Flexible Technologies to Increase Optical Network Capacity

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***Abstract*—Increased global traffic puts tough requirements not just on fibre communications links, but on the entire network. This manifests itself in multiple ways including how to optimise wavelength routing around the network; how to maximise the benefits arising from fine-control DSP with increasingly accurate real-time monitoring; and how to best deploy Multiband or multiple fibre connectivity. This paper will summarise research into all these areas to present a full picture of how future optical networks will play their role in supporting the continuing traffic demands of broadband, 5G and associated applications.**

***Index Terms*—Optical Networks, Flexgrid, Bit Rate Variable Transceivers, Network Optimisation**

I. INTRODUCTION

Optical fibre networks are indisputably the technology of choice when it comes to transporting high volumes of data across long distances. Over recent decades, fibre spectrum in optical networks is allocated according to the ITU-T Dense Wavelength Division Multiplexing (DWDM) [1] standard, which uses optical signals generated by Fixed Bit Rate (FBR) transponders, over fixed-spectrum 50 GHz channels, operating across the C band (1530-1565nm).

Up until recently, the standard core network solution consisted of 100 Gb/s channels, each occupying a standardised 50 GHz spectral slot in the C-band, of which there are around 100 available: this equates to approximately 10 Tb/s per fibre. Continual traffic demand growth now requires more capacity than this, and this is supported by a range of developments in optical transmission technologies, summarised by an increase in flexibility both in the apportioning of optical spectrum and also in the data rate of the transponders. This new network paradigm is known as the Elastic Optical Network (EON), recognising the ability to flex the resources according to requirements and channel characteristics.

Flexible use of the optical spectrum is known as Flexgrid, in which spectral slots of almost arbitrary width can be established (dynamically if required). The optical switching technology, based around Liquid Crystal on Silicon (LCoS) [2], can reduce the granularity from 50 GHz down to 6.25 GHz or lower (if required), but it can also extend the channel bandwidth to many hundreds of GHz. This led to the adoption of a new spectral grid based on smaller spectrum slots of 12.5 GHz in the ITU-T standard [1]. Benefits of this approach are two-fold:

1) It allows the reduction in the spectral gaps between demands that can arise from a fixed grid approach as with 50 GHz spacing and thereby can increase overall capacity as illustrated in Fig. 1
2) It also allows larger bandwidth assignments to be made, enabling concepts such as super-channels: multiple channels linked tightly and transported across the network together. This will be beneficial as overall traffic demands between node pairs exceeds the rate possible from a single transponder; additionally, it will simplify the overall network management due to a reduced number of overall circuit connections.

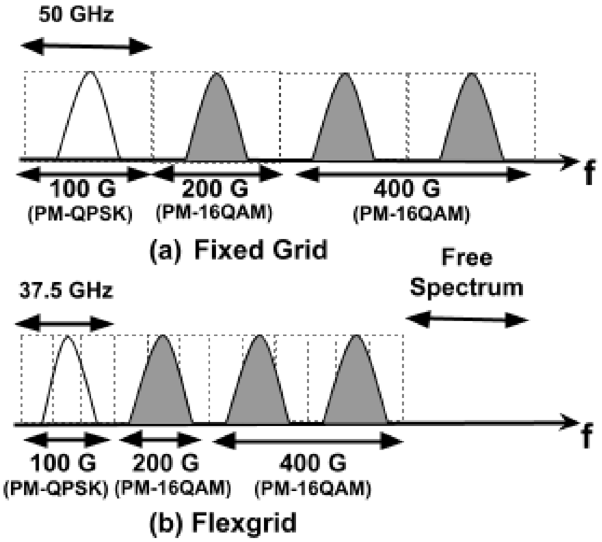

Fig. 1: Comparison between Fixed Grid and Flexgrid. The shaded region indicates the required client demand bandwidth and region between adjacent vertical dotted lines indicate the allocated spectral bandwidth.

Flexible transponders that can provide a range of bit rates are known as Flexrate transponders or alternatively as Bit Rate Variable Transponders (BVTs) [3], [4]; these devices are characterised by their symbol rate and modulation format, both of which determine the overall data rate of the transponder. The symbol rate determines the bandwidth occupied by the transponder and this could in principle be dynamically

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changed for a given device, although operation might be at the maximum rate available. The signal-to-noise performance of the required optical path determines the modulation format: higher QAM modulation requires better noise performance and is therefore more likely to be used in shorter paths.

A key question is how best to make use of these two new types of flexibility in an optical network? There are two extremes, and a range of hybrid options between them. The two main options are (i) Fixed grid – maintaining a fixed channel slot for each transponder, and (ii) Flexgrid – allowing the channel slot to vary. The fixed grid solution would not necessarily need new flexible wavelength switches, but could still benefit from them. Both approaches would use the Flexrate capability in transponders.

In this paper we examine the benefits of these new flexible technologies (Flexgrid channels and Flexrate transponders) as applied on a network scale. Networks consist of a number of optical paths running over a wide range of distances, with wavelengths multiplexed, routed and demultiplexed as required. The challenge is to maximise the overall network throughput, defined as the summation of the capacities running across each link in the network. In fact, actual networks have an associated traffic matrix, which reflects the range of demands to be carried. Considering this, the objective is to accommodate traffic growth for as long as possible before needing to add more fibre transmission capability.

This leads to questions concerning use of the highest spectral efficiency for each wavelength channel and then efficiently packing wavelengths together whilst maintaining the required performance.

In the Flexgrid approach, the objective is to save spectrum; thus a shorter distance path, with associated higher OSNR, can be serviced by a transponder operating under high QAM modulation, and reduced symbol rate and hence spectrum occupancy. A longer path will use lower QAM modulation, and a higher symbol rate and hence more spectrum used. For each channel, this approach delivers the minimum optical spectrum to provide the required data rate.

In the fixed grid approach, the symbol rate operates at the highest level available for the transponder technology, leading to a fixed wavelength grid, and with changes to the QAM modulation catering for different link lengths. This results in potentially fewer channels than for Flexgrid.

One problem with Flexgrid is that the different channel widths can lead to unusable spectral slots in an overall network, and this is referred to as fragmentation [5] . Fragmentation is an unwanted side effect of Flexgrid and although there is a great deal of academic literature on how to reduce this or even how to carry out defragmentation of a fragmented Flexgrid network, operators will want to avoid this as it could compromise network operations.

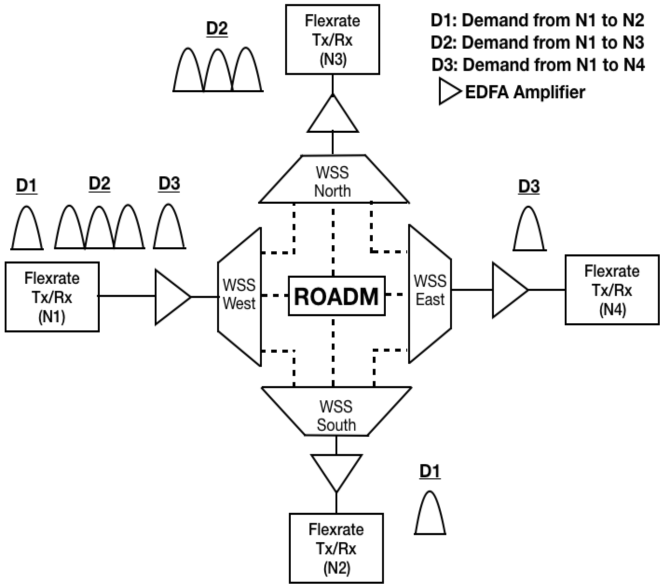


Fig. 2: Mesh Network with Flexgrid

Table I illustrates the various trade-offs when considering these two paradigms. The overall message from this table is that Flexgrid can save significant spectrum compared to higher symbol-rate fixed grid; this is particularly the case for shorter links that do not require extremely high capacity. Although this spare spectrum could be used for other demands, as the network traffic grows, the original demand might be unable to increase, due to adjacent channels.

In this paper we discuss the various technical directions that are emerging to improve resource efficiency in optical networks. In Section II we summarise optical mesh networks, with their component technologies and overall architectures. In Section III, novel algorithms for routing and spectrum allocation are discussed while highlighting their advantages in increasing network capacity. In Section IV, the concept of low margin network operation is discussed with the focus on adapting the margin while considering network size and condition of inline equipment. Finally in Section V, we discuss the application of Flexgrid technology across a multi-band environment, comparing this to a spatial approach with multiple fibres. Section VI concludes the paper.

