Novel Physical-Layer Impairment-Aware Routing Algorithm for Translucent Optical Networks with 43 Gb/s and 107 Gb/s Channels

Stephan Pachnicke*, Nicolas Luck, Peter M. Krummrich

* TU Dortmund, High Frequency Institute, Friedrich-Wöhler-Weg 4, 44221 Dortmund, Germany
Tel: +49 (231) 755 6675, Fax: +49 (231) 755 4631, e-mail: stephan.pachnicke@tu-dortmund.de

ABSTRACT
We present a novel constraint-based routing (CBR) algorithm, which accurately estimates linear and nonlinear physical-layer impairments of 43 and 107 Gb/s channels with duobinary and DQPSK modulation formats by combining fast analytical models for assessing the linear transmission impairments with a split-step Fourier approach optimized for computational speed to estimate the nonlinear intra-channel effects. Our CBR algorithm allows a significant increase in average and maximum transparent distance and thus a reduction in the number of required regenerators.

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

1. INTRODUCTION
Translucent optical networks are currently the most cost efficient solution for long-haul data transport. To improve flexibility of the network on-demand wavelength provisioning by the user is an interesting feature. However, the continuous growth of the internet introduces challenges to next-generation networks in terms of capacity. To meet the soaring bandwidth demands higher channel bit rates (e.g., 43 Gb/s or 107 Gb/s) and more sophisticated modulation formats (e.g., DQPSK, QAM, etc.) are proposed. Automatic setup of translucent paths requires accurate consideration of the physical-layer impairments to exploit maximum transparent reach. We present a novel constraint-based routing algorithm, which estimates the physical-layer induced impairments of 43 Gb/s and 107 Gb/s channels with duobinary (DB) and DQPSK modulation formats by combining analytical models for linear transmission impairments with a split-step Fourier method approach optimized for low calculation time to assess the nonlinear intrachannel effects. It is prohibitive to pre-compute the signal quality of all possible paths and wavelengths due to the computational complexity and the extremely high number of paths. Our CBR algorithm allows evaluating the transmission quality of a desired path on the fly in offline mode and almost real-time in online mode. As a topology of our study, we have selected the NOBEL Germany network [1]. For this network demands have been defined based on a population model [2]. Electrical regenerators extending the limited transparent reach have been placed sparsely at selected nodes to keep costs low. The locations are computed by our regenerator placement heuristic [3] considering the worst-case physical-layer impairments. We show that our novel CBR algorithm can increase the average transparent distance up to 38% in an optical network with 43 Gb/s and 107 Gb/s channels (compared to worst-case design) and allows to relax system requirements such as DCF granularity.

2. INVESTIGATED NETWORK
We have selected the NOBEL Germany network [1] with 17 nodes and 26 links in a mesh topology with a maximum link length of approximately 400 km (Fig. 1, left) as reference network. In this reference topology only the node positions and demands 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 a standard deviation of 5 km) to generate replacements for the missing data. For the DCF modules a granularity of 85 ps/nm has been assumed. The DCF modules have been chosen in such a way that some residual dispersion is left in each span (distributed undercompensation scheme). At the nodes the residual dispersion is minimized. The distribution of the polarization mode dispersion (PMD) values is based on data from a real German network published in [4]. In that network a considerable amount of legacy fibers with high PMD values above 0.5 ps/√km has been deployed. Because these fibers induce a very high OSNR penalty in high bit rate transmission of 43 Gb/s or 107 Gb/s we restricted the distribution of the PMD values to newer fibers with PMD values below 0.5 ps/√km. An average PMD value of 0.0825 ps/√km occurs in our reference network after the PMD values have been assigned to each fiber span by a random process. The mean DGD values of the bidirectional links are depicted in Fig. 1 (right). We chose the entire network to consist of SSMF with \( D = 17 \text{ ps/} \text{nm/km}, S = 0.056 \text{ ps/} \text{nm}^2/\text{km}, \alpha = 0.23 \text{ dB/km}, \gamma = 1.37 (W\cdot\text{km})^{-1} \). The DCF modules have the following parameters: \( D' = 0.12 \text{ ps/} \text{nm/km}, S' = -0.35 \text{ ps/} \text{nm}^2/\text{km}, \alpha' = 0.5 \text{ dB/km}, \gamma' = 5.24 (W\cdot\text{km})^{-1} \). We assume a channel plan with a maximum of 40 wavelengths per link spaced at 100 GHz. For the optical filters second-order super Gaussian filters with 3 dB bandwidths of 85 GHz have been used. The electrical filters have tenth-order Bessel low-pass characteristics with 40 GHz bandwidth. The EDFAs have been set to \( P_{\text{launch}} = 1 \text{ dBm/ch} \) (\( P_{\text{launch,DCF}} = -1 \text{ dBm/ch} \)).
and a noise figure of $F_0 = 5.5$ dB has been assumed. As modulation format we used either RZ-DQPSK (50% duty cycle) for 107 Gb/s or 43 Gb/s DB, which is generated by electrical filtering with 30% of the bit rate. No (electrical or optical) PMD compensation is used. The investigated scenario exhibits some paths with very high signal quality degradation (and a pretty low transparent distance) and other long paths lying well above the required Q-factor of 10 dB (pre-FEC). For 107 Gb/s RZ-DQPSK modulation there e.g. exists a path which only allows bridging 180 km transparently due to high PMD impairments. As will be shown below, however, there exist paths allowing a transparent reach of 642 km showing clearly that routing with fixed transparent reach constraints only will lead to inefficient utilization of transparent reach.

