ANALYSIS AND COMPARISON OF FLEX GRID AND FIX GRID NETWORK SYSTEM

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Abstract: Core networks offer high capacities, thanks mainly to the optical technologies they utilize, but they consume a non-negligible amount of energy. The traffic volume in metro and core networks is forecast to grow at very high rates, exceeding 30% per year for the next five years, and if the corresponding energy requirements grow analogously, they will sooner rather than later form a bottleneck for network communications. Thus, energy efficiency in optical networks is mandatory for the sustainability of the future Internet. The objectives of the current work are to identify the main causes of energy consumption for current fixed-grid wavelength division multiplexing and future flex-grid optical networks, and to propose and compare techniques for improving their energy efficiency. Wavelength Division Multiplexing (WDM) networks of the future are likely to use Flexgrid, providing operators with additional flexibility when assigning spectrum compared to traditional WDM networks using the 50GHz ITU grid. Flexgrid breaks the spectrum up into smaller (typically 12.5GHz) slots, but its key feature is that contiguous slots can be joined together to form arbitrary sized blocks of spectrum. This additional flexibility will allow faster transponders that utilise high spectral efficiency modulation techniques, but no longer fit within a 50GHz slot due to their larger spectral width requirements, to be carried by the optical network. From the use of these newspectrum efficient modulation formats and finer control overspectrum allocations, a key benefit that Flexgrid offers network operators is that their WDM networks can carry more traffic.

I. GENERAL OVERVIEW
The Internet is continuously transforming our daily working reality and lifestyle, increasing productivity, and supporting economic development across the world. Between 1993 and 2013 the size of the data traffic increased by 113 GB/day to 13,888 GB/s, while Cisco predicts global IP traffic to nearly triple from 2013 to 2018 [1] (see Fig. 1). The global economic downturn seems unlikely to slow the growth of Internet traffic, which leads to increased energy consumption for the infrastructures and devices needed to operate the Internet. ICT can of course help save energy through telecommuting, the introduction of smart grids, and many other ways, but the need for ICT to keep its own power consumption growth under control is also becoming increasingly evident [2]. It is estimated that the power consumption of the Internet is around 4% of the total energy consumption in broadband-enabled countries, and backbone network infrastructures (i.e., routers, transmission systems, optical switches) consume approximately 12% of total Internet energy consumption (estimated to increase to 20% in 2020) [3]. The continuing deployment and upgrade of network infrastructure drive up power consumption in a way that makes telecom operators worry that future power consumption levels may pose constraints on the growth of the Internet. Thus, it seems that an energy-aware approach is increasingly needed during the design, implementation, and operation of networks in general, and optical networks in particular, which carry more than 80% of the world’s long-distance traffic. Two different approaches can be explored to reduce power consumption in optical networks: the improvement of the energy efficiency of the equipment and the energy awareness of the algorithms used.

II. FIXED-GRID AND FLEX-GRID OPTICAL NETWORKS
The current optical transport networks are based on wavelength division multiplexing (WDM) technology to concurrently transport information on different wavelengths. In the past decades, research has focused on increasing network capacity by increasing the individual wavelength’s capacity. Hence, WDM-based networks have evolved from 1 to 2.5 to 10 to 40 GB/s, while 100 GB/s transceivers are just reaching the market. The next step is 400 GB/s systems and then even higher rates. However, such transmissions would not fit in the 50 GHz wavelength grid of current WDM systems (initial designs of 400 GB/s transceivers were for 75 GHz). Going back to the 100 GHz grid that was used in WDM systems in the past is not viable solution. Moreover, WDM systems present an inefficiency problem due to the coarse granularity of the light-paths (as optical connections are typically referred to), which are allocated a whole wavelength. Traffic manipulation at lower capacity levels is performed at the electronic

Fig. 1. Global Internet traffic growth and Cisco’s VNI Global IP traffic growth forecasts (2013–2018)
Aggregation switches at the edges of the optical network and is, in most cases, done independently of and on different timescales than lightpath provisioning of the optical WDM network. Therefore, to support future optical trans-missions and improve efficiency, a more flexible optical network with finer granularity is needed.