II. FLEXIBLE OPTICAL NETWORKS

In this section we examine how these new flexible technologies can be utilised in a network. A typical network comprises a number of nodes, located in strategic places in a country. Numbers can vary from between 10 to around 100 nodes (for example the BT metro-core comprises around 100 nodes). These are interconnected with fibre, but not in a full mesh. Each node connects to a small number of adjacent nodes; this is known as the node degree and a typical average node degree for a core network is between 3 and 5, though some nodes will have higher connectivity than this.

Optical circuits can in principle connect between any node-pair in a network and to facilitate this, each node has a Remotely Configurable Optical Add Drop Multiplexer (ROADM) which allows wavelengths or spectrum from the incoming signals to be switched to the different output fibres, thereby facilitating an all-optical layer, as shown in Fig. 2. Long fibre links between network nodes will include Erbium Doped Fibre Amplifiers (EDFAs) to maintain signal power.

Together with this topology and infrastructure comes a traffic matrix which describes planned traffic between all node-

TABLE I: Spectrum usage under different operating paradigms - numbers are purely to illustrate the concepts

	Shorter path	Longer path	Comment
Original Fixed Grid (50GHz spacing)	25Gbaud symbol rate, QPSK, total data rate 100 Gb/s	25Gbaud symbol rate, QPSK, total data rate 100 Gb/s	Four of these channels would give 400 Gb/s. Total spectrum 200GHz.
Flexgrid	25Gbaud symbol rate, 64QAM, 37.5GHz spectrum (3 x 12.5GHz slots [ref new ITU grid])	100Gbaud symbol rate, QPSK, 125GHz spectrum	300 Gb/s maintained for each path with one transponder. Shorter path only occupies 37.5GHz and longer path 125GHz.
Fixed grid	100Gbaud symbol rate, 64QAM, 125GHz spectrum and provides 1.2Tb/s	100Gbaud, QPSK, 125GHz spectrum providing 400 Gb/s	Shorter path provides 1.2Tb/s which might not be required, and an increase of 87.5GHz spectrum compared to Flexgrid. Longer path formats are identical

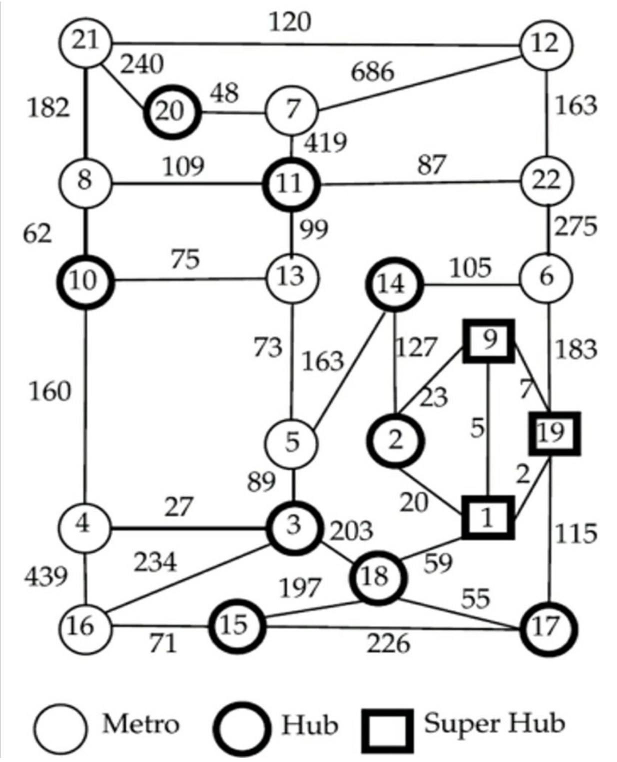


Fig. 3: BT-UK Network with link lengths in km

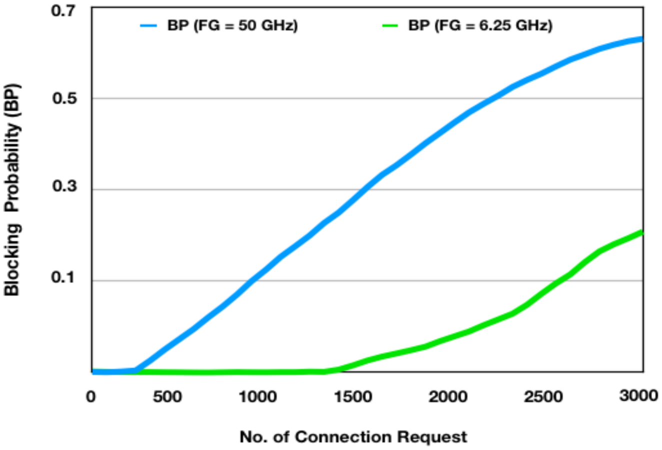


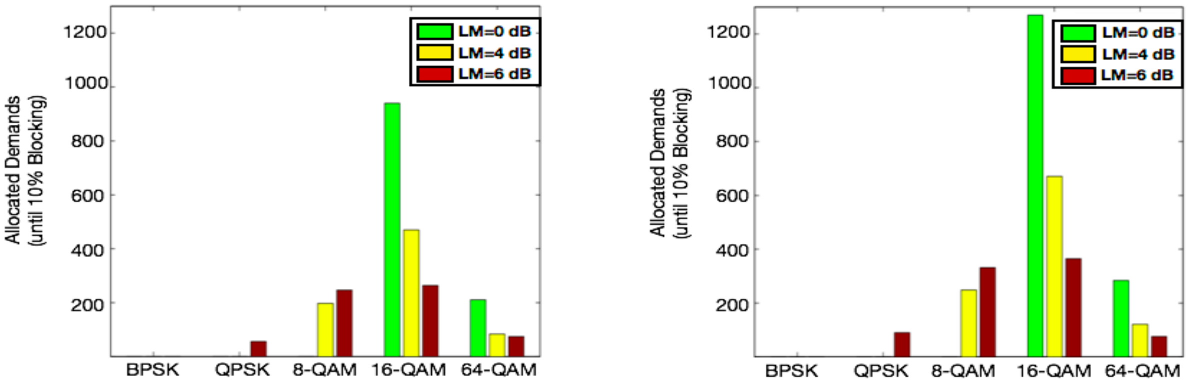
Fig. 4: Performance of BT-UK Network Blocking Probability for FG 50 GHz and 6.25 GHz

pairs in the network. This traffic matrix has both a list of starting values, but also has some assumptions around traffic growth. Traffic in core networks is expected to continue to rise exponentially, with typical values of between 20 and 40% per annum. However, traffic variations are expected around this average. Short time-scale variations are handled by the IP layer; longer time scale variations, such as time-of-day are handled by ensuring the optical layer is over provisioned.

The critical question is then: how much traffic can be accommodated by the network? One simple way to address this is to add traffic demands from the traffic matrix, finding a route through the network using route optimisation techniques, the simplest of which is Dijkstra's shortest path algorithm [6]. The procedure is then to continue to add traffic until the network starts blocking the connection requests. In this paper we refer to the term Blocking Probability (BP) which is the proportion of connection requests blocked to the total connection requests assigned to the network. Simulations are repeated multiple times over various traffic matrices to yield a high confidence interval of more than 95%; an average value of BP is recorded as traffic grows in the network. The average number of connection requests assigned until a network reaches a BP of 0.1 (10%) gives a measure of the overall network capacity.

The network performance of BT-UK network shown in Fig. 3 [7] has been evaluated in Fig. 4 which gives an example of the effect of fine spectral control to increase spectral efficiency while considering traffic matrices generated using 100 seeds with uniform distribution for selecting source and destination pairs and considering fixed connection requests of 100 Gb/s [8]. Based on the prediction of OSNR and mapping it to the modulation format which can be operated for a given lightpath, the transponder may vary the symbol rate, thereby achieving high Spectral Efficiency (SE) for higher Polarization Multiplexed-M-ary modulation. Further, the lower Frequency Granularity (FG) of Flexgrid will further enhance the SE while closely matching the allocated optical spectrum to the required symbol rate. Fig. 4 indicates that using a lower FG of 6.25 GHz, the BP in the BT-UK network does not rise sharply as compared to the use of a standard grid of 50 GHz, indicating that higher number of allocated demands can be achieved in the network while using Flexgrid and maintaining the same BP.

