Traffic Grooming For Optical Networks Foundations Techniques And Frontiers

Wavelength Division Multiplexing (WDM) is the most viable technique for utilizing the enormous amounts of bandwidth inherently available in optical fibers. However, the band-width offered by a single wavelength in WDM networks is on the order of tens of Gigabits per second, while most of the applications' bandwidth requirements are still subwavelength. Therefore, cost-effective design and provisioning of WDM networks require that traffic from different sessions share bandwidth of a single wavelength by employing electronic multiplexing at higher layers. This is known as traffic grooming. Optical networks supporting traffic grooming are usually designed in a way such that the cost of the higher layer equipment used to support a given traffic matrix is reduced. In this thesis, we propose a number of optimal and heuristic solutions for the design and provisioning of optical networks for traffic grooming with an objective of network cost reduction. In doing so, we address several practical issues. Specifically, we address the design and provisioning of WDM networks on unidirectional and bidirectional rings for arbitrary unicast traffic grooming, and on mesh topologies for arbitrary multipoint traffic grooming. In multipoint traffic grooming, we address both multicast and many-to-one traffic grooming problems. We provide a unified frame work for optimal and approximate network dimensioning and channel provisioning for the generic multicast traffic grooming problem, as well as some variants of the problem. For many-to-one traffic grooming we propose optimal as well as heuristic solutions. Optimal formulations which are inherently non-linear are mapped to an optimal linear formulation. In the heuristic solutions, we employ different problem specific search strategies to explore the solution space. We provide a number of experimental results to show the efficacy of our proposed techniques for the traffic grooming problem in WDM networks.

Optical networks based on wavelength-division multiplexing (WDM) tech nology offer the promise to satisfy the bandwidth requirements of the Inter net infrastructure, and provide a scalable solution to support the bandwidth needs of future applications in the local and wide areas. In a waveleng- routed network, an optical channel, referred to as a lightpath, is set up between two network nodes for communication. Using WDM technology, an optical fiber link can support multiple non-overlapping wavelength channels, each of which can be operated at the data rate of 10 Gbps or 40 Gbps today. On the other hand, only a fraction of customers are expected to have a need for such a high bandwidth. Due to the large cost of the optical backbone infrastruc ture and enormous WDM channel capacity, connection requests with diverse low-speed bandwidth requirements need to be efficiently groomed onto hi- capacity wavelength channels. This book investigates the optimized design, provisioning, and performance analysis of traffic-groomable WDM networks, and proposes and evaluates new WDM network architectures. Organization of the Book Significant amount of research effort has been devoted to traffic grooming in SONET/WDM ring networks since the current telecom networks are mainly deployed in the form of ring topologies or interconnected rings. As the long-haul backbone networks are evolving to irregular mesh topologies, traffic grooming in optical WDM mesh networks becomes an extremely important and practical research topic for both industry and academia.

While a single fiber strand in wavelength division multiplexing (WDM) has over a terabit-per-second bandwidth and a wavelength channel has over a gigabit-per-second transmission speed, the network may still be required to support traffic requests at rates that are lower than the full wavelength capacity. To avoid assigning an entire lightpath to a small request, many researchers have looked at adding traffic grooming to the routing and wavelength assignment (RWA) problem. In this work, we consider the RWA problem with traffic grooming (GRWA) for mesh networks under static and dynamic lightpath connection requests. The GRWA problem is NP-Complete since it is a generalization of the RWA problem which is known to be NP-Complete. We propose an integer linear programming (ILP) model that accurately depicts the GRWA problem. Because it is very hard to find a solution for large networks using ILP, we solve the GRWA problem by proposing two novel heuristics. The strength of the proposed heuristics stems from their simplicity, efficiency and applicability to large-scale networks. Our simulation results demonstrate that deploying traffic grooming resources on the edge of optical networks is more cost effective and results in a similar blocking performance to that obtained when distributing the grooming resources throughout the optical network domain.

