Planning Fixed to Flexgrid Gradual Migration: Drivers and Open Issues

Marc Ruiz and Luis Velasco, Universitat Politècnica de Catalunya

Andrew Lord, British Telecom Innovate & Design

Daniel Fonseca, Coriant Portugal

Michal Pióro, Warsaw University of Technology

Roland Wessäly, atesio

Juan P. Fernández-Palacios, Telefónica Investigación y Desarrollo

ABSTRACT

Flexgrid technology has recently been presented as the most promising option for upgrading the currently operating fixed grid optical networks and extending their capacity to be able to deal with the massive traffic volumes forecast for the next decade. Although the current traffic is successfully supported on fixed grid networks, flexgrid technology brings features that are not offered by the fixed grid networks, such as transporting optical connections with a capacity beyond 100 Gb/s and elasticity against time-varying traffic. In light of this, a gradual fixed grid to flexgrid migration is generally accepted in order to add these useful features to the network. In this article, we study the migration process where flexgrid is deployed in the network progressively, and review the main drivers and open issues induced by its deployment.

INTRODUCTION

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 slots with 6.25 GHz central frequency granularity in contrast to the coarser 50 GHz in fixed grid [1]. Such frequency slots can be combined in groups of contiguous slots to form channels with 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 channel in a flexgrid network with the 12.5 GHz grid, instead of the 50 GHz needed with fixed grid.

In addition to increasing network capacity, subsystems currently being developed will foster devising novel network architectures. These are:
• Liquid crystal on silicon (LCoS)-based wave-length selective switches (WSSs) to build flexgrid-ready optical cross-connects (OXCs) [2]
• The development of advanced modulation formats to increase efficiency and capable of extending the reach of optical signals [3]
• Sliceable bandwidth-variable transponders (SBVTs) able to deal with several flows in parallel, thus adding even more flexibility and reducing costs [4]

The resulting flexgrid networks will allow mixing optical connections of different bit rates (e.g., 10, 40, 100 Gb/s) by allocating frequency slots and using different modulation formats such as 16-state quadrature amplitude modulation (16-QAM) or DP-QPSK more flexibly. Furthermore, larger bit rates (e.g., 400 Gb/s or even 1 Tb/s) can be conceived by extending the channel width beyond 50 GHz. In addition, the capability to elastically allocate frequency slots on demand and/or modify the modulation format of optical connections according to traffic demands allows resources to be used efficiently in response to traffic variations.

While all these concepts appear to add some benefit, it is very unlikely that they all will be required across the entire network on day one. Some operators are currently evolving their core networks from 10 Gb/s using direct modulation to 40 and 100 Gb/s using coherent detection, and the added capacity will be sufficient for several years. In fact, recent studies show that expected traffic volumes for the short and medium terms (a few terabits per second of total traffic) are not enough to justify deploying flexgrid. For example, the authors in [5] estimate that capacity exhaustion in current fixed grid-based network will not occur before 2019. Notwithstanding, as also concluded in [5], current spectrum capacity operated with flexgrid could extend network lifetime.

Starting from a network with enough capacity, the most likely scenario is that some links in the network grow more quickly than others and

become congested, acting as bottlenecks to future network growth. It is in those links where flexgrid can be first deployed to extend network lifetime.

A migration strategy is thus required so that new technology can be introduced where it has most benefit, without having to start again with a new network build [6]. Unfortunately, such a migration has been infeasible in the past, mainly due to the lack of interoperability between old and new network technologies. There are, however, some synergies between fixed grid and flexgrid, partly due to the potential of coherent transmission and flexgrid WSSs. Therefore, this opens the possibility to follow a gradual migration of the network.