A similar study with a fixed transmitter symbol rate of 28 GBaud with 7% FEC has been simulated while considering the BT-UK network[9]. Here two FG of 50 GHz and 12.5 GHz



(a) Channel Bandwidth of 50 GHz (FG=50 GHz)

(b) Channel Bandwidth of 37.5 GHz (FG=12.5 GHz)

Fig. 5: Allocated demands for various modulation formats and Link Margin (LM)

have been considered to generate a 50 GHz grid and 37.5 GHz grid, enough to cover the fixed 28 GBaud bandwidth requirement. As can be seen in Fig. 5 higher numbers of allocated demands are achieved while operating with a 37.5 GHz channel bandwidth. Also in terms of modulation format distribution, PM-16QAM is the dominant modulation format in the BT-UK network. Overall while using FG=12.5 GHz a capacity gain of 35% is estimated compared to operation with FG=50 GHz when 10% of the connection requests to the network are blocked in the BT-UK network. Overall, flexible grid spectrum in combination with bandwidth variable transponders with adaptive symbol-rate and modulation format can bring significant benefits to network capacity. Similar studies highlighting the benefit of flexible optical networks have been studied in [10] [11] and [12] and [13].

III. ALGORITHMIC SOLUTIONS FOR FLEXIBLE RESOURCE ALLOCATION IN EONS

The adoption of new flexible technologies (Flexrate and Flexgrid, as described in previous Section) calls for new algorithms and methodologies to solve the network-scale optimization problems that emerge when allocating resources to incoming traffic requests in EONs. Before delving into the description of current solutions, we briefly discuss the main categories of resource allocation problems in optical networks [14]:

- *Network Planning* which consists of identifying the minimum-cost equipment (typically transponders) deployment and resource allocation, that can support a given set of traffic demands between various pairs of nodes (also called a “traffic matrix”). In other words, it must be decided how much capacity to put on each network link, as well as routing of traffic and assigning spectrum. This is a long-term problem, typically solved once every several months, or even years.
- *Network Operation*, i.e., assigning network resources on-demand to traffic requests. This is essentially a dynamic routing and spectrum assignment problem (also referred to as provisioning or traffic engineering), whose decision-making time is very quick, down to the order of minutes (or even seconds). This problem might have to be solved frequently, e.g., up to multiple times in a day.

Note that Network Planning can be applied in both greenfield or brownfield scenarios. In greenfield, the network is designed from scratch, hence the network operator has more degrees of freedom (e.g., links and node locations can change, equipment can be freely chosen). In brownfield, the operator is faced with the problem of augmenting network resources to serve an increasing traffic load (network “upgrade”), considering the constraints coming from the already deployed equipment. For both greenfield and brownfield planning, we can identify two further sub-cases: i) if there is no (or at least very limited) uncertainty on future traffic evolution, we refer to this problem as *multi-period planning*, while ii) in case of uncertain of future traffic (or even of physical layer state, e.g., due to aging effects), we refer to this problem as *incremental planning*.

In all the above categories, the core underlying EON optimization problem is the Routing and Spectrum Assignment (RSA), which consists of assigning, for each ligthpath request, an appropriate amount of spectrum and a path along which the lightpath must be routed. The adoption of Flexgrid and Flexrate in EONs has greatly increased RSA complexity. As an example, when upgrading a 4THz C-band from fixed grid to Flexgrid, the number of frequency slots increases from 80 to 320. Similarly, Flexrate transponders, that support multiple modulation formats and multiple coding rates, require the modeling of all the possible transmission configurations of the transponders, increasing the combinatorial complexity of RSA. To remark these differences, RSA in EON is now often renamed as RMCSA (Routing, Modulation Format, Code Rate, and Spectrum Assignment).

In short, if, on the one hand, the adoption of Flexrate and Flexgrid technologies increase the efficiency and flexibility by which spectral resources are managed, on the other hand, this efficiency and flexibility is gained at the cost of significant additional, combinatorial complexity for network planning, operation and upgrade problems. In the next subsection, we first overview the pros and cons of current optimization/planning techniques, then we discuss rising research directions to enable new and more scalable optimization methodologies for EONs.

A. Current Algorithmic Solutions for Flexible Resource Allocation in EONs

Currently, optimization problems in optical networking, such as RSA [15], are solved leveraging either *exact* or *heuristic* algorithms developed in the area of Operation Research (OR).

1) Exact Algorithms: Techniques from mathematical programming, such as Integer Linear Programming (ILP), allow us to formulate analytically an optimization problem, then the problem formulation is given as an input to a solver to get a solution. As a main advantage, these techniques allow us to achieve a theoretically-guaranteed optimum for the problem, however they tend to scale very poorly with the problem size (number of nodes, links, input lightpath requests), thus they are not suitable for large problems. Moreover, in presence of non-linear equations, scalability becomes even more of an issue. In the case of ILP, most solvers employ an algorithm of exponential combinatorial complexity, called "Branch and Bound". Even though several other techniques e.g., Branch-and-Cut-and-Price [16], have been proposed to improve scalability, these techniques typically require time-consuming and problem-dependent fine-tuning of the algorithm's parameters, and cannot be easily automated, hence it may not be possible to know a-priori whether their application can be beneficial. Overall, as of today, the main application of ILP is restricted to the benchmarking of the solution quality of heuristic strategies (see below) over small network instances.

2) Heuristic Algorithms: Heuristics are handcrafted strategies for solving optimization problems (typically leveraging existing graph-theoretical solutions to simpler sub-problems) that aim to produce good quality solutions in reasonable computing times. The field of heuristics is wide, covering both deterministic approaches and more effective statistical approaches (e.g., the so called metaheuristics, as Simulated Annealing, or bio-inspired heuristic techniques such as genetic algorithms). The main drawbacks for heuristics are: i) the impossibility to guarantee that the problem optimum is reached, which means that the solution quality is difficult to evaluate, and ii) the lack of generality, as the designer must have knowledge of the problem at hand for the algorithm to generate effective solutions. Moreover, heuristics require manual tuning of several parameters (e.g., cooling schedule for Simulated Annealing), which may severely impact solution quality. Designing heuristics specialized for optical-networking problems requires human intuition and in-field expertise, and the process is far from being automated.

A legitimate question at this point is: how much resource savings can an operator expect using an effective optimisation algorithm? The answer is challenging as savings depend on the algorithm employed, on the network characteristics and on the considered metric. Some quantitative estimations of the resource savings obtained using different metaheuristics are provided in Table II, showing saving ranging from 5 to 20%. Although savings around 20% might seem small, they could still represent a large absolute CapEx saving, and additionally reduce the need to use additional fibre and build new network infrastructure. Moreover, if one attempts to perform multi-layer optimization, i.e., to jointly optimize the resource allocation at multiple network layers (e.g., EON and IP layer), larger savings can be achieved (paid off, inevitably, by even larger combinatorial complexity [17]).

TABLE II: Resource Savings from RSA Optimization

Algorithm	**Metric**	**Savings, %**
Simulated annealing [20]	Total used spectrum	15-20
Genetic Algorithm [21]	Maximum number of occupied slots in fibre	5-15
Genetic Algorithm [18]	1. Total used spectrum 2. Maximum number of occupied slots in fibre	1. 5-10 2. 15-20

In the previous examples, resource allocation is optimized for a static traffic scenario, neglecting traffic growth and/or traffic fluctuations. Regarding traffic growth, it has been shown that highly optimized resource allocation at deployment ("at year 0") leads to lower excess capacity, and hence reduced savings in the following years, calling for new optimization techniques considering traffic anticipation during resource allocation [18]. Regarding traffic fluctuations, new flexible optical-network technologies offer several new opportunities to dynamically adjust and reconfigure capacity of existing lightpaths, which, in turn, can increase network capacity (readers are referred to [19] for a comprehensive description of all reconfiguration actions that can be take to address traffic changes with flexible technologies).

