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Citation for published version (APA):

Zaitsev, D., Shmeleva, T., & Groote, J. F. (2019). Verification of hypertorus communication grids by infinite Petri nets and process algebra. *IEEE/CAA Journal of Automatica Sinica*, 6(3), 733-742. [8707130].
<https://doi.org/10.1109/JAS.2019.1911486>

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DOI:
[10.1109/JAS.2019.1911486](https://doi.org/10.1109/JAS.2019.1911486)

Document status and date:
Published: 01/05/2019

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

Please check the document version of this publication:

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Verification of Hypertorus Communication Grids by Infinite Petri Nets and Process Algebra

Dmitry A. Zaitsev, *Senior Member, IEEE*, Tatiana R. Shmeleva, and Jan Friso Groote

Abstract—A model of a hypertorus communication grid has been constructed in the form of an infinite Petri net. A grid cell represents either a packet switching device or a bioplast cell. A parametric expression is obtained to allow a finite specification of an infinite Petri net. To prove properties of an ideal communication protocol, we derive an infinite Diophantine system of equations from it, which is subsequently solved. Then we present the programs *htgen* and *ht-mcrl2-gen*, developed in the C language, which generate Petri net and process algebra models of a hypertorus with a given number of dimensions and grid size. These are the inputs for the respective modeling tools *Tina* and *mCRL2*, which provide model visualization, step simulation, state space generation and reduction, and structural analysis techniques. Benchmarks to compare the two approaches are obtained. An ad-hoc induction-like technique on invariants, obtained for a series of generated models, allows the calculation of a solution of the Diophantine system in a parametric form. It is proven that the basic solutions of the infinite system have been found and that the infinite Petri net is bounded and conservative. Some remarks regarding liveness and liveness enforcing techniques are also presented.

Index Terms—Computing grid, conservativeness, deadlock, hypertorus, infinite Petri nets, process algebra, systems biology.

I. INTRODUCTION

HYPERCUBE Petri net models [1]–[5] are suited for parallel and distributed computer systems [6], [7], computing grids [7], and systems biology [8]. The nature of a cell is different, but the structures of triangular, square, and hexagonal grids on a plane or a hypercube for a greater number of dimensions, look alike. Communication devices and cells have similar behavior: a computing or communication device transmits packets, while a bioplast cell transmits substances and impulses. In [6] it is stated that a torus network is the best topology for supercomputing and that using such networks decreases communication overhead considerably; the majority

of the top supercomputers, including IBM Blue Gene/Q, use a multidimensional torus.

Open grids with pending contact places represent auxiliary constructs. For modeling real-life systems, certain edge conditions are specified. Among various studied edge conditions [1]–[5] we choose a simple yet powerful condition that produces a hypertorus by closing the hypercube in each dimension and connecting its opposite edges. The (hyper)torus plays a key role in applications of nuclear physics [9], [10] and represents a convenient construct for modeling the human brain. It is a closed system where each cell has many connections. Greater numbers of dimensions allow one to represent more connections; the regularity of a structure gives the possibility of imposing any network of connections among cells similar to programmable logic matrices. The cell model could be easily replaced while the model structure remains the same.

The principles of generating Petri net models in the logical and graphical format of *Tina* [11], [12] are described in [2] for models of open square planar grids. In this article, we describe a program that generates hypertorus models in d -dimensional space [13]. Its applications allow one to obtain the basic solutions of infinite linear Diophantine systems and then prove properties of ideal communication protocols for hypertorus grids.

The results are double checked with hypertorus grid models using process algebra constructed in the modeling system *mCRL2* [14]–[16]. Obtained benchmarks are compared and the benefits of a combined approach are discussed.

The remainder of this paper is organized as follows: Section II defines a hypertorus grid model; Section III considers computation of place invariants of the grid model in a parametric form; Section IV describes a program *htgen* that is used for composing the parametric solutions of the infinite system of linear equations for calculating place invariants; in Section V a hypertorus grid model in *mCRL2* is constructed and a program *ht-mcrl2-gen* that generates these models is described; in Section VI, benchmarking is described, and the benchmarks obtained for *Tina* and *mCRL2* are compared.

II. COMPOSITION OF A HYPERTORUS GRID MODEL

A cell model [1]–[5] represents a packet switching device working in a full-duplex mode based on a store-and-forward principle. From a spatial point of view it is a unit-size hypercube in a d -dimensional space denoted as H_d that consists of an internal buffer of packets and ports situated on the facets of the hypercube, which correspond to the Von-Neumann neighborhood. Below we use the following notation

Manuscript received November 8, 2018; revised January 13, 2019; accepted January 20, 2019. This work was supported in part by NATO (ICS.NUKR.CLG982689). Recommended by Associate Editor MengChu Zhou. (Corresponding author: Dmitry A. Zaitsev.)

Citation: D. A. Zaitsev, T. R. Shmeleva, and J. F. Groote, "Verification of hypertorus communication grids by infinite petri nets and process algebra," *IEEE/CAA J. Autom. Sinica*, vol. 6, no. 3, pp. 733–742, May 2019.