The expected benefits of a gradual migration approach are manifold, for example:

• Increase the capacity of specific links in the network where bottlenecks appear
• Use higher bit rates (400 Gb/s and beyond) and advanced modulation formats for specific connections
• Take advantage of elasticity in those areas with high traffic variations
• Reduce the economic impact by distributing expenses rather than paying up front

Only a small amount of attention has been given to the important problem of migration. Recent works [6, 7] give some of the limited work in this area, using techniques such as real options and multi-period planning. These can tackle the general question, but the key questions of which parts of a given network should be upgraded, and when, need to be addressed. To handle the enormous complexities thrown up by these difficult questions, a strong planning tool with in-built scope to explore migration questions is required. As this becomes a more important topic, and as more operators ask the questions expressed above, we will start to see significantly more work published in this area.

MIGRATING TOWARD FLEXGRID TECHNOLOGY

Current national European fixed grid networks are small, typically less than 50 nodes. As traffic grows, some of the core network links will become congested, and critical questions arise: Is it worth simply upgrading the bottleneck links to be flexgrid enabled? Would a parallel fiber be a better option for these links? If the bottleneck links are not connected, does this reduce the benefits due to the inability to have a flexgrid path between them? And therefore, does it make more sense to introduce islands of flexgrid capability, and if so, where would those islands be, how large should they be to be of benefit, and at what stage should they be introduced?

A further question involves looking at the overall network architecture including access, metro, and core nodes. National networks could potentially involve connecting several hundreds or even 1000 nodes, and this is logically separated between metro/backhaul and metro/core fixed grid, with electrical aggregation at the interface. Recent work [8] has shown that flexgrid architectures have a very different sweet spot from fixed grid. This implies that the future network might migrate in a way that begins with a small core, but gradually grows to a larger one, reducing metro/backhaul clusters.

Many operators structure their core networks in single-vendor subdomains, and in some cases optical transparency is not a requirement between such subdomains. In such scenarios, each subdomain can have its own migration strategy. However, when transparency is needed for some long-haul connections passing through domains with different technologies, the spectrum adaptability in flexgrid islands poses no additional constraints on the more restrictive spectrum allocation in the fixed domains.

The latest installed fixed grid OXCs are already equipped with LCoS-based WSSs. In most cases, the installed LCoS-based WSSs are prepared to operate in flexgrid as the price difference compared to non-flexgrid LCoS is reduced, allowing switching channels of variable sizes and thus facilitating the migration toward flexgrid. In such cases, migrating fixed grid OXCs equipped with LCoS-based WSSs can be done, in general, by upgrading the software, resulting in low-cost migration. Older OXCs, however, are equipped with WSSs based on micro-electromechanical systems (MEMS) or non-flexgrid LCoS-based WSSs. Many of those OXCs can be migrated to flexgrid by just replacing the WSSs, as the remaining hardware existing in the optical nodes is automatically flexgrid in nature (optical amplifiers, splitters, etc.) or, alternatively, coexist in the network with flexgrid-ready OXCs. Such solutions present a flexible approach for operators to migrate to flexgrid, presenting alternatives to complete OXC replacement.

Figure 1 illustrates three intermediate scenarios that might appear when migrating the core network to flexgrid. Subnetwork upgrading consists of migrating a set of connected OXCs to flexgrid, increasing the capacity in that part of the network. Some other parts of the network could need enlargement, and thus, new flexgrid-ready OXCs can be installed. Finally, the core network can be extended toward the metro by replacing metro nodes with flexgrid-ready OXCs.

A preliminary evaluation of the expected gains of this migration strategy can be done by reviewing some key results in recently published works. The authors in [9] show capacity increments as high as 200 percent when flexgrid is used. This overall gain, however, cannot be equally distributed among all network links, since numerical results illustrate the large disparity between low and high loaded fibers. Thus, a partial migration of only those highest loaded links will lead to benefits in the range described above with the subsequent capital expenditures (CAPEX) savings. Additionally, the authors in [8] reported around 30 percent CAPEX savings when extending the core network to metro areas by means of deploying new flexgrid equipment.