Recent research efforts on optical networks have focused on architectures that support variable spectrum connections as a way to increase spectral efficiency, support future transmission rates, and reduce capital costs. Flex-grid (elastic or flexible are also terms used in the literature and will be used in this paper interchangeably) optical net-works appear to be a promising technology for meeting the requirements of next-generation networks that will span across both the core and the metro segments. A flex-grid network migrates from the fixed 50 GHz grid that traditional WDM networks utilize [4], and has granularity of 12.5 GHz, as standardized by the International Telecommunication Union (ITU-T) [5]. Moreover, flex-grid can also combine spectrum units, referred to as slots, to create wider channels on an as-needed basis (Fig. 2). This technology enables a fine-granular, cost and power efficient network able to carry traffic that may vary in time, direction, and magnitude. Flex-grid networks [6] are built using bandwidth variable switches that are configured to create appropriately sized end-to-end optical paths of sufficient spectrum slots. Bandwidth variable switches operate in a transparent manner for transit (bypassing) traffic that is switched while remaining in the optical domain.

In fixed-grid WDM networks and assuming a specific type of transceiver, there is one way of serving a demand: the bit rate is fixed, the optical reach is fixed, and the occupied spectrum is fixed (a single wavelength). Flexible transceivers envisioned for flex-grid networks, also referred to as bandwidth variable transponders (BVTs), allow multiple choices when serving a demand: they can decide some or all of the following: the modulation format, baud rate, spectrum, or even the forward error correction (FEC), and choose those that give sufficient performance to reach the required distance.

The problem of establishing connections in fixed-grid WDM networks is typically referred to as the routing and wavelength assignment (RWA) problem, which is known to be an NP-hard problem. In the past, WDM systems were designed to use a single type of transponder, that is, they utilized a single-line rate (SLR). Recent advances in transmission technologies and coherent reception have made possible the use of more than one type of transponder simultaneously, exploiting trade-offs between reach and cost available in the different devices to improve the efficiency and decrease the total network cost. Such networks are typically referred to as mixed-line rate (MLR), as opposed to the SLR case discussed above. The RWA problem for MLR WDM networks is more complicated than for SLR, since it involves making decisions for the type of transponder to use for each connection.

### III. FIXED GRID TO FLEX GRID NETWORKS

#### Brown-Field Migration

Due to the increasing pressure on network operators to provide higher bandwidth with more efficient resource utilization, replacing the legacy fixed-grid equipment with flexible-grid equipment in their transport networks is just a matter of time. However, the operator’s decision to migrate to flexible-grid technology will be influenced by key factors such as trade-off between benefit and equipment cost, compatibility with legacy systems, and complexity of network management. On one hand, the key enabling equipment (e.g., bandwidth variable-wavelength-selective switches [BV-WSSs] supporting different grid definitions) has not yet reached a price point that allows massive deployment. It may not be economically viable to make one-time complete upgrade to full flexible-grid technology for the entire network. On the other hand, before the current optical transport network capacity is exhausted, the current fixed-grid network could be kept maximally operational during the migration to preserve the already made investment.

#### Network Architecture

In practice, a likely scenario is that traffic load on some nodes/links are significantly higher than others, so they become bottlenecks [10]. For example, a common scenario concerns nodes associated with data centres, which tend to generate a large amount of traffic and can benefit from high-bandwidth super-channels interconnecting them. In these situations, the equipment causing the bottleneck could be replaced with flexible-grid equipment. As a result, brownfield flexible-grid deployment on top of the existing fixed-grid network could happen as shown in Fig. 1a. While the sparse deployment of flexible-grid nodes can cost-effectively increase the capacity of only selected nodes/links, one challenge we will face is in the operational issues due to the coexistence of fixed-grid and flexible-grid technologies. Fixed- and flexible-grid nodes require different technologies. In particular, reconfigurable optical add/drop multiplexers (ROADMs) are the key equipment to perform wavelength switching at intermediate nodes. Fixed-grid ROADMs follow the traditional rigid ITU-T Telecommunication Standardization Sector (ITU-T)-defined...
central frequencies and spectrum grids (e.g., 50 or 100 GHz) regardless of the actual bit rate carried by each individual channel. Network devices (e.g., optical switches, multiplexers, and transponders) have to comply with this grid, as shown in Fig. 1b.