Considering the increased problem complexity in EONs and considering that several large cloud and telecom operators are currently challenged by resource-allocation problems over EONs of several hundreds, or even thousands of nodes, new optimization techniques, that can provide some sort of theoretical bound to their quality as well as fast solving times, are currently a hot research topic.

B. Future Research Directions for Flexible Resource Allocation in EONs

How to develop new scalable and (quasi)optimal optimization algorithms is an open question for EONs. A promising, and still mostly unexplored in optical networking, research direction points towards the *integration of Machine Learning (ML) and OR*, that has shown, in other fields (see, e.g., [16]) the potential to revolutionize traditional optimization, by either building better heuristics or by enhancing existing exact algorithms (e.g., by shortening their computing times). EONs present a fertile environment for these methodologies to flourish, as they feature complex cross-layer optimization problems (see the low-margin network design discussed in next section, that requires joint consideration of network-level resource allocation and physical layer modelling).

New optimization methodologies are emerging that integrate ML and OR techniques for generic combinatorial optimization (not only applied to optical networking) [22]. We can envision three main ways for integrating ML into OR, that can be seen as promising directions in optical networking:

- *End-to-End Learning*, where ML models completely substitute OR-based approaches and they are trained to output solutions directly by seeing repeated instances of input-output decisions (Fig. 6a). Deep Reinforcement Learning (DRL) is a primary candidate in this category and some works on DRL application for EON problems have recently appeared [23]. It is unclear if these techniques can provide generalizable solutions to the problem (i.e., if a DRL model trained on, e.g., a specific network will work on other networks). In this direction, also Graph Neural Networks [24]) seem particularly suited for EON optimization, as they are known to possess higher generalization capabilities over novel (and possibly larger) network instances than the ones seen during training.

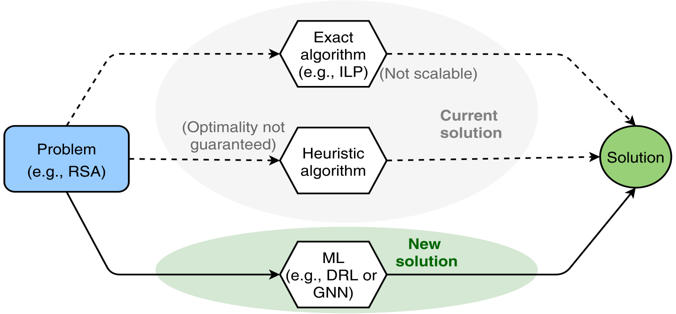
- *Learning for Algorithm Configuration*, where ML models are employed for taking decisions regarding parameters of the employed OR approach (Fig. 6b), that are otherwise computationally expensive or impossible to evaluate a-priori (hence leaving the network engineer to rely on his/her learnt experience). For example, in a multi-layer IP-over-EON routing problem, most heuristic approaches would rely on multi-layer auxiliary graphs that require cumbersome fine-tuning of the link cost according to the network topology and the objective function to be minimized (see e.g., [25]). ML (and possibly, Transfer Learning) promise to automate the link cost assignment in these auxiliary graphs, or to allow us to prune part of the graph to speed up computation [26] .
- *ML alongside OR*, where ML models are repeatedly queried by OR methodologies for taking multiple low level decisions (Fig. 6c), because their outcome cannot be known a-priori and is generally learnt from experience. For example, in [15] a ML model is repeatedly queried for estimating optical signal quality, cutting risky lightpaths from the search space.

Initial applications of the three approaches above are starting to appear. Most of the current literature has focused on the End-to-End Learning approach, based on either Supervised Learning (as in [27]) or Deep Reinforcement Learning (as in [28]). Ref. [27] shows that Supervised Learning, to achieve satisfactory performance in terms of optimality gap, requires an enormous amount of ground-truth data and advanced models, hence its gain over existing approaches is still unclear. As for DRL, Ref. [28] offers a thorough numerical comparison of DRL versus both ILP, heuristics and metaheuristics. The main finding is that DRL can achieve a performance similar to advanced metaheuristics (as, e.g., Genetic Algorithms) with smaller computational times, but the main advantage of DRL resides in its ability to generalize to instances of traffic, close to the original one (i.e, the DRL model can be re-used without re-training even if the input parameters are changed, at least if changes are confined within a certain extent).

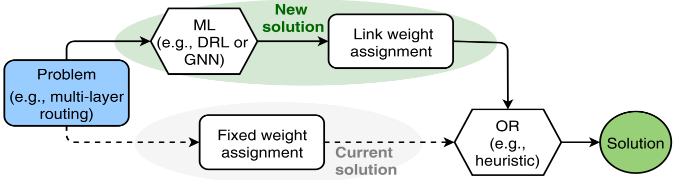
The application of ML in optical networks is becoming widespread [29], [30] and not limited purely to the solution of combinatorial problems as mentioned in this subsection.

C. Defragmentation

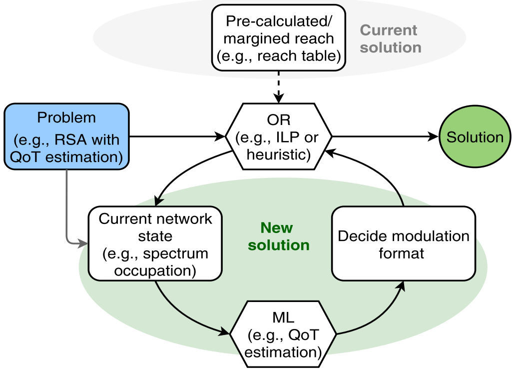
As a direct side-effect of dynamic arrival and departure of lightpaths, optical networks experience spectrum fragmentation, i.e., small fragments of the free links spectrum are formed that are difficult (or impossible) to be reused. Fragmentation might cause new lightpaths to be rejected (resulting in lost revenues) even if there is enough free spectrum along a candidate path. As lightpaths with heterogeneous bandwidths become more common in EONs, and as optical-layer dynamicity increases to support on-demand network slicing, the problem of spectrum fragmentation exacerbates and research interest grows around it.



a) End-to-end learning



b) Learning for algorithm configuration



c)Machine learning and optimization algorithms

Fig. 6: ML as an enabler for new optimization techniques (re-adapted from [22])

Defragmentation refers to the attempt to rearrange deployed lightpaths to remove spectrum fragments and improve spectral efficiency [1]. Defragmentation can be performed proactively (e.g., periodically) or reactively (e.g., when fragmentation exceeds a certain threshold, or to avoid rejection of a new lightpath). Several network-wide fragmentation metrics have been proposed, which typically depend on the size of spectrum gaps and on the highest slot occupied across network links, but devising a reliable metric that captures the impact of defragmentation on network throughput is still an open research issue. Moreover, new advances in optical communi-

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[1] The same process is often referred to as re-optimization, even though the term “re-optimization” tends to indicate a more generic resource re-allocation process, not necessarily targeting the removal spectrum gaps

cations, such as multiband and SDM transmission, call for new defragmentation metrics [31] tailored for these new scenarios.

Defragmentation algorithms leverage two main re-allocation operations, namely spectrum reallocation and/or rerouting of one or more lightpaths. These operations can be carried out in a) make-before-break, b) break-before-make or c) push-pull manner. With make-before-break, transmission on the original lightpath is not interrupted, and it is torn down only after a new ligthpath is established. With break-before-make, a lightpath operation is terminated, and its spectrum can be reused for new ligthpaths, at the cost of disrupting traffic. Finally, push-pull approach implies a continuous re-tuning of transceiver and receiver that allows to “slide” an active lightpath in the spectrum. As expected strategies a) and c) (known as also as “hitless”), avoid traffic disruption, but lead to higher blocking with respect to break-before-make approaches [5]. More quantitatively, it has been shown [32] that defragmentation (specifically, hitless make-before-break) can make room for about 10% more lightpaths, in both fixed grid and Flexgrid networks, but its application on operational networks is still debated due to several operational challenges (interruption of living traffic is highly undesirable, because a change of resource allocation in the physical layer might lead to an unexpected disruption of existing lightpaths).

