Physical Impairment Based Regenerator Placement and Routing in Translucent Optical Networks

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Abstract: A novel constraint-based routing (CBR) algorithm taking into account the dominant linear and nonlinear fiber optical transmission impairments has been analyzed. It is shown that CBR and intelligent regenerator placement decrease the blocking probability significantly.

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1. Introduction

In future transparent optical transmission systems automatic wavelength switching will be introduced (automatically switched optical network, ASON). The rapidly increasing traffic demands require solutions, which reduce the operational expenditure by efficient routing. In the past, opaque (employing optoelectronic conversions at each node), fully-transparent or translucent (with selective regeneration) networks have been investigated. Because of the high cost of optoelectronic conversions and limited reach in fully-transparent networks the translucent topology seems to be the most promising candidate for future wavelength agile long-haul networks.

Physical degradation effects such as noise, linear impairments and nonlinear fiber effects affect the signal quality along the transmission path. Depending on the channel load and transmission distance some paths cannot be set up fully transparently because the transmission quality requirements (i.e. pre-FEC bit error ratio (BER) = 10^{-9} or Q-factor = 15.56 dB) cannot be fulfilled. In the last couple of years the inclusion of physical layer effects in the network operation and routing has been a topic of intensive research (e.g., [1],[2]). In this paper we propose a combined approach of regenerator placement based on the estimated signal degradation along the links and nodes and constraint-based routing (CBR) to set up paths according to the demands. We show – for the first time to our knowledge – that the combined approach of regenerator placement and routing, both based on physical degradation effects, may significantly decrease the blocking probability in a realistic network scenario with a varying dispersion map and different span lengths.

2. Investigated network

For the investigations the COST266 reference network (large topology) has been chosen [3]. This network has pan-European dimensions (37 nodes and 57 links) in a mesh topology (Fig. 1, left). System simulations have shown that for very long paths in the COST266 network the nonlinear fiber effects of cross-phase modulation (XPM) and four-wave mixing (FWM) cannot be neglected when 10 Gb/s NRZ-OOK modulation is employed (Fig. 2). This is why we included the analytical models presented in [4] in our CBR approach to assess XPM and FWM. From Fig. 2 an average transparent reach of approximately 1820 km for SSMF can be observed. However, there are short paths with poor signal quality (min. 1280 km) and long paths with good quality (max. 2220 km) making an accurate assessment of the actual signal quality desirable. In the COST266 reference network only link lengths and demands have been defined. For the assessment of the signal quality, however, it is essential to know the physical parameters of the links. For this purpose a heuristic approach has been chosen to determine the span and DCF lengths based on realistic assumptions for deployed networks. We assumed a network consisting of SSMF (D = 17 ps/nm/km) or NZDSF (D = 4 ps/nm/km). Furthermore, the following parameters have been used: launch power $P_{\mathrm{NZDSF/SSMF}}$ = 3 dBm/ch, launch power P_{DCF} = -3 dBm/ch, nonlinearity constant $\gamma_{\mathrm{SSMF}} = 1.37\ (\mathrm{W{\cdot}km})^{-1}$ and nonlinearity constant $\gamma_{\mathrm{NZDSF}} = 2\ (\mathrm{W{\cdot}km})^{-1}$. The span lengths have been generated once from a random process with a Gaussian distribution with a mean value of 80 km and a standard deviation of 5 km. For the DCF modules a granularity of 10 km SSMF-equivalent (i.e. -170 ps/nm) has been assumed yielding an average undercompensation of approximately 85 ps/nm/span along the links and a minimal residual dispersion at the nodes. The investigated modulation format is 10 Gb/s NRZ-OOK. The channel spacing is 50 GHz. A maximum of 80 wavelengths has been assigned to each link. For the EDFAs a noise figure of 5 dB has been assumed. It is important to mention that such a network scenario requires very flexible models because the system parameters vary from span to span. Furthermore, it is not possible to calculate the transmission performance for a single span and to easily scale it to the total distance because the dispersion management is varying.

