

## **A NEW SIMULATION ALGORITHM FOR PDEVS MODELS WITH TIME ADVANCE ZERO**

Cristina Ruiz Martin  
Guillermo G. Trabes  
Gabriel A. Wainer

Department of Systems and Computer Engineering  
1125 Colonel By Dr.  
Ottawa, K1S 5B6, CANADA

### **ABSTRACT**

Discrete Event Systems Specification (DEVS) is a well-known formalism to develop models using the discrete event approach. One advantage of DEVS is a clear separation between the modeling and simulation activities. The user only needs to develop models and general algorithms execute the simulations. The PDEVS simulation protocol is a well-know and widely accepted algorithm to execute DEVS simulations. However, when events are scheduled with time advance equal to zero, this algorithm handles them sequentially. Events that occur at the same time are processed one after the other. This may result in unwanted simulation results. In this work, we propose a new algorithm that assures that the output bag of a model is transmitted only when all the outputs corresponding to a given simulation time have been collected.

### **1 INTRODUCTION**

Modeling and Simulation (M&S) has become an essential tool in science and engineering. Its ability to represent problems in several disciplines and perform scientific exploration has increase its popularity. There are many methodologies to develop M&S solutions, and some of them allow defining the models formally, which has a few advantages. In particular, the Discrete Event System Specification (DEVS) (Zeigler et al. 2000) provides a theoretical framework to develop discrete-event M&S and it was used in many applications since its creation.

In DEVS, models are defined using two kinds of components: atomic models and coupled models. Atomic models define the behavior of the elements of the system, whereas coupled models define their structure. The various components of the model interact with each other through well-defined modular interfaces. In some versions of DEVS, such interfaces include the definition of input/output ports.

The formal definition of DEVS provides many advantages. One of them is the capacity to separate model definition, implementation, and experimentation. Models that are valid under a given experimental frame are defined using a formal notation and then simulated using algorithms that have been formally verified. This separation of concerns boosts the reusability of models and ease the verification of the models.

Sometimes, when building a discrete-event model, we need to represent the occurrence of simultaneous events. In classic DEVS, when simultaneous events occur, the simulation algorithm executes the models involved in according to the specifications defined in a tie-break function. This function specifies the order of execution of the model's components when they have simultaneous events to be executed. This way of handling collisions might not be adequate to reflect the actual response of the system to simultaneous events. To deal with this problem, Parallel DEVS (PDEVS) was introduced to deal with simultaneous events more elegantly (Chow and Ziegler 1994). One of the changes of PDEVS is that enables the modeler to define the behavior of the components when there are collisions of events. To do so, PDEVS adds a new

function in atomic components that deals with the collision, removing the need for the tie breaking function. Another major change is that PDEVS models also modifies the way in which inputs and outputs are defined. PDEVS allows the transmission of bags of events as inputs and outputs, allowing transferring information about multiple input/output events simultaneously.

According to the PDEVS specifications, all outputs for a specific time are stored in an output bag and transmitted simultaneously. However, the PDEVS simulation algorithm in (Chow et al. 1994), which is used in numerous DEVS implementations, does not completely follow the above-mentioned specifications. In some cases, the output bag of a model is transmitted before all the outputs for at a given time are collected. The result is that we transmit multiple output bags at the same simulation time, which make the models more complex to define as the simulation execution does not match the PDEVS specification exactly.

One approach to solve the above-mentioned issue is to use super dense time (Nutaro 2020). Super dense time augments the real numbers with information for ordering events that would otherwise appear to be simultaneous. Therefore, this theory solves the issue considering events sequential even if they have the same simulation time. However, sometimes, the modeler needs to treat all the events with the same simulation time as simultaneous.

We present a revised version of the PDEVS Abstract Simulator that addresses this issue. The revised version of the algorithm assures that the output bag of a model is transmitted only when all the outputs corresponding to a given simulation time have been collected.

The rest of the paper is organized as follows. In section 2, we summarize DEVS and PDEVS. We also explain the original PDEVS simulation algorithm. In section 3 we explain the issues with the current algorithm through two examples. In section 4, we introduce the proposed modification to the algorithm, and in section 5, we define the execution traces of the new algorithm through two examples. Finally, in section 6, we present the conclusions and future research lines of this work.

## 2 BACKGROUND AND RELATED WORK

### 2.1 DEVS

Discrete Event System Specification (DEVS) (Zeigler et al. 2000) is a well-known mathematical formalism that provides a theoretical framework to think about modeling using a hierarchical, modular approach. In DEVS, atomic models provide behavior and coupled models provided structure.

Atomic models are defined as a tuple:  $A = \langle S, X, Y, \delta_{int}, \delta_{ext}, \lambda, ta \rangle$  where:  $S$  is the set of states,  $X$  is the set of input ports and values,  $Y$  is the set of output ports and values,  $\delta_{int}: S \rightarrow S$  is the internal transition function,  $Q = \{(s, e) \mid s \in S, 0 \leq e \leq ta(s)\}$  is the local state set (where  $e$  is the time elapsed since the last transition),  $\delta_{ext}: Q \times X \rightarrow S$  is the external transition function,  $\lambda: S \rightarrow Y$  is the output function, and  $ta: S \rightarrow \mathbb{R}^+$  is the time-advance function. An atomic model, also known as basic model, is always in a specific state waiting to complete the lifespan delay returned by the  $ta$  function, unless an input of a new external event occurs. If no external event is received during the lifespan delay, the output function  $\lambda$  is called first, and then the state is changed according to the value returned by the  $\delta_{int}$  function. If an external event is received, then the state is changed according to the value returned by the  $\delta_{ext}$  function, but no output is generated.

Coupled models define a network structure in which nodes are atomic or coupled models and directed links represent the routing of events between outputs and inputs or to/from the upper level. Formally, a coupled model is represented by the tuple  $C = \langle X, Y, D, \{M_i\}, \{I_i\}, \{Z_{ij}\}, SELECT \rangle$ , where:  $X$  is the set of input events,  $Y$  is the set of output events,  $D$  is an index for the components,  $M_i \mid i \in D$ , is a Classical-DEVS models as defined previously,  $I_i$ , are the influencees of model  $i$ ,  $\forall j \in I_i$ ,  $Z_{ij}: Y_i \rightarrow X_j$  is the  $i$  to  $j$  translation function and  $SELECT: 2^D \setminus \emptyset \rightarrow D$  is the tie-breaker function that sets priority in case of simultaneous events.