IV. LOW MARGIN OPERATION

Traditionally optical networks have utilized system margin to account for uncertainty, resulting in a conservative estimate of performance [33]. These margins typically account for uncertainties both in the amount of traffic to be supported, but also in the knowledge of some of the physical parameters of the fibre plant, that might differ from the initial design value and/or might change over time due to the aging of equipment [34]. One way to reduce these margins is to collect detailed monitoring data [35] (monitors can be deployed at receivers, as well as at ROADMs, in the form of spectrum analyzers), then using Machine Learning (ML) to estimate relevant parameters [36] whose current knowledge is otherwise inaccurate.

A. *Transceiver based performance monitoring*

A key aspect of a digital coherent transceiver is the ability to estimate parameters of the optical path linking the transmitter and receiver [37].

1) Signal to noise ratio (SNR) estimation: Numerous techniques have been proposed for estimating SNR, using moment-based approaches[38], [39], but also data-aided approaches[40], [41]. More recently various machine learning based approaches including Neural Networks[42], Support Vector Machines[43] and also Convolutional Neural Networks[44] have been proposed to complement the traditional approaches based on an error vector magnitude based approach[45].

2) Accumulated chromatic dispersion: Given that the receiver compensates for the chromatic dispersion, inherently it is able to estimate the accumulated chromatic dispersion present in the signal [46], either using blind methods [47], [48], data aided [49], [40] or using training symbols [50].

3) Power evolution: While the estimate of SNR provides a useful measure, it provides no insight as to how the optical power (and therefore associated SNR) varies along the line system. In order to characterize the power evolution, the nonlinearity of the fibre is exploited, with the first approach being a pulse collision type measurement [51] in which the phase shift incurred on a probe channel is measured, being analogous to well established methods for characterizing the nonlinear properties of a fibre. Other approaches infer the nonlinear channel by attempting to invert it either using a nonlinear Volterra equalizer [52] or through digital backpropagation to resolve the power evolution along the fibre [53].

B. *Possible gains from low-margin operation*

To indicate the possible gains from low-margin links we reproduce the analysis from [54], where it is assumed that the capacity per polarization is given by the Shannon capacity for the additive white Gaussian noise channel [55]

$$C = B\log_2(1+SNR) \tag{1}$$

where B is the bandwidth and SNR is the signal to noise ratio. In order to account for a system margin of M_{dB} decibels then

$$C_M = B\log_2\left(1+\frac{SNR}{M}\right) \tag{2}$$

where M is related to M_{dB} such that $M_{dB} = 10\log_{10}(M)$. This allows the fraction of the capacity available due the the margin M to be given by

$$\frac{C_M}{C} = \frac{\log_2\left(1+\frac{SNR}{M}\right)}{\log_2\left(1+SNR\right)} \tag{3}$$

As can be seen in Fig. 7 where we have plotted equation (3 for a range of SNR values, for systems operating with high SNR, the impact on the overall capacity caused by including system margin is significantly reduced to lower SNR systems.

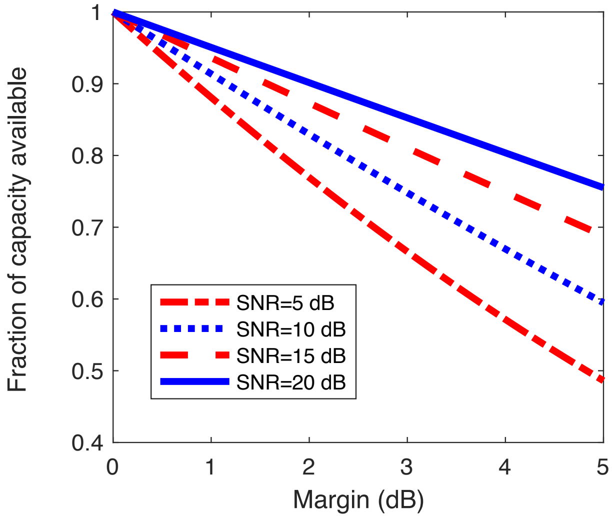

Fig. 7: Effect of margin on the fraction of capacity available for a range of SNR values

Further insight can be obtained by performing an asymptotic expansion of equation (3) for the case of $SNR \gg 1$ which gives[54]

$$\frac{C_M}{C} \approx 1 - \frac{M_{dB}}{SNR_{dB}} \tag{4}$$

where $SNR_{dB} = 10\log_{10}(SNR)$. Equation (4) indicates the maximum throughput relative to the case with no margin falls off approximately linearly with the margin M_{dB} given in decibels, with similar trends observed in network throughput [54] albeit the SNR_{dB} takes into account the 'effective SNR' for the network when using practical modulation formats. The key consequence of equation (4) is that for larger scale networks where the "effective SNR" is lower the impact of margin on the network throughput is more significant.

V. IMPACT OF MULTIBAND AND MULTIFIBRE

The overall objective of flexible networks is to use flexibility to increase overall network throughput in order that the fibre, ROADM and EDFA infrastructure is utilised as efficiently as possible. This then delays the need for an operator to add additional capacity. Current networks typically consist of a single pair of optical fibres between network nodes, with regularly spaced EDFAs providing bandwidth in the C band. Optimisation of the utilisation of this single C-band network can improve throughput significantly, as described in this paper, but ultimately even this will not be sufficient. The industry is now faced with a range of options to increase network capacity which includes (i) simply adding optical fibres and continuing to just use the C-band, (ii) extending each fibre to use other bands above and below the C band, (iii) using new fibre types such as multi-core fibre. Each solution has its own advantages and trade-offs. Therefore in the paper we discuss these solutions while suggesting that a targeted deployment strategy has to be considered by network planners. Most importantly the cost to equipment procurement, equipment deployment (CapEx) and network operation (OpEx) needs to match the data traffic growth and lead towards a pay-as-you-grow strategy. Deployment of additional parallel optical fibres operating with C-Band seems a straightforward approach from the viewpoint that it can make use of parallelism while utilising off-the-shelf equipment. The cost to procure new equipment will be less compared to using new technologies. Optical fibres are usually installed in ducts which are located underground. Considering that each duct has a finite space, adding parallel C-Band fibres may lead to exhaustion of the duct capacity. Not all operators own their own duct, and will have to factor in the costs of fibre leasing. As an alternative one can activate the existing spectral resources in the existing fibre's O,E,S,C and L bands. This is known as Multiband operation in which overall fibre is saved, but new optical technologies will be needed to facilitate the additional bands (e.g. new transceivers, amplifiers, ROADMs). Multiband can provide network operators with additional network capacity, delaying the need for additional fibre deployment. However, this is not trivial for a range of reasons including the increased inter-channel cross-talk via effects such as Interchannel Stimulated Raman Scattering (ISRS) [56], [57]. Additionally, increased complexity arises with variation in fibre attenuation, dispersion coefficient and use of diverse lumped amplification technologies as shown in Fig. 8. Therefore effective management of power and spectrum is required while assessing the benefits of Multiband optical networks.

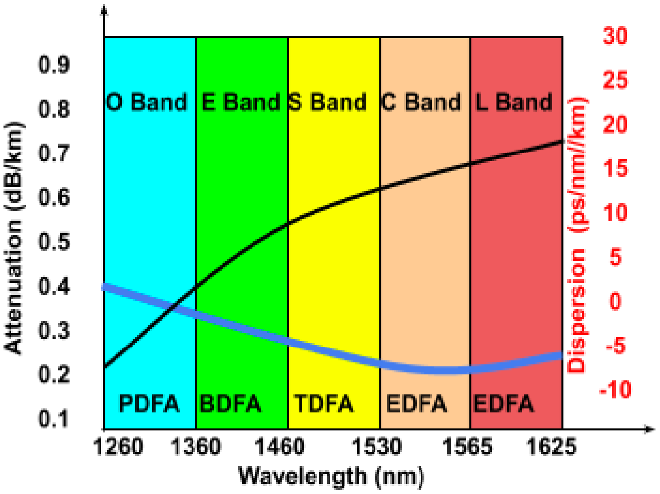

Fig. 8: Multiband optical spectrum of single mode fibre

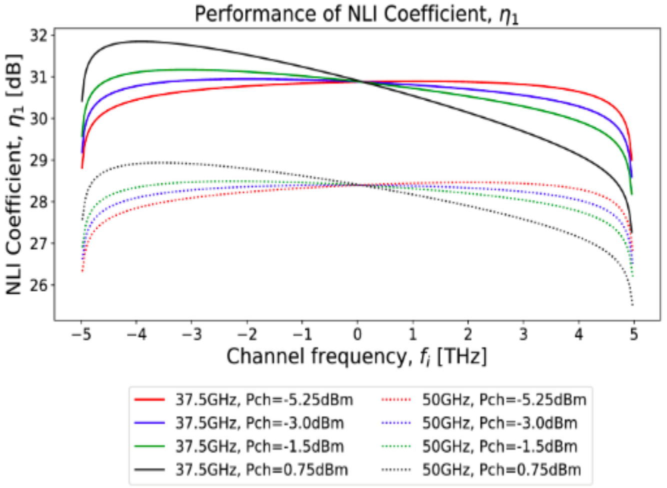

Fig. 9: Comparison of NLI coefficient for channel bandwidth 50 GHz (FG=50 GHz) and 37.5 GHz (FG=12.5 GHz)

