Annotated Bibliography on Stochastic Petri Nets*

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Abstract

An annotated bibliography on stochastic Petri nets is given.

1 Definition

Originally, no notion of time was included in the definition of Petri nets and their use was limited to the study of the logical (qualitative) properties of systems. Their application to the analysis of real systems soon made clear the necessity of incorporating time specifications in the definition of the formalism to make it useful for the assessment of the performance (quantitative evaluation) of systems. Several authors proposed the association of time with the nodes of the models described with the Petri net formalism. Among these first proposals are worth mentioning those due to Noe and Nutt [172], Ramchandany [175], Merlin and Farber [165].

The idea of associating a random delay with the firing of the transitions was independently proposed by several authors [48, 169, 170, 184] and led to the definition of Stochastic Petri Nets (SPN) [117, 168] in which a Markov chain that is isomorphic to the state space of the net can be defined starting from the time specifications of the model. Alternative definitions of timed Petri nets associated with underlying stochastic processes are also due to [190, 176, 192].

The use of Stochastic Petri Nets for the performance analysis of interesting problems coming mostly from the area of computer architecture, led to the definition of Generalized Stochastic Petri Nets (GSPN) in which the transitions may be of two different types (timed and immediate) depending on whether a delay is specified for their firing or not [14]. Subsequently, Extended Stochastic Petri Nets were proposed in which the most important additional feature is represented by the presence of probabilistic arcs that upon firing of a transition may deposit tokens on subsets of its output set depending on a probability distribution [111]. Similar ideas are also contained in the Stochastic Activity Nets [166] that have been developed for the evaluation of systems affected by failures.

Trying to understand the deep implications that the extensions proposed by these last models have on the qualitative as well as quantitative properties of this generalized formalism,

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several papers have been published in which different aspects of the problem have been discussed [5, 3, 10, 7, 49, 73, 98]. The current definition of the GSPN formalism is contained in [86] and characterizes a modelling tool that is now well understood and well established.

Dealing with increasingly complex models has led several researchers to propose additional extensions of the basic stochastic Petri net formalism including the idea of colored tokens (Colored Stochastic Petri Nets - CSPN) [191] and of controlling transition firings by means of boolean expressions introduced in the models at the moment of their specification (Predicate/Transition Stochastic Petri Nets - P/TSPN) [159, 160]. In order to keep under control the growth of the complexity of the stochastic process underlying these models and to obtain a modelling formalism that is well suited for the representation of highly symmetrical systems, some restrictions on the specification of the colors of the tokens and of the functions that are used for their manipulation have been introduced in the definition of CSPN, leading to the proposal of Well Formed Stochastic Petri Nets that are today one of the most used modelling tools for the high-level description of complex systems [113, 81, 82, 85].

2 Numerical Solution

In the early proposals of the SPN modelling technique, the Markovian numerical analysis based on the construction of the Reachability Graph was adopted as the standard analysis tool [12, 90, 110, 102, 179, 122]. The technique is relatively easy to implement and to use if properly embedded into a tool with a good graphic interface that allows the user to ignore the mathematical details of the technique and concentrate on the examination of the performance results represented at the net level [167, 89].

Unfortunately the application of the technique is severely limited by the memory requirements of the Reachability Graph computation algorithm and the complexity of the numerical solution of the Markov chain. Early attempts to address the size problem include the idea of using approximate hybrid solutions exploiting computationally efficient algorithms based on product form queueing networks [41, 42, 43]. The technique has been subsequently applied also in [56] and related to hierarchical model decomposition in the framework of colored net models [55].

Another point of interest in the case of GSPN models comprising immediate transitions is the elimination of the *vanishing* states (the ones in which the model spends zero time due to the enabling of immediate transitions). Earlier algorithms performed this elimination globally [14, 97, 96]. A time decomposition approach was proposed in [24]. On the fly elimination based on static identification of extended conflict sets where proposed in [39] and implemented in [94] yielding substantial advantage in terms of memory space for models with large numbers of vanishing states. In general, the idea of static structural analysis of GSPN models to compute properties [86] that can be exploited at run time to reduce the complexity of the Reachability Graph enumeration algorithm [92] is the key for the success of the GreatSPN tool in its present form [94]. For the transient analysis, the *randomization* algorithm has proven to be superior to other algorithms previously used [161].

