Link Design and Legacy Amplifier Limitation in Flex-grid Optical Networks

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Abstract: Flex-grid technology is an effective mean to improve the spectral efficiency of optical communications. For a given amplifier spectral bandwidth, it gives rise to the increase of the number of optical channels as it reduces the channel spacing. Therefore, in order to reap full benefits from flex-grid saved spectrum, further amplification power is required with respect to conventional fixed grid. This is a strong limitation if the legacy amplifiers cannot meet this new requirement due to their optical power limits. In this work, we demonstrate that exploiting the link margins allows supporting this increase while maintaining in use legacy amplifiers.

Index Terms: Optical power limitation, link design, flex-grid, network dimensioning.

1. Introduction

Flex-grid is a promising technology for the future generation of transport optical networks [1]. Its main idea consists in adapting the optical channel spacing to its real spectrum requirements in such a way that spectral efficiency is maximized. However, the deployment of new Reconfigurable Optical Add-Drop Multiplexers (ROADMs) with flex-grid wavelength selective switches, and more powerful optical amplifiers, in addition to the operational cost, makes flex-grid technology expensive for network operators in spite of its capacity increase promises.

Keeping legacy optical amplifiers is an interesting case to study in this respect, and should be taken into account in migration policies, when moving from the conventional fixed grid to the flex-grid technology. Indeed, considering the same spectral bandwidth (e.g., C band), the total required optical power per fiber span depends on the number of optical channels the fiber span is carrying. For this reason, physical links in flex-grid optical networks need more optical power than before on account of the increase of the number of channels, and the total required power may exceed the maximum power of legacy amplifiers if they are not replaced by more powerful ones. In other words, using the freed spectrum in flex-grid links may be the underlying reason for signal degradation of all spectrum channels, due to the lack of optical power.

Besides, during the offline system design, every physical link between two adjacent ROADMs is designed to support the same maximum capacity a wavelength division multiplexing system can transport while maximizing the optical reach. Therefore, the offline design does not depend on the actual requirement of traffic demands as it prepares resource provisioning for the worst case (i.e., full capacity, and maximum transmission reach). This consequently leads to power resource overdimensioning with considerable power margins on some links, due to the non-uniform distribution of traffic demands and their required reaches.

Different strategies have been discussed with the aim of reducing link margins, taking benefit from transponder flexibility [2]. Power management in mixed line rate fixed grid optical networks, has been discussed in [3]. The optimal combination of launch powers depending on required channel datarates, is shown to lead to considerable savings in network overall cost. Considering a load-dependent reach, the number of signal regenerations in the network can be significantly reduced for lower-order modulation formats thanks to power optimization [4]. Adapting the Signal to Noise Ratio (SNR) to the signals and adapting the signals to the available SNR are shown to be equivalent in terms of network throughput with further complexity in the former approach [5]. Link margins can also be used to significantly increase network capacity using high order modulation formats at SNR limit [6].

To the best of our knowledge, we are the first to address the optical power limitation issue in flex-grid optical networks [7], [8].

In this paper, we present an extension of our previous work [7], which evaluates how optical power margins can be used to support flex-grid additional channels over uncompensated links and non-identical fiber spans. We thoroughly describe our link design method and provide further details on the power adaptation approach. Moreover, we evaluate an additional benchmarking scenario and consider the cost of dual-stage Erbium Doped Fiber Amplifiers (EDFA). Further results on optical power usage and flex-grid saved spectrum are also presented and discussed.

2. Link Design

A physical link is a set of different successive fiber spans and amplifiers installed between two ROADMs (Fig. 1). The link design consists in specifying the channel launch power and the set of amplifiers that optimize signal performance at the receiver side, in such a way that amplifier limits are not exceeded. Under specific assumptions, signal performance is estimated by SNR, considering both amplification and non-linear noises. We use the LOGON strategy which performs a local optimization of the SNR, assuming that the spans are independent from each other [9]. The optimum power spectral density is given in (1), where h, ν, F_n, and $\rho_{NLI,n}$ stand for the Planck's constant, the electromagnetic wave frequency, the noise figure of the amplifier at the output of the n^{th} span, and its non-linear effect contribution, respectively [9].

