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Motivation

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1.1 Motivation

The huge amount of research done in the last decade in the field of optical transmission has made available a set of technologies jointly known as flexgrid, where the optical spectrum is divided into 12.5 GHz frequency slices with 6.25 GHz central frequency granularity, in contrast to the coarser 50 GHz in fixed grid Wavelength Division Multiplexing (WDM) [G694.1]. Such frequency slices can be combined in groups of contiguous slices to form frequency slots of the desired spectral width, thus increasing fiber links' capacity. To illustrate the magnitude of the capacity increment, a 40 Gb/s connection modulated using Dual-Polarization Quadrature Phase Shift Keying (DP-QPSK) can be transported on a 25 GHz slot in flexgrid, instead of 50 GHz needed with WDM [Ru14.1].

In addition to increasing network capacity, subsystems currently being developed will foster devising novel network architectures. These are as follows:

- Liquid Crystal on Silicon (LCoS)-based Wavelength Selective Switches (WSS) to build flexgrid-ready Optical Cross-Connects (OXCs) [Ji09].
- The development of advanced modulation formats to increase efficiency, which are capable of extending the reach of optical signals [Ge12].
- Sliceable Bandwidth-Variable Transponders (SBVTs) able to deal with several flows in parallel, thus adding, even more, flexibility and reducing costs [Sa15].

The resulting flexgrid networks will allow mixing optical connections of different bitrates (e.g., 10, 40, 100 Gb/s), by allocating frequency slices and using different modulation formats such as 16-State Quadrature Amplitude

Modulation (QAM16) or DP-QPSK more flexibly. Furthermore, larger bitrates (e.g., 400 Gb/s or even 1 Tb/s) can be conceived by extending the slot width beyond 50 GHz. In addition, the capability to elastically allocate frequency slices on demand and/or modify the modulation format of optical connections according to variations in the traffic of the demands allows resources to be used efficiently in response to traffic variations; this is named as Elastic Optical Networks (EONs) [Na15], [Lo16].

To understand how the finer spectrum granularity together with the flexible slot allocation of EONs can impact the network architecture, let us compare national Multi-Protocol Label Switching (MPLS) network designs when the underlying optical network is based either on a WDM network or on an EON [Ve13.1]. MPLS networks typically receive client flows from access networks and perform flow aggregation and routing. The problem of designing MPLS networks consists in finding the configurations of the whole set of routers and links to transport a given traffic matrix whilst minimizing capital expenditures (CAPEX). To minimize the number of ports a router hierarchy consisting of *metro* routers, performing client flow aggregation, and *transit* routers, providing routing flexibility, is typically created.

As a consequence of link lengths, national MPLS networks have been designed on top of WDM networks, and, thus, the design problem has been typically addressed through a multilayer MPLS-over-WDM approach where transit routers are placed alongside OXCs. Besides, multilayer MPLS-over-WDM networks take advantage of grooming to achieve high spectrum efficiency, filling the gap between users' flows and optical connections' capacity.

The advent of flexgrid technology providing a finer granularity, however, makes it possible to flatten the multilayer approach and advance toward single layer networks consisting of a number of MPLS areas connected through a core EON (Figure 1.1).

To compare the designs of national MPLS networks when such flatten network architecture is adopted, we define the overall network spectral efficiency of the interarea optical connections, as:

$$Sp.Eff = \frac{\sum_{a \in A} \sum_{\substack{a' \in A \\ a' \neq a}} \frac{b_{aa'}}{\Delta f \cdot B_{\text{mod}}}}{\sum_{a \in A} \sum_{\substack{a' \in A \\ a' \neq a}} \left\lceil \frac{b_{aa'}}{\Delta f \cdot B_{\text{mod}}} \right\rceil}, \quad (1.1)$$

where $b_{aa'}$ represents the bitrate between two different areas a and a' in the set of areas A , Δf is the considered spectrum granularity (i.e., 50 GHz for WDM and 12.5 GHz for EON), and B_{mod} is the spectral efficiency (b/s/Hz) of the chosen modulation format. Note that the ceiling operation computes the number

