Online Physical-Layer Impairment-Aware Routing with Quality of Transmission Constraints in Translucent Optical Networks

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ABSTRACT
We propose a novel online physical-layer impairment-aware routing algorithm taking into account a minimum quality of transmission (QoT) constraint, which must be satisfied in all cases, even if the network load is changing, and new channels are activated. Our online constraint-based routing (CBR) algorithm considers the actual network load to get a more exact prediction of the signal quality degradation due to (multi-channel) nonlinear fiber impairments. We present results showing that the proposed online CBR algorithm is superior to shortest path routing with maximum transparent distance constraints as well as offline CBR algorithms, which are based on worst-case Q-factor penalties, in terms of blocking probability.

Keywords: all-optical networks, optical fiber nonlinearity, routing and wavelength assignment, quality of transmission.

1. INTRODUCTION
Optically transparent paths are currently the most cost efficient solution for long-haul data transport networks. In translucent optical networks with large dimensions such as pan-European networks, the signal quality has a strong impact on the feasibility of transparent paths. Typically only a limited number of regeneration sites are deployed in these networks due to the high cost of 3R regeneration. In the future, dynamic light path establishment is envisioned in which wavelength demands are provisioned dynamically depending on the signal quality and triggered by the customer demand [1]. For automatic provisioning of these paths routing and wavelength assignment algorithms are needed considering the physical-layer impairments to exploit maximum transparent reach (i.e. minimum number of required 3R regenerators) [2]. Previous studies have already investigated the routing and wavelength assignment (RWA) problem [3]. However, in many studies the physical-layer impairments are neglected or treated as static.

In this paper we present a novel online constraint-based routing (CBR) algorithm considering the current channel load to accurately model the inter-channel effects and which guarantees that connections, which have been established ones, will exhibit a minimum required signal quality even if new connections are provisioned. This QoT guarantee is a crucial factor for the operators of the networks and is an important advancement to previously published algorithms. Our CBR algorithm takes into account linear (amplified spontaneous emission noise, polarization mode dispersion, residual chromatic dispersion, filter crosstalk) as well as nonlinear impairments (four-wave mixing, cross-phase modulation, self-phase modulation). To accurately assess these degradation effects we propose a combination of fast analytical models for linear transmission impairments and multi-channel nonlinear effects with an optimized split-step Fourier method approach to estimate the impact of the nonlinear intrachannel effects (i.e. SPM). We show for the first time that our novel online CBR algorithm allows reducing the blocking probability and leads to a better utilization of the network resources because more traffic can be accommodated.

2. INVESTIGATED SCENARIO
For our investigations we selected the COST266 European core network [4] with 28 nodes and 41 bidirectional edges in a mesh topology (Fig. 1, left). In the reference network no physical parameters have been defined. This is why we assigned span lengths by a heuristic approach based on assumptions motivated by deployed networks (mean span length of 80 km and standard deviation of 5 km) to generate replacements for the missing data. For the dispersion compensating fiber (DCF) modules a granularity of 170 ps/nm has been assumed (equivalent to 10 km of standard single mode fiber, SSMF) leading to an average undercompensation of -85 ps/nm/span. A dispersion pre-compensation of -650 ps/nm has been employed (as suggested by [5]). At the nodes the dispersion has been fully-compensated. The distribution of polarization mode dispersion (PMD) values is based on data from a real German network published in [6]. An average PMD value of 0.17 ps·km⁻¹/² occurs in our reference network after the PMD values have been assigned to each fiber span by a random process. We assume that the PMD values in forward and backward directions are similar because the fibers will probably belong to the same cable and have very similar properties. The mean differential group delay (DGD) values of the reference network after the PMD values have been assigned to each fiber span by a random process. We assume that the PMD values in forward and backward directions are similar because the fibers will probably belong to the same cable and have very similar properties. The mean differential group delay (DGD) values of the reference network after the PMD values have been assigned to each fiber span by a random process.
We assume a channel plan with a maximum of 40 wavelengths per link spaced at 50 GHz. For the optical filters, second-order super Gaussian filters with 3 dB bandwidths of 42.5 GHz have been used. The electrical filters have a tenth-order Bessel low-pass characteristics with 7.5 GHz bandwidth. The EDFAs have been set to $P_{\text{launch}} = 1 \text{ dBm/ch}$ ($P_{\text{launch,DCF}} = -4 \text{ dBm/ch}$), and a noise figure of $F_0 = 5.5 \text{ dB}$ has been assumed. As a modulation format, 10.7 Gb/s NRZ-OOK has been used. A minimum Q-factor of 10 dB (pre-FEC) is required in our studies.

