Randall Berry · Eytan Modiano · Murtaza Zafer

Energy–Efficient Scheduling under Delay Constraints for Wireless Networks

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Energy-Efficient Scheduling Under Delay Constraints for Wireless Networks Randall Berry,Eytan Modiano,Murtaza Zafer,2012-10 Provides a comprehensive study of dynamic rate control for energy minimization under packet delay constraints It presents several formulations and approaches adopted in the literature ranging from discrete time formulations and dynamic programming based solutions to continuous time approaches utilizing ideas from network calculus and stochastic optimal control theory   Energy-Efficient Scheduling Under Delay Constraints for Wireless Networks Randal Berry,Eytan Modiano,Murtaza Zafer,2012 Packet delay and energy consumption are important considerations in wireless and sensor networks as these metrics directly affect the quality of service of the application and the resource consumption of the network especially for a rapidly growing class of real time applications that impose strict restrictions on packet delays Dynamic rate control is a novel technique for adapting the transmission rate of wireless devices almost in real time to opportunistically exploit time varying channel conditions as well as changing traffic patterns Since power consumption is not a linear function of the rate and varies significantly with the channel conditions adapting the rate has significant benefits in minimizing energy consumption These benefits have prompted significant research in developing algorithms for achieving optimal rate adaptation while satisfying quality of service requirements In this book we provide a comprehensive study of dynamic rate control for energy minimization under packet delay constraints We present several formulations and approaches adopted in the literature ranging from discrete time formulations and dynamic programming based solutions to continuous time approaches utilizing ideas from network calculus and stochastic optimal control theory The goal of this book is to expose the reader to the important problem of wireless data transmission with delay constraints and to the rich set of tools developed in recent years to address it Table of Contents Introduction Transmission Rate Adaptation under Deadline Constraints Average Delay Constraints   **Energy-Efficient Scheduling under Delay Constraints for Wireless Networks** Randal Berry,Eytan Modiano,Murtaza Zafer,2022-05-31 Packet delay and energy consumption are important considerations in wireless and sensor networks as these metrics directly affect the quality of service of the application and the resource consumption of the network especially for a rapidly growing class of real time applications that impose strict restrictions on packet delays Dynamic rate control is a novel technique for adapting the transmission rate of wireless devices almost in real time to opportunistically exploit time varying channel conditions as well as changing traffic patterns Since power consumption is not a linear function of the rate and varies significantly with the channel conditions adapting the rate has significant benefits in minimizing energy consumption These benefits have prompted significant research in developing algorithms for achieving optimal rate adaptation while satisfying quality of service requirements In this book we provide a comprehensive study of dynamic rate control for energy minimization under packet delay constraints We present several formulations and approaches adopted in the literature ranging from discrete time formulations and dynamic programming

based solutions to continuous time approaches utilizing ideas from network calculus and stochastic optimal control theory The goal of this book is to expose the reader to the important problem of wireless data transmission with delay constraints and to the rich set of tools developed in recent years to address it Table of Contents Introduction Transmission Rate Adaptation under Deadline Constraints Average Delay Constraints *Age of Information* Yin Sun,Igor Kadota,Rajat Talak,Eytan Modiano,2022-06-01 Information usually has the highest value when it is fresh For example real time knowledge about the location orientation and speed of motor vehicles is imperative in autonomous driving and the access to timely information about stock prices and interest rate movements is essential for developing trading strategies on the stock market The Age of Information AoI concept together with its recent extensions provides a means of quantifying the freshness of information and an opportunity to improve the performance of real time systems and networks Recent research advances on AoI suggest that many well known design principles of traditional data networks for e g providing high throughput and low delay need to be re examined for enhancing information freshness in rapidly emerging real time applications This book provides a suite of analytical tools and insightful results on the generation of information update packets at the source nodes and the design of network protocols forwarding the packets to their destinations The book also points out interesting connections between AoI concept and information theory signal processing and control theory which are worthy of future investigation *Wireless Network Pricing* Jianwei Huang,Lin Gao,2022-06-01 Today s wireless communications and networking practices are tightly coupled with economic considerations to the extent that it is almost impossible to make a sound technology choice without understanding the corresponding economic implications This book aims at providing a foundational introduction on how microeconomics and pricing theory in particular can help us to understand and build better wireless networks The book can be used as lecture notes for a course in the field of network economics or a reference book for wireless engineers and applied economists to understand how pricing mechanisms influence the fast growing modern wireless industry This book first covers the basics of wireless communication technologies and microeconomics before going in depth about several pricing models and their wireless applications The pricing models include social optimal pricing monopoly pricing price differentiation oligopoly pricing and network externalities supported by introductory discussions of convex optimization and game theory The wireless applications include wireless video streaming service provider competitions cellular usage based pricing network partial price differentiation wireless spectrum leasing distributed power control and cellular technology upgrade More information related to the book including references slides and videos can be found at ncel ie cuhk edu hk content wireless network pricing *Diffusion Source Localization in Large Networks* Lei Ying,Kai Zhu,2022-05-31 Diffusion processes in large networks have been used to model many real world phenomena including how rumors spread on the Internet epidemics among human beings emotional contagion through social networks and even gene regulatory processes Fundamental estimation principles and efficient algorithms for locating diffusion sources

