Options for Cost-effective Capacity Upgrades in Backbone Optical Networks

(Invited Article)

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***Abstract*—Upgrading the capacity of backbone optical networks while delivering contents to the end-users with a reduced cost per bit is a day-by-day challenge of network operators. In this paper, we first discuss several mid-term options for capacity upgrades including migration to multi-fibre and multi-band systems (utilizing amplification systems with bandwidth extending over the C+L or the S+C+L bands). The multi-band approach is shown to be more cost-effective than the multi-fibre approach under certain circumstances. We then focus on space-division multiplexing (SDM) based networks as the ultimate solution to address the "capacity crunch". We compare the performance and infrastructure cost of possible SDM switching options for a solution based on bundles of single-mode fibres as a first pragmatic generation of SDM networks. We show that the use of spatial-group switching reduces the switching-related infrastructure cost of the SDM network and can also lead to extra cost savings due to sharing of elements in other parts of the network.**

Keywords—Multi-band, Raman systems, SDM switches, Spatial super-channel, network cost

I. INTRODUCTION

The traffic carried by core optical networks as well as the per-channel interface rates required by IP routers are growing at a remarkable pace year-over-year. Optical transmission and switching advancements have so far satisfied this huge traffic growth by delivering the content over the network infrastructure in a cost and energy efficient manner utilizing to the maximum extent the capabilities of optoelectronic and photonic subsystems and the available bandwidth of deployed optical fibres. However, we are rapidly approaching fundamental spectral efficiency (SE) limits of single-mode fibres (SMF) and the scientific and industrial telecommunications community foresees that the growth capabilities of conventional WDM networks operating on a fixed frequency grid are quite limited [1].

To address such limitations, over the last couple of years a large number of significant innovations able to offer, in practice, a capacity increase by a factor of around 10-20 (compared to legacy WDM systems at 10 Gbps on a 50-GHz grid) have emerged [2]. Initial efforts targeted innovative modulation/coding techniques, novel switching subsystems and routing algorithms supporting flexible frequency allocations, in an effort to increase the spectral density/utilization in the optical network. This eventually led to the definition of spectrally flexible/elastic optical networks utilizing optical super-channels (Sp-Ch) together with spectrally flexible/elastic multiplexing schemes (e.g. OFDM and Nyquist WDM) and advanced modulation formats, thus enabling the dynamic and adaptive allocation of end-to-end demands with variable connection characteristics (e.g. requested data rates) [3]. However, while the spectrally flexible/elastic optical networking approaches can optimize network resources through increased spectral utilization compared to conventional fixed-grid networks, it has limited growth potential due to the nonlinear Shannon limit, which imposes an upper bound on the transport capacity of a SMF within the limited gain bandwidth of C-band EDFA optical amplifiers. A solution to increase the fibre capacity is to extend the amplification bandwidth. EDFA amplifiers working on the C+L band or Raman-based amplification systems with different designs —e.g. all-Raman, hybrid Raman with EDFA amplifiers, or remote optically pumped amplifiers (ROPA)— can increase network capacity by amplifying broader spectral bands [4][5] compared to conventional C-band EDFA systems.

Even though current trends show that, as a mid-term option, capacity upgrades may occur with the introduction of multi-band systems [5][6], the only evident long-term solution

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to extend the capacity of optical communication systems relies on the use of some form of spatial division multiplexing (SDM). The simplest way to achieve spatial multiplexing is to deploy multiple systems in parallel. However, by simply increasing the number of systems, the cost and power consumption also increases linearly. In order to limit the increase in cost and power consumption, component sharing and integration have to be introduced. To this extent, significant research efforts have focused on the development and performance evaluation of few-mode fibres (FMF) and multi-core fibres (MCF), which can be seen as 'integrated fibre' media, for SDM systems. The development of relevant flexible optical switches for SDM is an active research field and there are several solutions available today able to perform the switching of spectral/spatial Sp-Chs with variable bandwidth characteristics at a fine granularity [7], while providing support for all-optical grooming enabling the aggregation and distribution of traffic directly at the optical layer [8]. In addition, significant efforts are being made on the development of the proper control plane framework to orchestrate the operation of such spectrally and spatially flexible networks in order to bring out their full-potential (i.e. capacity increase and other capabilities such as network virtualization) [9].