![Diagram of NOBEL Germany 17 node reference network and distribution of the mean DGD values for bidirectional links](image)

**3. CONSTRAINT-BASED ROUTING ALGORITHM**

Our proposed CBR algorithm estimates the transmission quality as follows. For each path in the network the ASE-noise induced OSNR value at the receiver is determined analytically. To this value an OSNR penalty due to PMD is added. The analytical calculation of the (first-order) PMD induced OSNR penalty is described in [5].

The (semi-analytical) PMD calculation outlined in [5] requires a pulse form factor, which is set to $A = 1.2$ for 107 Gb/s RZ-DQPSK signals and $A = 2.6$ for 43 Gb/s DB signals. These values are equivalent to a 1 dB penalty for a DGD value of 8 ps in the case of 107 Gb/s RZ-DQPSK and 7 ps for 43 Gb/s DB modulation, respectively. Subsequently, the OSNR value is converted to a Q-factor as shown in [3] neglecting nonlinear phase-noise impairments. Afterwards a Q-penalty due to nonlinear intrachannel impairments and group-velocity dispersion (GVD) is added, which can be pre-calculated for each link and each WDM channel. The Q-penalty is determined by a split-step Fourier method approach with a low number of simulated bits (here: 64) and samples per bit (also 64). The (single channel) numerical simulations allow estimating the nonlinear intrachannel and GVD impairments. For this purpose the coupled nonlinear Schrödinger equation is used comprising only the terms for dispersion, attenuation and self-phase modulation (SPM). The execution time of the numerical simulation is less than a second for a single span on a state of the art desktop computer (Intel Core 2 Quad Q6600 with 2.4 GHz clock rate). The computational time may be optimized further, if the split step-size is increased, however reducing the accuracy of the results slightly. We employed a maximum admissible nonlinear phase shift of 5 mrad between two split-steps. The proposed SSFM parameters allow to estimate the intrachannel impairments in the matter of a few seconds for a typical path in the network compared to almost an hour needed for an accurate SSFM based simulation of a WDM system with 40 wavelengths and some 10 spans (which is the length of a typical path).

Our CBR algorithm offers both “offline” or “online” modes. In both cases a $k$-shortest path algorithm is used to calculate three candidate paths based on pre-computed worst-case impairments as edge weights. Afterwards a suitable (continuous) wavelength is searched for, which is assigned from a list of free wavelengths beginning with the longest wavelength. If a regenerator is present along the selected route, it is assumed that wavelength conversion may occur at this point. In offline mode the nonlinear penalties are pre-computed as explained above for each link and wavelength. If a desired path consists of more than one link, the Q-penalties are added for each link (in logarithmic units). This is a worst-case approximation of the transmission quality (similar – but more accurate – to using the nonlinear phase shift for a uniform fiber link as a criterion as proposed by [6]). In a real system the Q-penalty of a concatenation of links is smaller because the dispersion map (in our case a distributed undercompensation) has a significant (and beneficial) impact on the accumulation of the penalties. This is why
we also implemented an “online” calculation mode. If the signal quality of a candidate path is below a certain threshold (in our case $Q = 10 \text{ dB}$, pre-FEC) and the connection request is rejected by the “offline” module, a calculation of the nonlinear $Q$-penalty for the entire path (comprising several links) is started. This “online” calculation yields a better estimation of the intrachannel and GVD impairments and allows to setup many of the paths, which have been rejected previously. The computational time for an “online” calculation typically lies in the range of only a few seconds (as a rule of thumb approximately 1 s/span in the used configuration). As we did not assume a system with a mix of different modulation formats and channel bit rates (especially with neighboring NRZ channels) it is assumed that XPM impairments are negligible. As shown in the next paragraph the online CBR algorithm allows to reduce the number of required regenerators and also to relax other system requirements such as DCF granularity at the expense of a slightly increased computational effort.