can answer a wide range of important questions such as identifying the source of a widely spread rumor on online social networks This book provides an overview of recent progress on source localization in large networks focusing on theoretical principles and fundamental limits The book covers both discrete time diffusion models and continuous time diffusion models For discrete time diffusion models the book focuses on the Jordan infection center for continuous time diffusion models it focuses on the rumor center Most theoretical results on source localization are based on these two types of estimators or their variants This book also includes algorithms that leverage partial time information for source localization and a brief discussion of interesting unresolved problems in this area   Advances in Multi-Channel Resource Allocation Bo Ji,Xiaojun Lin,Ness B. Shroff,2022-05-31 The last decade has seen an unprecedented growth in the demand for wireless services These services are fueled by applications that often require not only high data rates but also very low latency to function as desired However as wireless networks grow and support increasingly large numbers of users these control algorithms must also incur only low complexity in order to be implemented in practice Therefore there is a pressing need to develop wireless control algorithms that can achieve both high throughput and low delay but with low complexity operations While these three performance metrics i e throughput delay and complexity are widely acknowledged as being among the most important for modern wireless networks existing approaches often have had to sacrifice a subset of them in order to optimize the others leading to wireless resource allocation algorithms that either suffer poor performance or are difficult to implement In contrast the recent results presented in this book demonstrate that by cleverly taking advantage of multiple physical or virtual channels one can develop new low complexity algorithms that attain both provably high throughput and provably low delay The book covers both the intra cell and network wide settings In each case after the pitfalls of existing approaches are examined new systematic methodologies are provided to develop algorithms that perform provably well in all three dimensions   **Communication Networks** Jean Walrand,Shyam Parekh,2022-05-31 This book results from many years of teaching an upper division course on communication networks in the EECS department at the University of California Berkeley It is motivated by the perceived need for an easily accessible textbook that puts emphasis on the core concepts behind current and next generation networks After an overview of how today s Internet works and a discussion of the main principles behind its architecture we discuss the key ideas behind Ethernet WiFi networks routing internetworking and TCP To make the book as self contained as possible brief discussions of probability and Markov chain concepts are included in the appendices This is followed by a brief discussion of mathematical models that provide insight into the operations of network protocols Next the main ideas behind the new generation of wireless networks based on LTE and the notion of QoS are presented A concise discussion of the physical layer technologies underlying various networks is alsoincluded Finally a sampling of topics is presented that may have significant influence on the future evolution of networks including overlay networks like content delivery and peer to peer networks sensor networks distributed algorithms Byzantine agreement

source compression SDN and NFV and Internet of Things   **Analytical Methods for Network Congestion Control** Steven H. Low,2022-05-31 The congestion control mechanism has been responsible for maintaining stability as the Internet scaled up by many orders of magnitude in size speed traffic volume coverage and complexity over the last three decades In this book we develop a coherent theory of congestion control from the ground up to help understand and design these algorithms We model network traffic as fluids that flow from sources to destinations and model congestion control algorithms as feedback dynamical systems We show that the model is well defined We characterize its equilibrium points and prove their stability We will use several real protocols for illustration but the emphasis will be on various mathematical techniques for algorithm analysis Specifically we are interested in four questions 1 How are congestion control algorithms modelled 2 Are the models well defined 3 How are the equilibrium points of a congestion control model characterized 4 How are the stability of these equilibrium points analyzed For each topic we first present analytical tools from convex optimization to control and dynamical systems Lyapunov and Nyquist stability theorems and to projection and contraction theorems We then apply these basic tools to congestion control algorithms and rigorously prove their equilibrium and stability properties A notable feature of this book is the careful treatment of projected dynamics that introduces discontinuity in our differential equations Even though our development is carried out in the context of congestion control the set of system theoretic tools employed and the process of understanding a physical system building mathematical models and analyzing these models for insights have a much wider applicability than to congestion control   **Poisson Line Cox Process** Harpreet S. Dhillon,Vishnu Vardhan Chetlur,2022-06-01 This book provides a comprehensive treatment of the Poisson line Cox process PLCP and its applications to vehicular networks The PLCP is constructed by placing points on each line of a Poisson line process PLP as per an independent Poisson point process PPP For vehicular applications one can imagine the layout of the road network as a PLP and the vehicles on the roads as the points of the PLCP First a brief historical account of the evolution of the theory of PLP is provided to familiarize readers with the seminal contributions in this area In order to provide a self contained treatment of this topic the construction and key fundamental properties of both PLP and PLCP are discussed in detail The rest of the book is devoted to the applications of these models to a variety of wireless networks including vehicular communication networks and localization networks Specifically modeling the locations of vehicular nodes and roadside units RSUs using PLCP the signal to interference plus noise ratio SINR based coverage analysis is presented for both ad hoc and cellular network models For a similar setting the load on the cellular macro base stations MBSs and RSUs in a vehicular network is also characterized analytically For the localization networks PLP is used to model blockages which is shown to facilitate the characterization of asymptotic blind spot probability in a localization application Finally the path distance characteristics for a special case of PLCP are analyzed which can be leveraged to answer critical questions in the areas of transportation networks and urban planning The book is concluded with concrete suggestions on future directions of research Based largely on the original