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Digital Object Identifier 10.1109/JAS.2019.1911486

for variables. The first character ‘*p*’ means a place and the first character ‘*t*’ means a transition. The second character specifies whether it is an input (‘*i*’) or an output (‘*o*’), while the character ‘*b*’ indicates that it is an internal buffer. The third letter ‘*l*’ specifies the limitation on buffer capacity. The following expression completely specifies H_d .

$$\left(\left(\begin{array}{l} (to_{j,n} : pb_{j,n}, pol_{j,n} \rightarrow po_{j,n}, pbl), \\ (ti_{j,n,j',n'} : pi_{j,n}, pbl \rightarrow pb_{j',n'}, pil_{j,n}) \\ 1 \leq j \leq d, 1 \leq n \leq 2, \\ 1 \leq j' \leq d, 1 \leq n' \leq 2, (j', n') \neq (j, n). \end{array} \right) : \right) \quad (1)$$

In (1), the input places of a transition are listed to the left of the “ $\rightarrow$ ” symbol. Its output places are listed after the “ $\rightarrow$ ” symbol. For indexed elements, the ranges of the indices are specified using parameters. Equation (1) has a single parameter d equal to the number of dimensions.

Places $pb_{j,n}$ and pbl model the internal buffers and the limitation on its size, respectively; transitions $to_{j,n}$ specify the output tracts of ports while transitions $ti_{j,n,j',n'}$ specify the input tracts implementing the packet forwarding decision; contact places $po_{j,n}(pol_{j,n})$ and $pi_{j,n}(pil_{j,n})$ correspond to the port input and output buffers (limitation of their sizes), respectively. Ports, situated on the hypercube facet, are indexed by a pair of numbers j and n where j denotes the dimension the port facet is perpendicular to and n enumerates the corresponding two facets in the following way: value 1 corresponds to a facet which is closer to the origin and value 2 corresponds to a facet which is distant from the origin (on the coordinate j). We use a pair of indices j' and n' to specify the ports where a packet can be forwarded. Since the lower indices specify elements inside a cell and the upper indices specify the cells order within a grid, we use the multi-character notation of variables for clarity and compatibility with [1]–[5].

An example of a cell model for a 2-dimensional case is represented in Fig. 1. The grid composition is implemented via the merging of contact places of neighboring cells as described in [1]–[5]. An example grid obtained as a result of the composition for a 2-dimensional case is represented in Fig. 2.

A general hypertorus model in a d -dimensional space of size k is denoted as $HT_{d,k}$ and specified by expression (2) where an additional parameter k_j equals to the hypertorus size within dimension j . In software implementations we suppose for simplicity that $k_1 = k_2 = \dots = k_d = k$.

$$\left(\left(\begin{array}{l} (to_{j,1}^i : pb_{j,1}^i, pol_{j,1}^i \rightarrow po_{j,1}^i, pbl^i) \\ (ti_{j,1,j',n'}^i : pi_{j,1}^i, pbl^i \rightarrow pb_{j',n'}^i, pil_{j,1}^i) \\ (to_{j,2}^i : pb_{j,2}^i, pil_{j,1}^{xi(i,j)} \rightarrow pi_{j,1}^{xi(i,j)}, pbl^i) \\ (ti_{j,2,j',n'}^i : po_{j,1}^{xi(i,j)}, pbl^i \rightarrow pb_{j',n'}^i, pol_{j,1}^{xi(i,j)}) \\ \mathbf{i} = (i_1, \dots, i_d), 1 \leq i_j \leq k_j, \\ 1 \leq j \leq d, \\ 1 \leq j' \leq d, \\ 1 \leq n' \leq 2, (j', n') \neq (j, n). \end{array} \right) : \right), \quad (2)$$

$$xi(\mathbf{i}, j) = \mathbf{i}', \quad i'_l = \begin{cases} i_l, & l \neq j, \\ xij(i_l, j), & l = j. \end{cases}$$

$$xij(i, j) = \begin{cases} i + 1, & i < k_j, \\ 1, & i = k_j. \end{cases}$$

where its initial marking is specified by

$$\left(\left(\begin{array}{l} (c * pb_{j,n}^i, b * pbl^i) : 1 \leq n \leq 2, \\ (pil_{j,n}^i, pol_{j,n}^i) : n = 1 \\ \mathbf{i} = (i_1, \dots, i_d), 1 \leq i_j \leq k_j, 1 \leq j \leq d \end{array} \right) : \right) \quad (3)$$

Fig. 1. Model of a cell in H_2 .

Fig. 2. Composition of a 2-dimensional structure $HT_{2,2}$.

In the initial marking, there are c packets in each buffer section and the remaining available buffer size is equal to b . The notation is compatible with data formats of Tina [11], [12] where only nonzero magnitudes are listed and $v * p$ means that the value for place p equals to v , where the unit values are omitted.

Compared to hypercube models [2], [3], Equation (2) contains the following functions: function $xi(i,j)$ defines the index of the next cell in the Von-Neumann neighborhood with only one coordinate changed; function $xij(i,j)$ defines the next cell for the number j of the coordinate axis and supposes an increment for all values with exception of value k_j , for which it closes the (hyper) torus surface returning 1. Generalized neighborhoods [17] are considered as a future research direction.