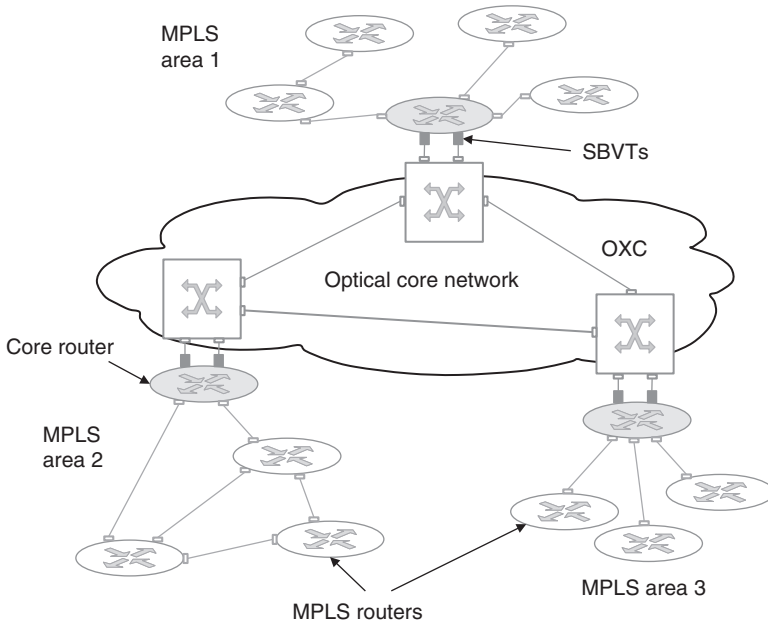


Figure 1.1 Three MPLS areas connected through a core optical network.

of slices/wavelengths needed to convey the requested data flow under the chosen technology.

Let us analyze the results obtained from solving a close-to-real problem instance consisting of 1113 locations, based on the British Telecom (BT) network. Those locations (323), with a connectivity degree of 4 or above, were selected as potential core locations. A 3.22 Pb/s traffic matrix was obtained by considering the number of residential and business premises in the proximity of each location. Locations could only be parented to a potential area if they were within a 100 km radius.

Figure 1.2 plots the amount of aggregated traffic injected to the optical core network for each solution as a function of the number of areas. The relationship between the amount of aggregated traffic and the number of areas is clearly shown; more areas entail higher aggregated traffic to be exchanged because less traffic is retained within an area since the areas are smaller. Nonetheless, the amount of aggregated traffic when all the 323 areas are opened is only 6% with respect to just opening 20 areas.

Plots in Figure 1.2 show the maximum spectral efficiency of the solutions for each technology and the number of areas selected. As illustrated, network spectral efficiency decreases sharply when the number of areas is increased since more flows with a lower amount of traffic are needed to be transported over the

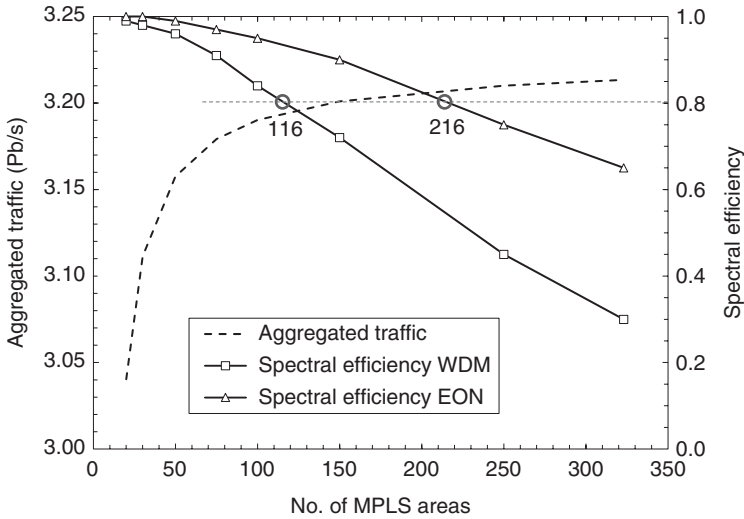


Figure 1.2 Aggregated traffic and network spectral efficiency.