In the case of colored Petri net models, intrinsic symmetries can be exploited to reduce the cost and complexity of the numerical solution algorithms [191, 160, 83, 68]. In particular, lumping techniques can be automatically exploited in the case of *well-formed* net models

[112, 81, 82]. Prototype implementations of the technique [87] have already proven the tremendous gain that can be obtained in case of highly symmetric models [85].

Another way of extending the feasibility of numerical analysis for SPNs and GSPNs yielding a huge state space is to resort to parallel processing. In [70] a first attempt to use a massively parallel SIMD architecture for the generation of the Reachability Graph of GSPNs is described. One order of magnitude gain in the number of states that can be handled is claimed for a Connection Machine CM-2 with respect to powerful workstations, so that models with several millions of states can be analyzed. Kronecker algebra is used in [108, 107] to guide the implementation of a distributed version of the Markovian solution on Transputer based MIMD architectures.

The numerical analysis of open (i.e., unbounded) SPN models has been addressed in [120], where a technique is proposed in the case of SPNs with a single unbounded place. An original matrix method for closed SPN models has been proposed in [118] as an alternative to the usual Markovian numerical approach. Its viability in terms of CPU time and memory requirements with respect to the usual approach has not been demonstrated yet, however.

3 Product Form Results

Product form results for the equilibrium distribution of stochastic Petri nets have been derived first for some special cases [6, 91, 118] and subsequently for a few classes of stochastic Petri nets by analogy with results for queueing networks (Baskett *et al.* [46], Gordon and Newell [128], Jackson [141], Kelly [147], Serfozo [182], Van Dijk [186], Whittle [189]). These results are closely related but not equivalent due to the incorporation of structural properties (e.g., T-invariants) in the product form results for stochastic Petri nets. Similar to the results for queueing networks, a product form stochastic Petri net offers enormous computational advantages.

Product form results for stochastic Petri nets can be separated into three classes. The first set of results covers Petri nets in which in each transition a single token can move from one place to another. The second set of results allows multiple tokens to move in each transition. The equilibrium distribution in these results can usually be presented as a product over the places of the Petri net. The third set of results covers Petri nets for which the equilibrium distribution is a product over subnetworks.

Li and Woodside [155] present product form results for *state machines*, the equivalent for queueing networks in the Petri net formalism, and for *serial-parallel* Petri nets, obtained by adding places to a state machine such that the underlying Markov chain remains isomorphic to the Markov chain for the state machine. Lazar and Robertazzi [153], [152], [178] obtain product forms for *safe* stochastic Petri nets that are comprised of *task sequences sharing common buffers*. These results require the state space of the underlying Markov chain to be a multidimensional toroidal manifold. These results are extended and formalized by Frosch [126], [124], [125]. The framework of Frosch is that of *synchronized systems of sequential processes*: state machines that share buffer places. The evolution of these nets resembles the evolution of state machines.

The Petri net equivalent of batch routing queueing networks is analyzed by Henderson *et al.* [134], [137]. In these nets multiple tokens are involved in each transition. Boucherie and

Sereno [51] show that these Petri nets can be characterized via *minimal closed support T-invariants.* Coleman *et al.* [101] provide sufficient conditions for the equilibrium distribution to be a product of Jackson-type (a product over places).

The Petri nets of Henderson *et al.* and Frosch are mainly disjoint classes of nets that share state machines only. A comparison between these classes is given by Donatelli and Sereno [106]. Boucherie and Sereno [52] extend and unify these two classes via the framework of batch routing queueing networks with state-dependent routing (Boucherie and van Dijk [53]). This generalization incorporates inhibitor arcs in the product form formalism, and allows general marking dependent firing rates, and marking dependent enabling of transitions (as long as the product form conditions are satisfied).