III. ANALYSIS OF HYPERTORUS GRID MODEL

For finite Petri nets, which represent models of either artificial or natural systems, three basic properties are the most significant: boundedness, conservativeness, and liveness [18], [19]. A *live* Petri net never halts, and in any state, each of its transitions can be enabled after a finite number of transition firings. The marking of a *bounded* net is limited by a certain constant; a *conservative* net preserves the (weighted) number of tokens during the evolution of a net.

Two basic techniques are employed for the analysis of Petri nets [20]: 1) the generation of the complete state space represented with a reachability graph and 2) the solution of linear equations and inequalities. The first approach allows investigating all the properties for bounded Petri nets, but the state space grows exponentially. The second approach provides a more efficient way to solve certain tasks, especially in subclasses of Petri nets [21]. Two auxiliary techniques, named *decomposition* and *reduction*, can help one to deal with exponential complexity. Decomposition [20]–[23] divides a net into a few subnets, which allows for conclusions on the properties of the entire net based on properties of its subnets, and reduction compresses a net while preserving its properties [20], [24], [25].

In Fig. 3 and Fig. 4, we give two examples of a state space for a 2-dimensional case and a grid of size 1. In Fig. 3, we have only one token simulating a packet, and in Fig. 4 we have 4 tokens simulating packets. In both cases, the additional buffer size equals zero. For Fig. 3, we obtain the state space of 8 states and 16 transitions, which exhibits a cubic form. For Fig. 4, we obtain 192 states and 1,008 transitions and its graphical representation looks rather tangled. For analogous initial markings in a 3-D space, we obtain the following states/transitions pairs: 12/36 and 5336/60 588, respectively. Note that example grids contain a single square and cube; for a planar grid of size 2×2 , the number of states is estimated to be 10^{11} with Tina's experimental *sift* tool [11], [12]. Constructs for representing a state space of an infinite Petri net is considered as a future research direction.

Solving the systems of linear equations and inequalities is a more promising approach for demonstrating the advantages of parametric expressions. The simplest homogeneous systems are composed straight on the Petri net incidence matrix C [20]:

$$\bar{x} \cdot C = 0$$

to obtain the vector $\bar{x}$ of p -invariants and

$$C \cdot \bar{y} = 0$$

to obtain the vector $\bar{y}$ of t -invariants. A net, having a p -invariant whose components are all positive, possesses an important property, i.e., boundedness. A positive t -invariant is a necessary condition for a net to be reversible, i.e., able to return to its initial marking from any reachable marking.

Fig. 3. Examples of Petri nets state space ($d = 2$ and $k = 1$) for $pb_{1,1}^{1,1} = 1$.

Fig. 4. Examples of Petri nets state space ($d = 2$ and $k = 1$) for $pb_{j,n}^{1,1} = 1$, $1 \leq j \leq 2$, $1 \leq n \leq 2$.

Expression (2) describes a sparse matrix C on rows. Thus, a system for computing p -invariants (specified in a parametric form) is directly obtained on the expression, and its parametric solution is sought. Had we found its parametric solution, we could infer the model properties for any given parameter that allows a conclusion for the properties of infinite Petri nets. For $H_{d,k}$ specified by (2)–(3), the system and its parametric

solution are represented by (4) and (5), respectively.

$$\left\{ \begin{array}{l} -xpb_{j,1}^i - xpol_{j,1}^i + xpo_{j,1}^i + xpb_{j,1}^i = 0 \\ -xpi_{j,1}^i - xpb_{j,1}^i + xpb_{j,n'}^i + xpil_{j,1}^i = 0 \\ -xpb_{j,2}^i - xpi_{j,1}^{xi(i,j)} + xpi_{j,1}^{xi(i,j)} + xpb_{j,1}^i = 0 \\ -xpo_{j,1}^{xi(i,j)} - xpb_{j,1}^i + xpb_{j,n'}^i + xpol_{j,1}^{xi(i,j)} = 0 \\ \mathbf{i} = (i_1, \dots, i_d), 1 \leq i_j \leq k_j, \\ 1 \leq j \leq d, \\ 1 \leq j' \leq d, \\ 1 \leq n' \leq 2, (j', n') \neq (j, n). \end{array} \right. : \quad (4)$$

$$\left(\begin{array}{l} (pi_{j,1}^i, pil_{j,1}^i) : \mathbf{i} = (i_1, \dots, i_d), 1 \leq i_j \leq k_j, 1 \leq j \leq d, \\ (po_{j,1}^i, pol_{j,1}^i) : \mathbf{i} = (i_1, \dots, i_d), 1 \leq i_j \leq k_j, 1 \leq j \leq d, \\ (\{pb_{j,n}^i, pbl^i\} : 1 \leq j \leq d, 1 \leq n \leq 2), \\ \mathbf{i} = (i_1, \dots, i_d), 1 \leq i_j \leq k_j, \\ (\{pbl^i, pil_{j,1}^i, pol_{j,1}^i\} : \\ \mathbf{i} = (i_1, \dots, i_d), 1 \leq i_j \leq k_j, 1 \leq j \leq d) \\ (\{pb_{j,n}^i, pi_{j,1}^i, po_{j,1}^i\} : \\ \mathbf{i} = (i_1, \dots, i_d), 1 \leq i_j \leq k_j, 1 \leq j \leq d, 1 \leq n \leq 2) \end{array} \right) \quad (5)$$

The parametric system (4) is directly constructed on expression (2). The prefix “x” is added to denote the components of p -invariants. The specifics of system (4) follow from the fact that it is composed over a ring of integers. Moreover, its solutions are sought in a monoid of nonnegative integer numbers. Generally, there are no known methods to obtain a basic solution of (4). Using an ad-hoc technique on a series of models generated by the program htgen described in Section IV, we compose a parametric solution and then prove that it is a solution of the given system. For system (4), the composed solution is shown in (5).

