

Lei Lei
Chuang Lin
Zhangdui Zhong

Stochastic Petri Nets for Wireless Networks

SpringerBriefs in Electrical and Computer Engineering

More information about this series at <http://www.springer.com/series/10059>

Lei Lei • Chuang Lin • Zhangdui Zhong

Stochastic Petri Nets for Wireless Networks

 Springer

Lei Lei
State Key Laboratory of Rail
Traffic Control and Safety
Beijing Jiaotong University
Beijing, China

Chuang Lin
Department of Computer Science
and Technology
Tsinghua University
Beijing, China

Zhangdui Zhong
School of Computer
and Information Technology
Beijing Jiaotong University
Beijing, China

ISSN 2191-8112 ISSN 2191-8120 (electronic)
SpringerBriefs in Electrical and Computer Engineering
ISBN 978-3-319-16882-1 ISBN 978-3-319-16883-8 (eBook)
DOI 10.1007/978-3-319-16883-8

Library of Congress Control Number: 2015937432

Springer Cham Heidelberg New York Dordrecht London
© The Author(s) 2015

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Recommended by Xuemin (Sherman) Shen

Preface

Stochastic Petri Nets (SPNs), introduced in 1980, are a modeling formalism that can be conveniently used for the performance and reliability evaluation of discrete event systems. They admit a graphical representation that is well suited to top-down and bottom-up modeling of complex systems, and present a very straightforward mapping between events in the SPN model and events in the underlying Markov process. Although SPNs have become a useful tool for researchers in computer science, they are unknown to most wireless researchers and are not widely used to model wireless communication systems. On the other hand, the next-generation wireless networks such as the 5th Generation (5G) cellular systems will become increasingly complex in order to support for an increasingly diverse set of services, applications, and users—all with extremely diverging performance requirements. Since SPNs are found to be powerful in modeling performance of computer systems with a wealth of numerical solution techniques, it is very interesting to explore their applicability in wireless systems. This book was motivated by a desire to bridge the gap between the research on SPN modeling formalism and on the performance modeling of wireless networks.

In this book, we present our research results on applying SPNs to the performance evaluation of wireless networks under bursty traffic, in terms of typical Quality-of-Service (QoS) performance metrics such as mean throughput, average delay, packet dropping probability, etc. In the first chapter, we introduce the key motivations, challenges, and state-of-the-art research on using SPNs for cross-layer performance analysis in wireless networks. In Chap. 2, we first introduce the SPN basics, and then focus on two powerful techniques in SPNs to deal with the well-known state space explosion problem: (1) model decomposition and iteration; (2) model aggregation using Stochastic High-Level Petri Nets (SHLPNs). We apply the first technique to the performance analysis of opportunistic scheduling and Device-to-Device (D2D) communications with full frequency reuse between D2D links in Chaps. 3 and 4, respectively. The above two scenarios show two typical radio resource sharing paradigms in wireless networks: orthogonal sharing by scheduling and non-orthogonal sharing by frequency reuse. We show that SPNs can provide an intuitive and efficient way in modeling the multiuser wireless system,

especially facilitating the inclusion of different resource sharing paradigms between wireless links. Moreover, the original complex model whose state space grows exponentially with the number of users can be decomposed into multiple single user subsystems, and iteration methods can be used for performance approximation. In Chap. 5, we apply the second technique to formulate a wireless channel model for Orthogonal Frequency Division Multiplexing (OFDM) multi-carrier systems with SHLPN formalism in order to simplify the cross-layer performance analysis of modern wireless systems. Compared with existing Finite State Markov Channel (FSMC) model whose state space grows exponentially with the number of OFDM subchannels, our proposed SHLPN model uses state aggregation technique to deal with this problem. Closed-form expressions to calculate the transition probabilities among the compound markings of the SHLPN model are provided. When applied to derive the performance measures for OFDM system, the SHLPN model can accurately capture the correlated time-varying nature of wireless channels. We believe the example applications of SPNs to wireless networks and related findings will reveal useful insights for the design of radio resource management algorithms and spur a new line of thinking for the performance evaluation of future wireless networks.

Beijing, China

Lei Lei
Chuang Lin
Zhangdui Zhong

Acknowledgements

The authors would like to acknowledge the support of the NSFC (Projects No. 61272168, No. U1334202, and No. 61472199), the State Key Laboratory of Rail Traffic Control and Safety in Beijing Jiaotong University (No. RCS2014ZT10), and the Key Grant Project of Chinese Ministry of Education (No. 313006). Thanks also are due to the Master candidates: Miss Qingyun Hao and Mr. Huijian Wang for their contribution of editing work.