This strategy leads to global optimal solutions in case where all spans are identical (same span loss a_n), and associated with the same non-power-limited amplifiers. We point out that for two successive spans, the optimum launch powers of both spans depend on the gain G_n of the amplifier to be deployed between them. Therefore, they cannot be set independently, especially if the spans are not identical. It is shown in (2) where the gain of the n^{th} amplifier is computed as a function of the launch power of the $n+1^{th}$ span.

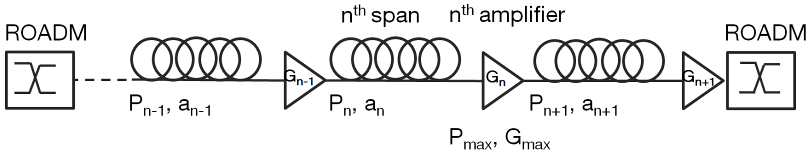

Fig. 1. Example of a physical link, between two ROADMs, with $n+1$ fiber spans and amplifiers.

$$P_n = \left(\frac{h\,\nu\,F_n}{2\,\rho_{NLI,n}}\right)^{\frac{1}{3}} \tag{1}$$

$$G_n = a_n\,\frac{P_{n+1}}{P_n} \tag{2}$$

$$F_n = F_1 + \frac{F_2\,D\,G_{max}}{G_n^2} \tag{3}$$

$$G_n^{op} = \sqrt{\frac{4\,F_2\,D\,G_{max}}{3\,F_1}}\,sinh\left(\frac{1}{3}\,asinh\left(\frac{\rho_{NLI,n}\,a_n^3\,P_{n+1}^3\,\sqrt{\frac{27\,F_1}{F_2^3\,D^3\,G_{max}^3}}}{h\,\nu}\right)\right) \tag{4}$$

We consider different types of variable gain dual-stage amplifiers without mid-stage access (Table I) with parameters $(F_1,\,F_2,\,G_{max},\,P_{max},\,D)$ where F_1 and F_2 are the noise figures for the first and the second stage respectively, G_{max} is the amplifier maximum gain, P_{max} is the amplifier maximum power, and D denotes the power ratio for both stages to take into account the difference between preamplifier and booster performance. The resulting noise figure, which varies according to gain adaptation [10], can be written as in (3).

The non-linear relationship between the variables of Fig. 1 can be noticed. On the one hand, the optimum power used in a given span is calculated in terms of the noise figure of the amplifier to be located next to it (i.e., P_n and F_n in (1)). On the other hand, this amplifier should deliver the optimum power required in the next span (i.e., P_{n+1} in Fig. 1). This last constraint is satisfied through amplifier gain adaptation (2), which impacts the noise figure (3) and, therefore, the already calculated optimum power for the previous span (i.e., P_n in (1)). Solving the non-linear equation resulting from the compilation of (1), (2) and (3), we obtain the optimum required gain (G_n^{op}) in (4). This last equation is the key element of our design method, as it ensures that optimum powers are used for all channels in every span while respecting the power propagation model in the physical link (2).

The link design is performed from the last span to the first one. We choose the amplifier type that can satisfy both required gain and optimum power while achieving smallest noise figure. If no amplifier can satisfy these requirements, the one with the closest maximum power (P_{max}) is chosen. This means that the amplifier on the constraining span is operated at its maximum power. The difference to the required power on the following (downstream) span(s) is subsequently recovered by re-tuning the gain(s) of the following amplifier(s) as explained in Algorithm 1. Apart from the robust mathematical aspect of the design method, it has been validated through intensive comparisons with real link design data stemming from an existing link design tool of Orange.

