Span power management scheme for rapid lightpath provisioning in multi-core fibre networks

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The activation time when creating lightpaths is adversely affected by the time optical amplifiers require to adjust the newly added signal power. This shortcoming is particularly true with multi-core erbium-doped amplifiers. A fibre span power management scheme is proposed based on the use of dummy wavelength signals, whose function is to alleviate this shortcoming and shorten the required lightpath activation time. An analytical model is developed to estimate the effectiveness of the proposed scheme in achieving this goal.

Introduction: Space division multiplexing (SDM) technologies such as multi-core fibres [1] are expected to overcome some physical barriers and enhance the overall capacity of optical transmission systems. Transmission over several thousand kilometres of multi-core fibre has been experimentally demonstrated [2]. To achieve such high transmission reach, optical signals must be amplified at periodic regeneration points along the fibre span, in order to compensate for the power loss experienced in multi-core fibre. At the regeneration point, one technique is to demultiplex the SDM signals into multiple single-core fibres and then amplify the signals in each fibre using conventional single-core erbium-doped fibre amplifiers (EDFAs). The amplified signals are then recombined and injected back into the span multi-core fibre. Single-core power transient-suppressed EDFAs (TS-EDFAs) can be deployed in order to limit the time that is required to adjust the point of operation of the amplifier when a newly added signal suddenly changes the total power at the EDFA input. TS-EDFAs can be effectively used to shorten the setup (and tear-down) time of lightpaths. This technique, however, requires a number of EDFAs to amplify the SDM signals at each regeneration point.

A more effective technique is to amplify the entire set of SDM signals using a single EDFA with multi-core fibre—3-core and 7-core EDFAs are already available [3]. The drawback of this technique is the lack of multi-core TS-EDFAs at the current time. Since the power transient time of multi-core EDFAs is longer than that of conventional TS-EDFAs [4], lightpath activation times comprising multi-core EDFAs are significantly longer when compared to those in TS-EDFA-based networks.

The objective of this Letter is to circumvent this drawback by pursuing a fibre span power management scheme that makes use of dummy wavelength signals. Dummy signals are launched into spans ahead of time and their power is rapidly adjusted when a newly added lightpath is activated in such a way that the multi-core EDFA power transient is avoided. As a result, the lightpath activation waiting time in the network is suppressed or at least greatly reduced.

Proposed scheme: The proposed scheme is intended to reduce the lightpath activation time by circumventing (at least in part) the relatively slow procedure that is required when adjusting the point of power operation of multi-core EDFAs. Two types of optical signals (or wavelengths) coexist in the fibre span: (i) wavelengths carrying modulated signals for data transmission used by the lightpaths and (ii) dummy wavelengths carrying unmodulated signals. One or more dummy wavelengths are activated ahead of lightpath provisioning and are used to adjust the total power in the span as follows. When a newly added lightpath is powered up in the span, its power is rapidly increased while at the same time the power of a dummy wavelength is decreased, causing the total power in the span to remain constant. By keeping the span power at a constant value, multi-core EDFA transients are avoided and the lightpath can be provisioned swiftly.

A straightforward approach in the proposed scheme is to prepare dummy wavelengths, each of which is associated with each lightpath wavelength, and then replace a dummy wavelength with a lightpath wavelength every time a lightpath needs to be provisioned. However, to activate each dummy wavelength in each span, a laser would be required for each wavelength and each output port of the optical cross-connect. This solution may prove to be too expensive both in terms of capital and operational expenditure.

Fig. 1 illustrates an alternative to this costly solution, which shows how a single standby dummy wavelength can be used in each span to achieve our objective. Suppose that one dummy wavelength is instantiated in the fibre span prior to the arrival of lightpath request 1. When lightpath request 1 arrives, the power level of the standby dummy wavelength is rapidly decreased, whereas that of lighpath request 1 is increased, so that the total power in the span remains constant during this procedure. The power ‘transfer’ from the dummy wavelength to the lightpath wavelength is achieved over a short period of time, which is denoted by t_a. At the end of period t_a, the power of the dummy wavelength is depleted and needs to be re-instantiated. The re-instantiation of the dummy wavelength takes place gradually to avoid sudden power transients in the EDFA. Let t_b be the time required to re-instantiate the dummy wavelength in each span used by the newly added lightpath, where $t_b \gg t_a$. Note that during the period t_b, the span does not have a fully powered dummy wavelength standing by. Any newly generated lightpath request that arrives during the period t_b must be delayed until the dummy wavelength is fully powered up. The actual value of t_b depends on a number of factors, including the type of EDFA amplifier, the power control algorithm used in the span and the current number of active wavelengths. Such a value can range from a few milliseconds to minutes.