The formal definitions of DEVS provides many advantages. DEVS has the capacity to separate model definition, implementation, and experimentation. Models that are valid under a given experimental frame are defined using a formal notation and then simulated using algorithms that have been formally verified.

This separation of concerns along with its hierarchical and modular approach boosts the reusability of models and ease the verification of the models.

## 2.2 PDEVS

Even though Classic-DEVS has been used in many applications and tools, it has a limitation when dealing with simultaneous events. Simultaneous events are handled sequentially based on the order specified in the tie-break SELECT function. This collision behavior may not accurately represent the behavior of the actual system. Parallel DEVS (PDEVS) (Chow and Ziegler 1994; Chow et al. 1994) was introduced to deal with tie-breaking and better handling of simultaneous events. PDEVS introduces two main characteristics:

- The inputs and outputs for every PDEVS model,  $X$ , and  $Y$  respectively, are defined as bags (multisets) instead of sets, as in classical DEVS. In this way, multiple elements can be transmitted at the same time.
- A confluent function is introduced which defines the model's behavior when an internal and external transition are scheduled at the same time.

With these new features PDEVS can handle the occurrence of multiple events at the same time in a simple way, and therefore, tie-break function SELECT, defined in classical DEVS, is no longer needed.

The PDEVS atomic models are defined as a tuple:  $A = \langle S, X, Y, \delta_{int}, \delta_{ext}, \delta_{conf}, \lambda, ta \rangle$  where:  $S$ ,  $\delta_{int}$ , and  $ta$  are defined as in classical DEVS. As mentioned,  $X$  and  $Y$  are defined as bags of elements. The output, external and the additional confluent function are defined respectively, as follows:  $\lambda: S \rightarrow Y^b$ ,  $\delta_{ext}: Q \times X^b \rightarrow S$  and  $\delta_{conf}: Q \times X^b \rightarrow S$ .

In addition to the development of the model itself, there have been many efforts in the development of a simulator. Following the ideas from classical DEVS, PDEVS makes a clear separation between the model and the simulation. The models are defined by users following the specifications defined by the formalism and, to execute simulations, a general mechanism is provided. This mechanism is known as the PDEVS Abstract Simulator. In this section, we review the Abstract Simulator defined by (Nutaro, 2019).

Given a PDEVS model, the PDEVS Abstract Simulator creates a structure that allows to execute the behavior of the model and to obtain the correct simulation results. The PDEVS Abstract Simulator consists of three types of components: simulators, coordinators, and root-coordinator. Each atomic model is associated with a simulator and each coupled model is associated with a coordinator. One root-coordinator is placed at the root of the structure hierarchy.

This simulation procedure is implemented by exchanging several types of messages between the components. These are messages for initialization ( $i$ ), to compute output ( $*$ ) to execute a state transition ( $x$ ) and send outputs ( $y$ ). In contrast to classical DEVS where imminent models are sequentially activated, the coordinator enables concurrent execution of state transitions and output calculations for atomic models. The outputs of these models are collected into a bag called the mail. The mail is analyzed to determine the part going outside the scope of the coordinator due to external output coupling and the parts to be distributed internally due to internal coupling. The internal transition functions of the imminent models are not executed immediately since they may also receive input at the same simulation time. Similarly, as with the simulators, the coordinators react to  $i$ ,  $*$ ,  $x$  and  $y$  messages sent by a parent coordinator, and they reply to messages received from a subordinate. At the top of this hierarchy is a root-coordinator whose role is to initiate  $i$ ,  $*$ , and  $x$  messages in each simulation cycle. The algorithms of the root-coordinators, coordinators and simulators are presented in Fig. 1, 2 and 3, respectively.

1: Parallel-Devs-root-coordinator 2: <b>variables:</b> 3: $t$ 4: $child$ 5: $t = t_0$ 6: send initialization message (i,t) to subordinate	7: $t = t_n$ of its subordinate 8: <b>loop</b> 9: send(*,t) message to child 10: $t = t_n$ of its child 11: <b>end loop</b> 12: until end of simulation 13: end parallel-devs-root-coordinator
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Figure 1: Root-Coordinator for PDEVS.

1: Parallel-Devs-coordinator 2: <b>variables:</b> 3: $DEVN = (X, Y, D, \{M_d\}, \{I_d\}, \{Z_{i,d}\})$ 4: parent 5: $tl$ 6: $tn$ 7: $event-list$ 8: $IMM$ 9: $mail$ 10: $y_{parent}$ 11: $\{y_d\}$ 12: <b>when</b> receive i-message (i,t) at time $t$ 13: <b>for</b> $d \in D$ <b>do</b> 14: send i-message to child $d$ 15: <b>end for</b> 16: sort $event-list$ according to $tn_d$ 17: $tl = \max\{tld   d \in D\}$ 18: $tn = \min\{tnd   d \in D\}$ 19: <b>when</b> receive *-message (*,t) 20: <b>if</b> $t \neq tn$ <b>then</b> 21: error: bad synchronization 22: <b>end if</b> 23: $IMM = \min(event-list)$ 24: <b>for</b> $r \in IMM$ <b>do</b> 25: send *-messages(*,t) to $r$ 26: <b>end for</b> 27: <b>when</b> receive x-message(x,t) 28: <b>if</b> $not(tl \leq t \leq tn)$ <b>then</b> 29: error: bad synchronization 30: <b>end if</b> 31: $receivers = \{r   r \in children, N \in I_r, Z_{N,r}(x) \neq \emptyset\}$ 32: <b>for</b> $r$ in $receivers$ <b>do</b> 33: send x-messages( $Z_{N,r}(x)$ ,t) with input value $Z_{N,r}(x)$ to $r$ 34: <b>end for</b> 35: <b>for</b> $r \in IMM$ and not in $receivers$ <b>do</b> 36: send x-message ( $\emptyset$ , t) to $r$	37: <b>end for</b> 38: sort $event-list$ according to $tn_d$ 39: $tl = t$ 40: $tn = \min tn_d   d \in D$ 41: <b>when</b> receive y-message ( $y_d$ ,t) with output $y_d$ from $d$ 42: <b>if</b> this is not the last $d$ in $IMM$ <b>then</b> 43: add( $y_d$ , $d$ ) to $mail$ 44: mark $d$ as reporting 45: <b>else if</b> this is the last $d$ in $IMM$ <b>then</b> 46: $y_{parent} = \emptyset$ 47: <b>end if</b> 48: <b>for</b> $d \in I_N$ <b>then</b> 49: <b>if</b> $Z_{d,N}(y_d) \neq \emptyset$ <b>then</b> 50: add $y_d$ to $y_{parent}$ 51: <b>end if</b> 52: <b>end for</b> 53: send y-message ( $y_{parent}$ , t) to parent 54: <b>for</b> child $r$ , $x_r = \emptyset$ <b>do</b> 55: <b>for</b> $d$ such that $d \in I_r$ <b>do</b> 56: <b>if</b> $Z_{d,N}(y_d) \neq \emptyset$ <b>then</b> 57: add $y_d$ to $y_r$ 58: <b>end if</b> 59: <b>end for</b> 60: <b>end for</b> 61: $receivers = \{r   r \in children, y_r \neq \emptyset\}$ 62: <b>for</b> $r \in receivers$ <b>do</b> 63: send x-messages ( $y_r$ ,t) to $r$ 64: <b>end for</b> 65: <b>for</b> $r \in IMM$ and not in $receivers$ <b>do</b> 66: send x-messages ( $\emptyset$ ,t) to $r$ 67: <b>end for</b> 68: $tl = t$ 69: $tn = \min tn_d   d \in D$ 70: sort $event-list$ according to $tn_d$ 71: end Parallel-Devs-coordinator
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Figure 2: Coordinator for PDEVS.