This book presents advances in the field of optical networks - specifically on research and applications in elastic optical networks (EON). The material reflects the authors’ extensive research and industrial activities and includes contributions from preeminent researchers and practitioners in optical networking. The authors discuss the new research and applications that address the issue of increased bandwidth demand due to disruptive, high bandwidth applications, e.g., video and cloud applications. The book also discusses issues with traffic not only increasing but becoming much more dynamic, both in time and direction, and posits immediate, medium, and long-term solutions throughout the text. The book is intended to provide a reference for network architecture and planning, communication systems, and control and management approaches that are expected to steer the evolution of EONs.

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Telecommunication networks evolve as technology advances and society changes. Optical communications employing Wavelength Division Multiplexing (WDM) has become the dominant technology for use in backbone networks. As IP gains in popularity, the traffic pattern in carrier networks is increasingly becoming data centric. This has led to a change in the network infrastructure and many researchers believe that networks are evolving towards the slim two-layer model of IP over WDM. In this dissertation, we address several fundamentl issues of the grooming network design - the process of multiplexing, demultiplexing and switching lower rate traffic stream onto and off of higher capacity wavelengths, in the context of IP over WDM. We explain how wavelength continuity constraint and wavelength usage constraint affect network performance. Based on our research, we infer that, in practical WDM networks with wavelength usage constraint, increasing the total number of available wavelengths in a fiber is an attractive alternative to employing wavelength conversion. We investigate traffic grooming performed in IP layer, where the sub-wavelength level IP packets are grouped together in electrical domain before they are sent to the WDM layer. We study IP traffic grooming problem with the objective to minimize the number of transmitters and receivers needed in the WDM layer. We propose three routing strategies for allocating dynamic traffic requests and evaluate their blocking performance. The third issue addressed in this dissertaion is IP traffic

grooming in a recently proposed architecture called light trails. We define the light trail design problem and identify the minimum number of light trails to carry the given traffic demand. We formulate an ILP and develop two heuristic approaches for obtaining fast and near-optimal solutions in large networks. We finally address the issue of fault management in grooming networks. We study shared and dedicated protection against single link failure in WDM grooming networks and develop an ILP formulation for each of them. We extend our research on the full protection design to partial protection where the backup capacity is smaller than the primary capacity. We present ILP formulations and design a dynamic routing strategy named shortest-available-least congested routing.

Optical networks have moved from laboratory settings and theoretical research to real-world deployment and service-oriented explorations. New technologies such as Ethernet PON, traffic grooming, regional and metropolitan network architectures and optical packet switching are being explored, and the landscape is continuously and rapidly evolving. Some of the important issues involving these new technologies involve the architectural, protocol, and performance related issues. This book addresses many of these issues and presents a birds eye view of some of the more promising technologies. Researchers and those pursuing advanced degrees in this field will be able to see where progress is being made and new technologies are emerging. Emerging Optical Network Technologies: Architectures, Protocols and Performance provides state-of-the-art material written by the most prominent professionals in their respective areas.

This book presents an in-depth treatment of routing and wavelength assignment for optical networks, and focuses specifically on quality-of-service and fault resiliency issues. It reports on novel approaches for the development of routing and wavelength assignment schemes for fault-resilient optical networks, which improve their performance in terms of signal quality, call blocking, congestion level and reliability, without a substantial increase in network setup cost. The book first presents a solution for reducing the effect of the wavelength continuity constraint during the routing and wavelength assignment phase. Further, it reports on an approach allowing the incorporation of a traffic grooming mechanism with routing and wavelength assignment to enhance the effective channel utilization of a given capacity optical network using fewer electrical-optical-electrical conversions. As a third step, it addresses a quality of service provision scheme for wavelength-division multiplexing (WDM)-based optical networks. Lastly, the book describes the inclusion of a tree-based fault resilience scheme in priority-based dispersion-reduced wavelength assignment schemes for the purpose of improving network reliability, while maintaining a better utilization of network resources. Mainly intended for graduate students and researchers, the book provides them with extensive information on both fundamental and advanced technologies for routing and wavelength assignment in optical networks. The topics covered will also be of interest to network planners and designers.