Each of two first rows of (5) describes a few rows of a sparse matrix of basic solutions having only two nonzero (unitary) components. The third row represents a series of rows with a variable number of nonzero components. Each of the fourth and fifth row specifies a single row having a variable number (rather “big”) of nonzero components. Note that for the 2-dimensional case, (5) coincides with the expression obtained in [4], and it is accurate within the system of ports notations. For a plain case, a simpler clockwise enumeration of ports is applied in [4]. For a particular case when $d = 2$ and $k = 2$, the p -invariants obtained (generated) on (5) are listed in (6).

Note that there are a total of 22 vectors that coincide with the solutions calculated through Tina [11], [12].

Theorem 1: Equation (5) specifies solutions of (4).

Proof: We employ an exhaustive proof by substituting/inserting each row of the sparse matrix (5) into each parametric equation of (4). Here, we consider a case for the third row of (5):

$$\left\{ \begin{array}{l} -xpb_{j,1}^i + xpb_{j,1}^i = 0 \\ -xpb_{j,1}^i + xpb_{j,n'}^i = 0 \\ -xpb_{j,2}^i + xpb_{j,1}^i = 0 \\ -xpb_{j,1}^i + xpb_{j,n'}^i = 0 \end{array} \right. : \quad \begin{array}{l} \mathbf{i} = (i_1, \dots, i_d), 1 \leq i_j \leq k_j, \\ 1 \leq j \leq d, \\ 1 \leq j' \leq d, \\ 1 \leq n' \leq 2, (j', n') \neq (j, n). \end{array}$$

Because the third row of (5) contains nonnegative $xpb_{j,n}^i$ for all combinations of internal parameters j and n , we obtain

$-1 + 1 = 0$ in each equation. We proceed similarly with the rest of the vectors.

$$\begin{array}{l} (pi_{1,1}^{1,1}, pil_{1,1}^{1,1}), (pi_{1,1}^{1,2}, pil_{1,1}^{1,2}) \\ (pi_{1,1}^{2,1}, pil_{1,1}^{2,1}), (pi_{1,1}^{2,2}, pil_{1,1}^{2,2}) \\ (pi_{2,1}^{1,1}, pil_{2,1}^{1,1}), (pi_{2,1}^{1,2}, pil_{2,1}^{1,2}) \\ (pi_{2,1}^{2,1}, pil_{2,1}^{2,1}), (pi_{2,1}^{2,2}, pil_{2,1}^{2,2}) \\ (po_{1,1}^{1,1}, pol_{1,1}^{1,1}), (po_{1,1}^{1,2}, pol_{1,1}^{1,2}) \\ (po_{1,1}^{2,1}, pol_{1,1}^{2,1}), (po_{1,1}^{2,2}, pol_{1,1}^{2,2}) \\ (po_{2,1}^{1,1}, pol_{2,1}^{1,1}), (po_{2,1}^{1,2}, pol_{2,1}^{1,2}) \\ (po_{2,1}^{2,1}, pol_{2,1}^{2,1}), (po_{2,1}^{2,2}, pol_{2,1}^{2,2}) \\ (pb_{1,1}^{1,1}, pb_{1,1}^{1,2}, pb_{2,1}^{1,1}, pb_{2,1}^{1,2}, pbl^{1,1}) \\ (pb_{1,1}^{1,2}, pb_{1,1}^{2,1}, pb_{2,1}^{1,2}, pb_{2,1}^{2,1}, pbl^{1,2}) \\ (pb_{1,1}^{2,1}, pb_{1,1}^{2,2}, pb_{2,1}^{2,1}, pb_{2,1}^{2,2}, pbl^{2,1}) \\ (pb_{1,1}^{2,2}, pb_{1,1}^{1,2}, pb_{2,1}^{2,2}, pb_{2,1}^{1,2}, pbl^{2,2}) \\ (pbl^{1,1}, pbl^{1,2}, pbl^{2,1}, pbl^{2,2}, pil_{1,1}^{1,1}, pil_{1,1}^{1,2}, \\ pil_{1,1}^{2,1}, pil_{1,1}^{2,2}, pil_{2,1}^{1,1}, pil_{2,1}^{1,2}, pil_{2,1}^{2,1}, pil_{2,1}^{2,2}, \\ pol_{1,1}^{1,1}, pol_{1,1}^{1,2}, pol_{1,1}^{2,1}, pol_{1,1}^{2,2}, pol_{2,1}^{1,1}, pol_{2,1}^{1,2}, \\ pol_{2,1}^{2,1}, pol_{2,1}^{2,2}), \\ (pb_{1,1}^{1,1}, pb_{1,1}^{1,2}, pb_{1,1}^{2,1}, pb_{1,1}^{2,2}, pb_{1,1}^{1,2}, pb_{1,2}^{1,2}, pb_{1,2}^{2,2}, \\ pb_{2,1}^{1,1}, pb_{2,1}^{1,2}, pb_{2,1}^{2,1}, pb_{2,1}^{2,2}, pb_{2,2}^{1,1}, pb_{2,2}^{1,2}, pb_{2,2}^{2,1}, \\ pb_{2,2}^{2,2}, \\ pi_{1,1}^{1,1}, pi_{1,1}^{1,2}, pi_{1,1}^{2,1}, pi_{1,1}^{2,2}, pi_{2,1}^{1,1}, pi_{2,1}^{1,2}, pi_{2,1}^{2,1}, pi_{2,1}^{2,2}, \\ po_{1,1}^{1,1}, po_{1,1}^{1,2}, po_{1,1}^{2,1}, po_{1,1}^{2,2}, po_{2,1}^{1,1}, po_{2,1}^{1,2}, po_{2,1}^{2,1}, po_{2,1}^{2,2}) \end{array} \quad (6)$$