<pre> 1: Parallel-Devs-simulator 2: variables: 3:   parent 4:   tl 5:   tn 6:   DEVS 7:   y 8: when receive i-message (i,t) at time t 9:   tl = t - e 10:  tn = tl + ta(s) 11: when receive *-message 12:   if t = tn then 13:     y = λ(s) 14:     send y-message(y,t) to parent coordinator </pre>	<pre> 15:   end if 16: when receive x-message (x,t) 17:   if x = ∅ ∧ t = tn then 18:     s = δ<sub>int</sub>(s) 19:   else if x ≠ ∅ ∧ t = tn 20:     s = δ<sub>conf</sub>(s,x) 21:   else if x ≠ ∅ ∧ (tl ≤ t &lt; tn) 22:     e = t - tl 23:     s = δ<sub>ext</sub>(s,e,x) 24:   end if 25:   tl = t 26:   tn = tl + ta(s) 27: end Parallel-Devs-Simulator </pre>
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Figure 3: Simulator for PDEVS.

The PDEVS simulation algorithm was implemented in several simulators over the years such as DEVS-Suite Simulator (Kim et al. 2009), Adevs (Nutaro 2014), and Cadmium (Belloli et al. 2019). A detailed list of DEVS simulators can be found in <http://www.sce.carleton.ca/faculty/wainer/standard/tools.htm>.

### 3 THE PDEVS SIMULATION ALGORITHM

In this section, we show how the PDEVS simulation protocol works and how this protocol does not follow the definition of input/output bags as in the formal specification. We show how the algorithm handles output bags when there are states with time advance zero.

Let us assume that we want to model and simulate a DEVS couple model whose structure is shown in Figure 4. The model, named COUPLED includes two atomic models: GENERATOR and STORAGE. COUPLED does not have any inputs or outputs; GENERATOR does not have any inputs; and STORAGE does not have any outputs. The output of GENERATOR is connected to the input of STORAGE.

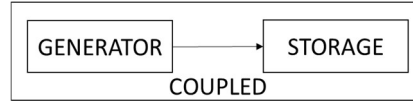


Figure 4: A DEVS model example.

The formal definition of these models is as follows:

$$\text{GENERATOR} = \langle S, X, Y, \delta_{int}, \delta_{ext}, \delta_{conf}, \lambda, ta \rangle$$

$S = \{0, 1\};$   
 $X = \emptyset;$   
 $Y = \{0, 1\};$   
 $\delta_{int}(0) = 1; \delta_{int}(1) = 0;$   
 $\delta_{ext}: \emptyset;$   
 $\delta_{conf}: \emptyset;$   
 $\lambda(0) = \{0\}; \lambda(1) = \{1\};$   
 $ta(0) = 1 \text{ s.}; ta(1) = 0 \text{ s.}$

GENERATOR has two states: 0 and 1 ( $S = \{0, 1\}$ ; initial state: 0). It changes its state through internal transitions every second if state is 0 ( $ta(0) = 1 \text{ s.}$ ) and immediately if state is 1 ( $ta(1) = 0 \text{ s.}$ ). The output of GENERATOR is the value of its state, also 0 or 1 ( $Y = \{0, 1\}$ ). When it is on state 0, it outputs a value of 0 ( $\lambda(0) = \{0\}$ ), and changes to 1 ( $\delta_{int}(0) = 1$ ); when it is on state 1 ( $\lambda(1) = \{1\}$ ), it outputs a 1, and it changes

to state 0 ( $\delta_{int}(1) = 0$ ). As this model does not have inputs, the external and confluent transition functions will never occur ( $X = \emptyset$ ;  $\delta_{ext}: \emptyset$ ;  $\delta_{conf}: \emptyset$ ).