This handbook is an authoritative, comprehensive reference on optical networks, the backbone of today's communication and information society. The book reviews the many underlying technologies that enable the global optical communications infrastructure, but also explains current research trends targeted towards continued capacity scaling and enhanced networking flexibility in support of an unabated traffic growth fueled by ever-emerging new applications. The book is divided into four parts: Optical Subsystems for Transmission and Switching, Core Networks, Datacenter and Super-Computer Networking, and Optical Access and Wireless Networks. Each chapter is written by world-renown experts that represent academia, industry, and international government and regulatory agencies. Every chapter provides a complete picture of its field, from entry-level information to a snapshot of the respective state-of-the-art technologies to emerging research trends, providing something useful for the novice who wants to get familiar with the field to the expert who wants to get a concise view of future trends.

Research and development on optical wavelength-division multiplexing (WDM) networks have matured considerably. While optics and electronics should be used appropriately for transmission and switching hardware, note that "intelligence" in any network comes from "software," for network control, management, signaling, traffic engineering, network planning, etc.The role of software in creating powerful network architectures for optical WDM networks is emphasized. Optical WDM Networks is a textbook for graduate level courses. Its focus is on the networking aspects of optical networking, but it also includes coverage of physical layers in optical networks. The author introduces WDM and its enabling technologies and discusses WDM local, access, metro, and long-haul network architectures. Each chapter is self-contained, has problems at the end of each chapter, and the material is organized for self study as well as classroom use. The material is the most recent and timely in capturing the state-of-the-art in the fast-moving field of optical WDM networking.

Optical spectrum is becoming scarce with traffic demand growing at 40% per year. Today, the optical spectrum of a fiber is divided using wavelength-division multiplexing (WDM) into optical channels of 50 GHz or 100 GHz. This fixed grid will not be able to efficiently support higher bit-rate transponders (namely, at 400 Gbps and 1 Tbps). Moreover, innovative elastic transponders capable of tuning their data rates by choosing appropriate modulation formats or spectrum width are also being investigated. To exploit the capabilities of elastic transponders and to fit transponders at beyond-100 Gbps rates, the conventional fixed grid has to evolve towards a flexible grid, where an arbitrary number of finer frequency slots (e.g., at 12.5 GHz) can be assigned to serve the client demands. At the same time of the disruptive development of the optical layer, two trends in the general networking/IT fields are prominent: 1. Vertical convergence: convergence of multiple layers of the network stack, e.g., packet and circuit (optical) convergence; 2. Horizontal convergence: convergence of computing, storage, and networking resources, e.g., cloud networking, and information-centric networking (ICN). Hence, we are motivated to study how to adapt the architecture, operation, and services of flexible-grid elastic optical networks to the two prominent trends. For vertical packet/optical convergence, we study dynamic traffic grooming in elastic optical networks. We propose to jointly solve the electrical-layer

routing and optical-layer routing and spectrum assignment (RSA). Also, we propose a spectrum reservation scheme that can efficiently utilize the bandwidth variability of lightpaths, reducing operational expenditure (OPEX) as well as increasing spectrum efficiency. We also propose a provisioning policy exploring grooming opportunities both in time and frequency domains in order to achieve high energy efficiency. We review the evolution of traffic-grooming paradigm. Sliceable optical layer based on sliceable transponders and bandwidth-variable reconfigurable optical add/drop multiplexer (BV-ROADM) is identified as a novel technology that could impact the future grooming paradigm by offloading considerable amount of traffic and part of electronic grooming function to the optical layer. We propose two novel network architectures based on sliceable optical layer and their optimal designs. It is found that packet over sliceable (PoS) network architecture consumes the fewest transponders and at the same time achieves either the "lowest-possible" latency or least spectrum usage. We also propose a new dense-wavelength-division multiplexing (DWDM)-centric converged metro/aggregation network, which reduces the usage of electronic packet processing, hence significantly reducing the corresponding OPEX. Both Integer Linear Program (ILP) and heuristics are proposed to address the complex network design problems involving two layers of routing (fiber routing and wavelength routing), wavelength assignment, and survivable design. For horizontal convergence, we investigate how to jointly allocate computing, storage, and networking resources for virtual infrastructures in the problems of network virtualization over both WDM and flexible-grid optical networks. We formulate the problems as mixed integer linear programs (MILP) and propose two heuristics, namely MaxMapping and MinMapping. Numerical examples show that MinMapping performs very close to the optimal results derived by the MILP in both kinds of optical networks, by exploring traffic grooming. Also, it is verified that flexible-grid optical networks can be more spectrum efficient than WDM networks as the substrate for network virtualization. Also, for large service providers (SP) who own their computing, storage, and networking resources, we propose to orchestrate their cache and networking resources in a coordinated way to solve their traffic-engineering (TE) and cache-orchestration (CO) problems in an ICN-enabled networking infrastructure using service popularity. We propose to deal with the joint problems at the service level, in which no specific information about individual contents of services is needed. Numerical results show that our proposed TE and CO schemes can significantly reduce network cost and increase cache hit ratio, with the constraints of satisfying service-level agreements (SLA).