The flexible grid ROADM is different, as shown in Fig. 1c. Embedded wavelength-selective switches (WSSs) in a flexible-grid ROADM do not need to strictly follow the ITU-T fixed grid, and can switch multiple concatenated slices as a single entity, where each slice may be 6.25 or 12.5 GHz.

These fixed-grid and flexible-grid nodes would need to interoperate before all nodes are upgraded to flexible grid. So the question is: how can newly added flexible-grid nodes be operated in a network with other legacy fixed-grid nodes? Below, we discuss the relevant challenges in terms of light path routing, wavelength assignment, and spectrum allocation.

Figure 2.1 Optical network with co-existing fixed-grid and flexible-grid technologies: a) network architecture; b) fixed-grid ROADM; c) flexible-grid ROADM; d) wavelength channel; e) 200-Gb/s super-channel; f) two 100-Gb/s channels; g) 40-Gb/s sub channel

IV. INTEROPERATION BETWEEN FIXED-GRID AND FLEXIBLE-GRID NODES

When a request arrives, we need to establish an optical path between its source and destination by determining a route through the network, and assigning/allocating a wavelength/frequency slot for this path. Here, a frequency slot is a spectrum allocation dedicated to a certain connection, and is specified by its nominal central frequency and slot width. Suppose a route is selected for a lightpath in an optical network with both fixed-grid and flexible-grid technologies, so there are several situations for wavelength assignment (WA)/spectrum allocation (SA):

- When the source is a fixed-grid node, we have the traditional WA problem. If the traffic demand is larger than 100 GB/s, it can be served by several lightpaths, each accommodating 100 GB/s or less (all following the same path, if possible).
- When the source is a flexible-grid node, there are two cases:
  - If the nodes on the path are flexible nodes, we have the SA problem, where a single-carrier channel or a super-channel with multiple subcarriers can be set up to accommodate the demands.
  - If there are both fixed- and flexible-grid nodes on the path, the spectrum is shared as common resources between fixed-and flexible-grid technologies, and the corresponding WA and SA problem becomes complex, different from WA in fixed-grid and SA in flexible grid. On the path from the flexible-grid node to the fixed-grid node, we have the SA problem; but from the fixed-grid node to the flexible-grid node, we have the WA problem. If the traffic demand is larger than 100 GB/s, we set up several lightpaths, each offering up to 100 GB/s rate.

Figures 1d–1g illustrate four possible cases in networks with fixed-/flexible-grid coexistence. We consider the spectral granularity of fixed-grid nodes to be 50 GHz and that of flexible-grid nodes to be 12.5 GHz. Figure 1d shows the spectrum utilization of links for a 100-Gb/s lightpath that originates from a fixed-grid node and goes through a flexible-grid node. It occupies 50 GHz on both a fixed-grid link (i.e., a link originating from a fixed-grid node) and a flexible-grid link (i.e., a link originating from a flexible-grid node). Figure 1e shows a 200-Gb/s light path that originates from a flexible-grid node and then goes through a flexible-grid node. Since we can set up a super-channel that comprises six 12.5 GHz slots, only 75 GHz of spectrum will be used instead of two 50 GHz channels in a fixed-grid network. However, when the path of a 200 GB/s demand originates from a flexible-grid node but goes through a fixed-grid node, as shown in Fig. 1f, two lightpaths are set up, with each offering up to 100 Gb/s. Figure 1g shows a 40-Gb/s light path originating from a flexible-grid node and going through a fixed-grid node. Here, 25 GHz spectrum will be assigned to the optical path on the flexible-grid link, and 50 GHz will be reassigned on the flexible-grid link, since the switching granularity of the fixed node cannot be smaller than 50 GHz.