We can notice that when this model is in state 1, it schedules its next state change in 0 seconds. This means that the next event is scheduled to occur at the same time as the previous one.

$$\text{STORAGE} = \langle S, X, Y, \delta_{int}, \delta_{ext}, \delta_{conf}, \lambda, ta \rangle$$

$$S = \{0, 1, 0.1\};$$

$$X = \{0, 1\};$$

$$Y = \emptyset;$$

$$\delta_{int}(s) = s;$$

$$\delta_{ext}(s \in S, e, \{0\}) = 0; \delta_{ext}(s \in S, e, \{1\}) = 1; \delta_{ext}(s \in S, e, \{0, 1\}) = 0.1;$$

$$\delta_{conf}(s \in S, e, X^b) = \delta_{ext}(s \in S, e, X^b);$$

$$\lambda: \emptyset;$$

$$ta(0) = ta(1) = ta(0.1) = \infty.$$

STORAGE has three states: 0, 1 and 0.1 (with initial state: 0). The model changes its state according to the inputs received: when it receives 0, the state is set to 0 (independently from the current state and elapsed time); when it receives 1, the state is set to 1; and when it receives an input bag = {0,1}, the state is set to 0.1 (representing it received both value). The confluent function defines the same behavior as the external transition. The model is always passivated, the time advance is always set to infinity. Therefore, there are no outputs ( $\lambda: \emptyset$ ) and the internal transition (which will never execute) does not change the state.

$$\text{COUPLED} = \langle X^b, Y^b, D, \{M_i\}, \{I_i\}, \{Z_{ij}\} \rangle$$

$$X^b = Y^b = \emptyset;$$

$$D = \{1, 2\};$$

$$\{M_i\} = \{M_1 = \text{GENERATOR}, M_2 = \text{STORAGE}\};$$

$$\{I_i\} = \{I_{\text{GENERATOR}} = \text{STORAGE}\};$$

$$\{Z_{ij}\} = \{\text{GENERATOR} \rightarrow \text{STORAGE}\}.$$

COUPLED describes the structure of the top model. It does not have any inputs or outputs. The model is composed by two atomic models, GENERATOR and STORAGE. Outputs of GENERATOR are connected to inputs of STORAGE.

To execute this model, an instance of the abstract PDEVS simulator must be created. Figure 5 shows the structure of PDEVS abstract simulator for this specific example. This structure is composed of a root-coordinator, a coordinator, and two simulators. COORDINATOR controls COUPLED; SIMULATOR\_1 executes GENERATOR and SIMULATOR\_2 executes STORAGE.

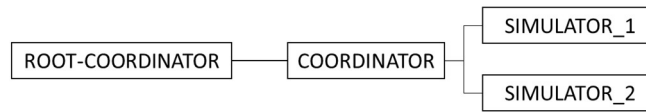


Figure 5: PDEVS abstract simulator for this example.

The simulation execution trace of this model according to the PDEVS simulation algorithm presented in (Chow et al. 1994) is shown in Figure 6, where we can see the interactions among the components. We set the simulation start time at 0. The initial state of both models is 0.

First, ROOT-COORDINATOR sets the initial simulation time to 0 and sends an initialization message to COORDINATOR (1), which transmits the message to SIMULATOR\_1 and SIMULATOR\_2 (2). These two simulators calculate  $ta$ ,  $tn$  and  $tl$  and report their time of next event  $tn$  to COORDINATOR (3), which

picks the first in its *event-list* (in this case,  $tn=1$ , as the SIMULATOR\_2 is passive). This value is sent to the ROOT-COORDINATOR, which updates the simulation time to 1 and starts a simulation cycle. To do so, it sends a *collect outputs* message  $(*, 1)$  to COORDINATOR (5), which updates its list of *imminent children* (IMM) and (6) sends  $*$ -messages to all children in IMM. Then, SIMULATOR\_1 runs the output function, whose value is sent to COORDINATOR (7), which updates the *receivers* set. Then it sends an *execute transition* message  $(x, 1)$  to every child in the *receivers* and IMM lists (8). It sends  $(\emptyset, 1)$  to SIMULATOR\_1 because it has no inputs, and  $(\{0\}, 1)$  to SIMULATOR\_2, because it receives the input bag  $\{0\}$  coming from the output of SIMULATOR\_1. Then, SIMULATOR\_1 runs the internal transition function and updates its state to 1 ( $s = \delta_{int}(0) = 1$ ). It also calculates the time advance of the new state ( $ta(1) = 0$ ), updates its  $tn$  and  $tl$  and report the time of next event  $tn$  to COORDINATOR (9). At the same time, SIMULATOR\_2 runs the external transition function with the input bag  $\{0\}$  and updates its state to 0 ( $\delta_{ext}(0, e, \{0\}) = 0$ ). It also calculates the time advance of the new state ( $ta(0) = \infty$ ), updates its  $tn$  and  $tl$  and report the time of next event  $tn$  to COORDINATOR (9), which picks the first in its *event-list* (in this case,  $tn=1$ , as the SIMULATOR\_2 is passive). This value is sent to the ROOT-COORDINATOR (10), which updates the simulation time to 1 and starts a simulation cycle. Note that a new simulation cycle starts without the simulation time advancing. The simulation time is still 1. To do so, it sends a *collect outputs* message  $(*, 1)$  to COORDINATOR (11). Steps (12) – (17) are a new simulation cycle like the one presented in steps (6)–(11). COORDINATOR updates its list of *imminent children* (IMM) (12) and sends  $*$ -messages to all