Note that this design method is based on the LOGON strategy, and it performs a local optimization at the amplifier level for each two successive spans. A global optimization for the end-to-end link is difficult to carry out due to the non-linear aspect between system variables, being complicated with the increase of the number of spans. Furthermore, ROADM nodes are assumed ideal with no contribution to the amplified spontaneous noise. Recent studies consider ROADM contribution to the SNR and optimize the optimum power at the ROADM level as well [11]. This approach could be integrated into our design method, even if the optimization would come to the downside of the LOGON main idea, which considers that a local optimization leads to near global optimum.

3. Network Optimization

As mentioned above, the optimum optical power may exceed the limitations of existing amplifiers, when moving from the conventional fixed grid to the flexible one. Indeed, when the initial fixed grid design is accomplished, most of the amplifiers have an extra power reserve, since the received power in the design is not necessarily equal to the maximum power of the amplifier. However,

TABLE I
dual-Stage EDFA Amplifier Model

Type	P_{max} (dBm)	G_{max} (dB)	F_1 (dB)	F_2 (dB)	D (dB)
A_1	17	30	5	6.5	3
A_2	19	25	5.5	7	5
A_3	20	23	6	7.5	7

Algorithm 1 Link Design Algorithm

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Require: Link, span characteristics (length, attenuation), and $SetOfAmpli$
$CurrentAmpliPosition \leftarrow LastPosition$
$RequiredPowerNextSpan \leftarrow ROADMPower$
while $CurrentAmpliPosition \neq FirstPosition - 1$ do
    for $Ampli$ in $SetOfAmplis$ do
        $CandidateAmpli \leftarrow \emptyset$
        calculate $G_n^{op}$ using Equation (4)
        if $(G_n^{op} \leq G_{max})$ and $(RequiredPowerNextSpan \leq P_{max})$ then
            push $Ampli$ onto $CandidateAmpli$
        end if
    end for
    if $CandidateAmplis \neq \emptyset$ then
        among $CandidateAmplis$ add to $Solutions$ the amplifier with the smallest $F_n$ calculated
        with Equation (3)
    else
        add to $Solutions$ the amplifier with $P_{max}$ closest to and strictly less than
        $RequiredPowerNextSpan$
        recover the difference by increasing the gain(s) of the next amplifier(s) stored in $Solutions$
    end if
    $CurrentAmpliPosition \leftarrow PreviousPosition$
    set $RequiredPowerNextSpan$ to the optimum power calculated with Equation (1)
end while
$RequiredPowerNextSpan$ is the design power that should be injected in the first span
return $Solutions$
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this power reserve varies from one span to another and can be insufficient to support flex-grid additional channels over some links. This is a strong limitation if flex-grid freed spectrum cannot be used over these links, due to the lack of power, bringing into question flex-grid expected savings.

A straightforward solution consists in replacing all the deployed amplifiers with more powerful ones, and performing a new design for the maximum number of channels that can be transported by flex-grid based links. However, this procedure is expensive and can lead to power resource overdimensioning.

Another possible and more pragmatic way consists in changing the design paradigm. Indeed, maximizing the SNR at the receiver side is not always effective, since it wastes power margins for the channels that do not have stringent requirements in terms of optical reach. Therefore, tailoring the SNR to the actual needs reducing per-channel power seems interesting to save on optical power, and consequently increase link capacity [4].

In the following, we mean by power reserve the difference between the amplifier maximum power and the optimum design power that considers the worst case (i.e., full capacity, and maximum transmission reach). Meanwhile, the power margin herein refers to the difference between optimum

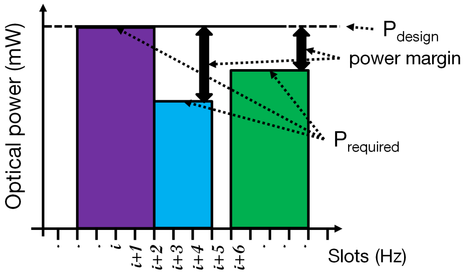

Fig. 2. Example of the power margin for one fiber span with three optical channels. Horizontal flexibility (flex-grid), and vertical flexibility (power adaptation) are illustrated.

design power and current power after power adaptation using the new design paradigm.