Figure 2.2 a) 5-node topology; b) traffic matrix; c) carried traffic by each node; d) U.S. network topology; e) optical channels in fixed-grid and flexible-grid technologies; f) connection demand ratios in different traffic profiles; g) traffic distribution in the non-uniform case.
V. FIX GRID AND FLEX GRID NETWORK

The inflation of data transfer is inevitable and brings significant challenges for transport networks. To meet the increasing requirements of users, new technology has to be deployed in backbone networks [1]. Elastic Optical Networks (EONs), based on optical-orthogonal frequency division multiplexing (OFDM) is able to accommodate high bandwidth demand applications. The basic concept of EONs is to fragment the available spectral resources into tight, width-constant spectral slices (optical channels represented in frequency domain) that correspond to different optical wavelengths. The slices are allocated over an optical lightpath, according to source, destination and capacity of a demand [2]. In this paper, we focus on showing the minimum requirements for EONs resources in order to achieve the best trade-off between the CAPEX/OPEX network costs and obtaining the various thresholds of Service Level Agreement (SLA).

In addition, the EONs technology is a next step in the evolution of optical networks, therefore we will present a comparison of network resource usage in current technology (Wavelength Division Multiplexing – WDM) and EONs. Methods of migration from WDM to EONs are presented in [3]. Comparisons of the performance of WDM and EONs in dynamic routing are presented in [4-5] The main novelty presented in this paper is consideration of forecasted traffic volumes for the next few years, as well as consideration of path protection (PP) methods. Moreover, we take into account anycast and unicast traffic. Any casting – defined as one-to-one-of-manytransmission – is a useful way to serve network services provisioned in data centres including popular cloud computing and content-oriented services.

We investigate two different scenarios for dynamic routing in EONs, i.e., requests are not provided with any protection and requests are protected by PP methods. Both scenarios are introduced and compared in section 3, preceded by a description of the network model in Section 2. In section 4, we provide and analyse results of extensive simulation experiments which run on two representative network topologies. We examine the performance of both scenarios in terms of two important metrics: spectrum and regenerators usage. Finally, the last section concludes this work.

Network Model

In this section, we describe network model used in our simulations. We also present the differences between WDM and EONs technologies.

Optical networks evolution

Over the last decade, optical networks have gone through a rapid evolution, starting with 16 wavelengths of 2.5 Gb/s in late 1990s to 80 wavelengths of 100Gb/s in 2012 [6-7]. Today, the term of optical networks denote high-capacity telecommunications networks based on optical technologies and components that can provide capacity, provisioning, routing, grooming, or restoration at the wavelength level. With estimated exponential traffic growths, future networks have to boost their capacity. The channel capacity will need to be increased beyond 100 GB/s per channel or higher, together with an increase of spectral efficiency. Currently used optical technology networks are Wavelength Division Multiplexing (WDM). The main idea underlying the concept of WDM networks is to communicate end-users in optical layer via all-optical WDM channels, which are referred to as lightpaths [8].

A connection in a wavelength-routed WDM network is supported by lightpath which may span multiple fibre links. In addition, when there are no wavelength converters, a lightpath must occupy the same wavelength on all the fibre links through which it traverses due to the wavelength-continuity constraint.

Despite all benefits of conventional WDM networks, their biggest problem is a low bandwidth efficiency due to fixed large granularity. Full wavelength capacity has to be dedicated for establishing a connection between end-nodes, even when the traffic between the nodes does not need to fill the full spectrum. It causes the poor utilization of the residual bandwidth of wavelength. Flexible-grid technologies can alleviate these limitations for demand provisioning. These technologies represent promising candidates for future optical networks supporting transmissions of 100-Gb/s and beyond. In this case, several wavelengths are aggregated and allocated according to the request. On the other hand, it is easy to perform segmentation of large requests in flexible-grid networks.

