Preface to the Second Edition

Optical networking has greatly matured since the early 2000s. Optical bypass, where connections remain in the optical domain as they traverse network nodes, is now a well-accepted technology for reducing the amount of electronic equipment in the network. The industry emphasis has shifted from transformative innovations to technological and architectural advancements that address operational and network management challenges. Some of the more important areas of development include network configurability, energy consumption, and fiber capacity.

Carriers readily appreciate the advantages afforded by automating the network provisioning process. Remote configurability of the network equipment via software reduces the amount of required manual intervention, thereby allowing more rapid provisioning of services and quicker revenue recognition. To reap the full benefits of a configurable network, the network equipment must be as flexible as possible, within the bounds of cost effectiveness. The network equipment that enabled optical bypass was a major departure from legacy equipment, with significant capital-cost reduction being the main driver of the technology. However, the main motivators guiding network element development today are reduced operational cost and greater network flexibility, where limitations imposed by the equipment are removed.

Recent developments with regard to network-element flexibility are covered extensively in Chap. 2. For example, the so-called colorless, directionless, contentionless, and gridless properties of optical-bypass-enabling equipment are covered in detail. This includes coverage of several architectural options for achieving these properties, as well as a discussion regarding the relative importance of incorporating this flexibility in the network elements.

The next frontier in automated connection setup is dynamic optical networking, where connections can be established on the order of a second. Furthermore, the requests for shifts in bandwidth come from the networking layers that sit atop the optical layer (e.g., the Internet Protocol (IP) layer), as opposed to operations personnel. Most carriers have been slow to embrace dynamic optical networking, similar to the initial skepticism regarding optical-bypass technology.

However, as applications such as cloud computing proliferate (where enterprises migrate much of their locally situated back-office functionality to remotely located data centers distributed throughout the network), the need will increase for a rapidly responsive network that can maintain a high quality of service as network conditions change. Furthermore, dynamic networking is one enabler of network virtualization, which provides the ability to customize the network topology and resources that are seen by a given customer. In the future, one can envision dynamic cognitive networks, where the network autonomously reacts to the current conditions, based on its knowledge of past performance. Once the machinery for increased dynamism is in place, it is likely that new revenue-generating opportunities will arise as well, which will accelerate the pace of adoption.

An entire new chapter in this second edition (Chap. 8) is devoted to discussing the merits and challenges of dynamic optical networking. Recent research results as well as standardization efforts are covered. This includes extensive discussion regarding which functions are best handled by a distributed protocol as opposed to a centralized one. The vexing topics of minimizing resource contention and implementing optical bypass in a distributed environment are discussed in detail. Dynamic optical networking across multiple domains is covered as well, where the domains may be under the control of different service providers or different administrative organizations within one service provider. The challenge is performing close to optimal routing and resource allocation without violating the security and administrative boundaries of the various entities that are involved.

Chapter 8 also covers Software-Defined Networking (SDN), which is a relatively new networking paradigm that is relevant to dynamic networking (among other aspects of future networks). One of the goals of SDN is to provide carriers and enterprises with greater control of their networks, which includes providing a centralized view of the network that extends down to the optical layer. This potentially enables dynamic multi-layer optimization, although the scalability of such an approach is still an open question.

The growing role of data centers as the repository for enterprise computing and storage resources also impacts more conventional aspects of network design, such as the algorithms used for routing traffic. For example, the concept of "manycasting" has grown in importance, where enterprises need to be connected to some subset of distributed data centers (i.e., gaining access to the desired resources is what is important not the particular data centers that provide them). Algorithms to provide this connectivity are covered in Chap. 3.

The topics mentioned thus far are proactive strategies to improve network economics and network control. However, there are at least two daunting developments that have caught the attention of the industry, driving much research in response. The first is the growing amount of energy consumed by information and communication technologies (ICT). While estimates vary, it is generally agreed that ICT energy usage represents at least 2 % of total worldwide usage. Despite its major role in network transmission, the optical layer is responsible for just a small portion of this energy consumption, due to the relative energy efficiency of optical technology. Thus, as compared with sectors of the ICT industry where reducing energy consumption is an imperative (leading to energy-saving solutions such as locating data centers near bodies of water to reduce the need for more conventional cooling methods), the approach with optics has been to consider *expanding* its role to reduce the energy strains in other portions of the network (e.g., pushing more switching from the electronic layers into the optical layer; introducing WDM technology in data centers; using optics for off- and on-chip interconnects). However, optical technology is not a panacea. For example, it is not ideal for applications that require data buffers, time shifting, and read/write operations. Discovering how best to harness the genuine advantages of optical technology is an ongoing task.

The topic of power consumption is brought up throughout this second edition. First, optical bypass, while initially implemented to reduce capital expenditures, has proved to be equally effective at reducing power consumption in the transport layer. The larger problem now is reducing power consumption in the IP layer. In the near term, one solution may be to insert an additional layer between the IP and optical layers to offload some of the burden from the IP routers, as discussed in Chap. 6. Other strategies include routing traffic away from certain regions of a network, e.g., to avoid the higher energy costs of a particular region, or to allow a subset of the equipment to be powered down. Such proposals are also discussed in Chap. 6. One particular longer-term solution that has generated a lot of follow-on research involves grooming (i.e., “traffic packing”) in the more energy-efficient optical layer as opposed to the electronic layer. This proposed scheme differs from other optical-grooming schemes in that the grooming is performed in the frequency domain as opposed to the time domain. A large portion of Chap. 9 (which is new to the second edition) is dedicated to discussing the potential benefits and the challenging realities of this scheme. This discussion is supplemented by a detailed network study in Chap. 10.

