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Stochastic Petri Nets for Wireless Networks

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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.

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Contents

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