Wavelength division multiplexing (WDM) has emerged as a viable solution to the increasing bandwidth demands of current backbone networks. Traffic grooming allows the resources available on a single wavelength to be utilized by multiple traffic streams. These networks will support large amounts of traffic from various sources. In view of this, our research focuses on the analysis of such types of networks, and in particular on a traffic-groomed tandem optical network that supports multiple sources each with unique resource requirements. We developed a decomposition algorithm for the analysis of this network using a modified version of Courtois' method. This work was extended to analyze tandem networks with a large number of wavelengths and resources per wavelength using a modified version of the recursion developed by Nilsson et. al. Finally, we extended our work to a traffic-groomed tandem optical network employing alternate routing and supporting traffic from multiple sources. For each method, numerical results show that, overall, our approximation provides good accuracy.

Keywords: lightpaths, virtual topology, NP-Completeness.

This book takes a pragmatic approach to deploying state-of-the-art optical networking equipment in metro-core and backbone networks. The book is oriented towards practical implementation of optical network design. Algorithms and methodologies related to routing, regeneration, wavelength assignment, sub rate-traffic grooming and protection are presented, with an emphasis on optical-bypass-enabled (or all-optical) networks. The author has emphasized the economics of optical networking, with a full chapter of economic studies that offer guidelines as to when and how optical-bypass technology should be deployed. This new edition contains: new chapter on dynamic optical networking and a new chapter on flexible/elastic optical networks. Expanded coverage of new physical-layer technology (e.g., coherent detection) and its impact on network design and enhanced coverage of ROADM architectures and properties, including colorless, directionless, contentionless and gridless. Covers ‘hot’ topics, such as Software Defined Networking and energy efficiency, algorithmic advancements and techniques, especially in the area of impairment-aware routing and wavelength assignment. Provides more illustrative examples of concepts are provided, using three reference networks (the topology files for the networks are provided on a web site, for further studies by the reader). Also exercises have been added at the end of the chapters to enhance the book’s utility as a course textbook.

The book discusses the recent research trends in various sub-domains of computing, communication and control. It includes research papers presented at the First International Conference on Emerging Trends in Engineering and Science. Focusing on areas such as optimization techniques, game theory, supply chain, green computing, 5g networks, Internet of Things, social networks, power electronics and robotics, it is a useful resource for academics and researchers alike.

"This book is a collection of the latest contributions to the area of survivability in optical networks, focusing on theoretical and practical aspects of network survivability methodologies applied to real world scenarios"--Provided by publisher.

