

Regenerative Simulation of Stochastic Petri Nets with Discrete and Continuous Timing

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Abstract

We present a regenerative simulation method applicable to a special class of non-Markovian stochastic Petri net (SPN) that may be useful in practice for constructing and solving performance models. Introduced in [1], this special SPN is called a phased delay Petri net (PDPN) and was conceived to allow efficient numerical analysis while increasing the modeling fidelity. The PDPN permits phase-type firing delays in both discrete and continuous time simultaneously in the same model. However, exact numerical analysis requires that the discrete-time transitions be synchronized when active. We propose here, instead, a new regenerative simulation technique that offers efficient analysis of PDPNs where numerical solution by exact means or other (known) types of regenerative simulation is too difficult.

1. Introduction

As far as we know, simulation of phase-type models has not been specifically addressed before in the literature—not surprisingly, since phase-type distributions are typically introduced to allow an exact numerical solution. One might ask: Why simulate models with phase-type probability distributions when completely general distributions could be sampled instead? Well, regenerative simulation of PDPNs is an interesting idea for at least two reasons. First, simulating a PDPN is easy and efficient, as only exponential random variables and uniform random variables between zero and one are needed; the former are used to determine the time until the next phase-change event in continuous time (this time is a constant τ for discrete-time delays), the latter are used to select the next phase from the stochastic transition matrix associated with each phase-type distribution. The second reason is that, unlike general SPNs, PDPNs possess properties that aid the identification of hidden regenerative structures and easier determination of regeneration times.

2. Background

We adopt the standard SPN definitions: a bipartite graph with two finite sets of nodes, places, P , and transitions, T , which are connected by directed arcs. Places can contain tokens and the marking $M \in \mathbb{N}^{|P|}$ denotes the number of tokens in each place. Marking changes occur when an enabled transition fires, possibly after delaying a (finite, random) amount of time, thereby removing tokens from input places and depositing tokens in output places according to the arc multiplicities. We assume that the transition selected to fire is the one with the minimum remaining firing time (RFT) over all enabled transitions.

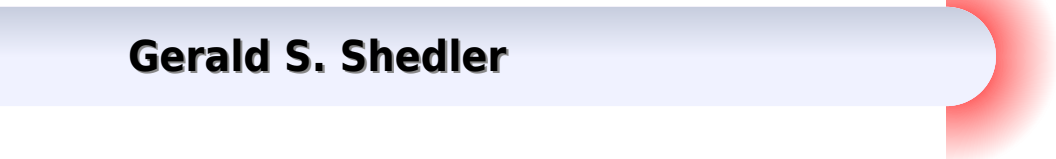
The marking process, $\{M(\theta) : \theta \geq 0\}$, observes the marking evolution over time. This gives rise to an underlying stochastic process amenable to mathematical analysis. Among the most convenient stochastic processes are the discrete-time Markov chain (DTMC), which results when firing delays are geometrically distributed, and the continuous-time Markov chain (CTMC), which results when firing delays are exponentially distributed. When the applicability of these Markovian models to more complex and realistic systems is questionable, other extensions attempt to incorporate non-Markovian behavior. However, the complexity of exact solutions to non-Markovian processes oftentimes limits the practical usefulness to problems with small dimensions unless simulation is employed.

A phase-type random variable is defined as the time to absorption of a given Markov chain with at least one absorbing state. We let `ph_int` and `ph_real` refer to phase-type random variables (or distributions) in discrete and continuous time, respectively. An absorbing CTMC (DTMC) is used to define a `ph_real` (`ph_int`) distribution, which includes initial state probabilities to be used when sampling the distribution. We let T_{real} denote the set of `ph_real` transitions and T_{int} , the set of `ph_int` transitions. The set T_{zero} contains the immediate transitions with zero firing delays, and $T = T_{\text{real}} \cup T_{\text{int}} \cup T_{\text{zero}}$.