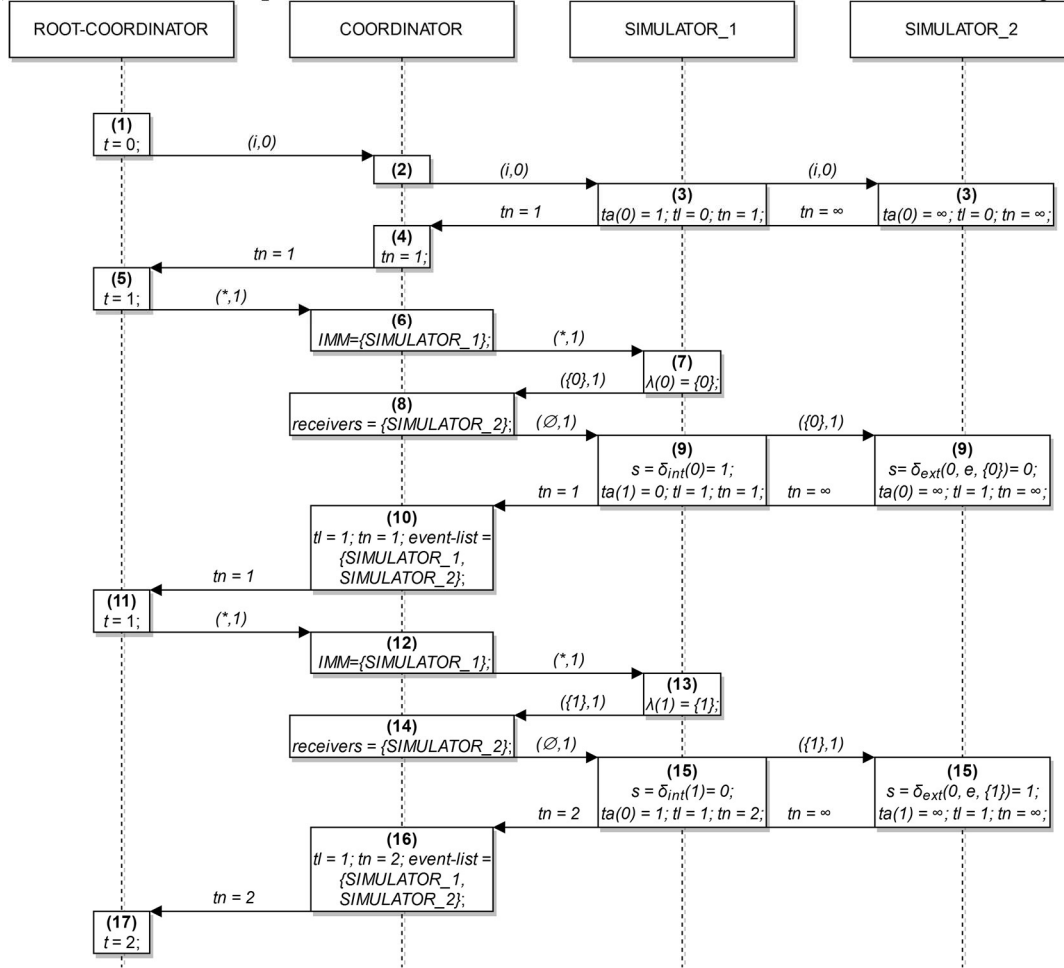


Figure 6: A PDEVS simulation protocol execution trace.

children in *IMM*. Then, *SIMULATOR\_1* runs the output function, whose value is sent to *COORDINATOR* (13), which updates the *receivers* set (14). Then it sends an *execute transition* message to every child in the *receivers* and *IMM* lists. It sends  $(\emptyset, 1)$  to *SIMULATOR\_1* because it has no inputs and a  $(\{1\}, 1)$  to *SIMULATOR\_2*, because it receives an input bag  $\{1\}$  coming from the output of *SIMULATOR\_1*. Then, *SIMULATOR\_1* runs the internal transition function and updates its state to 1 ( $s = \delta_{int}(1) = 0$ ). It also calculates the time advance of the new state ( $ta(0) = 1$ ), updates its *tn* and *tl* and report the time of next event *tn* to *COORDINATOR* (15). At the same time, *SIMULATOR\_2* runs the external transition function with the input bag  $\{1\}$  and updates its state to 1 ( $\delta_{ext}(0, e, \{1\}) = 1$ ). It also calculates the time advance of the new state ( $ta(1) = \infty$ ), updates its *tn* and *tl* and report the time of next event *tn* to *COORDINATOR* (15), which picks the first in its *event-list* (in this case,  $tn=2$ , as the *SIMULATOR\_2* is passive). This value is sent to the *ROOT-COORDINATOR* (16), which updates the simulation time to 2 and starts a simulation cycle (17). The simulation continues until the *tn* value of *COORDINATOR* is infinity or until the maximum simulation time is reached, whichever happens first.

In this execution trace we can see that *GENERATOR* produces 2 outputs at time 1:  $\{0\}$  (step 7) and  $\{1\}$ , (step 13). These outputs change the state twice on *STORAGE*. First, it changes to state 0 (step 9), and then, it changes to state 1 (step 15). However, as these outputs occur at the same moment (simulation time 1), a single output bag  $\{0, 1\}$  should have been produced by *GENERATOR* at time 1, which should generate a state change to 0.1 in *STORAGE*.

The issue in the PDEVS simulation protocol is that it handles time advance zero sequentially: events that occur at the same time are processed one at the time in different simulation cycles. Consequently, the result may not be the one desired, as in this example. This suggests that a modification is needed.

One solution to this problem may be to modify *GENERATOR* so it can output a single bag with  $\{0, 1\}$  value. For example, in this case *GENERATOR* may be modified to create the bag  $\{0, 1\}$  as the output for state 1 (i.e.  $\lambda(1) = \{0, 1\}$ ). However, this changes the semantics for this model, now the output for state 1 is not equal to the value of its state, as originally intended when it was designed. To achieve this, a new state should be included in the model, for example one called “0.1”, making it more complex. Therefore, this solution is not ideal: it introduces changes and makes the model more complex without achieving any benefit. It would be desirable to address this issue without modifying the models.

In this work, we propose a modification over the PDEVS simulation algorithm to solve this problem. We modify the algorithm in such a way that we generate complete output bags when there are states with time advance zero instead of handling them one at the time. Models will be able to generate several individual outputs at a specific simulation time, while guaranteeing that they will be transmitted together. In the next section, we detail the proposed algorithm.

## 4 PROPOSED SIMULATION ALGORITHM

The proposed PDEVS simulation algorithm is like the one presented in (Nutaro 2019) which follows (Chow et al. 1994). It includes simulators, coordinators, and a root-coordinator. The simulators are associated with atomic models and the coordinators to coupled models. The root-coordinator oversees the overall synchronization.

This simulation procedure is also defined by exchanging several types of messages between the components. These are messages for initialization (i), to compute output (\*) to execute a state transition (x) and send outputs (y). Three new messages have been added to the simulation procedure: (1) a message to notify the coordinator that the output bag from the simulator is not yet filled (*nf*), (2) a message to tell the simulator to update its state to be able to continue filling the bag (*su*), and (3) a message to notify the coordinator that the simulator is ready to continue filling the bag (*rcf*).

### 4.1 Abstract simulator

The new abstract simulator is shown in Figure 7. The modifications to the original simulator are underlined.