3.1. Power Adaptation and Migration Scenarios

Flex-grid technology introduces a degree of flexibility at the spectrum level, allocating different optical channels with different spectrum widths. Another degree of flexibility can also be introduced at the power level by the means of power adaptation. It consists in adapting the initial launch power to its minimum value given a minimum acceptable SNR at the receiver (Fig. 2). This SNR_{min} target depends on both modulation format, and decision decoding method. Once it is known, the initial launch power ($P_{required}$ in Fig. 2) can be simply determined as in (5), where P_{design} and SNR_{design} are the optimum launch power calculated with (1) and corresponding SNR, respectively.

$$P_{required} = \frac{P_{design} \times SNR_{min}}{SNR_{design}} \tag{5}$$

This approximate equation of the initial launch power results from the fact that the SNR target, calculated for one path of successive links, is the inverse of the sum of the inverse SNR of each link along the path [9]. However, it does not take into account non-linear penalty variation induced by power adaptation. Actually, it underestimates signal performance as the per-channel power is rather reduced with respect to the initial power design (P_{design}). This guarantees that the new SNR related to $P_{required}$ is greater or equal to SNR_{min}.

In order to evaluate the potential power adaptation impact on both cost and capacity of the network, we identify and study the following network migration scenarios:

- Fixed grid (FG): the initial design is performed for eighty channels over a 50 GHz grid. This scenario is representative of nowadays core optical networks, and it is used in this work as a benchmarking reference for the other scenarios. Blocking in this scenario can only be due to the lack of spectrum resources.
- Flex-grid with legacy design and non-power-limited amplifiers ($FX80$): this ”whatif” scenario considers the legacy design i.e., optimal per-channel power calculated with the FG design, but it allows that the amplifiers exceed their maximum power limits P_{max}. This scenario does not reflect any realistic case and it is only used for benchmarking purposes.
- Flex-grid with legacy design ($FX80D$): the existing amplifiers are maintained in use with respect to the FG initial design for eighty channels (no extra amplifier cost). In $FX80D$, the power aware dimensioning takes benefit from the extra power reserve of the amplifiers to establish more than eighty channels. The span with the smallest power reserve will however limit the other spans along the physical link. This scenario reflects what happens if flex-grid technology is deployed with the legacy amplifiers.
- Flex-grid with legacy design and power adaptation ($FX80DP$): it is an extension of $FX80D$ scenario with the possibility of adapting individual channel powers to the real requirements according to the minimum SNR acceptable value. Both $FX80D$ and $FX80DP$ can be blocked due to the lack of spectrum, to the spectrum fragmentation and to the lack of optical power.

- Flex-grid with new design ($FX106$): the links are designed to support the maximum number of channels in flex-grid optical networks (i.e., 106, considering the same 4 THz band as for FG and 37.5 GHz spacing). Network dimensioning is that of a greenfield deployment with new well-adapted to flex-grid amplifiers thus leading to an extra cost. Since the offline link design is performed to support the maximum number of channels, the only origins of blocking are the lack of spectrum and the spectrum fragmentation.

These network scenarios are compared using the planning tool, the 32 Gbaud 16QAM and QPSK transponder/superchannel types and the cost model presented in [12]. The cost of one EDFA amplifier is assumed equal to 10% of the cost of one 100 Gbps transponder.