In general, the state of an SPN model is the current

Regenerative Stochastic Simulation

Gerald S. Shedler



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Regenerative Stochastic Simulation Gerald S. Shedler, 1993 Discrete event simulations Regenerative stochastic processes Regenerative simulation Networks of queues Passage times Simulations with simultaneous events Limit theorems for stochastic processes Random number generation *Regenerative Stochastic Simulation: Discrete Event Systems* International Business Machines Corporation. Research Division, Gerald S. Shedler, 1990 *Regenerative Stochastic Simulation: the Generalized Semi-Markov Process Model* International Business Machines Corporation. Research Division, G. S. Shedler, 1991 **Regenerative Stochastic Simulation** G.S. Shedler, An Introduction to the Regenerative Method for Simulation Analysis M. A. Crane, A. J. Lemoine, 1977 The purpose of this report is to provide an introduction to the regenerative method for simulation analysis The simulations are simulations of stochastic systems i.e systems with random elements The regenerative approach leads to a statistical methodology for analyzing the output of those simulations which have the property of starting afresh probabilistically from time to time The class of such simulations is very large and very important including simulations of a broad variety of queues and queueing networks inventory systems inspection maintenance and repair operations and numerous other situations **Regenerative Stochastic Simulation: Simultaneous Trigger Events** G. S. Shedler, 1992 **Introduction to Discrete Event Systems** Christos G. Cassandras, Stéphane Lafortune, 2021-11-11 This unique textbook comprehensively introduces the field of discrete event systems offering a breadth of coverage that makes the material accessible to readers of varied backgrounds The book emphasizes a unified modeling framework that transcends specific application areas linking the following topics in a coherent manner language and automata theory supervisory control Petri net theory Markov chains and queueing theory discrete event simulation and concurrent estimation techniques Topics and features detailed treatment of automata and language theory in the context of discrete event systems including application to state estimation and diagnosis comprehensive coverage of centralized and decentralized supervisory control of partially observed systems timed models including timed automata and hybrid automata stochastic models for discrete event systems and controlled Markov chains discrete event simulation an introduction to stochastic hybrid systems sensitivity analysis and optimization of discrete event and hybrid systems new in the third edition opacity properties enhanced coverage of supervisory control overview of latest software tools This proven textbook is essential to advanced level students and researchers in a variety of disciplines where the study of discrete event systems is relevant control communications computer engineering computer science manufacturing engineering transportation networks operations research and industrial engineering Christos G Cassandras is Distinguished Professor of Engineering Professor of Systems Engineering and Professor of Electrical and Computer Engineering at Boston University St phane Lafortune is Professor of Electrical Engineering and Computer Science at the University of Michigan Ann Arbor ACM Transactions on Modeling and Computer Simulation ,2001 **Regeneration**

and Networks of Queues Gerald S. Shedler, 2012-12-06 Networks of queues arise frequently as models for a wide variety of congestion phenomena Discrete event simulation is often the only available means for studying the behavior of complex networks and many such simulations are non Markovian in the sense that the underlying stochastic process cannot be represented as a continuous time Markov chain with countable state space Based on representation of the underlying stochastic process of the simulation as a generalized semi Markov process this book develops probabilistic and statistical methods for discrete event simulation of networks of queues The emphasis is on the use of underlying regenerative stochastic process structure for the design of simulation experiments and the analysis of simulation output The most obvious methodological advantage of simulation is that in principle it is applicable to stochastic systems of arbitrary complexity In practice however it is often a decidedly nontrivial matter to obtain from a simulation information that is both useful and accurate and to obtain it in an efficient manner These difficulties arise primarily from the inherent variability in a stochastic system and it is necessary to seek theoretically sound and computationally efficient methods for carrying out the simulation Apart from implementation considerations important concerns for simulation relate to efficient methods for generating sample paths of the underlying stochastic process the design of simulation experiments and the analysis of simulation output **Hybrid Systems:**

Computation and Control Alberto Bemporad, Antonio Bicchi, Giorgio C Buttazzo, 2007-03-20 This book constitutes the refereed proceedings of the 10th International Conference on Hybrid Systems Computation and Control HSCC 2007 held in Pisa Italy in April 2007 The 44 revised full papers and 39 revised short papers presented together with the abstracts of 3 keynote talks were carefully reviewed and selected from 167 submissions Among the topics addressed are models of heterogeneous systems computability and complexity issues real time computing and control embedded and resource aware control control and estimation over wireless networks tools for analysis verification control and design programming languages support and implementation applications including automotive communication networks avionics energy systems transportation networks biology and other sciences manufacturing and robotics

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