core network. Note that the traffic matrix to be transported by the core network has $|A|^*(|A| - 1)$ unidirectional flows. Let us consider a target threshold for network spectral efficiency of 80% (horizontal dotted line in Figure 1.2). Then, the largest number of areas are 116 and 216 when WDM and EON, respectively, are selected. Obviously, the coarser the spectrum granularity chosen for the optical network, the larger the areas need to be for the spectral efficiency threshold selected, and, thus, the lower the number of areas to be opened.

Figure 1.3 presents the details of the solutions as a function of the number of areas, while Table 1.1 focuses on the characteristics of those solutions in the defined spectral efficiency threshold for each technology. Note that plots in Figure 1.3 are valid irrespective of the technology selected since no spectral efficiency threshold was required.

In Figure 1.3a, the size of the areas is represented. Note that in the reference interval [116, 216] the average number of locations in each area is lower than 10, being lower than 20 for the largest area. This limited area size simplifies the design of MPLS networks. Besides, switching capacity of core MPLS routers is proportional to the size of the areas as shown in Figure 1.3b. They require capacities of up to 58 Tb/s (28.5 Tb/s on average) for WDM, decreasing to 35.5 Tb/s (15.7 Tb/s on average) for EON. Hence, finer spectrum granularity might keep routers to single chassis size—far more efficient and cost effective.

Figure 1.3c surveys the size of the area internal data flows (flows where at least one end router is in a given area). The size of the internal flows is up to 72 Gb/s, 32 Gb/s on average, for WDM decreasing to 50 Gb/s, 21 Gb/s on average, for EON.

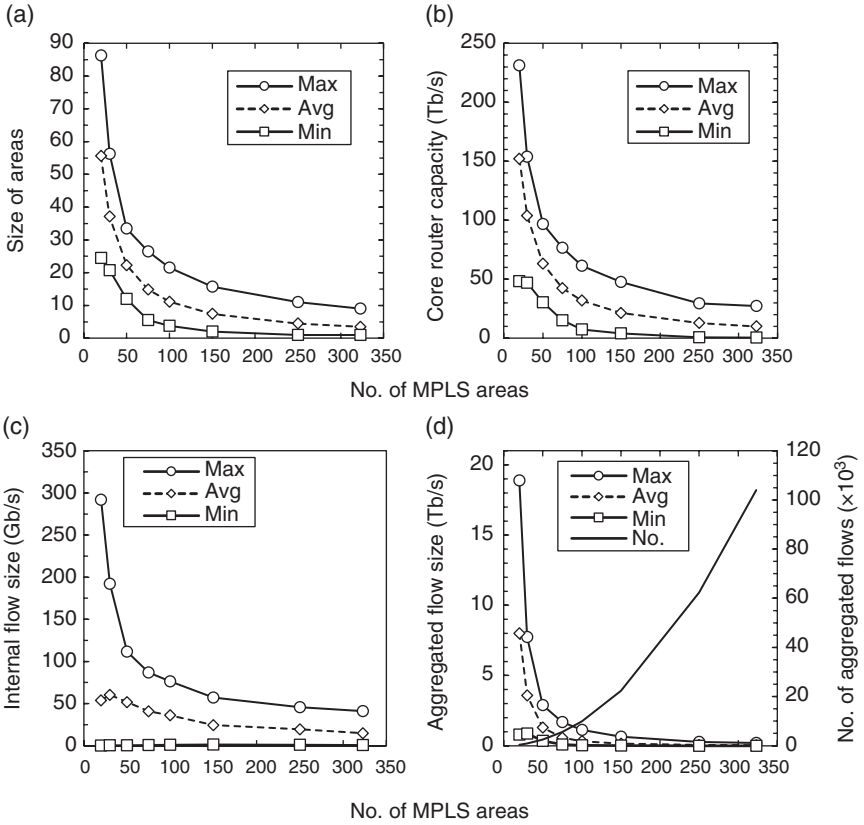


Figure 1.3 Details of the solutions against the number of MPLS areas: (a) size of the areas, (b) switching capacity of core MPLS routers, (c) size of the internal data flows, and (d) size of the aggregated data flows.