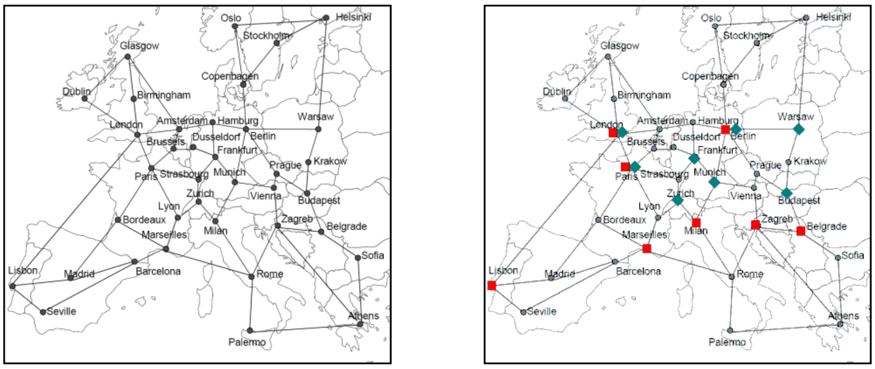

Fig. 1. COST266 reference network [3] (left) and
network with selective regeneration for SSMF (red squares) and NZDSF (green diamonds) (right)

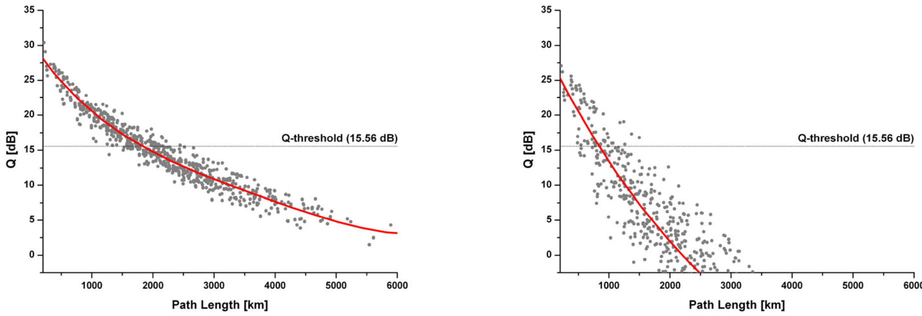

Fig. 2. Maximal reach in the investigated network; SSMF (right), NZDSF (left). Each point represents a path in the COST266 network.

3. Regenerator placement and constraint-based routing model

We used a combined regenerator placement and CBR approach. In our model the dominant degradation effects of ASE-noise, filter crosstalk, XPM and FWM have been included [4][5]. In our scenario chromatic dispersion (CD) does not impose significant penalties due to the modulation format and the dispersion management described above. Furthermore, we assume that an ASON will be built with newer fiber types with low PMD values (i.e. $0.05\ ps/\sqrt{km}$). This is why CD and PMD have not been included in the CBR model. In a first step each link has been annotated with a Q-factor penalty

$$Q_{penalty,dB} = 20 \cdot \log \frac{Q_{behind,linear}}{Q_{before,linear}}. \qquad (1)$$

For XPM and FWM the Q-factors have been obtained from analytical models based on a transfer function in the frequency domain derived from a pump-probe configuration for XPM [6] and a cw-approximation for FWM [7]. Each node has been assigned a 1 dB penalty accounting for the signal degradation due to crosstalk [8]. Furthermore, an insertion loss of 10 dB has been associated with each node.

Based on these parameters the regenerator placement has been started. The algorithm works as follows (inspired by [9]). A new graph is created with the location of the nodes determined by the investigated reference network. Then the (greedy) heuristic algorithm tries to set up a complete graph with vertices between any combinations of the nodes under the constraint that signal quality is above the minimal Q-factor (here: $Q > 6$). If the constraint is not satisfied, the considered connection can only be established, if a regenerator is placed within the link. The regenerator is placed at that node that will enable the maximal number of rejected connections. It is tried to minimize the total number of regenerator sites and to concentrate a regenerator pool at a limited number of nodes only (maximizing the number of feasible connections) to reduce costs related to maintenance. In our case a total of eight regenerators has been placed in the network corresponding to approximately 20% of all nodes. The positions of the regenerators are indicated in Fig. 1 (right). Different positions have been obtained for networks consisting of either NZDSF or SSMF. For the latter case full connectivity is achieved with eight regenerators. For NZDSF, however, at least 25 regenerators were needed for full connectivity. Due to cost-restrictions we only deployed eight regenerators in the NZDSF-based network resulting in limited connectivity.