In this paper, we discuss possible mid-term capacity upgrade solutions based on multi-band amplification systems. We compare them with several multi-fibre deployment approaches in terms of performance and migration cost. Next, we investigate SDM network, which we consider to be the ultimate option for capacity upgrade. Enabling SDM switching technologies are described and a comparison of performance and switching-related infrastructure cost is presented.

The rest of the paper is organised as follows. In section II, we discuss options for mid-term capacity upgrades. In section III, we focus on long-term options (SDM networks), including enabling technologies and different approaches to design and operate these future networks. We conclude the study by weighing the pros and cons of mid-term and long-term options for capacity upgrade in terms of cost and performance.

II. MID-TERM CAPACITY UPGRADE

A. *Motivation*

The requirement of higher capacities at a lower cost per bit is the main challenge in any network migration scenario. 100-Gbps polarization multiplexing quadrature phase shift keying (PM-QPSK) coherent technology is currently dominating the capacity upgrades in operator networks. However, the continuous increase in network traffic demands requires the upgrade of network capacities to even higher values. Current trends show that, as a near-term option, capacity upgrades can be prompted by the introduction of 200 Gbps technology. Mid-term options, however, are not so clear at the moment and relevant discussions towards the selection of the appropriate choices are open. 400-Gbps single-carrier (SC) systems have been proposed as a possible solution, but the transparent optical reach of this solution is quite limited. Table I shows that the use of 400 Gbps-SC interfaces results in fewer channels in the amplification band of EDFAs operating in the C-band, since, instead of 50-GHz channel spacing, 75-GHz channel spacing is required to avoid inter-channel crosstalk and to increase the optical reach. Even though higher bit rates per transceiver can be achieved in a flex-grid SC configuration by increasing the modulation level (thereby increasing the SE, at the price of reducing the transmission reach) and the baud rate (which results in increased non-linear impairments and component requirements) [10], the most viable solution is to resort to multi-carrier (MC) or super-channel transmission, whereby a signal is divided into sub-channel constituents at a lower baud rate and modulation level by means of compact multiplexing techniques such as Nyquist WDM or OFDM. However, as indicated in section I, we are approaching a fundamental SE limit in the C-band.

TABLE I.
NUMBER OF POSSIBLE CHANNELS CONSIDERING VARIOUS AMPLIFICATION SYSTEMS SUPPORTING C BAND, C+L BAND AND S+C+L BAND. BY MOVING TO VERY HIGH CHANNEL RATE INTERFACES, DUE TO THE SIGNIFICANT PHYSICAL LAYER IMPAIRMENTS, THE NUMBER OF SUPPORT CHANNELS DECREASES.

Channel rate / Amplification band	10G	100G	200G	400G	1T
C	80	80	80	53	26
C+L	160	160	160	106	52
S+C+L	240	240	240	159	78

Capacity upgrades will have to be realized with the addition of more spectrum in the system, either by adding more amplification bands [11] or more fibres [12], mainly on the 'hot links' of the network. Therefore, while MC systems seem to be the first option to be explored, in the mid-term we will inevitably have to consider multi-band or multi-fibre systems and use them in a complementary way.

The multi-band deployment approach depends on an appropriate and reliable amplification technology operating in the S and/or L bands of the SMF. Conventional C-band EDFA based systems usually have an amplification bandwidth limited to around 32nm over the C-Band, corresponding to 80 WDM channels. On the other hand, Raman-based systems with different designs (all-Raman, hybrid, ROPA) can amplify broader spectral bands depending on the number of cascaded pumps, with reported solutions with bandwidths extending to 61 nm (C+L bands, i.e. 160 WDM channels) or 100 nm (S+C+L bands, i.e. 240 WDM channels) [5]. 50-GHz WDM channels can support up to 200 Gbps with a reasonable transparent optical reach, so that a number of 80, 160, and 240 channels can be amplified using amplification systems supporting C, C+L, and S+C+L bands, respectively (cf. Table I). As we increase the channel bit rate to 400 Gbps and 1 Tbps, the number of channels decreases due to the higher required channel spacing to support those bit-rates (75-GHz and 150-GHz for 400G and 1T, respectively), as shown in Table I.