![Figure 1. COST 266 core reference network [4](left) and distribution of mean DGD values for bidirectional links (right).]

### 3. ONLINE CONSTRAINT-BASED ROUTING ALGORITHM

Our novel online CBR algorithm calculates three candidate paths with an (edge-disjoint) $k$-shortest path algorithm for any combination of source and destination nodes based on pre-computed worst-case impairments (Q-penalties) as edge weights. The Q-penalties for the individual nonlinear impairments (XPM, SPM, FWM) and linear degradation effects (group velocity dispersion (GVD), filter crosstalk) can be pre-calculated for a fully-loaded system. Analytical equations are used for XPM, FWM and filter crosstalk [7]. For the nonlinear intra-channel impairments (i.e. SPM) a split-step Fourier method approach with a low number of simulated bits and samples per bit is employed because no accurate analytical models have been found up to now for assessing the intra-channel degradations in arbitrary configurations.

Our CBR algorithm can operate in offline (based on worst-case penalties) and online modes (based on the current traffic situation). First the working principle of the offline mode is outlined here. If a new connection request arrives, our CBR algorithm first tries to find a suitable (continuous) wavelength on the shortest path (i.e. the transparent subsections, if regenerators are used along the route), which is assigned from a list of free wavelengths beginning with the longest one. In a second step it is checked, whether the required transmission quality can be guaranteed by estimating the Q-factor at the receiving node. The computation of the Q-factor requires – in a first step – to analytically determine the optical signal-to-noise ratio (OSNR) value at the receiver for the desired path [7]. To this value an OSNR penalty due to PMD is added. The calculation of the (first-order) PMD induced OSNR penalty has been described in [8]. The (semi-analytical) PMD calculation outlined in [8] requires a pulse form factor, which is set to $A = 26$ in our simulations. Subsequently, the OSNR value is converted to a Q-factor as shown in [7] neglecting nonlinear phase-noise impairments. From this Q-factor the (pre-computed) Q-penalties for the other linear and nonlinear effects are deducted. If these calculations predict that the desired connection request is feasible and the Q-factor lies above the required threshold – which is true in most cases – it is setup automatically. Otherwise it is tried to find an alternate suitable route on one of the other $k$-shortest paths.

If this also fails and if the online mode is activated, at this point a calculation is started for the (multi-channel) nonlinear degradation effects taking into account the current traffic situation. In many cases this online calculation allows establishing the connection, although worst-case assumptions would lead to a rejection. A connection, which is setup with this online approach, is added to a special list of online connections. If a new connection request occurs, which has any link in common with a connection on this online list, it has to be checked, whether provisioning the new connection request will affect the online established connection (i.e. degrade the connection by nonlinear crosstalk). If our calculations indicate, that the new connection request would significantly deteriorate any existing connection established by the online routing algorithm (below the required Q-factor of 10 dB), the new connection request cannot be setup on the presumed route. In that case an alternative route needs to be found, which is possible in most cases, or the new connection request is ultimately blocked. Connections, which have been setup by the offline algorithm, do not need to be considered here because they already assume a fully-loaded system. The online calculation of the nonlinear degradation effects is
based on fast analytical models [9] making it possible to assess the nonlinear degradation by XPM and FWM in typically a fraction of a second on a typical desktop PC. At this point it shall be stressed that this approach can also be applied to networks with protection in the optical-layer as shown in [10]. Furthermore, it is possible to include results from optical performance monitoring (OPM) into the online calculation.