If we look at the optical spectrum, a mix of optical connections needs to coexist as a consequence of the creation of flexgrid islands. Figure 2 shows some examples. In Fig. 2a a fiber link is represented where two DP-QPSK 40 Gb/s optical connections (A and B) are transported in 50

Figure 1. *Migration scenarios creating flexgrid islands.*

GHz channels. Figure 2b shows the case where the link is now inside a flexgrid island and both connections end in OXCs inside that island. In such a case, existing connections transported in 25 GHz channels are shifted and the optical spectrum is defragmented [10]. In the case where the link transport connections end outside of the flexgrid island, those connections need to be transported transparently, although they can coexist with flexgrid connecting OXCs inside the island.

Figure 2c shows a case where connection A ends in OXCs outside the flexgrid island, whereas connection B ends in flexgrid OXCs, and has been elastically increased from 40 Gb/s to 400 Gb/s and transported in a 75 GHz channel [11].

Finally, Fig. 2d shows an example where fixed grid connections A and B are transported transparently through the flexgrid island and coexist with flexgrid connections C and D. Although in the example connection D uses a portion of the fixed channel allocated for connection B, the latter will be dropped inside the flexgrid island.

BVTs allow extending resource adaptability to actual traffic needs since they are able to tune their bandwidth by adjusting their transmission bit rate and modulation format. However, the total capacity of the BVT is efficiently used when the connection bit rate is close to the maximum rate of the transponder; otherwise, the remaining capacity is not used [4]. SBVTs have recently been introduced to allow a single transponder to be shared by several connections provided that its total capacity is not exceeded.

An SVBT can be built with the same basic configuration of BVTs (i.e., multiple light sources, modulators, optical filters, and a coupler), but including tuning to allow the transmission of multiple carriers toward different destinations using different spectral allocations. Photonic integrated circuits allow multiple carriers to be included in the same component, which in turn can be set up independently selecting the proper modulation format. Therefore, the availability of commercial SBVTs in the near future seems to be likely. The advent of commercial SBVT technology in the medium term will be crucial to increase the reach of flexgrid areas to

those parts where, although spectrum will not be exhausted yet, the capability of splitting multiple flows into SBVTs will be beneficial.
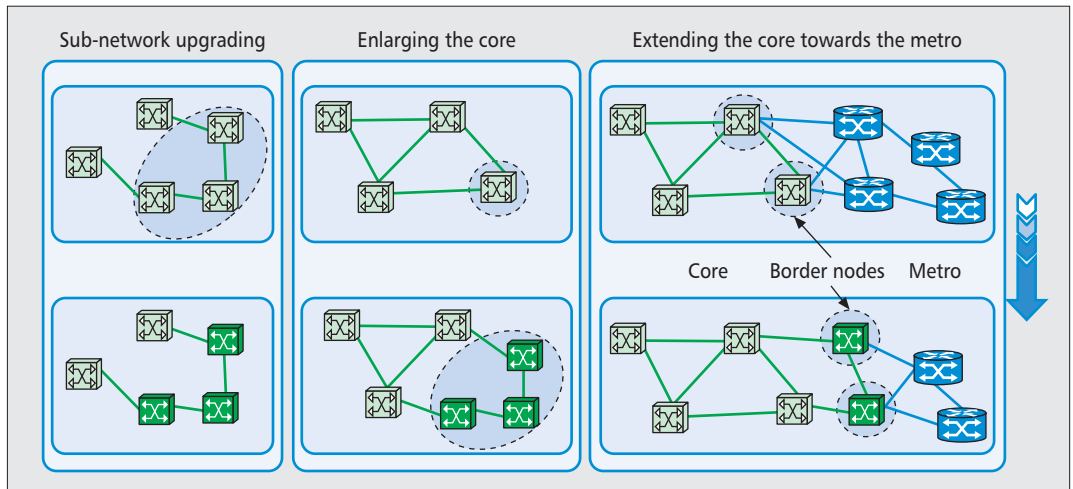
In the long term, capacity exhaustion as a result of dealing with expected traffic volumes of hundreds of terabits per second will definitely require deploying flexgrid in the network, possibly on different network architectures. For that future, legacy fixed grid equipment would be completely upgraded to flexgrid in the core. Table 1 illustrates an example of gradual migration.