From a practical perspective, the noise figure (NF) of a typical EDFA can be ~5dB, while Raman-based amplifiers can show a much better noise performance, with feasible effective NF ranging from -1 to 4dB depending on the actual design [4][13]. Based on what is reported in the literature [13][14], a transmission reach increase of 50-150% using Raman-based

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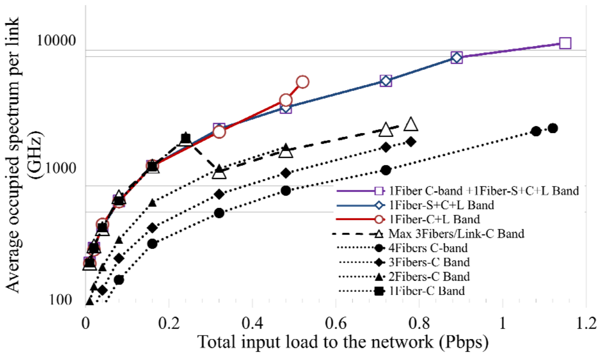


Fig. 1. Average occupied spectrum per link per fibre vs. offered load.

amplification can be achieved due to NF improvement and NL impairment reduction depending on span length, number of channels, fibre damage threshold and amplification gain.

Using the case of a conventional single SMF system operated over C-band as a benchmark, in [6], we compared the multi-band and multi-fibre system migration solutions for the mid-term network evolution considering a typical national reference network encountered in a European country (Telefónica Spain national network). Two multi-band systems (with amplification extending over C+L bands and over S+C+L bands) and two multi-fibre systems (with 2 and 3 fibres per link and amplification over the C-band) were considered. Additionally, we explored a multi-fibre migration scenario in which fibres are added only to congested links (with a maximum of 3 fibres per link).

B. *Cost and performance evaluations*

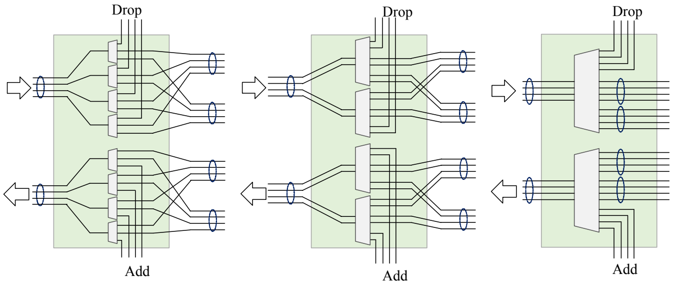
Fig. 1 shows the performance of the multi-band and multi-fibre solutions explained above. The simulation environment and assumptions are the same as [6].The introduction of two and three fibres per link, or one or two additional spectral bands, results in an increase in network performance of approximately twice or three times, respectively. However, the multi-band scenario spanning the S+C+L bands is capable to accommodate 8% and 14% more traffic to the network (for 60% and 100% reach increase, respectively) compared to the C-band EDFA-based parallel system with three fibres. Since having a network-wide parallel system installation might not be a realistic option that operators will choose, we have also analyzed a C-band EDFA-based scenario in which fibres are added to a link (with a maximum degree of parallelism of 3) only in the case that congestion arises on that particular link. We observe that 55% of the links require the addition of three fibres, whereas only 9% of them make use of two fibres.

To estimate the additional cost of migrating to a multi-band and multi-fibre system, we developed, in the framework of the EU project INSPACE, a cost model for the WSSs and amplifiers [6]. Using the cost of commercial LCoS-based C-band 1×9 WSSs as a reference, the cost of a C+L- or S+C+L-band WSS was estimated to be 1.5 since both require a redesign of the grating and the LCoS regardless of the number of bands. Furthermore, the C-band EDFA amplifiers have a cost of 0.5 and the Raman amplifiers were assumed to cost 1.5 for the C+L band and 3 for the S+C+L band due to the very high pump powers required [14] and the need for special pumps and fibre lasers used for 2nd-order pumping [3][5]. Taking this model into account, the extra cost of deploying two and three fibres across all links is 402 and 804, whereas the case of adding up to three fibres per link depending on the specific link requirements has a cost of only 469 (58% of the cost of a network-wide three-fibre system, while offering the same network performance). C+L- and S+C+L-band systems show the higher deployment cost (870, 1404 –100% reach increase– and 1012 –60%–, respectively) because the existing network elements (both WSS and amplifiers) need to be replaced. Network operators may however want to accommodate the existing network infrastructure in the planning of future networks. To examine this case, we compared a scenario in which 1) three fibres were added to have four parallel fibres network-wide with amplification systems operating on C-band, and 2) one fibre with amplifiers operating over the S+C+L bands was added to the existing fibre with amplifiers operating over the C-band. In this case, the replacement of the existing network elements is not required and the migration cost of having and extra fibre with amplifiers operating over the S+C+L-band is 1056, whereas adding three more fibres with amplification system operating over the C-band is 1100.