4. SIMULATION RESULTS

To evaluate the performance of our routing algorithm we have chosen the pan-European COST266 network as a topology example and placed only 4 regenerator pools (as shown by the blue nodes in Fig. 1, right). For the reference network demands have been defined based on a population based model [11]. A Poisson process for the arrivals of the (dynamic) connection requests and negative exponential distributions for the holding times are assumed. A demand scaling factor has been used to investigate the performance of the network in the future when the traffic has grown by a factor of $S$. In our studies we investigated the total blocking probability and the reasons for blocking, which may be traffic blocking (due to limited network resources) or degradation blocking (due to impairments in the physical layer). Furthermore, the average and maximum transparent distance have been analyzed. In all figures also the 95% confidence intervals are depicted.

As can be seen from Fig. 2 (left) the blocking probability of the offline (worst-case) routing algorithm is approximately 0.5 percentage points higher than the curve for online routing for a demand scaling factor above approximately 270. If a maximum blocking probability of 2% is regarded as acceptable, this means that a maximum demand scaling factor of 300 for offline routing and 330 for online routing can be reached. In other words 10% more traffic can be accommodated by online routing (without changing any other parameter in the network). Furthermore, the curves are depicted for online routing “with QoT guarantee” and “w/o QoT guarantee”. “With QoT guarantee” means that the quality of transmission is ensured for online routed connections as described above even if new connections (wavelengths) are activated. In the “w/o QoT guarantee” the Q-factor is only checked once when the connection is established. Provisioning of new wavelengths is assumed to not degrade the Q-factor of the existing connections below the given threshold in this case. The difference between both online curves is rather small with the “with QoT guarantee” curve yielding a slightly higher blocking probability in most areas.

To further investigate these results, the blocking causes have been analyzed (Fig. 2, right). In this analysis the total blocking probability is split up into physical-layer degradation blocking and network resource blocking. It is not surprising that in this context offline routing shows the highest physical layer degradation blocking percentage because always a fully loaded system is assumed. The gap between offline and online routing becomes larger for higher demand scaling factors. The reason may be that some links are already fully-loaded and longer alternate routes need to be taken, which are blocked in offline routing. Regarding the two online CBR algorithms no significant differences can be observed. The reason may be that only very few connections need to be rejected in the “with QoT guarantee” case (compared to “w/o QoT guarantee”) and in most cases alternate routes can be taken. Furthermore, a rejection of a certain demand (due to QoT reasons) may enable to setup another demand. A further analysis shows that in the “with QoT guarantee” case the average transparent distance is slightly reduced (1220 km) compared to the “w/o QoT guarantee” case (1230 km) indicating that some longer transparent connections have either been rejected or rerouted through a regenerator.

To compare our CBR algorithm to the commonly used shortest-path routing with a maximum transparent reach constraint further simulations have been conducted. These simulations show that a transparent reach of approximately 3000 km is needed to achieve a similar performance (Fig. 3, right). Shorter transparent reach leads to a significantly increased blocking probability. Our analysis, however, also shows that for the assumed simulation parameters there are rather long paths with a good transmission quality (up to 3800 km) and short paths with a bad quality (only 900 km) as can be seen in Fig. 3 (left). In a dynamic transparent mesh network,
it is not possible to tailor the parameters (i.e. the dispersion map) of certain paths to yield a higher Q-factor for very long connections. For the regarded scenario thus a guaranteed transparent length of 3000 km is not feasible as for this distance the majority of paths shows a Q-factor below threshold level. This is why shortest-path routing will lead to a much higher blocking probability (higher than 10%) compared to the offline and online CBR algorithms or requires a significantly higher number of deployed regenerators.

Figure 3. Distribution of the Q-factors vs. length of transmission path (left) and total blocking probability for length-based routing with maximum transparent reach given in km (right).

5. CONCLUSIONS

We have presented a study of a new online constraint-based routing (CBR) algorithm with quality of transmission (QoT) constraints. Our algorithm allows a more accurate assessment of the (multi-channel) nonlinear degradation effects by taking into account the current network load. We have shown that our approach is significantly superior to classic shortest-path routing with maximum transparent distance constraints and also outperforms a CBR algorithm based on worst-case transmission penalties. The reduced blocking probability requires a higher computational effort, though. Because our CBR algorithm only executes the online computation of a path, if the offline test yields a Q-factor below the given threshold and the online assessment is based on fast analytical models, however, the time for processing a new demand is in most cases well below a second on a typical desktop PC.

REFERENCES