MIGRATION PLANNING

As anticipated in the introduction, migration to flexgrid technology as a set of gradual consecutive upgrading steps cannot be planned at the starting time because of several aspects, such as traffic uncertainty, which make it impossible to compute precise solutions for the future. As a result, solving each migration step taking as input precise data for the next period seems to be the most practical way to deal with the migration problem.

Figure 3 shows the migration flow chart considered in this work, where the following list of inputs involved in the process is assumed:
- The network management system (NMS) managing the core network, implementing fault, configuration, administration, performance, and security (FCAPS) functions
- A planning department administrating the planning process (i.e., analyzing the network performance and finding bottlenecks, receiving potential clients' needs, evaluating network extensions and new architecture, etc.)
- An inventory database containing all equipment already installed in the network, regardless whether or not they are in operation
- An engineering department, performing actions related to equipment installation and setup
- A planning tool in charge of computing solutions for each migration step
Several sub-problems related to network recon-

	Short term (2014–2016)	Medium term (2017–2019)	Long term (> 2020)
Key driver	Cost-effective 400 Gb/s signals	Sliceable BVT	Full capacity exploitation
Migration action	Highly congested network areas	Extensive network areas	Legacy fixed grid equipment
CAPEX	Low	Moderate	Moderate

Table 1. *Example of gradual migration from fixed to flexgrid.*
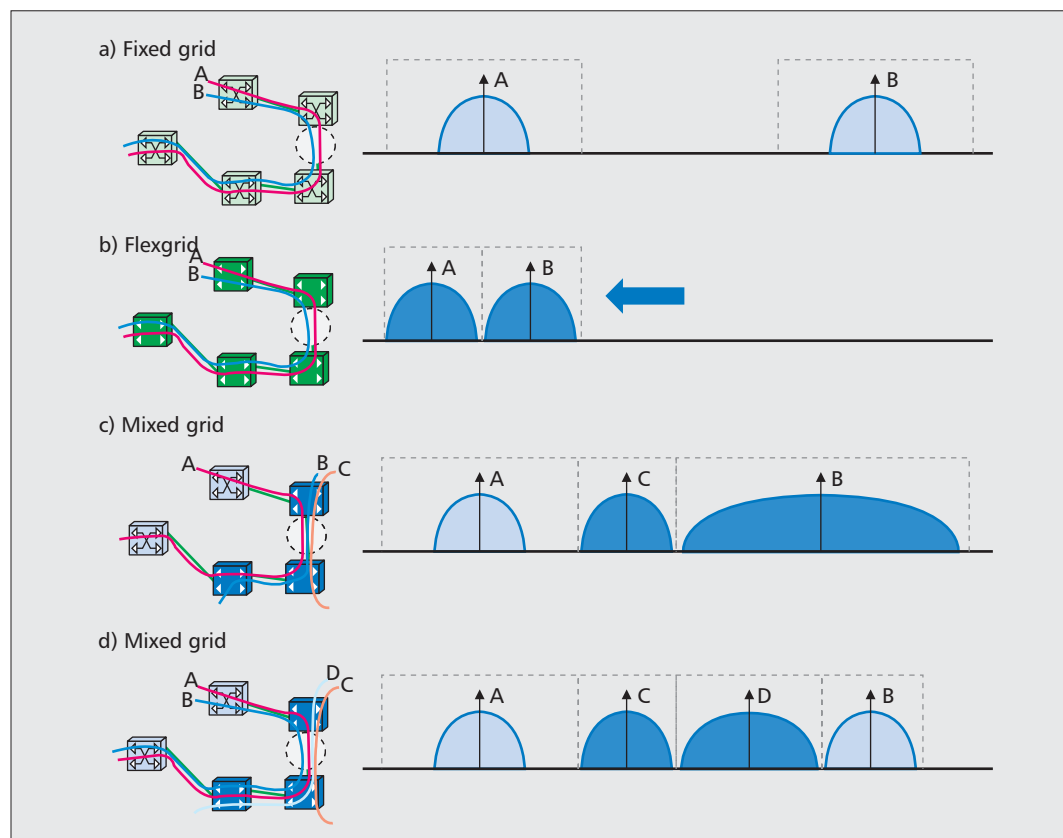

Figure 2. *Migrating connections and mixed scenarios.*

figuration, planning, and dimensioning, among others, need to be solved.