Table 1.1 Solutions details (network spectral efficiency = 0.8).

		WDM	EON
Number of IP/MPLS areas		116	216
Areas size	Max	19.66	15.04
	Avg	9.94	5.46
Core router capacity (Tb/s)	Max	58.0	35.3
	Avg	28.5	15.7
Area flows (Gb/s)	Max	72.33	50.52
	Avg	32.68	21.12
Aggregated flows (Gb/s)	Max	989.06	404.51
	Avg	264.95	82.73
	#	13,884	48,684

Finally, Figure 1.3d examines the size of the aggregated data flows in the optical core network. When the number of areas is low, the size of the aggregated flows is quite large, but the overall size of the traffic matrix is quite small: the largest flow conveys 1 Tb/s and there are 13,880 aggregated data flows when WDM is used. In this case, since the largest capacity that WDM network can convey is usually limited to 100 Gb/s, each 1 Tb/s flow has to be split into 10×100 Gb/s flows, which increases aggregated data flow count to 138,800.

In comparison, when the number of areas is larger in the case of EON, the size of the largest flow is smaller, but the size of the core network traffic matrix is very large: the largest flow conveys 400 Gb/s, but there are as many as 48,000 aggregated data flows.

As a conclusion, simpler and smaller MPLS areas containing 10–15 locations are enough to obtain good spectral efficiency when the EON-based core network are implemented. In addition, large aggregated flows need to be conveyed by the optical core network, which entails a rather limited traffic dynamicity and explains why these networks are configured and managed statically. As a result, long planning cycles are used to upgrade the network and prepare it for the next planning period. Aiming at guaranteeing that the network can support the forecast traffic and deal with failure scenarios, spare capacity is usually installed, thus increasing network CAPEX. Moreover, note that results from network capacity planning are deployed manually in the network, which limits the network agility.

However, the scenario is rapidly changing because of the maturity of the Internet of services, where cloud providers play a critical role in making services accessible to end-users by deploying platforms and services in their datacenters (DCs). The new model and the requirements derived from cloud services are contributing to the increasing amount of data that require connectivity from transport networks. Evolution toward cloud-ready transport networks entails dynamically controlling network resources, considering cloud requests in the network configuration process. Hence, that evolution is based on elastic data, control, and management planes.

In a scenario where dynamic capabilities are available, the network can be reconfigured and reoptimized in an automatic fashion in response to traffic changes. Hence, resource overprovisioning can be minimized, which reduces overall network costs; this was called as *in-operation network planning* in [Ve14.2].

In fact, network operators are deploying their own small DCs and integrating them into their networks to provide ultra-low latency new generation services, such as cloud computing or video distribution. The so-called *Telecom Cloud* infrastructure [Ve15] must support a large number of small, distributed DCs placed close to the end-users to reduce traffic in the core network and to provide services and applications that can take advantage from very low latency (Figure 1.4).