Theorem 2: $H_{d,k}$ is a bounded and conservative Petri net for any number of dimensions d , and sizes k .

To prove Theorem 2, we do not need a matrix of basic solutions for (4). We compose an invariant, namely, the sum of the fourth and fifth rows of (5), and have all components equal to the unit. To double check the technique, we note that $H_{d,k}$ is a priori bounded and safe because each of its transitions has the same number of incoming and outgoing arcs.

In the same way, using dual parametric expressions [1], a parametric system for computing t -invariants is composed. In a majority of studied cases, for rather small instances of Petri nets, an explosion of basic solutions is observed that hampers their parametric description. To deal with t -invariants and observe deadlocks for infinite Petri nets, auxiliary graphs are introduced and studied in [5].

T-invariance is a necessary condition of liveness of bounded nets. A *deadlock*, which occurs when no transition can fire, represents a negative property. A method to find and overcome deadlocks, called “liveness-enforcing,” is studied in [21], [25]–[29]. The technique is based on solving systems of equations and inequalities that can be easily composed in a parametric form based on the parametric representation of the incidence matrix.

IV. PROGRAM TO GENERATE HYPERTORUS PETRI NETS

As mentioned in Section III, basic methods of analyzing infinite Petri nets [1], [2] consist of solving linear systems of equations (inequalities) for finding place and transition invariants to prove properties of an ideal protocol. At present time, universal methods of solving infinite (parametric) Diophantine systems in nonnegative integer numbers are unknown. That is why our inductive ad-hoc approach is based on generating

a sequence of models of growing size, finding invariants for each model, and finally abstracting for generalizing a sequence of solutions in a parametric form. After this not completely formalized process, we prove that the obtained parametric matrix represents a basic solution of the infinite system as shown in Section III. To automate the process of composing models for different values of parameters, we need a program that allows us to avoid manual creation of models. Below, we describe such a program called *htgen* and its usage.

A. Description of Use

The program *htgen* generates a hypertorus Petri net model in the textual .net format of Tina [21] with a given number of dimensions d and the same size k on all dimensions. Additional parameters specify the initial marking. The program is written in the language ANSI C and compiled with the following command:

```
>gcc -o htgen htgen.c
```

The program *htgen* is run on the command line using the following command:

```
>htgen d k p b > ht_model.net
```

Here d specifies the number of dimensions, k specifies the hypertorus size in each dimension, p specifies the number of packets in each internal buffer of each cell, and b specifies the available size of the internal buffer for each cell. The resulting file *ht_model.net* is processed either in the integrated environment *nd* of Tina or using its separate modules such as *struct*, *tina*, and *sift* or plug-ins of Tina such as *Deborah* and *Adriana*. It could be exported as well in a few other formats common for the exchange of Petri net models.

B. The Output Format and the Principles of Operation

The textual format of time Petri nets in Tina [11], [12] specifies a Petri net with lines starting with the keyword “tr”

```
tr {t-name} {p-name}[*’<weight>],... ->
{p-name}[*’<weight>],...
```

and the initial marking of the Petri net is specified with lines starting with “pl”:

```
pl {p-name} (<marking>)
```

The fields in the lines starting with “tr” and “pl” directly correspond to the structure of the parametric expressions (2) and (3), respectively.

The operation of the program *htgen* consists of generating all the lines of (2) and (3) according to the index ranges given in the input parameters. Each place (p -) and transition (t -) includes the upper index in the d -dimensional grid and the lower index either of a port (surface) for output tracts or a pair of ports for an input tract. The port index is specified with pair (j, n) , where the number j defines the dimension and the number n defines the direction (1 for the origin and 2 for infinity).

While the port index represents a pair, the grid cell index is a collection having d components. We use the macros PUTINDEX and PUTINDEXNEXT. The macro PUTINDEX generates a variable length index of the current grid cell and the macro PUTINDEXNEXT generates a variable length index of the next grid cell. The indices of a cell are printed sequentially

after the cell with a dot separator, where first the lower index (indices) of a port (a pair of ports) and then the upper index of the grid cell are printed. The character ‘d’ is printed after the number indicating the dimension and the character ‘n’ is printed after the number for the direction. For instance “ti.d1.n1.d1.n2.1.3” corresponds to $t_{1,1,1,2}^{1,3}$.