Notation

We use similar notations as in [9]. The physical network is modelled as graph G(V, E, B,L) where V denotes a set of nodes, E is a set of fibre links, each fibre link can accommodate B frequency slices (slots) at most, and L= [l(1),l(2),…,l(|E|)] represents link lengths for each e∈E. We assume that R data centres are already located at some nodes of the network. In addition, we assume that data centres (DCs) are equally connected to network nodes, to which are connected to, which means that we do not take the physical connection between the server and the backbone network node. Furthermore, we assume that each anycast request can be assigned to each DC, because DCs provide the same service of content.

Network Scenarios

In the simulations, we use a pan-European Nobel-EU network that contains 28 nodes and 82 directed links, and a US national backbone network consisting of 26 nodes and 84 directed links with 7 DCs located in each network. The networks have three points that are interconnected to other networks, which are used to carry international traffic. The data provided by [10] determines the location of DCs and interconnection points. We take into consideration the physical impairment of links (fiber attenuation, component insertion loss) and we use regenerators to regenerate the signal on paths that – due to using higher modulation formats (MFs) – exceed the transmission range of a particular MF.

We estimate the number of regenerators in each node required to obtain particular SLA in terms of dynamic routing. For each network, the number of available spectrum in each link is set either to 2 THz or to 4 THz. We use a similar traffic model to [9]. The traffic model is created under the forecast in “Cisco Visual Networking Index: Forecast and Methodology, 2014-2019 White Paper”. For Euro28 traffic in 2015 is set to 50 Tb/s and for the US26 it
equals 60 Tb/s. It increases over the years accordingly to Cisco reports.

The simulations are made for dynamic traffic, using reference algorithm from the literature - AMRA [11]. For WDM we use Least Loaded (LL) algorithm [12-13]. In this paper, we assume a WDM network with spectrum of 2 and 4 THz and bands of 50 GHz, each allowing to transmit 100 GB/s and EONs with two configurations – 2 and 4 THz with 6.25 GHz bands allowing to transmit up to 400 GB/s. In one scenario, we check the need for regenerators and the spectrum without PP methods, while in the second scenario, we check the same requirements with PP. Moreover, we test two methods to ensure the network survivability, i.e., one that uses more resources and gives 100% protection and a second, which is more efficient in terms of spectrum and regenerator usage, but does not provide 100% protection. Note that the main performance metric is Bandwidth Blocking Probability (BBP) defined as the volume of rejected traffic divided by the volume of all traffic offered to the network. Note that the request blocking can occur due to two reasons: lack of spectrum resources and/or lack of regenerators required to regenerate long distant requests. For more details on this issue see [11].

Description of Algorithms
In this section we outline the algorithms we used in ourstudies for minimizing the energy consumption when planning SLR and MLR fixed-grid WDM and flex-grid optical networks. In particular, the algorithms are referred to as EA-RWA for the MLR and SLR fixed-grid WDM networksand EA-RSA for the flex-grid network. We start by giving a general definition of the network planning problem that is common in all cases, and thenwe focus on the differences among the algorithms. The switch architectures, in which the only difference between the fixed- and flex-grid cases is the use of bandwidth-variable WSSs in the latter case. Finally, we assume that, in the case of fixed-grid networks (SLR and MLR), the system supports wavelengths, while in the flex-grid case, the network supports spectrum slots. The objective is to serve all traffic and minimize the energy consumed in the corresponding fixed-grid WDMand flex-grid optical networks. To do so, we reduce the number of power consuming components, such as transponders, regenerators, add/drop terminals, and amplifiers, which leads to the reduction of the energy consumed in the whole network. Especially for the caseof MLR networks, minimizing the energy consumption of the transponders is achieved by choosing the right type of transponder for each connection. In flex-grid networks, assuming the use of a single type but tunable transponder, the main issue is to choose the right configuration of the transponder for each connection.