4. Results

Simulations are performed on a 32-node and 42-link European backbone network [8], using single mode fiber (chromatic dispersion = $17\,ps.nm^{-1}.km^{-1}$, fiber attenuation = $0.22\,dB/km$, non-linearity coefficient = $1\,W^{-1}.km^{-1}$). Links are designed using the three amplifier types of Table I and assuming non-identical span lengths, randomly drawn according to a Gaussian distribution $\mathcal{N}\,(\mu = 100\,km,\, \sigma = 27\,km)$. This distribution is representative of some Orange networks with large span loss occurrence. SNR filtering penalties induced by transit across one ROADM are 0.05 dB and 0.64 dB for 50 GHz and 37.5 GHz channel spacing, respectively [12]. The minimum acceptable SNR at the receiver side, using 0.1 nm noise reference bandwidth, including operational margins, is fixed to 13.5 dB for QPSK and 22 dB for 16QAM for a bit error rate equal to 10^{-3}.

Dimensioning process is triggered for seven successive forecasted periods of time, assuming a 35% traffic growth rate. This is the maximum number of periods that all scenarios can support without blocking. This ensures a fair comparison between network scenarios as they would have to deal with the same traffic volume. Twenty initial traffic matrices, normalized to $6\,Tbps$, have been randomly drawn according to a realistic logical topology. Demands are optimally served choosing the set of transponders (with regenerator placement) that first minimizes cost and then minimizes spectrum occupancy [12].

Fig. 3 depicts the current power level for $FX80$, $FX80D$, and $FX80DP$ scenarios in each used span, the P_{max} and the P_{design} of corresponding amplifier (the one located at the input of the span) in the last planning period. Fiber spans are ordered in a decreasing way according to the total traffic demand volume they are carrying in $FX80DP$. Optical power usage varies from one span to another due to the variable design and the non-uniform distribution of traffic in the whole network. In spite of the non-null power reserve in each amplifier (filled area in Fig. 3), it can be noticed that about fifteen spans exceed the maximum power limit in the non-realistic scenario $FX80$. This means that a part of the saved spectrum in the other flex-grid scenario: $FX80D$ cannot be used due to the lack of power, as it is constrained by the characteristics of legacy amplifiers and the optimum launch powers. The significant emerging area with vertical hatched lines in Fig. 3 represents the optical power amount that is saved - and still not used - thanks to power adaptation approach in $FX80DP$. We can notice that the amplifier power reserve is relatively small in comparison with power adaptation savings.

It is commonly agreed that flex-grid cost savings are produced in the long term [13], [14], [15]. This is confirmed by our results which indicate that network cost is identical for all scenarios until the fifth planning period, except for $FX106$ which has an extra optical cost due to the replacement of legacy amplifiers with more powerful ones. This extra cost does not take into account the operational expenses of amplifier deployment and the subsequent interruption of the fiber link. Fig. 4 shows network cost evolution in the last three periods in which some scenarios start using longer paths looking for either spectrum or power, thus giving rise to an additional cost due to signal regeneration. In all periods, $FX80DP$ outperforms $FX106$ and saves up to 10% of cost with respect to conventional fixed grid (FG). This is obtained thanks to flex-grid saved spectrum, and power adaptation, which avoid some longer paths and consequently potential regenerators. In contrast, flex-grid has almost no cost savings when power adaptation is not allowed with the

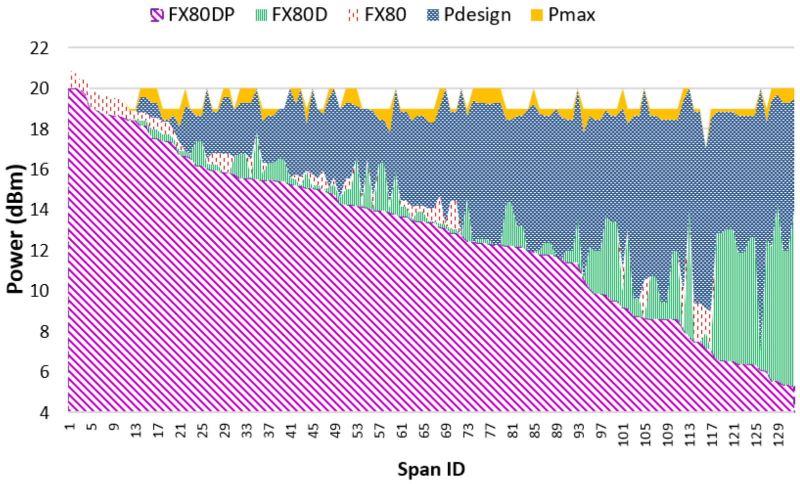

Fig. 3. Optical power level in each fiber span for different flex-grid scenarios constrained by legacy amplifiers. P_{max} and P_{design} correspond to the EDFA amplifier located at the input of the fiber span.