Petri nets for which the equilibrium distribution can be expressed as a *product over subnetworks* are analyzed by Boucherie [50], Henderson and Lucic [132], and Li and Georganas [158]. Boucherie [50] characterizes the product form via independence arguments for *competing Markov chains* representing Petri nets that are synchronized via buffer places. Henderson and Lucic [132] and Li and Georganas [158] use their product over subnets to obtain computational schemes related to aggregation of subnets.

The normalization constant for product form Petri nets is computed in Coleman [100], via a recursion in the number of places, and in Coleman *et al.* [101], Sereno and Balbo [180] via a recursion in the number of tokens (convolution algorithm) as well as in the number of places (Mean Value Analysis algorithm) [181]. The theoretical basis of this last approach is proposed in [36].

4 Bounds

There are numerous techniques for deriving bounds in stochastic Petri nets.

A first approach consists in the computation of insensitive (i.e. valid for all distribution functions) upper and lower bounds for the performance indices of timed Petri nets, based on linear programming techniques, net p-invariants, and Little's law. This approach was followed by Campos, Chiola and Silva in [63], [64], [62], [66] and [59]. This technique can be improved when something is known on the distribution of the activities as shown in [57] and [60]. It can also be extended to the case of well-formed colored Petri nets [80].

A second one is based on the derivation of upper and lower bounds for the conditional token probabilities in a subnet of a stochastic Petri net, from probabilistic arguments. This technique can be used to bound the error due to aggregation and time scale decomposition of nets (it is applicable to systems containing activities the durations of which differ by several orders of magnitude). This approach was followed by Campos, Silva and coauthors in [140].

A third technique consists in using stochastic graph representations of the net of interest in order to derive bounds. This was done by Rajsbaum in [174] in order to derive upper and lower bounds for the throughput of stochastic marked graphs with exponential, independent, and identically distributed random firing times. For marked graphs, other approaches based on stochastic recursions were developed by Baccelli and Liu in [31] using convex ordering and by Baccelli and Konstantopoulos using large deviations [30].

5 Stability

A first line of research concerns the computation of saturation conditions for particular classes of stochastic Petri nets with exponential and independent random times. The first papers on the matter were by Florin and Natkin [121], [119]. See also the paper by Campos and Silva [58]. Necessary and sufficient saturation conditions for stochastic Petri nets with general distributions, were also derived in some particular cases using techniques from stochastic processes (in particular, martingales theory) by Campos, Plo and San Miguel [61], [129], and by Baccelli, Bambos, and Walrand [34].

The approach by recursive equations which was developed for stochastic marked graphs by Baccelli [35] and for nets with switching by Baccelli, Cohen and Gaujal [33], allows for a complete analysis of stability (see the book by Baccelli, Cohen, Olsder and Quadrat [32] for marked graphs and the paper by Baccelli and Gaujal for free choice nets [29]). The technique also allows one to determine coupling times as shown in [151].

6 Analytical Results

Outside product form results, the main analytical results are based on the $(\max, +)$ approach. This approach was first used for deterministic marked graphs by Cohen, Dubois, Quadrat and Viot in [99], where the periodic regimes of event graphs are understood as spectral properties of matrices in this algebra. The extension to stochastic marked graphs was considered in [35]. A classification of the stationary regimes and necessary and sufficient conditions for their uniqueness was proposed by Mairesse in [163, 162]. A Markov chain analysis based on this representation was considered by Olsder, Resing, de Vries, Keane and Hooghiemstra in [173] and by Jean-Marie [142]. A survey and a bibliography on this approach can be found in the book by Baccelli, Cohen, Olsder and Quadrat [32].

7 Approximations

There is a large number of approximation techniques for stochastic Petri nets:

- Flow equivalent approximation techniques [144];
- Iterative approximation techniques for subclasses of stochastic Petri nets, based on decomposition and aggregation [156, 148, 149, 146, 65, 104, 145, 157];
- Iterative approximation techniques for subclasses of stochastic Petri nets, based on independence or near-independence of the underlying Markov chain (orthogonal concepts to decomposability and near-decomposability) [95];
- Approximative aggregation techniques for hierarchical well-formed colored nets, based on the regular structure of the generator matrix of the underlying MC [55, 54, 123].