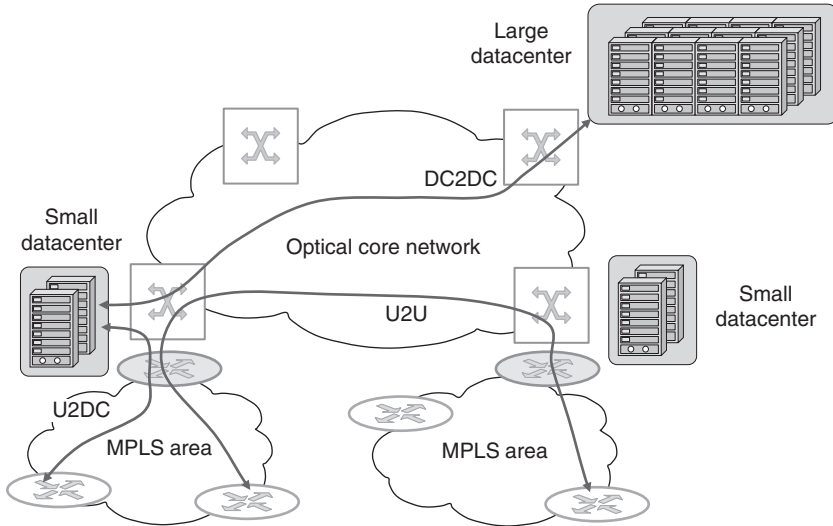


Figure 1.4 Distributed DC connected through an EON.

To support content distribution, digital contents, for example, films, need to be available in the DCs, so connectivity among DCs (DC2DC) and from users in the metro areas to the DCs (U2DC) are needed in the telecom cloud. Note that this is in addition to the connectivity among MPLS areas (denoted as U2U in Figure 1.4) considered in the previous study. In fact, the core optical network must support dynamic connectivity and time-varying traffic capacities, which might also entail changes in the traffic direction along the day.

This book is devoted to reviewing algorithms to solve provisioning problems, as well as in-operation network planning problems aiming at enhancing the performance of EONs. The feasibility of those algorithms is also validated in experimental environments.

In-operation network planning requires an architecture enabling the deployment of algorithms that must be solved in stringent times. That architecture can be based on a Path Computation Element (PCE) or a Software Defined Networks (SDN) controller. In both cases, a specialized planning tool is proposed to be responsible for solving in-operation planning problems efficiently. After the architecture to support provisioning and in-operation planning is assessed, we focus on studying a number of applications in single layer and multilayer scenarios.

The methodology followed in the book consists in proposing a problem statement and a mathematical formulation for the problems and, then, presenting algorithms for solving them. Next, performance evaluation results from the simulation are presented including a comparison of results for

different scenarios and architectures. In addition, experimental assessment is carried out on realistic testbeds.

In this book we will cover the topics discussed earlier and present:

- Provisioning point to point, anycast, and multicast connections, as well as transfer-based connections for DC interconnection in single layer EON.
- Recovery connections from failures and in-operation planning in single layer EON.
- Virtual network topology (VNT) reconfiguration and recovery in multilayer MPLS-over-EON scenarios.
- New topics currently under extensive research, including high capacity optical networks based on space division multiplexing (SDM), provisioning Customer Virtual Networks (CVNs), and the use of data analytics to bring cognition to the network.

1.2 Book Outline

The remainder of this book is organized into five parts. Part I includes Chapters 2–4 and gives an overview of the concepts that will be used along the book. Part II includes Chapters 5–7 and focuses on provisioning aspects in single layer EONs. Part III includes Chapters 8–10 and centers on recovery and in-operation planning issues in single layer EONs. Part IV includes Chapters 11 and 12 and targets at recovery and in-operation planning problems in multi-layer MPLS-over-EON. Finally, Part V includes Chapters 13–15 and presents future trends of optical networks.

Chapter 2 briefly introduces the main background of graph theory and optimization and their application to model a very basic routing problem following several approaches. Basic heuristic methods are introduced, and the two meta-heuristics commonly used throughout the book are presented. In addition, main concepts of the optical technology and networks' planning and operation, including provisioning and recovery, are reviewed.

Chapter 3 is devoted to the *routing and spectrum allocation* (RSA) problem. Regardless of additional constraints, the RSA problem involves two main constraints for spectrum allocation: *continuity* and the *contiguity* constraints. These two constraints highly increase the complexity of the optimization, so it is crucial that efficient methods are available to allow solving realistic problem instances in practical times. This chapter reviews several Integer Linear Programming (ILP) formulations of the RSA problem and evaluates the computational time to solve a basic offline problem. The basic RSA problem is extended to consider the capability of selecting the required modulation format among the available ones, and, therefore, the routing, modulation, and spectrum allocation (RMSA) problem is presented. This chapter is based on the work in [Ve12.1], [Ve14.1], and [Ve17].