<pre> 1: Parallel-Devs-simulator 2: variables: 3:   parent //parent coordinator 4:   tl      //time of the last event 5:   tn      //time of the next event 6:   DEVS    //associated DEVS atomic model with 7:           //total state (s,e) 8:   y        //output message bag 9:   <u>sp</u>      //potential next state 10:  <u>tp</u>      //potential time advance 11: when receive i-message (i,t) at time t 12:   if t = tn then 13:     y = y + λ(s) 14:     <u>sp = δ<sub>int</sub>(s)</u> 15:     <u>tp = ta(s)</u> 16:   end if 17:   if tp = 0 then 18:     <u>send nf-message (nf,t) to parent coordinator</u> 19:   else 20:     send y-message(y,t) to parent coordinator 21:   end if </pre>	<pre> 21: when receive su-message (su,t) at time t 22:   if tp = 0 then 23:     <u>s = sp</u> 24:     <u>send rcf-message(rcf,t) to parent coordinator</u> 25:   else 26:     <u>error: bad synchronization</u> 27:   end if 28: when receive x-message (x,t) 29:   <u>clear y</u> 30:   if x = ∅ ∧ t = tn then 31:     s = δ<sub>int</sub>(s) 32:   else if x ≠ ∅ ∧ t = tn 33:     s = δ<sub>conf</sub>(s,x) 34:   else if x ≠ ∅ ∧ (tl ≤ t &lt; tn) 35:     e = t - tl 36:     s = δ<sub>ext</sub>(s,e,x) 37:   end if 38:   tl = t 39:   tn = tl + ta(s) 40: end Parallel-Devs-Simulator </pre>
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Figure 7: New simulator for PDEVS.

The changes in the abstract simulator are to ensure that all output messages generated by a simulator at the same simulation time are filled into a single output bag before they are transmitted to the coordinator. This new algorithm works in the following way: when an *\*-message* is received, if the time of the *\*-message* is equal to the simulator's next time, it adds the output ( $\lambda(s)$ ) to the message bag ( $y$ ). It also checks if the bag is ready or if there are more messages to be added. To do so, it calculates the next state of the model through an internal transition ( $sp$ ) and its time advance ( $tp$ ). If  $tp$  is not equal to zero, then the bag is full. It means, the simulator will not generate more outputs at the same simulation time. Therefore, the simulation continues as in the original version. The simulator sends a  $y$ -message to the parent coordinator. And if the simulator receives a  $su$ -message, a synchronization error occurred because  $tp$  is not equal to zero. If  $tp$  is equal to zero, there are more messages to be added to the output message bag ( $y$ ) before the simulation time advances. In that case, an  $nf$ -message is sent to the parent coordinator (meaning that the simulator has more messages to add to the bag). In that case, when a  $su$ -message is received, the simulator updates the state of the model from  $s$  to  $sp$ , and an  $rcf$ -message is sent to the parent coordinator (meaning that the simulator is ready to continue filling the bag). The rest of the simulator algorithm is the same as in the original version. We clean the output bag before executing a transition and re-use the value of  $sp$  to avoid calculating the internal transition function again.

<pre> 1: Parallel-Devs-coordinator 2: <b>variables:</b> 3:  <i>DEVN</i>=(<i>X</i>,<i>Y</i>,<i>D</i>,<i>M<sub>d</sub></i>},{<i>I<sub>d</sub></i>},{<i>Z<sub>i,d</sub></i>})//associated DEVS coupled model 4:  <i>parent</i>      //parent coordinator 5:  <i>tl</i>          //time of last event 6:  <i>tn</i>          //time of next event 7:  <i>event-list</i> //element list(<i>d</i>,<i>tn<sub>d</sub></i>)sorted by <i>tn<sub>d</sub></i> 8:  <i>IMM</i>         //list of imminent children 9:  <i>mail</i>        //output mail bag 10: <i>y<sub>parent</sub></i>      //output message bag to parent       //coordinator 11: {<i>y<sub>d</sub></i>}        //set of output message bags for       //each child <i>d</i> 12: <b>when</b> receive i-message (<i>i</i>,<i>t</i>) at time <i>t</i> 13: <b>for</b> <i>d</i> ∈ <i>D</i> <b>do</b> 14:   send i-message to child <i>d</i> 15: <b>end for</b> 16: sort <i>event-list</i> according to <i>tn<sub>d</sub></i> 17: <i>tl</i> = <i>max</i>{<i>tld</i>   <i>d</i> ∈ <i>D</i>} 18: <i>tn</i> = <i>min</i>{<i>tn<sub>d</sub></i>   <i>d</i> ∈ <i>D</i>} 19: <b>when</b> receive *-message (*,<i>t</i>) 20: <b>if</b> <i>t</i> ≠ <i>tn</i> <b>then</b> 21:   error: bad synchronization 22: <b>end if</b> 23: <i>IMM</i> = <i>min</i>(<i>event-list</i>) 24: <b>for</b> <i>r</i> ∈ <i>IMM</i> <b>do</b> 25:   send *-messages(*,<i>t</i>) to <i>r</i> 26: <b>end for</b> 27: <b>when</b> receive <i>nf</i>-message(<i>fn</i>,<i>t</i>) from <i>d</i> ∈ <i>IMM</i> 28:   send <i>su</i>-message(<i>su</i>,<i>t</i>) to <i>d</i> 29: <b>when</b> receive <i>rcf</i>-message (<i>rcf</i>,<i>t</i>) from <i>d</i> ∈ <i>IMM</i> 30:   send *-message(*,<i>t</i>) to <i>d</i> 31: <b>when</b> receive <i>x</i>-message(<i>x</i>,<i>t</i>) 32:   <b>if</b> not(<i>tl</i> ≤ <i>t</i> ≤ <i>tn</i>) <b>then</b> 33:     error: bad synchronization 34:   <b>end if</b> 35:   <i>receivers</i>={<i>r</i>   <i>r</i> ∈ <i>children</i>, <i>N</i> ∈ <i>I<sub>r</sub></i>, <i>Z<sub>N,r</sub></i>(<i>x</i>)≠∅} 36: <b>for</b> <i>r</i> in <i>receivers</i> <b>do</b> 37:   send <i>x</i>-messages(<i>Z<sub>N,r</sub></i>(<i>x</i>),<i>t</i>) with input value       <i>Z<sub>N,r</sub></i>(<i>x</i>) to <i>r</i> </pre>	<pre> 38: <b>end for</b> 39: <b>for</b> <i>r</i> ∈ <i>IMM</i> and not in <i>receivers</i> <b>do</b> 40:   send <i>x</i>-message (∅, <i>t</i>) to <i>r</i> 41: <b>end for</b> 42: sort <i>event-list</i> according to <i>tn<sub>d</sub></i> 43: <i>tl</i> = <i>t</i> 44: <i>tn</i> = <i>min</i> <i>tn<sub>d</sub></i>   <i>d</i> ∈ <i>D</i> 45: <b>when</b> receive <i>y</i>-message (<i>y<sub>d</sub></i>,<i>t</i>) with output <i>y<sub>d</sub></i>       from <i>d</i> 46:   <b>if</b> this is not the last <i>d</i> in <i>IMM</i> <b>then</b> 47:     add(<i>y<sub>d</sub></i>, <i>d</i>) to <i>mail</i> 48:     mark <i>d</i> as reporting 49:   <b>else if</b> this is the last <i>d</i> in <i>IMM</i> <b>then</b> 50:     <i>y<sub>parent</sub></i> = ∅ 51:   <b>end if</b> 52:   <b>for</b> <i>d</i> ∈ <i>I<sub>N</sub></i> <b>then</b> 53:     <b>if</b> <i>Z<sub>d,N</sub></i>(<i>y<sub>d</sub></i>) ≠ ∅ <b>then</b> 54:       add <i>y<sub>d</sub></i> to <i>y<sub>parent</sub></i> 55:     <b>end if</b> 56:   <b>end for</b> 57:   send <i>y</i>-message (<i>y<sub>parent</sub></i>, <i>t</i>) to parent 58:   <b>for</b> child <i>r</i>, <i>xr</i> = ∅ <b>do</b> 59:     <b>for</b> <i>d</i> such that <i>d</i> ∈ <i>I<sub>r</sub></i> <b>do</b> 60:       <b>if</b> <i>Z<sub>d,N</sub></i>(<i>y<sub>d</sub></i>) ≠ ∅ <b>then</b> 61:         add <i>y<sub>d</sub></i> to <i>y<sub>r</sub></i> 62:       <b>end if</b> 63:     <b>end for</b> 64:   <b>end for</b> 65:   <i>receivers</i> = {<i>r</i>   <i>r</i> ∈ <i>children</i>, <i>y<sub>r</sub></i> ≠ ∅} 66:   <b>for</b> <i>r</i> ∈ <i>receivers</i> <b>do</b> 67:     send <i>x</i>-messages (<i>y<sub>r</sub></i>,<i>t</i>) to <i>r</i> 68:   <b>end for</b> 69:   <b>for</b> <i>r</i> ∈ <i>IMM</i> and not in <i>receivers</i> <b>do</b> 70:     send <i>x</i>-messages (∅,<i>t</i>) to <i>r</i> 71:   <b>end for</b> 72:   <i>tl</i> = <i>t</i> 73:   <i>tn</i> = <i>min</i> <i>tn<sub>d</sub></i>   <i>d</i> ∈ <i>D</i> 74:   sort <i>event-list</i> according to <i>tn<sub>d</sub></i> 75: <b>end Parallel-Devs-coordinator</b> </pre>
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Figure 8: New coordinator for PDEVs.

