCostPlus{type_x, type_y}()
  | done_i := (date_z default wait_i) cell ^done_i
  |)
```

where the `MAXn` denotes a process that returns the maximum value of `n` inputs, among those that are present at a given instant (it is not monochronous). The notations `type_x` and `type_y` represent respectively the types of `x` and `y`;

`date_clk_z` is a signal associated with the common clock of `x`, `y` and `z` by the morphism. Signals `wait_i` and `done_i` are associated with the current node and have the same type as date signals: `wait_i` accumulates dates coming from incoming precedences other than data dependencies, whereas `done_i` is a date required by the next nodes other than data dependencies (i.e. `done_i` is part of `wait_i+1`). The date of `z`, denoted by `date_z`, is the sum of the maximum date of inputs and the delay of the addition operation, some Δ_+. The quantity Δ_+ depends on the desired implementation, on a specific platform. It has to be provided in some way by the user, with respect to the considered architecture. In the current implementation in Polychrony, the value Δ_+ is provided by a function `getCostPlus` which has the types of the operands as parameters and which fetches the required value from some table.

The scheme illustrated above for monochronous operators handles also "control" operators. For constructs such as the `default` operator, which allow for control branching, the definition of the associated interpretation accounts for this branching (for `a default b`, the date at which the input value is available is given by `date_a default date_b`). Moreover, thanks to compositionality of Signal specifications, the above mechanism can be applied at any level of granularity.

5.2 Obtaining results

Figure 7 depicts a *co-simulation* of the application model composed with its associated temporal interpretation. At each iteration, the date of an output ($d(O_k)$) depends on the date of an input ($d(I_j)$) and the *control configuration* represented by a "valuation" of a condition vector $[c_1, \ldots, c_q]$ corresponding to intermediate boolean signals B (cf. Fig. 6) computed in the original program. In a straightforward approach, it is possible to provide a set of vectors that covers all the possible combinations for the control flow. A better way is to take into account the existing relationships between these booleans such as provided by the clock calculus (this is expressed through the composition of the original program and its temporal interpretation). In addition, specific *observer* processes, comparing dates or verifying some conditions (timing requirements) for example, can be inserted into the model.

Comments. Execution time estimation is an important metric for performances in real-time system design. Some current practices for timing predictability proceed by actually running programs on a set of test data and measuring execution times. One major drawback here concerns the degree of pertinence of this set of data w.r.t. the considered context. Other approaches such as [13] [12] have shown that timing issues can be successfully addressed at higher level languages (e.g. language C) rather than lower level languages (e.g. assembly language). In the case of the Signal language, the timing predictability problem consists in simulating a Signal program which reflects the temporal dimension of an initial program. On the other hand, the tools and

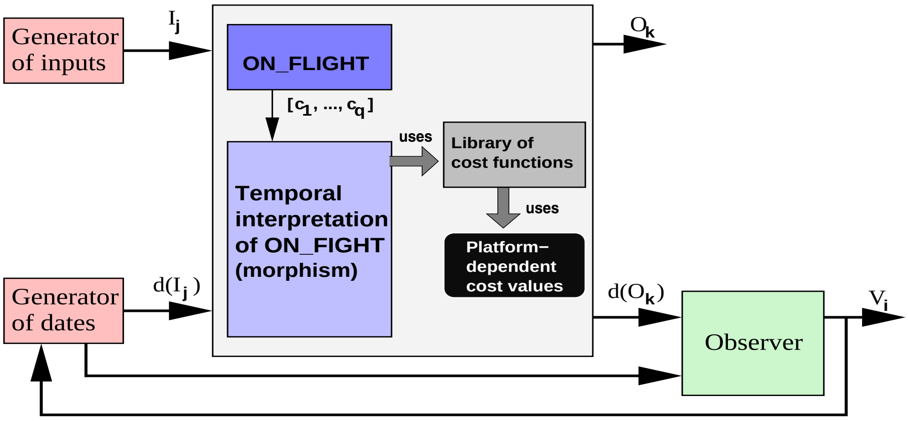


Figure 7. Co-simulation of the application with its temporal interpretation.

techniques available in Polychrony remain applicable on this temporal "image" (e.g. for the purpose of some formal verifications when the corresponding required abstractions are considered).

Several successful experiments have been done on sample Signal programs. For the ON_FLIGHT model, some simplifications have been made because of the complexity of used data structures. So, the cost of the accesses to those data structures and related effects is not taken into account. The cost function library currently considers simple data structures (e.g. integer, boolean, arrays). Others are considered as external. As a result, the current computed results are not relevant enough to be highlighted here. However, this library is being currently enhanced to allow more efficient experiments on programs with complex data structures. Thus, more relevant results will be available soon.

6 Conclusions

In this paper we illustrated an approach to the modeling of avionics applications for the purpose of formal verification and analysis. The whole approach relies on the use of a single formalism of the Signal language. This is part of a more general design methodology for distributed embedded applications, defined within Polychrony. This methodology proceeds by successive transformations on an initial Signal model that preserve semantic properties. During the transformations, "abstract" components can be instantiated in different ways from modules related to actual target architecture features, addressing various purposes (embedded code generation, temporal validation, etc.). We considered models of APEX services [4] to describe avionics applications. Then, we used the Polychrony tool-set to analyze applications, in particular, we focused on the real-time behavior. The technique [10] is still being implemented in order to take into account Signal programs with complex data structures (such as the model of the partition ON_FLIGHT described in this paper).

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