III. LONG-TERM CAPACITY UPGRADE (SDM-BASED OPTICAL TRANSPORT NETWORK)

Even though, multi-band amplification technologies (e.g., C+L+S-band amplifiers) or multi-fibre deployment approach as explained above may yield temporary relief to network capacity shortages, the only evident long-term solution to extend the capacity of optical communication systems relies on the use of some form of SDM. SDM has been introduced to address the vast increase in the amount of generated traffic, while effectively reducing the additional deployment cost required for the expansion of the network capacity. However, particular attention needs to be paid to the selection of a cost-effective technology for each element of an SDM network (e.g. transmission media, transceivers, amplifiers, or switches), while minimising SDM-related physical-layer constraints: (a) physical impairments introduced by the SDM transmission medium (e.g. MCF is mostly affected by inter-core crosstalk, while MMF is more strongly impacted by mode coupling and/or differential mode delay); (b) integration of SDM components (transponder, wavelength-selective switch (WSS), Mux/DeMux, etc.) and associated cost reduction; (c) digital signal processing (DSP) and multiple-input/multiple-output (MIMO) complexity; and (d) network-level performance.

Optical fibres in support of SDM transmission may come in many forms and many alternatives have been reported so far [15]. One of the key differentiating metrics between SDM-supporting fibres is whether the modes/cores remain uncoupled in transmission or potentially may be coupled due to manufacturing imperfections as well as environmental effects such as bends, stress, and temperature gradients. Considering that aspect, they can be categorized in three different classes, depending on whether they possess 1) uncoupled/weakly-coupled spatial channels, 2) strongly coupled spatial channels, and 3) sub-groups of strongly coupled spatial channels.



(a) (b) (c)

Fig. 2. ROADM architecture with S=4 and D=3 for a) Ind-Sw, b) FrJ-Sw w/ G=2, and c) J-Sw. Only 1 degree is shown. Ind-Sw, FrJ-Sw w/ G=2, and J-Sw require 8 1×3, 4 2×6, and 2 4×12 WSSs per degree, respectively.

In order to support different types of fibres and reduce the switching cost of the SDM network, different switching architectures have been proposed [7] allowing different levels of flexibility in switching spatial modes (defined as cores in MCFs, LP modes in FMFs and SMFs in bundles of SMFs): (a) independent switching (Ind-Sw): all spectral slots and spatial modes can be independently directed to any output port; (b) joint switching (J-Sw): all spatial modes are treated as a single entity, while spectral slots can be freely switched by the WSS; and (c) fractional joint switching (FrJ-Sw): a number G of groups of spatial modes, as well as all spectral slots, can be independently switched to all output ports (cf. Fig. 2).

Ind-Sw offers a high level of flexibility for routing, space, modulation-level and spectrum assignment (RSMSA) since it allows the allocation of demands over different spatial modes and spectral slices with variable widths. In contrast, J-Sw constrains the RSMSA to one spatial super-channel (Sp-Ch) connection (spread over a number of spatial modes) per spectral slice, and therefore the unused spatial modes over a certain spectral width cannot be allocated to other demands. Note that different transmission media will impose different requirements and will affect the applicability of the different switching schemes: e.g. J-Sw is necessary for coupled MCFs or FMFs on account of inter-core crosstalk and mode coupling [16], but any switching option is suitable with uncoupled MCFs or bundles of SMFs. While the choice of switching technology can restrict the flexibility of RSMSA algorithms (given that the coarse granularity of J- and FrJ-Sw), it can also boost the economic feasibility of SDM solutions. For instance, J-Sw and FrJ-Sw allow the use of different degrees of joint DSP, which can lead to cost and power consumption savings of integrated receivers in SDM networks [17].