A very special thanks to Prof. Xuemin (Sherman) Shen, the SpringerBriefs Series Editor on Wireless Communications. This book would not be possible without his kind support during the process. Thanks also to the Springer Editors and Staff, all of whom have been exceedingly helpful throughout the production of this book.

Contents

1	Introduction	1
1.1	Cross-Layer Performance Analysis of Wireless Networks Using Stochastic Models	1
1.2	Motivations and Challenges on Using SPNs for Performance Evaluation	3
1.3	Related Works on SPNs for Wireless Networks	4
1.3.1	Ad Hoc Networks	4
1.3.2	Cellular Networks	5
1.3.3	Multi-hop Wireless Networks	5
	References	6
2	Stochastic Petri Nets	9
2.1	SPN Basics	9
2.2	Model Decomposition and Iteration Technique	12
2.3	Stochastic High-Level Petri Nets	15
	References	18
3	Performance Analysis of Opportunistic Schedulers Using SPNs	19
3.1	Packet Level Performance Analysis of Opportunistic Schedulers	19
3.2	The DSPN Model Formulation	21
3.2.1	The M/MMDP/1/K Queuing System	21
3.2.2	The DSPN Model	22
3.2.3	Scheduling Strategies	23
3.3	Model Solution and Performance Analysis	25
3.3.1	Single User System	25
3.3.2	Model Decomposition and Iteration	27
3.4	Numerical Results	33
3.5	Summary	36
	References	39

- 4 Performance Analysis of Device-to-Device Communications with Dynamic Interference Using SPNs** 41
 - 4.1 Packet Level Performance Analysis of D2D Communications 41
 - 4.2 The Coupled Processor Queueing System 44
 - 4.3 Steady-State Solution of the Queueing System 48
 - 4.3.1 Transition Probability of the Queue State 50
 - 4.3.2 Transition Probability of the Server State 50
 - 4.3.3 Steady-State Probability of Markov Chain 58
 - 4.4 Model Decomposition and Performance Approximation Using DSPNs 58
 - 4.4.1 The DSPN Model 58
 - 4.4.2 Model Decomposition and Iteration 60
 - 4.5 Numerical Results 62
 - 4.6 Summary 66
 - References 76
- 5 Packet Level Wireless Channel Model for OFDM System Using SHLPNs** 79
 - 5.1 Packet Level Wireless Channel Model 79
 - 5.2 SHLPN Model of OFDM Wireless Channel 81
 - 5.2.1 SPN Model 81
 - 5.2.2 SHLPN Model 83
 - 5.3 Example Application to Cross-Layer Performance
 - Analysis of Cellular Downlink 89
 - 5.3.1 Model Description 89
 - 5.3.2 Numerical Results 91
 - 5.4 Summary 93
 - References 96
- 6 Conclusions and Outlook** 99
 - 6.1 Conclusions 99
 - 6.2 Outlook 100
 - References 101

Acronym

3G	3rd-Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
AMC	Adaptive Modulation and Coding
BS	Base Station
CA	Channel-Aware
CAC	Call Admission Control
CDMA	Code Division Multiple Access
CPN	Colored Petri Net
CQA	Channel/Queue-Aware
CR	Cognitive Radio
CTMC	Continuous-Time Markov Chain
D2D	Device-to-Device
DCA	Dynamic Channel Allocation
DCF	Distributed Coordination Function
DEDS	Discrete Event Dynamic Systems
DSPN	Deterministic and Stochastic Petri Net
DTMC	Discrete-Time Markov Chain
DTSPN	Discrete Time Stochastic Petri Net
FSMC	Finite State Markov Channel
FR	Full Reuse
GE	Gilbert-Elliot
GSPN	Generalized Stochastic Petri Net
HLPN	High-Level Petri Net
HSPDA	High Speed Downlink Packet Access
ISI	Inter-Symbol Interference
LCR	Level-Crossing Rate
LTE	Long Term Evolution
M2M	Machine-to-Machine
MAC	Medium Access Control

MC	Markov Chain
MDP	Markov Decision Process
MDPN	Markov Decision Petri Net
MMDP	Markov Modulated Deterministic Process
MIMO	Multiple-Input Multiple-Output
M-QAM	M-ary Quadrature Amplitude Modulation
NRT	Non-Realtime
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OS	Opportunistic Scheduling
PF	Proportional Fair
PN	Petri Net
QA	Queue-Aware
QoS	Quality-of-Service
RR	Round-Robin
RT	Realtime
SHLPN	Stochastic High-Level Petri Net
SINR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
SPN	Stochastic Petri Net
SRN	Stochastic Reward Net
SWN	Stochastic Well-Formed Petri Net
TDMA	Time Division Multiple Access
UE	User Equipment
UMTS	Universal Mobile Telecommunications System