A Poisson process with inter-arrival times of 1 time units for the arrivals of the connection requests and negative exponential distributions with a mean of 1 time units for the holding times are assumed. Thus, in the initial state the offered load (i.e. the product of mean holding time and arrival rate) is 1. Furthermore, the original demands defined in COST266 [3] are multiplied by a linear demand scaling factor *S* (as also used by [10]) to assess the blocking probability in the future when the total network traffic has increased leading to lower inter-arrival times because all demands need to be fulfilled in the same total simulation time. We assumed the lowest granularity of demands to be 10 Gb/s.

In all studies unprotected services have been assumed. The wavelengths are assigned by "first-fit". In a first approach a shortest-path (SP) algorithm with wavelength continuity constraint has been used. Afterwards we investigated two different CBR models based on worst-case physical transmission penalties ("off-line routing") or the current network status ("on-line routing"). Obviously the latter approach is computationally more challenging because the transmission quality has to be calculated "on-the-fly" when a connection is set up. This is why only in the case of a rejection of a connection based on the worst-case penalties the "on-line routing" is started for this connection request to reduce the computational time. The more exact "on-line routing" can then determine whether the desired connection really has to be rejected or the current traffic situation will permit to set up the connection request. In both cases the OSNR penalty due to ASE-noise is calculated separately and added to the *Q*-factor penalty at the receiving node. All investigations have been made with the translucent networks shown in Fig. 1 (right). Our simulations show that the SP algorithm leads to the highest (more or less constant) blocking probability of approximately 50% in the investigated parameter range ($1 < S < 160$). The reason for this is that certain long paths cannot fulfill the *Q*-factor requirements and are thus rejected. Both CBR approaches show much lower blocking probabilities (in the case of SSMF-based networks). As expected, the best performance is obtained from "on-line" CBR. The results are depicted in Fig. 3. Because of the lower local dispersion of NZDSF the fiber nonlinearities are more severe resulting in shorter reach and yielding a higher blocking probability for this type of fiber.

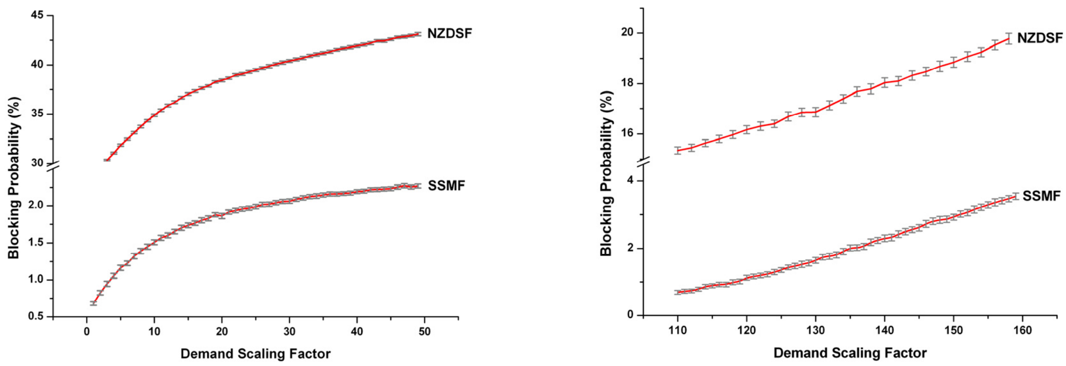

Fig. 3. Blocking probability for different routing algorithms; "off-line routing" (left), "on-line routing" (right). Depicted are also the 95% confidence intervals.

4. Conclusion

We have presented a study of a combined regenerator placement and CBR approach to satisfy the 10 Gb/s wavelength demands in an ASON. The proposed CBR algorithm can also be applied to heterogeneous network infrastructures with varying dispersion maps and different span lengths. It has been shown that this approach significantly reduces the blocking probability compared to other routing algorithms.

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