A. SDM Switching Technologies

Recent investigations on WSSs suitable for SDM have demonstrated the suitability of existing WSS technologies in combination with 2D SMF arrays to handle J-Sw and FrJ-Sw [7]. Under these switching paradigms, SDM WSSs are configured to operate as S × (M × N) WSSs, capable of directing M input ports, each carrying S spatial modes, toward N output ports [17]. This has the implication that for large S, WSSs with very high port count are required. For instance, assuming a route-and-select ROADM architecture with nodal degree D, two WSSs with port count of at least S×(1×D) per degree would be required for J-Sw; $2\cdot\lceil S/G \rceil$ WSSs with port count G×(1×D) per degree would be required for FrJ-Sw, and finally 2·S WSSs with port count 1×D per degree would be required for Ind-Sw (where $\lceil\cdot\rceil$ is the ceiling function). Therefore, if we assume bundles of 4 SMFs, G = 2, and D = 3, the following WSSs would be required: 2 WSSs with 4×(1×3) –i.e. 16– input/output ports per degree for J-Sw, 4 WSSs with 2×(1×3) –i.e. 8– ports for FrJ-Sw, and 8 WSSs with 1×3 –i.e. 4– ports for Ind-Sw, as depicted in Fig. 2. This leads to a far lower number of WSSs required by J-Sw and FrJ-Sw, which should bring the network cost down significantly especially as the number of spatial modes increases. However, increasing the port count affects the WSS cost, so it is necessary to evaluate whether the reduction in the number of ports can compensate for the increase in the WSS cost.

B. Resource allocation in SDM-networks

While the extra dimension introduced by SDM provides more capacity to respond to a large traffic increase, dynamic allocation policies also need to be explored to address the disparate behavior of traffic and its fluctuations. The two main technology areas limiting channel allocation and routing options are: a) fibre type —through the physical impairments imposed on the spectrally/spatially multiplexed channels—, and b) switching technology —determining the routing properties of the multiplexed channels at the nodes.

In order to allocate a demand in an SDM network, two basic super-channel (Sp-Ch) policies can be defined: spectral or spatial Sp-Ch allocation. A spectral Sp-Ch is the result of aggregating signals modulated on adjacent optical carriers in a single spatial mode, whereas a spatial Sp-Ch is the result of aggregating signals modulated on one optical carrier across several spatial modes of an SDM transmission medium. Combinations of these two basic policies lead to Sp-Ch allocation with arbitrarily shaped spectral/spatial Sp-Chs.

SDM networks based on spatial Sp-Ch allocation can benefit from significant cost reduction because network elements can be shared among spatial modes, but may also sacrifice SE depending on the incoming traffic profile.

In the following, we review spatial and hybrid spatial/spectral Sp-Ch allocation options as well as the cost and performance of networks based on them.

1) Spatially flexible Sp-Chs

Channel allocation constrained to the use of a single optical carrier may come in the following forms:

a) Multi-Channel SC Single-Line-Rate (MC-SC-SLR)

Resource provisioning of MC-SC-SLR transmission system with 50-GHz-WDM spectral channel width is shown in Fig. 3(a). MC-SC-SLR transmission systems utilise one optical carrier and employ a single modulation format (e.g. DP-QPSK) to carry a fixed maximum amount of data per Sp-Ch. It can be regarded as a conventional WDM system having *S* times more capacity than a conventional WDM channel. MC-SC-SLR treats each Sp-Ch as a single entity, as required in the case of strongly coupled cores/modes.

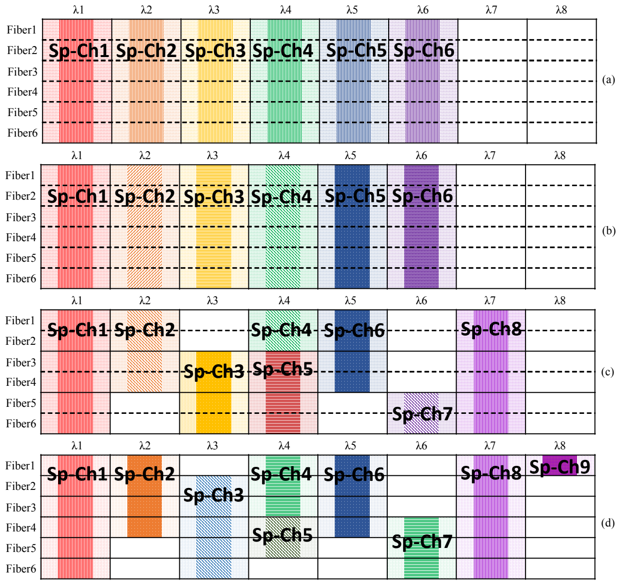


Fig. 3. Resource utilization of a) MC-SC-SLR, b) MC-SC-MLR employing different modulation formats, c) MC-SC-MLR employing groups of spatial channels and single/multiple modulation format, d) MC-SC-MLR employing arbitrary number of spatial channels and single/multiple modulation format.