C. The Description of the Data Structures and Macros

To generate a hypertorus with a given dimension d , the cell index i is dynamically allocated

```
i = (int *) malloc((d+1)* sizeof(int));
```

We start indexing directly from one but we allocate an extra index for zero which remains unused. To print the index of a current cell we use the following macro:

```
#define PUTINDEX {for(u=1; u<=d; u++)
printf("%.d", i[u] );}
```

The indices of each dimension are printed using a dot character as a separator. To print the index of the next cell we use the following macro:

```
#define PUTINDEXNEXT( r ) {for( u=1; u<=d; u++)
printf("%.d", (u!=(r)) ? i[u] :
(i[u]<k)? i[u]+1 : 1 );}
```

This macro encodes the torus composition rule: the next cell index is incremented if $i[u] < k$, and it is connected to the first cell if $i[u] = k$.

D. The Description of the Algorithm

The algorithm encodes expressions (2)–(3) which avoids the dependence of the variable in the loop on the actual number of dimensions when using d nested loops to enumerate all cells. Instead we consider the cell index as a d digit number in a radix system with radix $k+1$ without zero digits. We initialize the index i with the smallest value corresponding to all components equal to one:

```
for(j=1; j<=d; j++)i[j]=1;
```

At each pass of the main loop

```
while( loop ) {...
```

we print the model of the current cell and then calculate the next cell index by adding one to the lowest digit of the index and moving the carry to the left. In case this is impossible, when the maximal index having all components equal to k has been processed, the loop indicator *loop* is reset and the main loop is abandoned:

```
go = 1; j=d;
while(go){
(i[j])+++;
if(i[j]>k){if(j==1){loop=0; go=0;}
else {i[j]=1; j--;}
}
else go=0;}
```

The content of the model of the current cell is classified on elements bound to a facet and bound to the cell; there is only one vertex where the internal buffer size does not depend on the facet index, and it is generated as the last element as follows.

```
printf("pl {pbl}");
PUTINDEX;
```



```
printf("{} (%d)\n", b);
```

To enumerate all the ports of the current cell we use a loop over the dimension j

```
for(j=1; j<=d; j++){...}
```

and list explicitly two facets for directions 1 and 2.

At first, we generate lines for direction 1 using the macro PUTINDX because the indices of the ports in the direction of the origin coincide with the indices of the current cell. For the output tract, a transition “to.<j>d.ln.*” is generated. For the input tract, we use a double loop on the dimension v and the direction dir of the destination port, respectively; $2 \cdot d - 1$ transitions “ti.<j>d.ln.<v>d.<dir>n.*” are generated.

Then we proceed with lines for direction 2 in the same manner but use the macro PUTINDEXNEXT for contact places because they contain the next cell index. Note that, an input tract maps into the corresponding output tract of the next cell and vice versa.

E. Some Examples

The following command line:

```
>htgen 2 3 3 2 > ht2d3k3p2b.net
```

generates a hypertorus model of size 3 in a 2-dimensional space; each cell has 3 packets in each of its buffer section and the available size of the buffer equals 2.

Then we start module nd of the Tina toolbox [21] and load the model. To visualize the model, we choose the following sequence in the menu: “Edit—draw—neato”. The result is shown in Fig.5 for the 2-dimentional torus. Note that automatic visualization of the multidimensional models reflects the traces of a general structure and can be edited manually.

To watch the behavior of the model where we see tokens moving around, we choose the menu sequence: “Tools—stepper simulator—Rand”.

Moreover, within the Tina toolbox we can construct a state space of the model by using “reachability analysis” and we can calculate p - and t -invariants by using the tool for “structural analysis”.

For the analysis of a big model Tina offers a series of separate modules, for instance, the tool sift constructs a state space rather fast and the tool muse allows to query for the properties of the constructed state space.

To use other tools for Petri nets analysis, Tina exports nets in a few standard Petri net formats.

V. MODELING HYPERTORUS GRIDS BY PROCESS ALGEBRA

A motivation for modeling hypertorus grids with process algebra is the availability of efficient tools for protocols analysis. As it is shown in Section VI, modeling hypertorus grids in mCRL2 [14]–[16] brings better performance than applying one of the best tools for Petri nets—Tina [10], [12]. While we prove p - and t -invariance for any values of the grid size and dimension using the abstraction of infinite Petri nets, there is no known technique to prove liveness and the presence/absence of deadlocks. Using mCRL2 model-checking we can prove these properties for concrete values of parameters.

Fig. 5. Automatic visualization of the generated models in Tina of a 2-dimensional torus (ht2d3k3p2b.net).

mCRL2 [14], [15] is a formal specification language with an associated toolset which is based on the Algebra of Communicating Processes (ACP) extended to include data and time. The toolset can be used for modelling, validation and verification of concurrent systems and protocols. The toolset supports a collection of tools for linearization, simulation, state-space exploration and generation, and tools to optimize and analyze specifications. Moreover, state spaces can be manipulated, visualized and analyzed. A model consists of three basic parts for specification of actions (act), processes (proc), and initialization (init).