Since the related planning problems are NP-hard and weare considering realistic problem instances with networks of many nodes/links and heavy traffic, we decided to use heuristic algorithms, since searching for absolute optimums for several scenarios would be time consuming. In particular, the heuristic algorithms we used for the different cases follow a similar logic. They serve all the demands defined in the static traffic matrix one-by-one according to a specific ordering, remembering the choices made for previous served requests so that we can avoid wavelength contention, and incrementally calculate the energy consumption of the whole network. Note that the energy consumption (but also the spectrum and other network performance metrics) depends significantly on the ordering in which demands are served. This is because choices made for one connection, e.g., to serve it over a specific path that places regenerators at specific nodes so as to avoid adding add/drop terminals or utilizing a network interface over an other path, could differ later when the chosen path becomes congested and requires adding more add/drop terminals, while the avoided path turns out to be relatively empty. Since the ordering plays an important role, our algorithms use a simulating annealing (SA) metaheuristic to search among different orderings.

For the SLR-RWA algorithm we used the heuristic algorithm presented in [26]. This algorithm precalculates shortest paths for each demand. Then for each path, given the transmission reach of the specific SLR transponder, the algorithm allocates a regenerator at the previous node of the link that, when added, makes the path longer than the given transmission reach. The algorithm takes into account the optical switch architecture, the add/drop terminal NIs utilized up to that point, and the regeneration points of each of the paths. It selects the path that minimizes the incremental energy consumption of serving the demand at hand and continues serving the next demand.

VI. MODELLING AND SIMULATION
Comparison of Flex grid to Fix grid

Figure 5. Comparison of Flex grid to Fixed Grid

Above shown figure is comparison of Flex grid to fix grid, where we have used Poison process & Negative exponential algorithms for creating a flex grid scenario. Here, we have used a frequency slot of 12.5 GHz ranging for 1 to 12 for fix grid service. For fix grid we have kept the frequency slot a constant of number 8. At the same time we have used 12.5 GHz slot even in Fix grid which helps us comparing both grid network methods easily. The option of 50 GHz is discarded by us, because it won’t be a modern approach wherein we are trying to use a frequency slot of only 12.5 GHz. As can be seen from above figure Green dots are of
Flex grid network which shows that we are able to provide more live connections using flex grid method. Parameters for Load on network are some as Inter-arrival time. Holding time, live connections & other random parameters that comes with a use of grid network. Comparison shows us that Flex grid better utilizes provided frequency slots.

VII. CONCLUSION

Increasing the energy and spectral efficiency of optical transport networks has emerged as one of the most challenging tasks for telecom operators and industry. Optical transport networks are required to provide high resilience levels to guarantee an appropriate quality of service. Recently, EON has been presented as a promising solution to enable flexible and high-capacity transmission by means of its elastic bandwidth usage. Simulation results showed EON as an energy and spectral efficient solution, which allows for the transmission of more bits per GHz per Joule (energy efficiency perGHz) than any other WDM approach for all the protection schemes (dedicated and shared path ones).

Despite the potential advantages of energy and spectral efficiency showed by EON, cost is one of the main drivers to determine whether EON will be finally adopted by the operators. In this regard, the traffic conditions and the network topology will be decisive for the cost efficiency of EON, which is strongly dependent on its main cost contributor, the BVT. As shown in the presented results, the manner in which the bandwidth of this transponder is utilized has a significant impact on the final cost. Thus, even if the cost per bit of a BVT could be initially higher than that of a current WDM transponder, EON can be a cost-efficient solution if the transponder capacity is shared between multiple demands. Accordingly, in many circumstances, the data that can be transmitted per GHz with a single cost unit (cost efficiency perGHz) is higher in EON than in any other WDM network approach.

The higher spectral efficiency of EON results in lower blocking, which permits to accommodate more traffic in a single fiber. This fact has a relevant impact on both cost and energy efficiency, as the number of additional fibres and energy-consuming devices can be reduced for a given traffic load. Furthermore, there are some other potential factors that can turn this technology into a more cost-efficient solution, such as the possibility of deploying an agile transponder model in the network. Among the protection schemes, SP was shown as the most energy and cost-efficient, thanks to its lower power consumption and spectrum usage, and DP1Lastheleastenergy-and cost-efficient due to its duplicated transmission, despite offering the highest availability and fastest recovery. In general, migrating from dedicated to shared protection schemes may significantly improve the cost and energy efficiency of the network.

REFERENCES