research of the authors this is the first book that specifically focuses on the self contained mathematical treatment of the PLCP The ideal audience of this book is graduate students as well as researchers in academia and industry who are familiar with probability theory have some exposure to point processes and are interested in the field of stochastic geometry and vehicular networks Given the diverse backgrounds of the potential readers the focus has been on providing an accessible and pedagogical treatment of this topic by consciously avoiding the measure theoretic details without compromising mathematical rigor **Multi-Armed Bandits** Qing Zhao,2022-05-31 Multi armed bandit problems pertain to optimal sequential decision making and learning in unknown environments Since the first bandit problem posed by Thompson in 1933 for the application of clinical trials bandit problems have enjoyed lasting attention from multiple research communities and have found a wide range of applications across diverse domains This book covers classic results and recent development on both Bayesian and frequentist bandit problems We start in Chapter 1 with a brief overview on the history of bandit problems contrasting the two schools Bayesian and frequentist of approaches and highlighting foundational results and key applications Chapters 2 and 4 cover respectively the canonical Bayesian and frequentist bandit models In Chapters 3 and 5 we discuss major variants of the canonical bandit models that lead to new directions bring in new techniques and broaden the applications of this classical problem In Chapter 6 we present several representative application examples in communication networks and social economic systems aiming to illuminate the connections between the Bayesian and the frequentist formulations of bandit problems and how structural results pertaining to one may be leveraged to obtain solutions under the other **Network Connectivity** Chen Chen,Hanghang Tong,2022-01-26 Networks naturally appear in many high impact domains ranging from social network analysis to disease dissemination studies to infrastructure system design Within network studies network connectivity plays an important role in a myriad of applications The diversity of application areas has spurred numerous connectivity measures each designed for some specific tasks Depending on the complexity of connectivity measures the computational cost of calculating the connectivity score can vary significantly Moreover the complexity of the connectivity would predominantly affect the hardness of connectivity optimization which is a fundamental problem for network connectivity studies This book presents a thorough study in network connectivity including its concepts computation and optimization Specifically a unified connectivity measure model will be introduced to unveil the commonality among existing connectivity measures For the connectivity computation aspect the authors introduce the connectivity tracking problems and present several effective connectivity inference frameworks under different network settings Taking the connectivity optimization perspective the book analyzes the problem theoretically and introduces an approximation framework to effectively optimize the network connectivity Lastly the book discusses the new research frontiers and directions to explore for network connectivity studies This book is an accessible introduction to the study of connectivity in complex networks It is essential reading for advanced undergraduates Ph D students as well as researchers and practitioners