Let us consider a model of a 3×3 torus in a 2-dimensional space for a grid without buffers of ports. This is represented with the following listing:

```
act
in1, out1, in2, out2, in3, out3, in4, out4,
c13, c24, c31, c42: Nat#Nat;
map GridSize: Nat;
eqn GridSize=3;
map prev, next: Nat->Nat;
var n: Nat;
eqn prev(n)=if(n==1,GridSize, max(0,n-1));
next(n)=if(n==GridSize, 1, n+1);
proc
d(b1, b2, b3, b4, bl: Int, i, j: Nat)=
% output
((b1>0)->out1(prev(i), j).d(b1-1, b2, b3, b4, bl+1, i, j))+
((b2>0)->out2(i, prev(j)).d(b1, b2-1, b3, b4, bl+1, i, j))+
((b3>0)->out3(next(i), j).d(b1, b2, b3-1, b4, bl+1, i, j))+
((b4>0)->out4(i, next(j)).d(b1, b2, b3, b4-1, bl+1, i, j))+
% input & switching (nondeterministic)
((bl>0)->(
% from port 1
in1(i, j).d(b1, b2+1, b3, b4, bl-1, i, j)+
in1(i, j).d(b1, b2, b3+1, b4, bl-1, i, j)+
in1(i, j).d(b1, b2, b3, b4+1, bl-1, i, j)+
```

```

% from port 2
in2(i, j).d(b1+1, b2, b3, b4, bl-1, i, j)+
in2(i, j).d(b1, b2, b3+1, b4, bl-1, i, j)+
in2(i, j).d(b1, b2, b3, b4+1, bl-1, i, j)+
% from port 3
in3(i, j).d(b1+1, b2, b3, b4, bl-1, i, j)+
in3(i, j).d(b1, b2+1, b3, b4, bl-1, i, j)+
in3(i, j).d(b1, b2, b3, b4+1, bl-1, i, j)+
% from port 4
in4(i, j).d(b1+1, b2, b3, b4, bl-1, i, j)+
in4(i, j).d(b1, b2+1, b3, b4, bl-1, i, j)+
in4(i, j).d(b1, b2, b3+1, b4, bl-1, i, j)
));
init
allow({c13, c24, c31, c42},
comm({out1|in3 -> c13,
out2|in4 -> c24,
out3|in1 -> c31,
out4|in2 -> c42},
d(1, 0, 0, 0, 1, 1, 1)||
d(1, 0, 0, 0, 1, 1, 2)||
d(1, 0, 0, 0, 1, 1, 3)||
d(1, 0, 0, 0, 1, 2, 1)||
d(1, 0, 0, 0, 1, 2, 2)||
d(1, 0, 0, 0, 1, 2, 3)||
d(0, 0, 0, 0, 2, 3, 1)||
d(0, 0, 0, 0, 2, 3, 2)||
d(0, 0, 0, 0, 2, 3, 3)));
    
```

Basic actions are the input and output of a packet via one of the four ports, represented with `in1`, `out1`, `in2`, `out2`, `in3`, `out3`, `in4`, `out4` and the communications between adjacent ports of neighboring devices represented with `c13`, `c24`, `c31`, `c42`; note that the mentioned actions are indexed on the grid with a pair of natural indexes $\text{Nat}\#\text{Nat}$. A grid size is given as the mapping called `GridSize`. Then two functions `prev` and `next` are specified which return the number of the previous and the next node, respectively taking into consideration the fact that the opposite borders are closed.

As a basic process, a grid node d is specified describing its output and input separately; the parameters `b1`, `b2`, `b3`, `b4` and `bl` specify sections of the internal buffer and its current size, respectively while variables `i` and `j` give the node location within the grid. When a packet is output via port k , the node issues the corresponding action `outk`, which decrements the corresponding buffers section size b_k , and increments the buffer length `bl`. The packet input is more sophisticated because it is combined with a nondeterministic forwarding decision, and the corresponding action for input from port k is represented `k` is an index.

The initialization section with `ink(i, j)` specifies the allowed actions and the communication between neighboring nodes; for instance, the notation “`out1|in3 -> c13`” means that output via port 1 and input via port 3 of the neighboring node results in the communication `c13`. Note that the indices of actions are calculated by the functions `prev` and `next`. Then an explicit parallel composition of all participating processes follows. The last pair of indices specifies the position of the process in the

grid while the first 5 indices specify the initial state of the output buffers of each grid process.

The model has been analysed with the `mCRL2` tools. It functions completely in accordance with the behavior of the corresponding Petri net model [30] shown in Fig. 6.

Fig. 6. Model of the 3×3 grid in 2-dimensional space without ports' buffers.

In the same way as described in Section IV, a generator `ht-mcrl2-gen` of hypertorus grid models in `mCRL2` has been developed [13]; it is supplied with a generator of the corresponding Petri net model as well.

Mutual automatic transformations of a Petri net and `mCRL2` models represent a future work direction.