4. SIMULATION RESULTS

To enable transmission in the NOBEL Germany reference network 8 regenerator pools have been placed in the case of 107 Gb/s RZ-DQPSK channels and “online” CBR calculation. To achieve comparable blocking probabilities for the “offline” CBR algorithm three additional regenerator pools have been placed. The regenerator pools enable regeneration of all incoming wavelengths and can also be used as wavelength converters. Furthermore – in offline mode – the residual dispersion at the nodes has been reduced from $0 \pm 42 \text{ ps}/\text{nm}$ (“online”) to $0 \pm 8.5 \text{ ps}/\text{nm}$ (“offline”). The simulation results are depicted in Fig. 2 (left). The demand scaling factor can be used to investigate the performance of the network in the future when the traffic has grown by a factor of $S$. Demands are assumed to have full-wavelength granularity. It can be observed that both online and offline routing achieve similar blocking probabilities. However, keep in mind that for offline routing more regenerator pools have been placed and the residual dispersion at the receiver has been lowered. This is why the offline curve starts at a lower blocking probability for small demand scaling factors. Blocking may occur due to signal quality reasons stemming from physical-layer impairments or unavailability of network resources. It is interesting to mention that online routing also decreases network resource blocking because in many cases it allows taking detours to already fully-loaded links. A non-zero blocking probability at a demand scaling factor of $S = 1$ indicates that some paths are not feasible (which could be resolved by adding one additional regenerator pool). However, we assumed a blocking probability of below 2% as acceptable for dynamic network operation and set the minimum number of required regenerators accordingly. In our simulations the average path length is 485 km. The average transparent distance using “online” routing is 242 km versus 175 km in “offline” routing, which is equivalent to increasing the transparent reach by one more span. Even more striking is the difference, if the transparent distance for the longest established path is regarded. This time “online” routing yields 642 km versus 393 km in the “offline” case.

![Figure 2. Blocking probability for 107 Gb/s RZ-DQPSK modulation format (left) and 43 Gb/s duobinary modulation (right).](image)

For 43 Gb/s DB transmission similar results have been obtained (shown in Fig. 2, right). The results for “online” routing have been obtained with the same configuration as for 107 Gb/s RZ-DQPSK channels. For low demand scaling factors the “online” blocking probability is lower than for 107 Gb/s RZ-DQPSK, however the blocking probability is increasing faster than in the 107 Gb/s configuration. The reason may be found in the shrinkage of the dispersion tolerance in the presence of nonlinearity, which is more pronounced for DB than for DQPSK and becomes relevant when alternative routes to already fully loaded links have to be used. In the case of “offline” routing some modifications to the setup have been used. Again three additional regenerator pools have been deployed. Furthermore, the dispersion map has been changed. DB shows a considerable back-to-back penalty due to the V-shape of the eye. This is why we introduced an additional residual dispersion at the receiver of
102 ps/nm for the dropped channels. The average transparent distance using “online” routing is 224 km versus 183 km in “offline” routing. Even more impressive is the difference, if the transparent distance for the longest established path is regarded. This time “online” routing yields 745 km versus 352 km in the “offline” case.

5. CONCLUSIONS AND OUTLOOK

We have presented a novel physical-layer impairment based routing algorithm, which estimates the signal quality of 107 Gb/s DQPSK and 43 Gb/s duobinary transmission systems. Our CBR algorithm uses a version of the split-step Fourier method (SSFM) optimized for low computational time to assess the intrachannel nonlinear effects for which so far no analytical model for the estimation of the signal quality is known. The proposed SSFM parameters allow to estimate the intrachannel impairments in the matter of a few seconds for a typical path in the network. We have shown that our CBR algorithm allows to increase the average transparent reach in the network by 38% compared to the worst-case design and to relax system requirements such as the DCF granularity at the receiver. Future studies will extend these models to an arbitrary mix of channel bit rates and modulation formats coexisting in a network.

REFERENCES