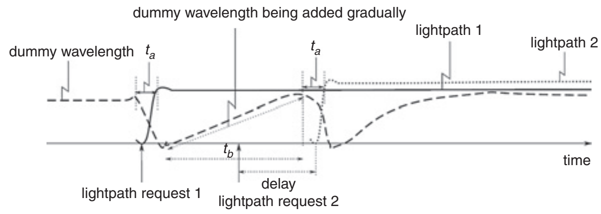

Fig. 1 *Usages of dummy wavelength for lightpath setup*

One can derive the following observations from the example illustrated in Fig. 1. The number of standby dummy wavelengths in the span affects the lightpath activation time t_c, which must be clearly in the range $t_a \le t_c \le t_a + t_b$. As the number of dummy wavelengths increases, $t_c \to t_a$. Another important factor is the inter-arrival time of the lightpath requests. If such a time greatly exceeds t_b, a relatively small number of dummy wavelengths suffice to guarantee $t_c \to t_a$. If such a time is in the order of t_b or less, a large number of standby dummy wavelengths is required in the span in order to guarantee $t_c \to t_a$.

Note that when a provisioned lightpath is released, its power can be gradually decreased in order to avoid sudden power transients in the span. Being similar to the procedure followed when creating dummy wavelengths, the lightpath release procedure may take a time interval in the order of t_b. This mode of operation is simple and does not affect the lightpath activation waiting time.

In conclusion, the lightpath activation waiting time mainly depends on the number of dummy wavelengths, denoted by S, inter-arrival time of the lightpath requests and t_b. For estimating more precisely the lightpath activation waiting time as a function of these system parameters, an analytical model is derived in the following Section.

Analysis of proposed scheme: We assume that lightpath requests arrive to the system as a Poisson process with rate λ. The incoming lightpath requests are then enqueued into the queue and are served based on a first-come-first-serve policy. The re-instantiation time of the dummy wavelength follows an exponential distribution with average value μ^{-1}. If any dummy wavelength is available, then the available dummy wavelength is used to serve the lightpath request first, and thus the dummy wavelength is occupied. Before completing the gradual power increase of the dummy wavelength, if any lightpath request arrives, it needs to wait until the dummy wavelength is ready. This process is continued for all the lightpath requests in the queue. The waiting time of lightpath requests in the queue and transition states of this model are equivalent to those of the M/M/S queueing model. As $t_a \ll t_b$, our model does not consider t_a. In the following Sections, we focus our discussion on the single-span model followed by the multi-span model.

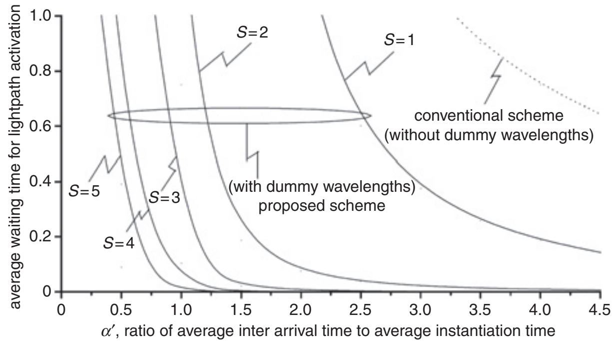

Fig. 2 *Average waiting time for lightpath activation against α′, with and without consideration of dummy wavelengths*

Modelling for single-hop fibre span: The average number of lightpath requests, denoted by L, in the queue is estimated by

$$L = P_0 \cdot \frac{(1/\alpha)^S}{S!} \cdot \frac{\rho}{(1-\rho)^2} \tag{1}$$

where

$$P_0 = \left(\sum_{n=0}^{S-1} \frac{(1/\alpha)^n}{n!} + \frac{(1/\alpha)^S}{S!} \cdot \frac{1}{1-\rho} \right)^{-1}, \quad \rho = \frac{1}{S \cdot \alpha}, \quad \alpha = \frac{\mu}{\lambda}$$

The average waiting time for lightpath activation, denoted by W, is estimated by Little's formula as L/λ. The average waiting time, which is normalised to the average inter-arrival time, $1/\lambda$, is given by

$$W = \frac{(1/\alpha)^S \cdot \rho}{S! \cdot (1-\rho)^2 \left(\sum_{n=0}^{S-1} ((1/\alpha)^n / n!) + ((1/\alpha)^S / S!) \cdot (1/1-\rho) \right)} \tag{2}$$

Modelling for network analysis: To derive the basic characteristics of the proposed scheme in the network, where multi-hop spans are generally considered, we assume that the lightpath requests arrive in the system independently. Therefore, we use convolutions to obtain the waiting time for lightpath activation. The lightpath request arrival rate on span e, denoted by λ_e, is estimated by

$$\lambda_e = \sum_{\text{all path}_{sd}^k \text{ on } e \in E} \lambda_{sd}^k \tag{3}$$

where λ_{sd}^k is the average lightpath request rate for the kth path (route) of the source–destination (s–d) pair, which is denoted by path_{sd}^k.