VI. BENCHMARKS FOR STATE SPACE ANALYSIS AND FINDING DEADLOCKS WITH TINA AND MCRL2

Thorough analysis of the benchmarks results revealed that it is useful to employ both Petri nets and process algebra analysis techniques. Two systems have been chosen as representatives of the corresponding classes: Tina for Petri nets as a winner of the Model-Checking Contest [31] and `mCRL2` [14], [15] for process algebra. We use simplified models without buffers of ports as studied in Section V.

Three tests have been implemented on series of models with increasing dimension and size:

- T1) The construction of a complete state space;
- T2) A state space query — to check liveness and check boundedness;
- T3) “on-the-fly” search of the first deadlock.

Note that `mCRL2` implements a very powerful highway search [16] technique. We use a Dell Inspiron 15, Series 500 laptop with an Intel Core i5-5200U 2.2 GHz processor (2 cores) and 8 Gigabytes of RAM. The required script commands are represented in Table I. The obtained benchmarks shown in Fig. 7 acknowledge the considerable advantages of `mCRL2`.

TABLE I
COMMAND LINES FOR TESTS

Test	System	Command lines
T1	Tina	>sift -R \$1.ndr
	mCRL2	>mcr122lps -v \$1.mcr12 \$1.lps
T2	Tina	>selt \$1.ktz \$2.ltl
		>lps2pbes \$1.lps -c -f\$2.mcf \$1_\$1.pbes
	mCRL2	>pbessolve -v
		-evidence-file=\$1_\$2_counter_example.lps -f\$1.lps -s2 -rjitty \$1_\$2.pbes
T3	Tina	>sift -R -df -dead \$1.ndr
	mCRL2	> lps2lts -D -vrjitty -todo-max=2 \$1.lps -t1

Fig. 7. Benchmarks (in times of slow-down).

Within the command lines the parameter indicated by “\$1” specifies the model file name, while the parameter indicated by “\$2” specifies a file containing a query on the state space of the model. The state space of a Petri net is represented by its reachability graph [20] and stored as a Kripke transition system in binary format “.ktz”; queries are written in the linear time temporal logic notation (LTL) in a file with extension “.ltl”.

For mCRL2 we have the following file formats: a linear process specification “.lps” that is a symbolic representations of a state space for mCRL2 models; a labelled transition system “.lts” is used for visualization and export; a modal μ -calculus formula “.mcf” specifies queries; parameterized Boolean equation systems “.pbes” specifies the model state space integrated with a query. Note that mCRL2 offers a nice 3D utility *ltsview* for state space visualization; an example of the state space visualization of *ht2d2k1p2b.mcr12* is shown in Fig. 8; a “helmet” with “belts” allows us to observe deadlocks as “bids”. Moreover, when a negative answer is obtained, the first counter-example is stored and can be visualized as well in 2D visualization program *ltsgraph*.

The queries to check liveness for Tina are formulated in LTL as follows:

```

[]<>{ti_1,1^1,1}\
[]<>{ti_1,2^1,1}\
...
[]<>{ti_2,2^2,2};

```

The queries in mCRL2 have the following form as modal μ -calculus formulas:

```

([true*]forall x,y:Nat.val(x<=2 && y<=2) ==>
<true*.exists d:Direction.c1n1t1n2(x,y,d)>true)&&
([true*]forall x,y:Nat.val(x<=2 && y<=2) ==>
<true*.exists d:Direction.c1n2t1n1(x,y,d)>true)&&
([true*]forall x,y:Nat.val(x<=2 && y<=2) ==>
<true*.exists d:Direction.c2n1t2n2(x,y,d)>true)&&
([true*]forall x,y:Nat.val(x<=2 && y<=2) ==>
<true*.exists d:Direction.c2n2t2n1(x,y,d)>true)&& true

```

The benchmarks show that mCRL2 takes more time to build the state space. We consider a state space as a labelled transition system which is used for exchange with other systems, and when building an “.lps” file, which is used to generate systems of equations to evaluate queries, it runs about hundred times faster than Tina. When implementing state space queries, and especially when finding the first deadlock, mCRL2 also runs considerably faster.

Thus, we recommend using both approaches because of their mutually complementing nature.

Fig. 8. Visualization of *ht2d2k1p2b.mcr12* state space with *ltsview*.

VII. CONCLUSION

A hypertorus communication grid is specified by an infinite Petri net. Inductive composition of p- and t-invariants gives a uniform solution in a parametric form to draw conclusions on infinite nets such as boundedness, conservativeness and consistency for any number of dimensions and any size of grid. Some remarks regarding liveness and liveness enforcing are presented.

The developed programs *htgen* and *ht-mcr12-gen* automatically generate Petri net and process algebra models with a hypertorus grid structure. The models have been analyzed with Tina and mCRL2, and the obtained benchmarks have been compared. The results show certain benefits of mCRL2 for finding deadlocks while Tina is faster for state space queries. This justifies the application of both approaches.

Large-size Petri net and process algebra models with known properties provide a testset for model-checking software. Applications in systems biology, artificial intelligence, and thermonuclear physics are foreseen and should be sought.

ACKNOWLEDGMENT

The authors thank the Fulbright Program and Prof. MengChu Zhou for the opportunity to present infinite Petri nets at a dedicated seminar in NJIT on October 11, 2017, by the first author.

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