b) Multi-Channel SC Multi-Line-Rate (MC-SC-MLR)

Resource provisioning for MC-SC-MLR transmission systems with 50-GHz WDM spectrum occupation per spatial mode is shown in Fig. 3(b-d). The bit rate in MC-SC-MLR can be tailored to the traffic demands to be served in one of the following three ways: i) a fixed number S of spatial modes are used to transmit SC channels employing one of a series of available modulation formats to form spatial Sp-Chs as shown in Fig. 3(b), this option being suitable for strongly coupled MCFs or FMFs; ii) a fixed sub-group of spatial modes (e.g. sub-groups of 2 or 3 if $S = 6$) are used to transmit SC channels employing a single modulation format or, in a more flexible scenario, one of a series of modulation formats to form spatial Sp-Chs as shown in Fig. 3(c), this option being suitable for networks deploying, e.g., FM-MCF; and iii) an arbitrary number of spatial modes are used to transmit SC channels employing a single modulation format or one of a series of modulation formats to form spatial Sp-Chs as shown in Fig. 3(d), this option being the most flexible transmission system and suitable for uncoupled or weakly coupled transmission media. Generally speaking, option iii) includes i) and ii).

2) Spectrally-spatially flexible Sp-Chs

Spectral-spatial Sp-Ch transmission systems carry information across several spatial modes and optical carriers. Different possibilities of such systems are discussed below:

a) Multi-Channel MC Single-Line-Rate (MC-MC-SLR)

Resource provisioning for MC-MC-SLR transmission systems with 50-GHz WDM spectrum occupation per spatial mode is shown in Fig. 4(a). MC-MC-SLR transmission systems utilise one modulation format and a fixed number of optical carriers (e.g. 2 optical carriers in Fig. 4(a)) to carry a fixed amount of data in the form of a spectral-spatial Sp-Ch. It can be regarded as a system having S times more capacity than a spectral Sp-Ch with two carriers (Fig. 4(a)). MC-MC-SLR treats all spatial channels as a single entity and is suitable for strongly coupled MCFs or FMFs.

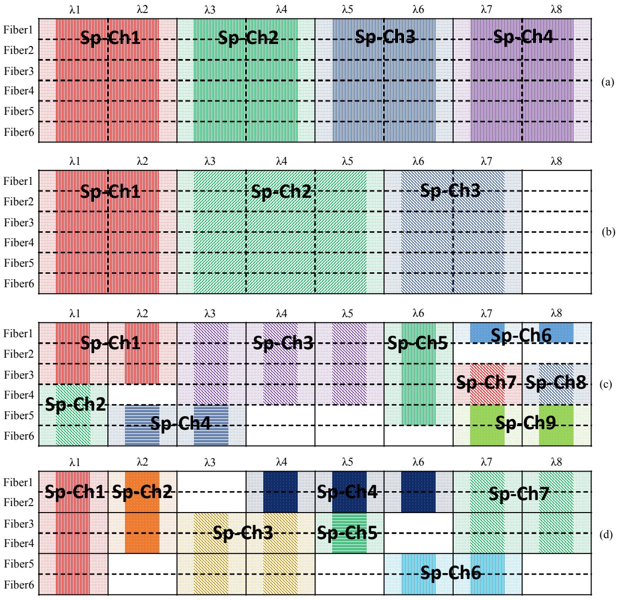


Fig. 4. Resource utilization of a) MC-MC-SLR, b) MC-MC-MLR employing different modulation formats and number of optical carriers, c) MC-MC-MLR employing arbitrary number of spatial channels and single/multiple modulation format, d) MC-MC-MLR employing groups of spatial channels and single/multiple modulation formats.

b) Multi-Channel MC Multi-Line-Rate (MC-MC-MLR)