Comparison of Multiband and multiple fibre C-band is a subject of current research [58]. One important aspect is the development of efficient optimisation strategies to manage the channel launch powers across multiple bands. In the paper [57] we highlighted the benefits of operating over C+L Bands and compared with only the C-Band. Fig. 9 indicates the impact of ISRS on each C+L band channel, where the central channel (f_i=0) indicates the wavelength interfacing between the C and L Band. As shown in Fig. 9, the slope of η_1, which is the normalised NLI coefficient indicating the ISRS impact, reduces with channel launch power while considering two channel bandwidths of 50 GHz (FG=50 GHz) and 37.5 GHz (FG=12.5 GHz) for 28 GBaud transceiver systems. In addition the η_1 values for 37.5GHz channel bandwidth is higher than for 50 GHz due to the presence of a higher number of active

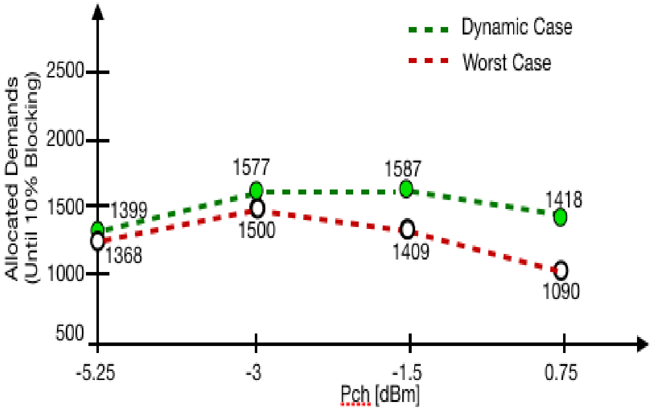

Fig. 10: Performance of BT-UK Network with FG=50 GHz and variation in channel launch power Pch

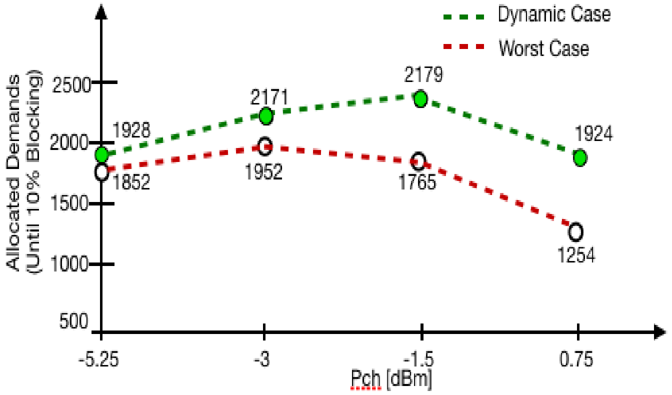

Fig. 11: Performance of BT-UK Network with FG=37.5 GHz and variation in channel launch power Pch

channels within 10 THz bandwidth of C+L bands. However, as seen in Fig. 10 and Fig. 11, the spectral benefits provided by using smaller FG lead to higher network capacity, assuming channel launch power management. While NLI slope reduces with launch power as shown in Fig. 9, the resulting slope needs to be traded off against overall network capacity. As can be seen in both Fig. 10 and Fig. 11 there a launch power that maximizes allocated demands, being -1.5 dBm and -3 dBm for dynamic and worst case respectively.

One has to consider that typically C+L band systems will involve a higher number of EDFA modules as compared to only C-band solutions. Therefore C+L band solutions can become cost effective only when the cost incurred in fibre leasing is greater than the cost incurred for additional EDFA procurement [59]. It is shown in Fig. 12 and Fig. 13 that, for larger networks, C+L operation is beneficial even for low fibre lease costs, whereas in smaller networks C+L only costs in when the fibre lease cost is high. Another challenge is to develop an economic upgrade strategy involving Multiband and parallel fibres. Deferring network upgrade through optimum spectrum provisioning and management strategy may be beneficial for operators: deferral should benefit from cheaper network equipment. A similar strategy was proposed in [7] where maximum cost benefits were available while choosing network link upgrade based on highest spectral utilisation per link.

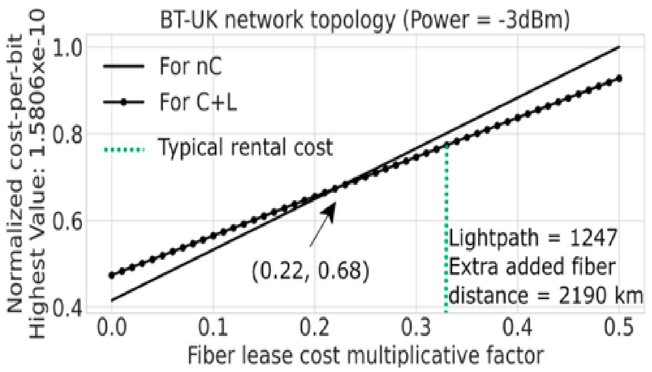

Fig. 12: Normalised cost-per-bit performance of BT-UK Network with variation in fibre lease cost

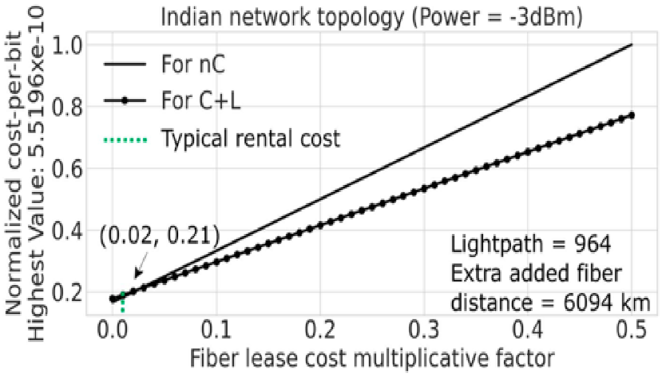

Fig. 13: Normalised cost-per-bit performance of Indian Network with variation in fibre lease cost

Extension from C+L to include O, E and S bands increase spectral resources, but may lead to a reduction in the spectral efficiency of each channel due to strong ISRS, offsetting the benefit gained to an extent. This is worse when the entire fibre is full, which is not the case over all links. Therefore through careful power and spectrum management, the capacity benefits over Multiband are possible, particularly for smaller networks. Whether these are cost-effective remains to be seen, and this is an active research topic.

VI. CONCLUSION

The advent of flexible spectrum manipulation combined with transceivers capable of a wide range of symbol rates and QAM-based modulation formats, has opened up a range of new operating paradigms on optical core networks. Options include being optical spectrum efficient (the Flexgrid mode) and adjusting the transceiver to best fit the channel (the Flexrate mode). Coupled to this, transceiver symbol rates have continued to climb. Additionally, overall traffic demands on core networks are starting to exceed the capabilities of a single C-band fibre. The paper has presented the options currently under study by the community, together with the tools being used to make the comparisons. Flexrate transceivers offer significant benefits in increasing overall network throughput, particularly when the channel is known with sufficient accuracy to allow a smaller margin of operation. Flexgrid operation can also give benefits, but these are likely to be smaller, with a risk of fragmentation to the overall spectrum allocation. In the future, continued traffic growth adds the complexities of multiple parallel fibres and Multiband operation in a single fibre. The optimal solution is still an open question, which in any case is likely to be operator-specific, and a function of the network geography size, coupled with fibre lease costs. Future work will account for these new challenges to form a complete picture on the optimum way to utilise flexible spectrum and transceivers to maximise the utilisation of networks, saving as much as possible on this expensive infrastructure.