We consider that a migration step begins when the planning tool receives a request that can be originated in different systems responding to different reasons:

• Operators analyzing data gathered by the NMS detect that a migration step can be attempted to improve the performance of the current network. For example, bottlenecks have been detected in some parts of the network, and its current configuration will not be able to allocate expected traffic, so *reconfiguration* can be attempted. Note that these triggers arise asynchronously (i.e., without a predefined schedule).

• Planners request network replanning to serve new clients or cover new areas. Contrary to reconfigurations coming from NMS, *planning requests* can be better synchronized with other network departments, such as the engineering department.

The planning tool solves the migration problem in two phases. First, the *network reconfiguration* aims at reconfiguring the existing network resources and served traffic to meet target requirements. The solution of this problem consists in a set of actions that can be done in the network without purchasing and installing new flexgrid equipment. Therefore, the aim of this process is to exploit the possibilities of the currently available resources as much as possible before purchasing and installing new equipment.

Among others, some of the possible actions that could form a solution of this reconfiguration phase are:

• Modifying the physical intra-connectivity at central stations

• Moving physical devices (e.g., transponders, from one location to another in a different part of the network)

• Set up and tear down optical connections

Additionally, already purchased and installed network resources not yet activated can be put in operation in this phase. Thus, the reconfiguration process should process inventory data to
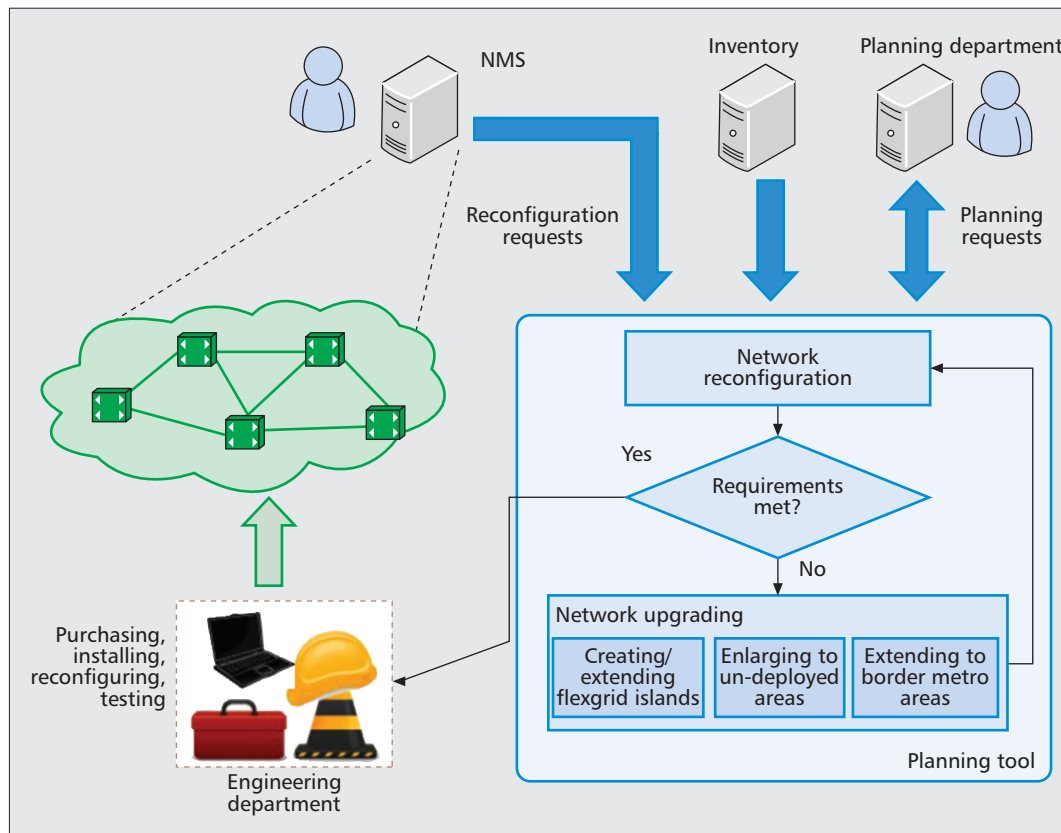
Figure 3. *Migration flow chart.*