who are interested in graph mining data mining and machine learning **BATS Codes** Shenghao Yang,Raymond W. Yeung,2022-06-01 This book discusses an efficient random linear network coding scheme called BATched Sparse code or BATS code which is proposed for communication through multi hop networks with packet loss Multi hop wireless networks have applications in the Internet of Things IoT space and under water network communications where the packet loss rate per network link is high and feedbacks have long delays and are unreliable Traditional schemes like retransmission and fountain codes are not sufficient to resolve the packet loss so that the existing communication solutions for multi hop wireless networks have either long delay or low throughput when the network length is longer than a few hops These issues can be resolved by employing network coding in the network but the high computational and storage costs of such schemes prohibit their implementation in many devices in particular IoT devices that typically have low computational power and very limited storage A BATS code consists of an outer code and an inner code As a matrix generalization of a fountain code the outer code generates a potentially unlimited number of batches each of which consists of a certain number called the batch size of coded packets The inner code comprises random linear network coding at the intermediate network nodes which is applied on packets belonging to the same batch When the batch size is 1 the outer code reduces to an LT code or Raptor code if precode is applied and network coding of the batches reduces to packet forwarding BATS codes preserve the salient features of fountain codes in particular their rateless property and low encoding decoding complexity BATS codes also achieve the throughput gain of random linear network coding This book focuses on the fundamental features and performance analysis of BATS codes and includes some guidelines and examples on how to design a network protocol using BATS codes

Modeling and Optimization in Software-Defined Networks Konstantinos Poularakis,Leandros Tassiulas,T.V. Lakshman,2022-06-01 This book provides a quick reference and insights into modeling and optimization of software defined networks SDNs It covers various algorithms and approaches that have been developed for optimizations related to the control plane the considerable research related to data plane optimization and topics that have significant potential for research and advances to the state of the art in SDN Over the past ten years network programmability has transitioned from research concepts to more mainstream technology through the advent of technologies amenable to programmability such as service chaining virtual network functions and programmability of the data plane However the rapid development in SDN technologies has been the key driver behind its evolution The logically centralized abstraction of network states enabled by SDN facilitates programmability and use of sophisticated optimization and control algorithms for enhancing network performance policy management and security Furthermore the centralized aggregation of network telemetry facilitates use of data driven machine learning based methods To fully unleash the power of this new SDN paradigm though various architectural design deployment and operations questions need to be addressed Associated with these are various modeling resource allocation and optimization opportunities The book covers these opportunities and associated challenges which

represent a call to arms for the SDN community to develop new modeling and optimization methods that will complement or improve on the current norms *A Primer on Physical-Layer Network Coding* Soung Chang Liew,Lu Lu,Shengli Zhang,2022-05-31 The concept of physical layer network coding PNC was proposed in 2006 for application in wireless networks Since then it has developed into a subfield of communications and networking with a wide following This book is a primer on PNC It is the outcome of a set of lecture notes for a course for beginning graduate students at The Chinese University of Hong Kong The target audience is expected to have some prior background knowledge in communication theory and wireless communications but not working knowledge at the research level Indeed a goal of this book course is to allow the reader to gain a deeper appreciation of the various nuances of wireless communications and networking by focusing on problems arising from the study of PNC Specifically we introduce the tools and techniques needed to solve problems in PNC and many of these tools and techniques are drawn from the more general disciplines of signal processing communications and networking PNC is used as a pivot to learn about the fundamentals of signal processing techniques and wireless communications in general We feel that such a problem centric approach will give the reader a more in depth understanding of these disciplines and allow him her to see first hand how the techniques of these disciplines can be applied to solve real research problems As a primer this book does not cover many advanced materials related to PNC PNC is an active research field and many new results will no doubt be forthcoming in the near future We believe that this book will provide a good contextual framework for the interpretation of these advanced results should the reader decide to probe further into the field of PNC **Packets with Deadlines** I-Hong Hou,P.R. Kumar,2022-05-31 With the explosive increase in the number of mobile devices and applications it is anticipated that wireless traffic will increase exponentially in the coming years Moreover future wireless networks all carry a wide variety of flows such as video streaming online gaming and VoIP which have various quality of service QoS requirements Therefore a new mechanism that can provide satisfactory performance to the complete variety of all kinds of flows in a coherent and unified framework is needed In this book we introduce a framework for real time wireless networks This consists of a model that jointly addresses several practical concerns for real time wireless networks including per packet delay bounds throughput requirements and heterogeneity of wireless channels We detail how this framework can be employed to address a wide range of problems including admission control packet scheduling and utility maximization Table of Contents Preface Introduction A Study of the Base Case Admission Control Scheduling Policies Utility Maximization without Rate Adaptation Utility Maximization with Rate Adaptation Systems with Both Real Time Flows and Non Real Time Flows Broadcasting and Network Coding Bibliography Authors Biographies Embracing Risk Mingyan Liu,2022-06-01 This book provides an introduction to the theory and practice of cyber insurance Insurance as an economic instrument designed for risk management through risk spreading has existed for centuries Cyber insurance is one of the newest sub categories of this old instrument It emerged in the 1990s in