## 4.2 Abstract coordinator

The implementation of the new abstract coordinator is presented in Figure 8. The coordinator now handles *nf-messages* and *rcf-messages* from imminent children. When an *nf-message* is received from an imminent child, the coordinator sends a *su-message* to that child to indicate that they can update the state and get ready to be able to continue filling the bag. Instead, when a *rcf-message* is received, the coordinator sends a \*-message to the children, so it can continue filling the bag.

## 4.3 Root coordinator

The root coordinator stays the same as the one proposed in (Chow et al., 1994), and explained in section 2.

## 5 EXECUTION TRACE WITH THE PROPOSED ALGORITHM

In this section, we show how our proposed PDEVs simulation protocol (see Section 4) works and what are the differences with the original one explained in section 3 through an example. To exemplify how the new

PDEVS Simulation Protocol works when a time advance zero occurs, we use the same model as the one presented in section 3 (see Figure 4).

To execute this model, an instance of the new abstract PDEVS simulator must be created. The structure of the abstract simulator remains the same as in Section 3: one root coordinator, a coordinator and two simulators (see Figure 5).

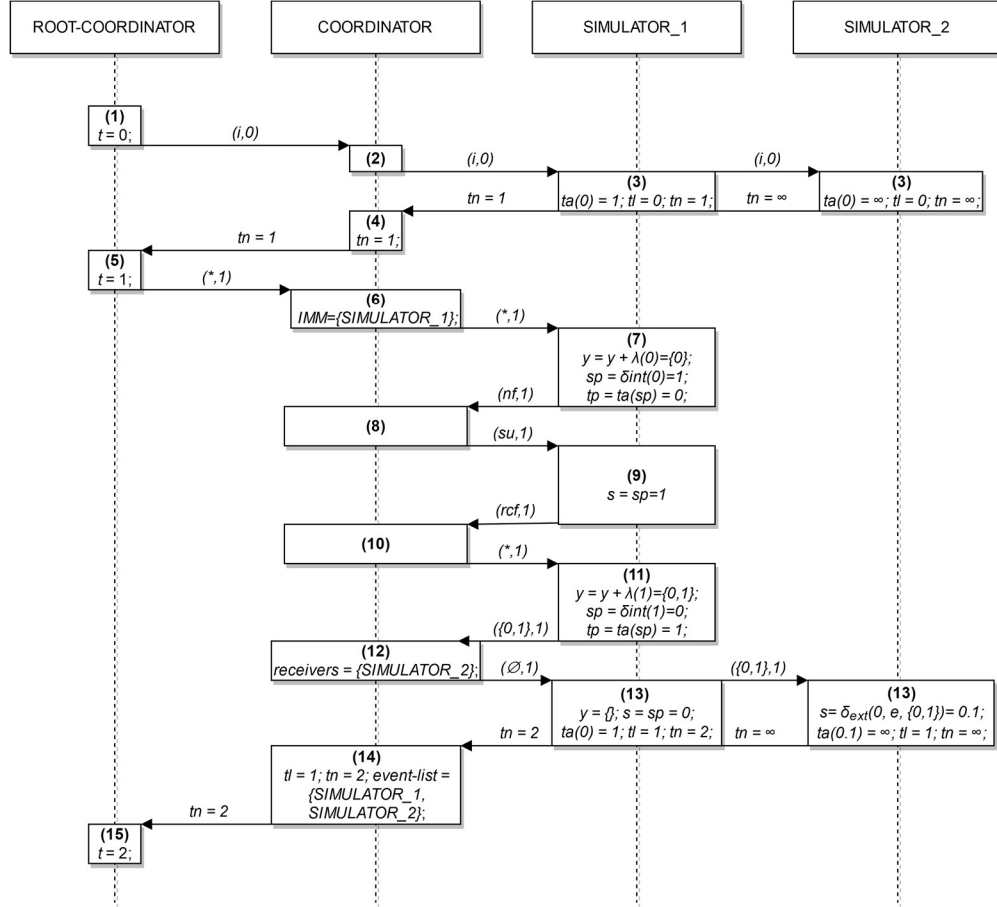


Figure 9: A new PDEVS simulation protocol execution trace.

The simulation execution trace of this model show in Figure 9, where we can see the interactions among the components. We set the simulation start time at 0. The initial state of both models is 0.

The simulation algorithm starts as we presented in section 3 until step (6), when COORDINATOR sends \*-messages to all children in *IMM*. Then, SIMULATOR\_1 runs the output function and instead of sending the *y*-message to COORDINATOR, SIMULATOR\_1 adds the value of the output function to its output bag and checks is the bag is full. To do so, it calculates the potential next state using the internal transition function ( $sp = \delta_{int}(0) = 1$ ) and the time advance associate to the potential state ( $tp = ta(sp) = ta(1) = 0$ ) (7). Because *tp* is equal to zero, it means that the output bag is not full. Therefore SIMULATOR\_1 send a *nf*-message to COORDINATOR. When COORDINATOR receives the *nf*-message, it sends a *su*-message to SIMULATOR\_1 to indicate it should update the state (9). Then, SIMULATOR\_1 updates its state with the potential state compute previously (10) and sends a *rcf*-message to COORDINATOR to indicate its ready to continue filling the bag. After this, COORDINATOR sends another *collect outputs* message (\*,1) to SIMULATOR\_1, which computes the output function and adds to its output bag and checks is the bag is full. To do so, it calculates the potential next state using the internal transition function ( $sp = \delta_{int}(1) = 0$ ) and the time advance associate to the potential state ( $tp = ta(sp) = ta(0) = 1$ ) (11). Because

tp is not zero, it means that the output bag is full. Therefore, SIMULATOR\_1 sends its output bag ( $\{0,1\},1$ ) to COORDINATOR, which updates the *receivers* set (12). Then it sends an *execute transition* message ( $x, 1$ ) to every child in the *receivers* and *IMM* lists. It sends ( $\emptyset,1$ ) to SIMULATOR\_1 because it has no inputs, and ( $\{0,1\},1$ ) to SIMULATOR\_2, because it receives the input bag  $\{0,1\}$  coming from the output of SIMULATOR\_1. Then, SIMULATOR\_1 updates its state ( $s$ ) using the value of the internal transition function already calculated in step (11) and updates its state to 0 ( $s = sp$ ). It also updates the time advance of the new state ( $ta = tp$ ), its  $tn$  and  $tl$  and reports the time of next event  $tn$  to COORDINATOR (13). At the same time, SIMULATOR\_2 runs the external transition function with the input bag  $\{0,1\}$  and updates its state to 0.1 ( $\delta_{ext}(0, e, \{0,1\}) = 0.1$ ). It also calculates the time advance of the new state ( $ta(0.1) = \infty$ ), updates its  $tn$  and  $tl$  and reports the time of next event  $tn$  to COORDINATOR (13), which picks the first in its *event-list* (in this case,  $tn=2$ , as the SIMULATOR\_2 is passive). This value is sent to the ROOT-COORDINATOR (14), which updates the simulation time to 2 and starts a simulation cycle (15). The simulation continues until the  $tn$  value of COORDINATOR is infinity or until the maximum simulation time is reached, whichever happens first.

In this execution trace we can see that GENERATOR produces 2 outputs at time 1:  $\{0\}$  (step 7) and  $\{1\}$ , (step 11). However, unlike the execution with the original PDEVs simulation protocol presented in Section 3.2 these outputs produce only one state change in STORAGE. A single output bag  $\{0,1\}$  is produced by GENERATOR at time 1, which generates a state change to 0.1 in STORAGE.

## 6 CONCLUSIONS AND FUTURE WORK

One of the advantages of DEVS is that it clearly separates modeling and simulation. However, when executing models that have time advances zero, the PDEVs simulation protocol handles the outputs sequentially. This imposes restrictions to the modeler, it should keep in mind how the model will be executed, making the modeling and simulation activities less independent from one another.

In this work, we propose a new algorithm that assures that all outputs produced by a sequence of time advances zero due to internal transitions are gather in a single output bag. With this idea, the modeler does not need to worry about how the interaction between components occurs. Simple component models using time advances zero can be defined and coupled together. When the model is executed, the simulation algorithm assures that all outputs produced at the same simulation time are send together. In models without time advance zero, this algorithm works exactly as the PDEVs simulation protocol. As future work we propose to implement this algorithm to make it available in a practical simulation tool.

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## **AUTHOR BIOGRAPHIES**

**CRISTINA RUIZ MARTIN** is Instructor at the Department of Systems and Computer Engineering at Carleton University. Her email address is [cristinaruizmartin@sce.carleton.ca](mailto:cristinaruizmartin@sce.carleton.ca).

**GUILLERMO G. TRABES** is a Ph.D. student in Electrical and Computer Engineering (Carleton University) and Computer Science (Universidad Nacional de San Luis). His email address is [guillermotrabes@sce.carleton.ca](mailto:guillermotrabes@sce.carleton.ca).

**GABRIEL A. WAINER** is Professor at the Department of Systems and Computer Engineering at Carleton University. He is a Fellow of the Society for Modeling and Simulation International (SCS). His email address is [gwainer@sce.carleton.ca](mailto:gwainer@sce.carleton.ca).