Resource provisioning for MC-MC-MLR transmission systems with 50-GHz WDM spectrum occupation per spatial mode is shown in Fig. 4(b-d). The bit rate in MC-MC-MLR can be varied as follows: i) a fixed number S of spatial modes are used to transmit spectral channels composed of one or more carriers employing one of a series of available modulation formats to form spatial Sp-Chs as shown in Fig. 4(b), this option being suitable for strongly coupled MCFs or FMFs; ii) an arbitrary number of spatial modes are used to transmit spectral channels composed of one or more carriers employing a single modulation format or one of a series of modulation formats to form spatial Sp-Chs as shown in Fig. 4(c), this option being suitable for uncoupled or weakly coupled transmission media; and iii) a fixed sub-group of spatial modes (e.g. sub-groups of 2 in Fig. 4(d)) are used to transmit channels composed of one or more carriers employing a single modulation format or one of a series of modulation formats to form spatial Sp-Chs as shown in Fig. 4(d), this option being suitable for, e.g., FM-MCF networks.

3) Cost and performance evaluations

To estimate the cost of WSSs with port counts higher than 20, we used the cost of a 1×9 WSS as a reference and took into account the cost of commercial LCoS-based 1×20 WSSs (1.5). We observed that the HPC-WSS cost per port ranges between 0.10 and 0.15 [18], but, for simplicity and without affecting the results and conclusions, we assumed an average value of 0.125.

Fig. 5 presents the results of the study, where we observe that the performance of J-Sw and FrJ-Sw converges to that of

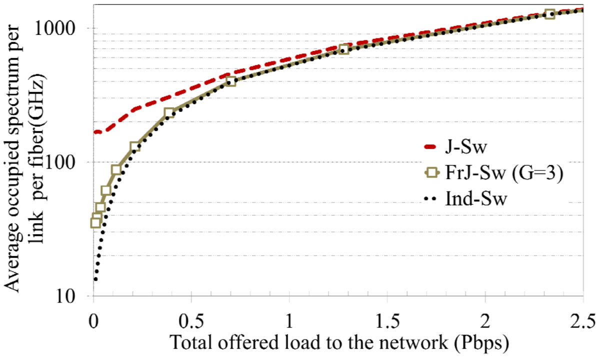


Fig. 5. Average occupied spectrum per link per fibre [18].

Ind-Sw as the traffic increases. In fact, when the total offered load to the network justifies the introduction of SDM (~300 Tbps), the performance of J-Sw and FrJ-Sw becomes similar to Ind-Sw. Regarding the cost of the network switching infrastructure, our results show that Ind-Sw is by far the most costly solution, since its relative network-wide cost is 2688 as compared to 1344 for FrJ-Sw or 1644 for bundles of S = 12 SMFs. This represents a 2× and 1.64× cost increase for Ind-Sw with respect to FrJ-Sw and J-Sw, respectively. Even though FrJ-Sw presents a better performance than J-Sw in terms of both spectral occupancy and cost, we expect that J-Sw, due to the possibility of reduced transceiver cost (coming from the use of joint DSP chips common for all spatial sub-channels and the use of a common laser), should lead to cost and power consumption savings in SDM networks since the network CAPEX is dominated by the transceiver cost.

CONCLUSIONS

In this paper, we discussed several options for mid-term and long-term capacity upgrades in optical transport networks. We investigated multi-band and multi-fibre systems as mid-term network migration solutions. Studies and comparisons showed that the total capacity that can be served with multi-band systems (S+C+L bands) is slightly larger than with multi-fibre systems with 3 fibres (by 8-14%). However, the former solution shows a significantly higher network migration cost because of higher costs of WSSs and amplifiers that need to be replaced and deployed. If the current infrastructure is reused (i.e. one more parallel fibre is deployed with amplification bandwidth over the S+C+L-bands), the multi-band approach is more cost-effective that a parallel fibre system with four fibres with amplification over the C-band. Finally, a long-term solution based on SDM with bundles of SMFs was investigated. We compared the performance of several SDM switching options in terms of spectral occupancy and network switching infrastructure cost, and demonstrated that the spectral occupancy under J-Sw and FrJ-Sw converges asymptotically to that for Ind-Sw, while the switching-related cost can be significantly reduced by using J-Sw or FrJ-Sw.

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