REFERENCES

[1] “ITU-T G.694.1: Spectral grids for WDM applications: DWDM frequency grid.” https://www.itu.int/rec/T-REC-G.694.1/en.

[2] S. Frisken, G. Baxter, D. Abakoumov, H. Zhou, I. Clarke, and S. Poole, “Flexible and grid-less wavelength selective switch using LCOS technology,” in *2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference*, pp. 1–3, Mar. 2011.

[3] M. Jinno, B. Kozicki, H. Takara, A. Watanabe, Y. Sone, T. Tanaka, and A. Hirano, “Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network [Topics in Optical Communications],” *IEEE Communications Magazine*, vol. 48, pp. 138–145, Aug. 2010.

[4] N. Sambo, A. D’Errico, C. Porzi, V. Vercesi, M. Imran, F. Cugini, A. Bogoni, L. Potì, and P. Castoldi, “Sliceable transponder architecture including multiwavelength source,” *IEEE/OSA Journal of Optical Communications and Networking*, vol. 6, pp. 590–600, July 2014.

[5] B. C. Chatterjee, S. Ba, and E. Oki, “Fragmentation Problems and Management Approaches in Elastic Optical Networks: A Survey,” *IEEE Communications Surveys Tutorials*, vol. 20, no. 1, pp. 183–210, 2018.

[6] R. K. Ahuja, T. L. Magnanti, and J. B. Orlin, *Network flows: theory, algorithms and applications*. Prentice Hall, 1993.

[7] T. Ahmed, A. Mitra, S. Rahman, M. Tornatore, A. Lord, and B. Mukherjee, “C+L-band upgrade strategies to sustain traffic growth in optical backbone networks,” *IEEE/OSA Journal of Optical Communications and Networking*, vol. 13, pp. 193–203, July 2021.

[8] A. Mitra, A. Lord, S. Kar, and P. Wright, “Effect of link margin and frequency granularity on the performance of a flexgrid optical network,” *Optics Express*, vol. 22, p. 41, Jan. 2014.

[9] A. Mitra, A. Lord, S. Kar, and P. Wright, “Effect of link margins and frequency granularity on the performance and modulation format sweet spot of multiple flexgrid optical networks,” in *OFC 2014*, pp. 1–3, Mar. 2014.

[10] J. Pesic, T. Zami, P. Ramantanis, and S. Bigo, “Faster return of investment in wdm networks when elastic transponders dynamically fit ageing of link margins,” in *2016 Optical Fiber Communications Conference and Exhibition (OFC)*, pp. 1–3, 2016.

[11] Y. Pointurier, “Design of low-margin optical networks,” *Journal of Optical Communications and Networking*, vol. 9, no. 1, pp. A9–A17, 2017.

[12] A. Napoli, M. Bohn, D. Rafique, A. Stavdas, N. Sambo, L. Poti, M. Nölle, J. K. Fischer, E. Riccardi, A. Pagano, A. Di Giglio, M. S. Moreolo, J. M. Fabrega, E. Hugues-Salas, G. Zervas, D. Simeonidou, P. Layec, A. D’Errico, T. Rahman, and J. P. F.-P. Giménez, “Next generation elastic optical networks: The vision of the european research project idealist,” *IEEE Communications Magazine*, vol. 53, no. 2, pp. 152–162, 2015.

[13] Z. Zhu, W. Lu, L. Zhang, and N. Ansari, “Dynamic service provisioning in elastic optical networks with hybrid single-/multi-path routing,” *Journal of Lightwave Technology*, vol. 31, no. 1, pp. 15–22, 2013.

[14] B. Mukherjee, *Optical WDM Networks*. Springer US, 2006.

[15] M. Salani, C. Rottondi, and M. Tornatore, “Routing and Spectrum Assignment Integrating Machine-Learning-Based QoT Estimation in Elastic Optical Networks,” in *IEEE INFOCOM 2019 - IEEE Conference on Computer Communications*, pp. 1738–1746, Apr. 2019.

[16] G. Gamrath and M. E. Lübbecke, “Experiments with a Generic Dantzig-Wolfe Decomposition for Integer Programs,” in *Experimental Algorithms* (D. Hutchison, T. Kanade, J. Kittler, J. M. Kleinberg, F. Mattern, J. C. Mitchell, M. Naor, O. Nierstrasz, C. Pandu Rangan, B. Steffen, M. Sudan, D. Terzopoulos, D. Tygar, M. Y. Vardi, G. Weikum, and P. Festa, eds.), vol. 6049, pp. 239–252, Berlin, Heidelberg: Springer Berlin Heidelberg, 2010.

[17] M. Tornatore, C. Rottondi, R. Goscien, K. Walkowiak, G. Rizzelli, and A. Morea, “On the complexity of routing and spectrum assignment in flexible-grid ring networks,” *J. Opt. Commun. Netw.*, vol. 7, pp. A256–A267, Feb 2015.

[18] O. Karandin, F. Musumeci, O. Ayoub, A. Ferrari, Y. Pointurier, and M. Tornatore, “Quantifying Resource Savings from Low-Margin Design in Optical Networks with Probabilistic Constellation Shaping,” in *47th European Conference on Optical Communication*, Sept. 2021.

[19] N. Shahriar, M. Zulfiqar, S. R. Chowdhury, S. Taeb, R. Boutaba, J. Mitra, and M. Hemmati, “Disruption minimized bandwidth scaling in eon-enabled transport network slices,” *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 9, pp. 2734–2747, 2021.

[20] M. Aibin and K. Walkowiak, “Simulated Annealing algorithm for optimization of elastic optical networks with unicast and anycast traffic,” in *2014 16th International Conference on Transparent Optical Networks (ICTON)*, pp. 1–4, July 2014.

[21] M. Klinkowski, “A Genetic Algorithm for Solving RSA Problem in Elastic Optical Networks with Dedicated Path Protection,” in *International Joint Conference CISIS’12-ICEUTE´12-SOCO´12 Special Sessions* (Á. Herrero, V. Snášel, A. Abraham, I. Zelinka, B. Baruque, H. Quintián, J. L. Calvo, J. Sedano, and E. Corchado, eds.), vol. 189, pp. 167–176, Berlin, Heidelberg: Springer Berlin Heidelberg, 2013.

[22] Y. Bengio, A. Lodi, and A. Prouvost, “Machine learning for combinatorial optimization: A methodological tour d’horizon,” *European Journal of Operational Research*, vol. 290, pp. 405–421, Apr. 2021.

[23] X. Chen, B. Li, R. Proietti, H. Lu, Z. Zhu, and S. J. B. Yoo, “DeepRMSA: A Deep Reinforcement Learning Framework for Routing, Modulation and Spectrum Assignment in Elastic Optical Networks,” *Journal of Lightwave Technology*, vol. 37, pp. 4155–4163, Aug. 2019.

[24] P. Veličković, G. Cucurull, A. Casanova, A. Romero, P. Liò, and Y. Bengio, “Graph Attention Networks,” *arXiv:1710.10903 [cs, stat]*, Feb. 2018.

[25] K. Zhu, H. Zhu, and B. Mukherjee, “Traffic engineering in multigranularity heterogeneous optical WDM mesh networks through dynamic traffic grooming,” *IEEE Network*, vol. 17, pp. 8–15, Mar. 2003.

[26] W. Feijen and G. Schäfer, “Using machine learning predictions to speed-up dijkstra’s shortest path algorithm,” *CoRR*, vol. abs/2112.11927, 2021.

[27] I. Martín, J. A. Hernández, S. Troia, F. Musumeci, G. Maier, and O. G. de Dios, “Is machine learning suitable for solving rwa problems in optical networks?,” in *2018 European Conference on Optical Communication (ECOC)*, pp. 1–3, 2018.

[28] N. Di Cicco, E. F. Mercan, O. Karandin, O. Ayoub, S. Troia, F. Musumeci, and M. Tornatore, “On deep reinforcement learning for static routing and wavelength assigment,” *IEEE Journal of Selected Topics in Quantum Electronics*, pp. 1–1, 2022.

[29] D. Rafique and L. Velasco, “Machine learning for network automation: overview, architecture, and applications [invited tutorial],” *Journal of Optical Communications and Networking*, vol. 10, no. 10, pp. D126–D143, 2018.