Another recent development is the realization that, at the current rate of traffic growth, the capacity limit of conventional fiber will be reached by the 2025 time-frame. For many years, fiber capacity appeared almost infinite in comparison with the level of traffic being carried. The number of wavelengths supported on a fiber and the bit-rate of each wavelength have greatly increased over the past two decades. Furthermore, these advancements have enabled a significant reduction in two key networking metrics: cost per bit/sec and power consumption per bit/sec. However, the pace of these advancements is likely to slow, as further improvements become more challenging to implement. While deploying multiple fibers can address the need for additional capacity, this approach does not provide economies of scale with respect to cost and power consumption. Better solutions are desired.

Architectures and technology aimed at addressing fiber capacity limits are covered in Chap. 9, primarily in the context of flexible optical networks. By engendering the network with more flexibility, the fiber capacity can be used more efficiently, thereby prolonging the time until the capacity limit is reached. Most of the solutions involve employing more flexible spectral grids. This includes the optical grooming scheme mentioned above for purposes of reducing power consumption, which is also being championed as a means of using capacity more efficiently (though the limitations of optical filtering technology may curb the capacity benefits that can actually be attained). In addition to these flexible schemes, which take relatively small steps towards alleviating capacity limits, Chap. 9 also discusses longer-term solutions, such as new fibers that can cost effectively increase the capacity of a single fiber by at least an order of magnitude (e.g., multi-core fiber).

One of the outgrowths of the various trends in optical networking is that network design has become more complex. For example, higher wavelength bit-rates and the introduction of more advanced transmission formats have resulted in needing to account for more optical impairments to maintain a high level of optical bypass. Additionally, mixed line-rate (MLR) networks, where wavelengths with different bit-rates and transmission formats are routed on one fiber, pose special challenges depending on the combination of formats that are present. These impediments need to be captured in the algorithms used for network design, as described in Chaps. 4 and 5.

Furthermore, some of the architectural schemes that have been proposed to add more networking flexibility concomitantly add more algorithmic complexity. While technology advancements often make network design more challenging, effective algorithms may in some instances lessen the need for technology-based solutions. For example, some of the networking limitations that are imposed by the optical-layer equipment can be sufficiently minimized through an algorithmic approach, rather than requiring costly upgrades to the equipment. Despite the added complexity, efficient optical network design is still a manageable process, as investigated throughout this book.

These trends, and their ramifications for network design, have motivated the second edition of this text.

Major Changes from the First Edition

Each of the eight original chapters in the first edition has been updated to address the latest technology and algorithmic approaches. Where appropriate, the terminology has been updated as well. For example, in keeping with popular usage, the term "ROADM" is generally used for any reconfigurable network element that allows optical bypass, regardless of its precise properties. The first edition had distinguished between ROADMs and All-Optical Switches, depending on the element functionality. Additionally, the term "edge configurable", used in the first edition in reference to a particular ROADM property, has been replaced by the term "directionless", which is now widely used in the industry.

As noted above, Chaps. 8 and 9 are new. Chap. 8 covers dynamic optical networking and Chap. 9 examines the trend towards greater flexibility in the underlying network, where much of the research is driven by the desire to use fiber capacity more efficiently. The original Chap. 8 (on economic studies) in the first edition is now Chap. 10. Additionally, the algorithm code that had been in an appendix is now in Chap. 11.

The second edition also includes more case studies throughout the text to illustrate the concepts. Three reference networks, presented in Chap. 1, are typically used for these studies. Readable text files containing the topologies for these networks (i.e., the nodes and links) can be found at: *www.monarchna.com/topology.html*

A few of the sections that were included in the first edition of the textbook have been removed. For example, the discussion regarding early generations of ROADM technology has been removed. A few of the network studies have also been eliminated from Chap. 10. For example, one of these studies had analyzed the economics of providing two types of transponders, one that supported the full nominal optical reach for the system and one that supported a shorter optical reach. Given the recent development of programmable transponders that can support a range of reach values and bit-rates, this study was no longer relevant. An additional study, on flexible networks, has been added.

Exercises

A set of exercises has been added to the end of almost all chapters, to test the understanding of the fundamental concepts. The exercises range in difficulty from simple application of an algorithm to thought-provoking architectural questions. Many of the exercises extend the discussion presented in the chapter text; e.g., an alternative architecture may be considered, along with questions that probe its performance. The exercises also include suggestions for future research.

The exercises that require some amount of network design use small networks to enable manual solution. Alternatively, the algorithm code that is provided in the last chapter can be used in some of these exercises. The code should be portable to any standard C compiler.

Some basic queuing theory is required to solve some of the exercises; for example, knowledge of Poisson processes and the Erlang-B formula.

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