decide whether some of these resources must be activated or not. It is worth highlighting that to implement such reconfigurations, the engineering department needs to perform manual actions that need to be scheduled and therefore not immediately processed. In fact, these manual interventions are usually performed during low activity periods since they might require temporally cutting some services, and therefore the whole reconfiguration process might last several weeks.

In the case when network reconfiguration is not sufficient to fulfill all the requirements, the network upgrading process, the second phase of the migration problem, is started. Network upgrading involves several network planning and dimensioning subproblems, such as migrating selected regions to flexgrid, enlarging the network to cover new areas, extending the core toward the borders, and more. Obviously, the overall objective is to find solutions minimizing the total cost of the migration, including purchasing, installing, and configuring new equipment.

When a solution is found, the reconfiguration phase is invoked to guarantee that all the requirements can be met. If the solution is acceptable, it usually requires to be accepted by operators at the planning department, who then send it to the engineering department, which, in turn, organizes and schedules the set of processes that will physically implement the solution in the network. Although this whole process may take several weeks or even months to be completed, a new migration request can be started as

soon as a subset of the new equipment is installed to partially reconfigure the network.

OPTIMIZATION ISSUES

Needless to say, the optimization subproblems resulting from the above characterized migration process are computationally hard, and this issue becomes profound in the large-scale networks with which we typically deal.

Both network reconfiguration and network upgrading phases require solving the routing and spectrum allocation (RSA) problem (which belongs to the class of so-called NP-hard computational problems) to ensure that the forecast traffic will be served in the planned network [12]. The difficulty of RSA is increased by the necessity of taking into consideration specific characteristics of equipment modules. To be able to optimize the network configuration in a guaranteed cost-efficient way, we need to use integer programming methods, that is, optimization problem formulations involving decision variables that assume discrete (typically binary) values.

Already developed optimization techniques to solve the routing and wavelength assignment (RWA) for fixed grid networks need to be enhanced to develop effective planning tools for flexgrid; the contiguity constraint for spectrum allocation makes the so-called linear relaxations of the considered integer programming formulations ineffective. Compared to the fixed grid case, this makes the fundamental technique of integer programming, the branch-and-bound algorithm, less effective in flexgrid.

Efficient solving of integer programming formulations heavily relies on using professional general-purpose solvers available on the market. Modern solvers often perform astonishingly efficiently and outperform specialized computer programs implemented for specific problems. The solvers apply sophisticated branching, bounding, and cutting techniques in combination with extremely efficient linear programming solvers and are constantly improved. It is worth mentioning that contemporary solvers are more than one million times faster than by the end of the 1980s, when such solvers first appeared; half is due to computer hardware, and the other half to improvement of the algorithms.

Improving the quality of formulations and using appropriately tailored decomposition techniques to optimization problem formulations can substantially improve the overall planning tool performance beyond the standard use of the solvers. In particular, such techniques as column generation, Lagrangean relaxation, and Benders decomposition [13–15] are of interest:

- Column generation is required for generating paths in the so-called path-flow formulations of network optimization problems. Its efficiency for solving RSA-based problems was recently demonstrated in [15].
- Lagrangean relaxation can improve lower bounds on the objective function (typically expressing the cost of equipment to be installed), the quality of which is decisive for the effectiveness of branch-and-bound.
- Benders decomposition and other decomposition methods are necessary to cope with large-scale networks involving hundreds of thousands of decision variables.