response to an increasing impact that information security started to have on business operations For much of its existence the practice of cyber insurance has been on how to obtain accurate actuarial information to inform specifics of a cyber insurance contract As the cybersecurity threat landscape continues to bring about novel forms of attacks and losses ransomware insurance being the latest example the insurance practice is also evolving in terms of what types of losses are covered what are excluded and how cyber insurance intersects with traditional casualty and property insurance The central focus however has continued to be risk management through risk transfer the key functionality of insurance The goal of this book is to shift the focus from this conventional view of using insurance as primarily a risk management mechanism to one of risk control and reduction by looking for ways to re align the incentives On this front we have encouraging results that suggest the validity of using insurance as an effective economic and incentive tool to control cyber risk This book is intended for someone interested in obtaining a quantitative understanding of cyber insurance and how innovation is possible around this centuries old financial instrument **Edge Intelligence in the Making** Sen Lin,Zhi Zhou,Zhaofeng Zhang,Xu Chen,Junshan Zhang,2022-06-01 With the explosive growth of mobile computing and Internet of Things IoT applications as exemplified by AR VR smart city and video audio surveillance billions of mobile and IoT devices are being connected to the Internet generating zillions of bytes of data at the network edge Driven by this trend there is an urgent need to push the frontiers of artificial intelligence AI to the network edge to fully unleash the potential of IoT big data Indeed the marriage of edge computing and AI has resulted in innovative solutions namely edge intelligence or edge AI Nevertheless research and practice on this emerging inter disciplinary field is still in its infancy stage To facilitate the dissemination of the recent advances in edge intelligence in both academia and industry this book conducts a comprehensive and detailed survey of the recent research efforts and also showcases the authors own research progress on edge intelligence Specifically the book first reviews the background and present motivation for AI running at the network edge Next it provides an overview of the overarching architectures frameworks and emerging key technologies for deep learning models toward training inference at the network edge To illustrate the research problems for edge intelligence the book also showcases four of the authors own research projects on edge intelligence ranging from rigorous theoretical analysis to studies based on realistic implementation Finally it discusses the applications marketplace and future research opportunities of edge intelligence This emerging interdisciplinary field offers many open problems and yet also tremendous opportunities and this book only touches the tip of iceberg Hopefully this book will elicit escalating attention stimulate fruitful discussions and open new directions on edge intelligence Performance Modeling, Stochastic Networks, and Statistical Multiplexing, Second Edition Ravi R. Mazumdar,2022-05-31 This monograph presents a concise mathematical approach for modeling and analyzing the performance of communication networks with the aim of introducing an appropriate mathematical framework for modeling and analysis as well as understanding the phenomenon of statistical multiplexing The models techniques and results

presented form the core of traffic engineering methods used to design control and allocate resources in communication networks The novelty of the monograph is the fresh approach and insights provided by a sample path methodology for queueing models that highlights the important ideas of Palm distributions associated with traffic models and their role in computing performance measures The monograph also covers stochastic network theory including Markovian networks Recent results on network utility optimization and connections to stochastic insensitivity are discussed Also presented are ideas of large buffer and many sources asymptotics that play an important role in understanding statistical multiplexing In particular the important concept of effective bandwidths as mappings from queueing level phenomena to loss network models is clearly presented along with a detailed discussion of accurate approximations for large networks **Sharing Network Resources** Abhey Parekh,Jean Walrand,2022-06-01 Resource Allocation lies at the heart of network control In the early days of the Internet the scarcest resource was bandwidth but as the network has evolved to become an essential utility in the lives of billions the nature of the resource allocation problem has changed This book attempts to describe the facets of resource allocation that are most relevant to modern networks It is targeted at graduate students and researchers who have an introductory background in networking and who desire to internalize core concepts before designing new protocols and applications We start from the fundamental question what problem does network resource allocation solve This leads us in Chapter 1 to examine what it means to satisfy a set of user applications that have different requirements of the network and to problems in Social Choice Theory We find that while capturing these preferences in terms of utility is clean and rigorous there are significant limitations to this choice Chapter 2 focuses on sharing divisible resources such as links and spectrum Both of these resources are somewhat atypical a link is most accurately modeled as a queue in our context but this leads to the analytical intractability of queueing theory and spectrum allocation methods involve dealing with interference a poorly understood phenomenon Chapters 3 and 4 are introductions to two allocation workhorses auctions and matching In these chapters we allow the users to game the system i e to be strategic but don t allow them to collude In Chapter 5 we relax this restriction and focus on collaboration Finally in Chapter 6 we discuss the theoretical yet fundamental issue of stability Here our contribution is mostly on making a mathematically abstruse subdiscipline more accessible without losing too much generality

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