Chapter 4 reviews control and management architectures to allow the network to be dynamically operated, as well as the capabilities of the Application-based Network Operations (ABNO) architecture proposed by the Internet Engineering Task Force (IETF). Using these dynamicity capabilities, the network can be reconfigured and reoptimized automatically in response to traffic changes. Nonetheless, dynamic connectivity is not enough to guarantee elastic DC operations and might lead to poor performance provided that not enough overprovisioning of network resources is performed. To alleviate it to some extent, the ability of EONs can be used to dynamically increase and decrease the amount of optical resources assigned to connections. This chapter is based on the work in [Ve14.2], [Gi14.1], [Ma14], and [Ve13.2].

Assuming traffic dynamicity, Chapter 5 presents basic algorithms for dynamic point-to-point (P2P) connection provisioning in EONs and extends their scope to deal with modulation formats and with dynamic spectrum adaptation, that is, elasticity. This chapter is based on the work in [Ca12.2], [Ca12.3], and [As13].

Chapter 6 presumes a DC interconnection scenario and proposes an Application Service Orchestrator (ASO) as an intermediate layer between the cloud and the network. In this architecture, DC resource managers request data transferences using an application-oriented semantic. Then, those requests are transformed into connection requests and forwarded to the ABNO in charge of the transport network. The proposed ASO can perform elastic operations on already established connections supporting transferences provided that the committed completion time is ensured. This chapter is based on the work in [Ve14.3] and [As14].

Chapter 7 explores the scenario where data needs to be conveyed from one source to multiple destinations or from one source to any destination among multiple destinations, for example, for database synchronization or content distribution. The point-to-multipoint (P2MP) RSA problem is proposed to find feasible light-trees to serve multicast demands, as well as the anycast RSA problem to find a feasible lightpath to one of the destinations. This chapter is based on the work in [Ru14.2], [Ru15], [Gi15.1], and [Gi16].

Dynamic operation of EONs might cause the optical spectrum to be divided into fragments, making it difficult to find a contiguous spectrum of the required width for incoming connection requests. To alleviate spectrum fragmentation to some extent, Chapter 8 proposes applying spectrum defragmentation, triggered before an incoming connection request is blocked, to change the spectrum allocation of already established optical connections, so as to make room for the new connection. This chapter is based on the work in [Ca12.2] and [Gi14.2].

Chapter 9 explores P2P connection recovery schemes specifically designed for EONs, in particular taking advantage of SBVTs. The bitrate squeezing and multipath restoration problem is proposed to improve restorability of large

bitrate connections. Next, that problem is extended by considering modulation formats and transponder availability. Finally, recovery for anycast optical connections is studied. This chapter is based on the work in [Ca12.1], [Pa14], [Gi15.2], and [Gi16].

When a link that had failed is finally repaired, its capacity becomes available for new connections, which increases the difference between lightly and heavily loaded links and decreases the probability of finding optical paths with continuous and contiguous spectrum for future connection requests. Chapter 10 studies the effects of reoptimizing the network after a link failure has been repaired. The problem is extended to consider scenarios where bitrate squeezing and multipath restoration had been applied after the failure. This chapter is based on the work in [Zo15] and [Gi15.3].

In the context of multilayer MPLS-over-EON networks, the introduction of new services requiring large and dynamic bitrate connectivity might cause changes in the direction of the traffic along the day. This leads to large overprovisioning in statically managed VNTs designed to cope with the traffic forecast. To reduce expenses while ensuring the required grade of service, Chapter 11 proposes the VNT reconfiguration based on real traffic measurements that regularly reconfigures the VNT for the next period to adapt the topology to the expected traffic volume and direction. This chapter is based on the work in [Mo17].