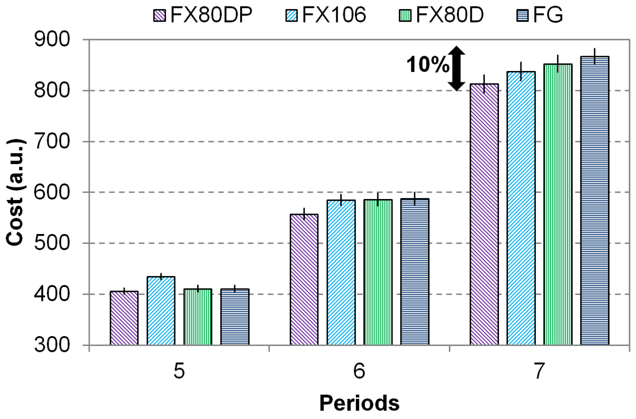

Fig. 4. Cost evolution over time for the different scenarios in the last three periods when the shortest paths are left due to the lack of either power or spectrum. Results are obtained with a 90% confidence interval.

traditional design ($FX80D$), meaning that the amplifier power reserve is not enough to exploit all flex-grid saved spectrum.

Fig. 5 shows the saved spectrum percentage for flex-grid scenarios in comparison with conventional fixed grid. As expected, all flex-grid scenarios provide the same spectrum savings with the shortest path routing corresponding to the first four planning periods. During this dimensioning phase, results show a steady spectrum saving decrease over time, since less spectrum effective transponders are more likely to be used with the exponential growth of traffic when optimizing network overall cost. The last three periods see a similar dramatic growth in the spectrum savings for both $FX80DP$ and $FX106$ as the reference (FG) is disadvantaged by longer path lengths. $FX80D$ scenario being limited by the amplifier reserves, fails to save as much spectrum as $FX80DP$ and $FX106$ do.

We then compute the amount of saved spectrum for which enough amplification power exists. Indeed, not all saved spectrum shown in Fig. 5 can be used to accommodate future traffic demands, as it relies on the available optical power at the moment these demands arrive. In case of $FX80D$ scenario, it is relatively easy to know whether a given part of the saved spectrum is usable or not. Actually, this scenario makes always use of the optimum launch power unlike $FX80DP$ whose power adaptation depends on the characteristics of the future traffic demands. To overcome this, we consider the worst case to which $FX80DP$ can be exposed. The worst case is produced using the optimum launch power assuming that power adaptation cannot be performed for future traffic demands. In this way, we can have a lower bound for the usable saved spectrum in $FX80DP$ as well. In contrast, such a limitation does not arise for $FX106$ scenario since the deployment of new amplifiers guarantees enough power for all optical channels.

Fig. 6 shows the exact usable saved spectrum for $FX80D$ and its lower bound for $FX80DP$. Contrary to $FX80D$, we observe a small impact on $FX80DP$ saved spectrum despite the pessimistic assumptions. In other words, at any given moment in network life cycle, the already saved optical power through per-channel power adaptation process is quite enough to reap near-full benefits from flex-grid saved spectrum for future traffic demands. This is understandable given the significant non-used saved power amount already shown in Fig. 3 (the area with vertical hatched lines). As expected, $FX106$ saved spectrum remains the same as it is in Fig. 5, since