Despite these promising developments, heuristic optimization methods are still important and even unavoidable for the considered planning purposes [8]. Their importance is threefold. First, heuristic methods usually do not require optimization solvers. Second, heuristics are able to deliver feasible network solutions even for very large-scale networks in a reasonable time. Even though the solutions thus obtained can be far from optimal, they provide upper bounds for the minimal cost of feasible network configurations. This is particularly valuable when exact solution methods are not available. Finally, heuristic solutions can speed up the exact branch-and-bound algorithm just because they give the upper bound information in a short time.

Designing a planning tool supporting strategic decision making, migration planning, and (re-)configuration planning is a complex issue. As the technology is to be planned, such a tool needs to be very flexible itself. In particular, for migration and (re-)configuration planning it needs to be able to deal with legacy equipment and the existing network configuration; on the other hand, it has to provide particular algorithms to optimally design cost-efficient flexgrid networks. Such a service-oriented network modeling and planning tool should be built using several loosely coupled system components, as shown in Fig. 4.

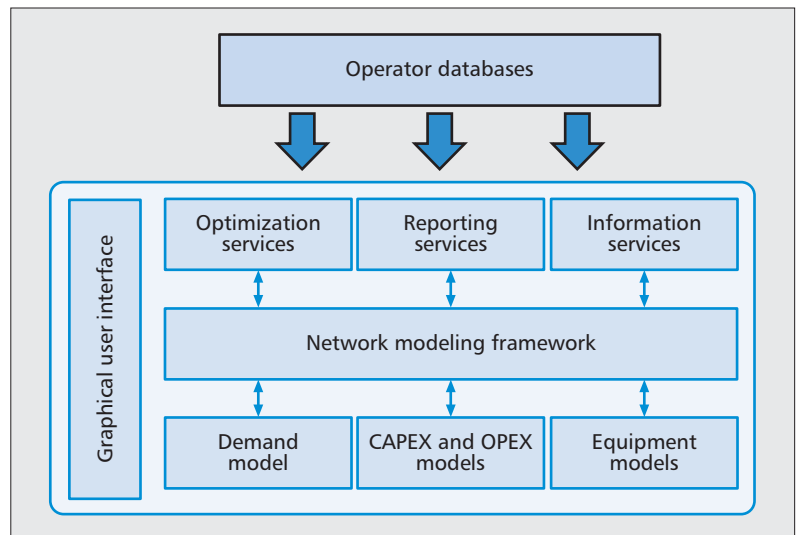**Network modeling framework:** This represents all equipment and connections. This com-

Figure 4. *Typical planning tool modules.*

ponent builds the core of the network modeling and planning tool and can also store historic data.

Services: The core concept of the tool is to design the network in a service oriented way. Any configuration task, any optimization question, any analysis of the current configuration (e.g., consistency, availability, recovery against failures, usage or waste of network resources) can be seen as a "service" to the user of the planning tool. In particular, it should be possible for the implementation of individual services to be done by different software vendors. Since not every vendor of a planning tool is the optimal choice for all planning and optimization tasks, it should be possible to plug together the best-of-breed services. Eventually, the connection of the network modeling and planning tool to live operator databases, such as the different NMSs, inventory, and/or performance and fault management systems, should be realized as services.

Demand/cost/equipment model: These three issues could be seen as part of the network modeling framework but are mentioned separately because of their distinguished role and since various services for optimization and analysis can be run using the same network but with different demand, costs, or equipment models.

(Geo-)graphical visualization: The input, the parameters, and all results need to be visualized in order to support easier editing as well as easier understanding of users.

To the best of our knowledge, such an adaptable service-oriented network planning tool is not available — not for the planning and optimization of today's legacy networks and particularly not for (future) optical networks based on flexgrid technology. Instead, the larger incumbent network operators typically have "huge" network planning tools that often are based on a slow and inflexible geographic information system (GIS). The GIS system dictates more of what can be solved as planning and optimization tasks than what should be provided as functionality. These systems are complex, difficult to maintain, and often supplied by a single software vendor. The latter is critical itself, but even more

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so if the supplier's core competences are in handling large databases and visualization of geodata (and not in networks and optimization). The nature of these planning tools is that today's manual and cumbersome planning steps are supported — they are more computer-aided network drawing systems.