The waiting time for lightpath activation on the kth path between an s–d pair, denoted by W_{sd}^k, is estimated by

$$W_{sd}^k = \sum_{e \text{ used by} \text{path}_{sd}^k} W_e \tag{4}$$

where W_e is the average waiting time for lightpath activation on span e.

The average waiting time for lightpath activation for all s–d pairs in the network, denoted by W_N, is estimated by

$$W_N = \frac{1}{\left(\sum_{(sd) \in Z} \sum_{k \in K_{sd}} \lambda_{sd}^k \right)} \sum_{(sd) \in Z} \sum_{k \in K_{sd}} W_{sd}^k \cdot \lambda_{sd}^k \tag{5}$$

where Z and K_{sd} are the sets of all s–d pairs in the network and paths for an s–d pair, respectively.

Analysis of conventional scheme: If the system does not consider any dummy wavelength, the average waiting time for lightpath activation is estimated based on the waiting time in queue and the service time of lightpath requests. In this case, the working principle of this model is equivalent to the M/M/1 queueing model.

The average waiting time for lightpath activation is estimated by $W = (\lambda/\mu(\mu - \lambda)) + (1/\mu)$, where the first and second terms indicate the waiting time in queue and the time to instantiate a lightpath wavelength, respectively. The average waiting time for lightpath activation, which is normalised by average inter-arrival time, $1/\lambda$, is given by $W = 1/(\alpha - 1)$.

Results and discussion: This Section observes how the number of dummy wavelengths can affect the waiting time for lightpath activation in the network. Our experimental setup consists of 14 nodes with 21 bidirectional physical links of NSFNET. The network wide average inter-arrival time for lightpath requests, denoted by λ_{avg}, is estimated by

$$\lambda_{avg} = \frac{1}{|Z|} \sum_{(sd) \in Z} \sum_{k \in K_{sd}} \lambda_{sd}^k \tag{6}$$

Fig. 2 shows the relationship between the average waiting time for lightpath activation (normalised to the average inter-arrival time) and parameter α', with and without consideration of dummy wavelengths. The parameter α' is the ratio of average inter-arrival time, λ^{-1}, to average instantiation time for each dummy wavelength in the proposed scheme (one for each lightpath wavelength in the conventional scheme), μ^{-1}. The proposed scheme considers dummy wavelengths in the system, whereas the conventional scheme does not consider any dummy wavelength. Fig. 2 indicates that the average waiting time for lightpath activation is drastically suppressed with the consideration of dummy wavelengths compared to without consideration of any dummy wavelength. Furthermore, we observe that as the number of dummy wavelengths increases, the average waiting time for lightpath activation decreases. This is because as the number of dummy wavelengths increases, the waiting time for lightpath activation in the queue decreases. On the other hand, we note that the average waiting time for lightpath activation decreases with increase in α' value. This is due to the decrease in average instantiation time for each dummy wavelength.

Conclusion: This Letter has proposed a span power management scheme whose aim is to reduce the waiting time when activating lightpaths. The scheme makes use of standby dummy wavelength signals whose power can be rapidly decreased to compensate for the additional power being required by the newly added lightpath. The lightpath activation time can then be significantly reduced. An analytical model is presented to estimate the achievable lightpath activation time reduction as a function of the number of dummy wavelengths used in each span. By numerically solving the model, one can conclude that the proposed scheme significantly reduces the average waiting time for lightpath activation in the network compared to a conventional scheme, which does not consider any dummy wavelength.

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References

1 Abedin, K., Taunay, T., Fishteyn, M., *et al.*: 'Cladding-pumped erbium-doped multicore fiber amplifier', *Opt. Express*, 2012, **20**, (18), pp. 20191–20200

2 Kobayashi, T., Takara, H., Sano, A., *et al.*: '2 × 344 Tb/s propagation-direction interleaved transmission over 1500 km MCF enhanced by multicarrier full electric-field digital back-propagation'. ECOC, London, UK, September, 2013, paper PD3. E

3 Abedin, K., Taunay, T., Fishteyn, M., *et al.*: 'Amplification and noise properties of an erbium-doped multicore fiber amplifier', *Opt. Express*, 2011, **19**, (17), pp. 16715–16721

4 Puttnam, B.J., Awaji, Y., Wada, N., and Zsigmond, S.: 'Investigating the limits of optical packet transmission through cascaded transient-suppressed EDFAs without regeneration or active gain control'. OFC, San Diego, CA, USA, March 2010, paper p. OThI6