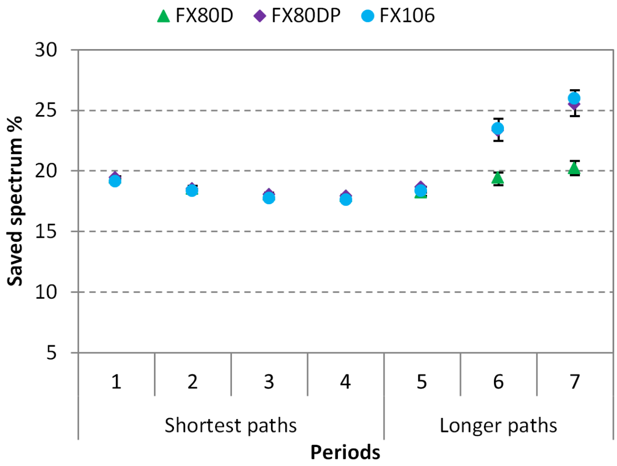

Fig. 5. Flex-grid saved spectrum evolution with respect to conventional fixed grid network (FG) using a 90% confidence interval. In the first four periods, the shortest paths are always selected. After that, the routing process selects longer paths looking for either power or spectrum depending on migration scenario.

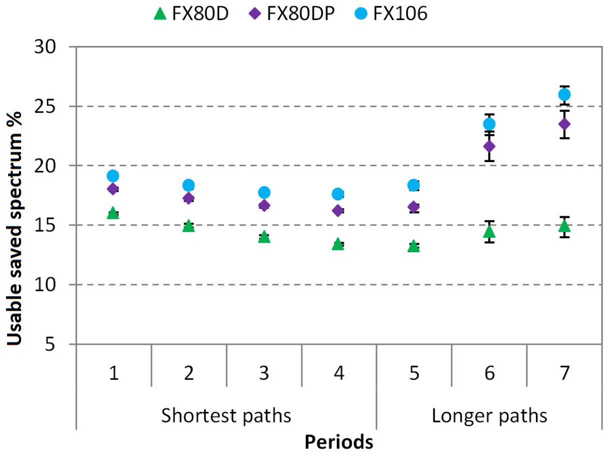

Fig. 6. Percentage of flex-grid saved spectrum that is usable with respect to conventional FG scenario. $FX106$ is the same as in Fig. 5 since the initial design is performed for all optical channels.

there is enough amplification power for all optical channels.

In a nutshell, in $FX80D$ where only amplifier power reserve is taken advantage of, a significant part of saved spectrum is unusable due to the lack of optical power. This impact constantly increases over time causing more than 40% loss of flex-grid saved spectrum in the last planning period. In contrast, the power adaptation approach in flex-grid optical networks ($FX80DP$) provides almost the same performance as the flex-grid specific design ($FX106$), while maintaining in use legacy amplifiers.

It is noteworthy that our proposal necessitates an optical power-aware control plane with suitable routing algorithm. We have addressed this in [8], and have proposed some modifications for the distributed Generalized Multi-Protocol Label Switching (GMPLS)-based control plane in order to take into account the optical power aspect as well.

5. Conclusions

In this paper, we have tackled the optical power limitation issue induced by the increase of the number of optical channels in flex-grid optical networks. This increase is due to the new narrower channel spacing with respect to the conventional fixed grid width.

We have proposed and thoroughly described a link design method based on the LOGON strategy [9] for different dual-stage EDFA amplifier types over non-identical span lengths. Results of the design have been given as input to an optical power aware multi-period planning tool with the aim of evaluating different flex-grid migration scenarios.

Simulations have indicated that flex-grid optical network savings in terms of cost and capacity can substantially decrease if legacy amplifiers are used with the traditional power design.

More importantly, we have shown that adapting optical launch powers to the actual per-channel requirements in terms of SNR is an effective approach to maintain in use the legacy amplifiers and reap full benefits from flex-grid saved spectrum.

Note that, this power adaptation approach can also be used with the extra amplifier bandwidth, which allows increasing the number of channels as well. In such a case, the arising problem is due to the under-design and it is not specific to flex-grid technology.

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