[30] F. Musumeci, C. Rottondi, A. Nag, I. Macaluso, D. Zibar, M. Ruffini, and M. Tornatore, “An overview on application of machine learning techniques in optical networks,” *IEEE Communications Surveys Tutorials*, vol. 21, no. 2, pp. 1383–1408, 2019.

[31] P. Lechowicz, M. Tornatore, A. Wlodarczyk, and K. Walkowiak, “Fragmentation metrics and fragmentation-aware algorithm for spectrally/spatially flexible optical networks,” *IEEE/OSA Journal of Optical Communications and Networking*, vol. 12, pp. 133–145, May 2020.

[32] T. Takagi, H. Hasegawa, K.-i. Sato, Y. Sone, A. Hirano, and M. Jinno, “Disruption minimized spectrum defragmentation in elastic optical path networks that adopt distance adaptive modulation,” in *2011 37th European Conference and Exhibition on Optical Communication*, pp. 1–3, Sept. 2011.

[33] R. E. Epworth, “ITT 140 Mbit/s Optical Fibre System,” in *National Telecommunications Conference*, Dec. 1977.

[34] Y. Pointurier, “Design of low-margin optical networks,” *IEEE/OSA Journal of Optical Communications and Networking*, vol. 9, pp. A9–A17, Jan. 2017.

[35] P. Ramantanis, C. Delezoide, P. Layec, and S. Bigo, “Revisiting the calculation of performance margins in monitoring-enabled optical networks,” *IEEE/OSA Journal of Optical Communications and Networking*, vol. 11, pp. C67–C75, Oct. 2019.

[36] T. Tanimura, T. Hoshida, T. Kato, S. Watanabe, and H. Morikawa, “Data-analytics-based Optical Performance Monitoring Technique for Optical Transport Networks,” in *2018 Optical Fiber Communications Conference and Exposition (OFC)*, pp. 1–3, Mar. 2018.

[37] F. N. Hauske, M. Kuschnerov, B. Spinnler, and B. Lankl, "Optical performance monitoring in digital coherent receivers," *Journal of Lightwave Technology*, vol. 27, no. 16, pp. 3623–3631, 2009.

[38] C. Zhu, A. V. Tran, S. Chen, L. B. Du, C. C. Do, T. Anderson, A. J. Lowery, and E. Skafidas, "Statistical moments-based osnr monitoring for coherent optical systems," *Opt. Express*, vol. 20, pp. 17711–17721, Jul 2012.

[39] M. S. Faruk, Y. Mori, and K. Kikuchi, "In-band estimation of optical signal-to-noise ratio from equalized signals in digital coherent receivers," *IEEE Photonics Journal*, vol. 6, no. 1, pp. 1–9, 2014.

[40] C. C. Do, A. V. Tran, C. Zhu, S. Chen, T. Anderson, D. Hewitt, and E. Skafidas, "Data-aided chromatic dispersion estimation for polarization multiplexed optical systems," *IEEE Photonics Journal*, vol. 4, no. 5, pp. 2037–2049, 2012.

[41] F. Pittalà, F. N. Hauske, Y. Ye, N. G. Gonzalez, and I. T. Monroy, "Joint pdl and in-band osnr monitoring supported by data-aided channel estimation," in *OFC/NFOEC*, pp. 1–3, 2012.

[42] F. J. Caballero, D. J. Ives, C. Laperle, D. Charlton, Q. Zhuge, M. O'Sullivan, and S. J. Savory, "Machine learning based linear and nonlinear noise estimation," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 10, no. 10, pp. D42–D51, 2018.

[43] X. Lin, O. A. Dobre, T. M. N. Ngatched, Y. A. Eldemerdash, and C. Li, "Joint modulation classification and osnr estimation enabled by support vector machine," *IEEE Photonics Technology Letters*, vol. 30, no. 24, pp. 2127–2130, 2018.

[44] T. Tanimura, T. Hoshida, T. Kato, S. Watanabe, and H. Morikawa, "Convolutional neural network-based optical performance monitoring for optical transport networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 11, no. 1, pp. A52–A59, 2019.

[45] R. Schmogrow, B. Nebendahl, M. Winter, A. Josten, D. Hillerkuss, S. Koenig, J. Meyer, M. Dreschmann, M. Huebner, C. Koos, J. Becker, W. Freude, and J. Leuthold, "Error vector magnitude as a performance measure for advanced modulation formats," *IEEE Photonics Technology Letters*, vol. 24, no. 1, pp. 61–63, 2012.

[46] R. Andres Soriano, F. N. Hauske, N. Guerrero Gonzalez, Z. Zhang, Y. Ye, and I. Tafur Monroy, "Chromatic dispersion estimation in digital coherent receivers," *Journal of Lightwave Technology*, vol. 29, no. 11, pp. 1627–1637, 2011.

[47] Q. Sui, A. P. T. Lau, and C. Lu, "Fast and robust blind chromatic dispersion estimation using auto-correlation of signal power waveform for digital coherent systems," *Journal of Lightwave Technology*, vol. 31, no. 2, pp. 306–312, 2013.

[48] C. Xie, "Chromatic dispersion estimation for single-carrier coherent optical communications," *IEEE Photonics Technology Letters*, vol. 25, no. 10, pp. 992–995, 2013.

[49] F. Pittalà, F. N. Hauske, Y. Ye, N. G. Gonzalez, and I. T. Monroy, "Fast and robust cd and dgd estimation based on data-aided channel estimation," in *2011 13th International Conference on Transparent Optical Networks*, pp. 1–4, 2011.

[50] F. Pittalà, I. Slim, A. Mezghani, and J. A. Nossek, "Training-aided frequency-domain channel estimation and equalization for single-carrier coherent optical transmission systems," *Journal of Lightwave Technology*, vol. 32, no. 24, pp. 4849–4863, 2014.

[51] A. D. Shiner, A. Borowiec, M. Reimer, D. Charlton, and M. O'Sullivan, "Nonlinear Spatially Resolved Interferometer for Distance Resolved Power and Gain Tilt Measurement," in *42nd European Conference on Optical Communication*, pp. 1–3, Sept. 2016.

[52] S. Gleb, P. Konstantin, J. Luo, and B. Zheng, "Fiber link anomaly detection and estimation based on signal nonlinearity," in *47th European Conference on Optical Communication*, Sept. 2021.

[53] T. Tanimura, S. Yoshida, K. Tajima, S. Oda, and T. Hoshida, "Concept and implementation study of advanced DSP-based fiber-longitudinal optical power profile monitoring toward optical network tomography [Invited]," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 13, pp. E132–E141, Oct. 2021.

[54] S. J. Savory, R. J. Vincent, and D. J. Ives, "Design considerations for low-margin elastic optical networks in the nonlinear regime," *J. Opt. Commun. Netw.*, vol. 11, pp. C76–C85, Oct 2019.

[55] C. E. Shannon, "A mathematical theory of communication," *Bell System Technical Journal*, vol. 27, no. 3, pp. 379–423, 1948.

[56] D. Semrau, R. I. Killey, and P. Bayvel, "The Gaussian Noise Model in the Presence of Inter-Channel Stimulated Raman Scattering," *Journal of Lightwave Technology*, vol. 36, pp. 3046–3055, July 2018.

[57] A. Mitra, D. Semrau, N. Gahlawat, A. Srivastava, P. Bayvel, and A. Lord, "Effect of Channel Launch Power on Fill Margin in C+L Band Elastic Optical Networks," *Journal of Lightwave Technology*, vol. 38, pp. 1032–1040, Mar. 2020.

[58] M. N. V. V. Mattia Cantono, Rene Schmogrow and T. Hofmeister, "Opportunities and challenges of c+l transmission systems," *Journal of Ligtwave Technology*, vol. 38, no. 5, pp. 1050–1060, 2020.

[59] R. K. Jana, A. Mitra, A. Pradhan, K. Grattan, A. Srivastava, B. Mukherjee, and A. Lord, "When Is Operation Over C+L Bands More Economical than Multifiber for Capacity Upgrade of an Optical Backbone Network?," in *2020 European Conference on Optical Communications (ECOC)*, pp. 1–4, Dec. 2020.