This book is intended as a graduate/post graduate level textbook for courses on high-speed optical networks as well as computer networks. The ten chapters cover basic principles of the technology as well as latest developments and further discuss network security, survivability, and reliability of optical networks and priority schemes used in wavelength routing. This book also goes on to examine Fiber To The Home (FTTH) standards and their deployment and research issues and includes examples in all the chapters to aid the understanding of problems and solutions. Presents advanced concepts of optical network devices Includes examples and exercises inall the chapters of the book to aid the understanding of basic problems and solutions for undergraduate and postgraduate students Discusses optical ring metropolitan area networks and queuing system and its interconnection with other networks Discusses routing and wavelength assignment Examines restoration schemes in the survivability of optical networks

The exponential growth of the Internet has resulted in an ever increasing demand for bandwidth. Carrier networks which form the backbone of the Internet, have been designed to carry only voice signals with predictable traffic patterns and anticipating slow growth of the network. With the advances in fiber optics and wavelength division multiplexing (WDM) optical networking is the key to satisfy the data-driven bandwidth demand. These technologies enable simultaneous transmission of signals on separate high-speed

channels at different wavelengths. While the bandwidth provided by these channels is very high, individual traffic demands are at the sub-wavelength level. This mismatch can be overcome by multiplexing several lower rate connections onto the high-speed channels in a cost-effective manner. This technique is referred to as traffic grooming. Traffic grooming in WDM networks has been a widely addressed problem in recent years. Traffic grooming and its constituent subproblems have been proven to be NP-complete for even the most elemental of network topologies. The ring topology has been the target of a large number of the studies because of its practical relevance. However, most existing studies concentrate on some objective function that is aggregated over all the network nodes, such as the total number of ADMs used or the total amount of opto-electro-optical (OEO) routing performed. From a practical point of view, it is likely that every network node would be provisioned similarly. Hence a min-max objective, seeking to minimize the OEO equipment needed at the node which needs the maximum of such equipment is more appropriate. Such objectives are usually harder to optimize than aggregate objectives which are themselves known to be computationally intractable. In this thesis, we study traffic grooming in a unidirectional ring network under different traffic patterns for the min-max objective. We define two heuristic approaches based on decomposition; one is based.

We consider the problem of minimizing network costs when grooming traffic in optical networks that support Wavelength Division Multiplexing (WDM). While the general problem has been shown to be NP-Hard for a number of cost measures, there still exist restricted problems for which no complexity bound is known. In this research, we restrict our attention to traffic grooming for path networks with egress (all-to-one) traffic. This restricted model has practical significance for high speed (optical) access networks and can also lead to better bounds and approximations on more general network topologies (such as ring and star networks) that can be decomposed into path networks. Three important cost measures for this restricted model are studied. The first cost measure is the total number of ADMs used by the solution. Minimizing this cost was known to be NP-Complete even for egress traffic without using cross connects. We show that allowing an unbounded number of wavelengths obviates the need for digital cross connects at the nodes and hence the problem remains NP-Complete even when cross connects are allowed. The second cost measure is the number of transceivers used by the solution. We show that the problem of minimizing the number of transceivers is NP-Complete, even when restricted to egress traffic. We then develop a simple approximation scheme where the transceiver cost exceeds the minimum by at most the number of required wavelengths. Finally, we show that under certain conditions, there exist solutions that simultaneously minimize both ADM and transceiver costs. The third cost model aims to minimize the total electronic switching in the network. For this cost measure, we develop a polynomial time algorithm to determine the cost and structure of an optimum solution when the wavelength capacity constraint is relaxed. A closed form expression to determine the minimum cost is presented for problem instances with uniform traffic. We observe that these costs provide a l.

In recent years, with the rapid growth of the Internet, the bandwidth demand for data traffic is exploding. Optical networks based on wavelength-division multiplexing (WDM) technology offer the promise to satisfy the bandwidth requirements of the Internet infrastructure. With WDM technology, signals are carried simultaneously on mUltiple wavelengths on a single fiber. WDM provides a practical approach of resolving the mismatch between the fiber ca pacity and the peak electronic processing speed. Mesh-based WDM networks have recently attracted much research and development interest since the In ternet topology is meshed in nature, and more importantly, mesh-based WDM networks are flexible with respect to routing and survivability. This book exam ines the management and survivability issues of mesh-based WDM networks and proposes new WDM network protocols and algorithms that could make telecommunication networks more efficient. Wavelength-routing has been one of the most important technologies to em ploy WDM in backbone networks. In wavelength-routed WDM networks, optical channels, which are referred to as lightpaths, are set up between WDM terminals. Most chapters of this bock are focused on various issues related to wavelength-routed networks, namely, routing and wavelength-assignment, con trol and management, fault management, and wavelength-converter placement. This book also presents an all-optical packet-switched network architecture based on the concept of photonic slot routing. The audience for this book are network designers and planners, research and development engineers active in the field of telecommunications, and students of optical networking at the graduate or senior undergraduate levels.