As a way out of this dilemma, we suggest that the fundamental change in the network architecture (complete restructuring of the network structure, including the introduction of flexgrid technology in the optical domain) should also be seen as a chance to make a change from manual to automatic planning and optimization; the network planning tool should be a planning assistance system where the planner gets the role of a pilot who gives the directions and sets the rules, while the planning assistance systems supports with different suggestions how to fulfill the requirements in a cost-effective way, and after assessment, the planner chooses the best suggestion.

SUMMARY

A gradual migration process from fixed grid to flexgrid technology has been presented as the way to upgrade core optical networks. The main features of flexgrid have been presented as key drivers for its potential deployment in the short, medium, and long terms, thus introducing the need for a progressive migration. The main flow of the migration problem has been described, as well as the architecture and relationship of all network elements involved in this process.

Since solving the whole migration problem becomes very complex, some techniques that could be used to develop tools to solve the related optimization subproblems have been reviewed. A high-level description of the architecture of planning tools solving the migration problem has, eventually, been introduced.

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BIOGRAPHIES

MARC RUIZ (mruiz@ac.upc.edu) is a research fellow at the Optical Communications Group (GCO) of Universitat Politècnica de Catalunya (UPC). He received his M.Sc. degree in statistics and operational research and Ph.D. degree in computer science from UPC in 2009 and 2012, respectively. His research interest includes optimization and performance of next generation optical networks.

ANDREW LORD graduated in physics from Oxford University in 1985, joining British Telecom. He has been involved in all major transport network designs as well as transmission and network research, including many large EU projects. He is currently head of BT's optical research. He is also a visiting professor at Essex University and Technical Program Co-Chair for OFC 2015.

DANIEL FONSECA is the research manager for network optimization topics in Coriant Portugal (previously the optical division of Nokia Siemens Networks). He joined the Siemens group in 2000 and since then has held several positions in research and development departments related to optical networking. His current research topics are multi-layer optimization and optical transmission design.

MICHAL PIÓRO is a professor in telecommunications at Warsaw University of Technology, Poland, and Lund University, Sweden. His research interests focus on network modeling, optimization, and performance evaluation. He is an author of a monograph *Routing, Flow, and Capacity Design in Communication and Computer Networks* (Morgan-Kaufmann, 2004) and over 200 research papers in the field. He is deeply engaged in European research projects dealing with telecommunication networks.

ROLAND WESSÄLY is managing director of the optimization company atesio, a spin-off of the mathematical research center ZIB in Berlin. Before founding atesio in 2000, he studied mathematics and received the Vodafone Innovations Award for fundamental contributions to the cost-optimal design of survivable communication networks. Within atesio he is, among other areas, responsible for the cost optimization (software) of FTTx networks, multi-layer transport networks, as well as the integrated architecture optimization of core and metro networks.

LUIS VELASCO received his M.Sc. degree in physics from Universidad Complutense de Madrid in 1993 and Ph.D. degree from UPC in 2009. In 1989 he joined Telefonica and was involved in the specifications and first office application of SDH. In 2004 he joined UPC, where he is an associate professor and senior researcher. His interests include planning, CAPEX/OPEX issues, routing, and resilience mechanisms in multilayer networks.

JUAN PEDRO FERNÁNDEZ-PALACIOS received his M.S. in telecommunications engineering from Polytechnic University of Valencia in 2000. In 2000 he joined Telefonica I+D, where he is currently leading the Core Network Evolution unit. He has been involved in several European projects such as NOBEL, NOBEL-2, STRONGEST and MAINS as well as in the design of core network architectures in the Telefónica Group. Currently he is coordinating the FP7 project IDEALIST and the standardization activities within the CAON cluster.