8 Discrete Event Simulation

Simulation was one of the earliest techniques proposed for the analysis of timed Petri net models [172]. It was introduced as a viable, practical way of dealing with time extensions that do not allow for exact numerical analysis [111, 130, 131].

In another approach, simulation was seen as the alternative to Markovian analysis in case of models with huge state space that prevents numerical solution on computer systems due to memory shortage [90, 89]. In this case efficiency is a crucial issue in order to handle large models not amenable to other analysis techniques. The idea was then pursued to try and exploit preliminary structural analysis to improve the efficiency of the simulation engine for SPN models [92, 37, 94, 93].

The next step has been the exploitation of model symmetries naturally described by the Well-formed Colored net formalism to speed-up simulation as well as numerical solution [87]. This approach led to the introduction of the concept of *symbolic* simulation for colored nets [84, 79]. According to this technique the average length of the list of scheduled events is kept smaller by scheduling only the first event per equivalence class up to a symmetric permutation of basic colors.

In case of large SPN models an intuitive way of speeding up the simulation is to apply classical *distributed simulation* techniques to a static partition of the model [127]. Both the conservative [72] and the optimistic [143] methods can be adapted to the simulation of SPNs [185, 171, 25, 114]. Also in this case the exploitation of statically precomputed structural properties seems to be the key for improving the performance and obtaining real speedup compared to sequential simulation [76, 74, 75]. In some particular cases such as for example Marked Graphs the gain can be dramatic [115]. A new distributed simulation protocol with intermediate characteristics with respect to the conservative and the optimistic ones that dynamically exploits lookahead information computed based on structural net properties has been proposed in the SPN framework [78]. Its implementation on the Connection Machine CM-5 is currently in progress [77].

Different simulation methods based on the recursive equation approach were recently derived by Baccelli and Canales in [28]. This method allows for a SIMD simulation of Event Graphs, and yields significant speed-up (up to three orders of magnitude when executed on a CM 2). More on this technique can be found in the thesis of M. Canales [67].

9 Applications

The use of stochastic Petri nets for the evaluation of interesting systems is reported in numerous papers that can be found in the proceedings of many international conferences and in important international journals. The application fields in which SPNs have proven to be successful are listed in [9, 8] where some simple examples of models analyzed with this technique can also be found. An exhaustive list of references of this type is difficult to produce, but some papers are mentioned in the rest of this section to point out the type of applications for which the use of SPNs turned out to be important.

The interconnection structure of both loosely and tightly coupled multiprocessor systems has been widely studied with the help of SPNs [15, 13, 16, 2, 17, 11, 20, 69, 71, 1, 27, 85].

SPNs have also been employed for the evaluation of strategies in the use of these complex systems [109, 183], for the analysis of configurations comprising clusters of computers [139], and for the analysis of specific architectural features such as the Floating Point Unit of a particular computer [47].

The problem of writing reliable and efficient concurrent software has been studied with the help of SPNs showing that qualitative and quantitative analysis of specific algorithms can be performed by means of the same model [40] and that the analysis of concurrent software can be done with this technique to identify first the exact structure of the application and to subsequently allow the efficient allocation of processes on the computational nodes of a parallel architecture [103, 45, 44, 116].

Another important field of application is that of communication systems where several communication protocols have been analyzed by means of SPN models [105, 18, 19, 138, 21, 22, 88, 150].

Flexible Manufacturing Systems have also been studied with the help of SPNs showing that a formalism and a technique originally developed for the analysis of parallel and distributed computing systems can be conveniently employed also in application fields that are apparently quite different, but that present instead quite a lot of commonality [23, 38, 154, 187, 164].

Finally SPNs have been found useful in the analysis of systems affected by failures as it is shown in [4, 26].

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