Core Access Networks and Switching Subsystems, Transmission Systems and Their Subsystems, Optical Fibers, Fiber Amplifiers, and Related Devices, Optical Active Devices and Modules, Passive Devices and Modules

Wavelength Division Multiplexing (WDM) using wavelength routing has emerged as the dominant technology for use in wide area and metropolitan area networks. Traffic demands in networks today are characterized by dynamic, heterogeneous flows. While each wavelength has transmission capacity at gigabit per second rates, users require connections at rates that are lower than the full wavelength capacity. In this thesis, we explore network design and operation methodologies to improve the network utilization and blocking performance of wavelength routing networks which employ a layered architecture with electronic and optical switching. First we provide an introduction to first generation SONET/SDH networks and wavelength routing networks, which employ optical crossconnects. We explain the need and role of wavelength conversion in optical networks and present an algorithm to optimally place wavelength conversion devices at the network nodes so as to optimize blocking performance. Our algorithm offers significant savings in computation time when compared to the exhaustive method. To make the network viable and cost-effective, it must be able to offer sub-wavelength services and be able to pack these services efficiently onto wavelengths. The act of multiplexing, demultiplexing and switching of sub-wavelength services onto wavelengths is defined as traffic grooming. Constrained grooming networks perform grooming only at the network edge. Sparse grooming networks perform grooming at the network edge and the core. We study and

compare the effect of traffic grooming on blocking performance in such networks through simulations and analyses. We also study the issue of capacity fairness in such networks and develop a connection admission control (CAC) algorithm to improve the fairness among connections with different capacities. We finally address the issues involved in dynamic routing and wavelength assignment in survivable WDM grooming networks. We develop two schemes for grooming primary and backup traffic steams onto wavelengths: Mixed Primary-Backup Grooming Policy (MGP) and Segregated Primary-Backup Grooming Policy (SGP). MGP is useful in topologies such as ring, characterized by low connectivity and high load correlation and SGP is useful in topologies, such as mesh-torus, with good connectivity and a significant amount of traffic switching and mixing at the nodes.

This book presents the practical motivation, theoretical description, and extant techniques for traffic grooming in optical networks. The description of the various topics of research will be authored by leading researchers in this area, and will contain comprehensive description of related literature for each area. This book is intended to be a definitive reference and text for traffic grooming both for the practitioner in industry and the student in academia.

The advent of fiber optic transmission systems and wavelength division multiplexing (WDM) have led to a dramatic increase in the usable bandwidth of single fiber systems. This book provides detailed coverage of survivability (dealing with the risk of losing large volumes of traffic data due to a failure of a node or a single fiber span) and traffic grooming (managing the increased complexity of smaller user requests over high capacity data pipes), both of which are key issues in modern optical networks. A framework is developed to deal with these problems in wide-area networks, where the topology used to service various high-bandwidth (but still small in relation to the capacity of the fiber) systems evolves toward making use of a general mesh. Effective solutions, exploiting complex optimization techniques, and heuristic methods are presented to keep network problems tractable. Newer networking technologies and efficient design methodologies are also described.

This work have analyzed the effect of increasing number of wavelength converters and grooming devices over the network performance. Deciding the amount and location of these devices to be used in a network is equally important. For this purpose, different placement schemes are used on the proposed network model and assumptions. Our work has been done through the simulations of different device placement scenarios and the results have been analyzed using blocking probability as the performance metric. We have reviewed the performance of wavelength converters with different grooming devices.