In multilayer networks, an optical link failure may cause the disruption of multiple aggregated MPLS connections. Thereby, efficient recovery schemes, such as multilayer restoration and survivable VNT design, are required. Chapter 12 focuses on such issues, specifically on multilayer MPLS-over-EON operated with a Generalized Multi-Protocol Label Switching (GMPLS) control plane, where a centralized PCE is in charge of computing the route of MPLS connections. As for survivable VNT design connecting DCs, Chapter 12 focuses on both, the problem of designing VNTs to ensure that any single failure in the optical layer will affect one single virtual link (vlink) at the most and providing a VNT mechanism that reconnects the VNT in the case of vlink failure. This chapter is based on the work in [Ca13], [Ca14], and [Gi16].

Chapter 13 reviews the recent progress in the development of SDM-based optical networks and describes the enabling technologies, including fibers and switches, for the efficient realization of such networks. It is unquestionable that the efficient use of the space domain requires some form of spatial integration of network elements. Particularly, this chapter describes three switching paradigms, which are highly correlated with three fiber categories proposed for SDM networks. This chapter is based on the work in [Kh16], [Sh16.2], and [Sh16.4].

In the context of future mobile networks, Chapter 14 studies dynamic CVNs to support the Cloud Radio Access Networks (C-RAN) architecture. CVN reconfiguration needs to be supported in both metro and core network

segments and must include Quality of Service (QoS) constraints to ensure specific delay requirements, as well as bitrate guarantees to avoid service interruption. This chapter is based on the work in [As16.2].

Finally, Chapter 15 explores the interesting and challenging data analytics discipline that finds patterns in heterogeneous data coming from monitoring the data plane, for example, received power and errors in the optical layer or service traffic in the MPLS layer. The output of data analytics can be used for automating network operation and reconfiguration, detecting traffic anomalies, or transmission degradation. This way of doing network management is collectively known as the *observe–analyze–act* (OAA) loop since it links together monitoring, data analytics, and operation (with or without reoptimization). Chapter 15 illustrates the OAA loop by applying it to a variety of use cases that result into a proposed architecture based on ABNO to support the OAA loop in EONs. This chapter is based on the work in [Va16], [Ru16.2], [Mo17], and [Ve17].

1.3 Book Itineraries

A quick reading of the table of contents of any chapter in this book is enough to realize the large variety of contents that they cover, including a description of new concepts and ideas, mathematical programming formulations, heuristic algorithms, simulation results, and experimental assessment details. We definitely understand that a potential reader would be interested in focusing on only part of the contents while skipping others that are far of his/her interests and skills. For this very reason, we devised the following tracks designed to cope with the expectations of three archetype readers:

- *Average reader track*: this track is conceived for the reader interested in the main concepts and ideas that each chapter tackles. Introductory subsections about the descriptions of the problems as well as a minimum notion of the algorithmic methods used are recommended. Additionally, those performance results required to fully understand subsequent key conclusions are considered in this track. We understand that this track contains the essentials of the book; therefore, it can be explored by either an uninitiated reader demanding a broad panorama of the book topics or an advanced reader for the first approach.
- *Theoretical reader track*: this track extends the contents recommended for the average reader with those related to the models and algorithms behind the proposed concepts and ideas. Mathematical programming formulations and pseudo-codes for heuristic algorithms are extensively presented within this track, as well as those results strictly related to algorithms' performance. Advanced readers looking for detailed answers about book contributions are encouraged to follow this track.

- *Practitioner reader track*: this track is intended for the reader interested in the implementation of the methods and their experimental assessment (the most singular contents of this track). It is worth noting that part of the contents recommended in the previous tracks is included in this one, for example, the basics of the presented concepts. However, only those mathematical and algorithmic methods that are finally validated by means of experimental assessment are usually included in this track.

At the beginning of each chapter, the itinerary of each track through the sections and subsections is provided together with the table of contents. With this kind suggestion, we hope that reading this book will be more comfortable and will closely fit with readers' interests and skills.

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