Design of Grouped Routing Entity (GRE)-based Optical Networks with 100% Signal Quality Guarantee

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*Abstract***— In bandwidth abundant optical networks it is important to develop design strategies that are not only cost effective but also able to account for the inherent characteristics of the optical transmission medium responsible for the signal quality degradation. With this objective in mind, the paper proposes a design algorithm able to determine an appropriate placement of regenerators in Grouped Routing Entity (GRE)-based optical networks. The objective of the algorithm is to guarantee a certain signal quality level to all connections while minimizing the number of fibers and switching ports required in the network. The proposed design strategy relies on a physical-layer impairment model, specifically introduced in the paper for this purpose, able to estimate the signal quality of an optical path in a GRE-based optical network. Simulation results indicate that compared with a single layer optical path network the proposed design algorithm can reduce at least 87% of the switch ports while the increment in the number of fibers is lower than 10%.**

Keywords—Physical-layer impairments, signal quality, Grouped Routing Entity (GRE), coarse granular routing, 3R regenerator

I. INTRODUCTION

The last few years have witnessed a tremendous growth in traffic volumes driven by an increased number of Internet users and by the latest advances in bandwidth-hungry applications (e.g., video presence, High-Definition Television (HDTV), and real-time data backup). To support this growth, optical transport networks utilizing Reconfigurable Optical Add/Drop Multiplexers (ROADMs) are evolving towards more aggregated and dense switching architectures, with a significant increase in the complexity and the size of the switching fabrics. In this regards, optical networks based on the *Grouped Routing Entity (GRE)* paradigm [1-2] represent a promising option to reduce the overall optical switching cost (i.e., number of optical switch ports) and a better alternative compared to waveband switching [1-2].

In GRE-based optical networks, the wavelength paths in a fiber are bundled into groups, i.e., *pipes.* Even if the presence of two traffic aggregation levels (i.e., wavelength and pipe) might resemble the more conventional waveband or grooming concept, GRE-based networking is fundamentally different as it does not rely on path termination functions (i.e., the ones defined in ITU-T Rec. G.783 [3] for digital paths). This allows for some extra degree of flexibility in the path design phase. For example, in GRE-based networks it is possible to fit in the same pipe wavelength paths for different destinations without requiring, at an intermediate node, any wavelength path level cross connect functions (i.e., typical for waveband architectures) or Optical/Electrical/Optical (O/E/O) conversion as in any grooming-based design strategy, i.e., *all optical operations.* This in turn translates in more cost-effective switching nodes without compromising on their (large) throughput performance [1-2].

Having all optical operations, on the other hand, means that during the network design phase special attention needs to be put on the role played by *optical impairments*, especially when the provided services require high levels of signal quality guarantee. More specifically a careful design of a GRE-based network needs to consider that GRE switching operations, which rely on Waveband Selective Switches (WBSSs) and optical couplers at the switching nodes, introduce non-negligible filtering effects.

Transmission impairments can be dealt with in two ways while designing a network. They can be modeled and used as a constraint while solving the routing and wavelength/waveband/GRE pipe assignment problem (i.e., *impairment-aware techniques*). However, it might not always be advisable to rely only on impairment-aware approaches, especially in very large network topologies where it may not be possible to find a transparent path with an acceptable transmission quality, e.g., Bit-Error-Rate (BER) $<10^{-3}$, for some distant node pairs. In such a case the impact of optical impairments on the optical signal can be mitigated by means of *signal regeneration* at selected intermediate nodes (i.e., re-amplification, re-shaping, and re-timing of the optical signal, also known as 3R). This latter choice presents an extra benefit. Namely, during 3R operations (normally performed in the electrical domain) it is possile to rearragnge the wavenlegth paths within a GRE pipe with obvious advantagess in terms resource usage efficiency.

In the literature both options have been studied extensively for conventional wavelength/waveband routed networks. The authors in [4] present an Impairment-Aware Routing and Waveband Assignment (IA-RWBA) algorithm which accounts for the presence of physical-layer impairments during the routing and waveband assignment phase (i.e., no regeneration is considered). This solution assures a 100% impairment satisfaction rate (i.e., the percentage of connection requests with signal quality better than the BER threshold) together with a drastic reduction in the network cost. The authors in [5] on the other hand propose an Integer Linear Programming (ILP) formulation and three heuristics with the objective to guarantee the signal quality for all routed connections with the minimum number of regenerators in a waveband-routed network. However, in the literature there are not any studies where physical-layer impairments are considered or even modeled while designing GRE-based optical networks.

The contribution of this paper is two-fold. First, a physical-layer impairment model is introduced to assess their impacts on the optical signal transmission quality. The model is developed assuming a specific GRE node architecture [6] that shows a good cost vs. performance trade off. The transmission quality is measured in terms of BER [7]. The proposed impairment model is then used to develop a GRE network design algorithm where the degradation of the optical signal is mitigated by means of 3R regeneration. More specifically, after computing the minimum number of required 3R regenerators, the proposed design technique aims at finding the locations for each 3R regenerator such that: (*i*) 100% impairment satisfaction rate is guaranteed, and (*ii*) the cost, measured in terms of number of fibers and switching ports, is kept at a minimum. Using experimental measurements as a benchmark, the proposed impairment model is found accurate in estimating the degradation of the optical signal quality. Also the proposed GRE network design approach shows good overall performance. When compared to conventional impairment un-aware design approaches, the proposed technique presents a significant reduction in the number of switch ports and a limited increase in the number of required fibers, while still providing 100% signal quality guarantee.

II. NETWORK ARCHITECTURE AND IMPAIRMENT MODEL

This section describes the considered network node architecture and link model, and presents the equations used to estimate the BER of an optical path routed in a GRE-based optical network.

A. Node and Link Models

Differently from a hierarchical optical path network (where switching operations may take place both at the wavelength and at the waveband level), all the wavelength paths in a GRE-based network can only be switched at the GRE pipe level, i.e., coarse granular switching operations. In order to add/drop a single wavelength path to/from a GRE pipe, a 1x2 Wavelength Selective Switch (WSS) is used. Alternatively, for the add function the WSS can be replaced by a cost-effective optical coupler. Fig. 1 shows the considered node architecture for the GRE-based network [1]. It consists of: (*i*) 1x2 WSSs used to add/drop selected wavelength paths to/from a GRE-pipe, (*ii*) waveband multiplexers/de-multiplexers, and (*iii*) a Grouped Routing Optical Cross Connect (GR-OXC) used for switching GRE pipes from an ingress to the corresponding egress port. The GR-OXC can be obtained by using optical couplers and Waveband Selective Switches (WBSSs) [6]. The detailed architecture of an 8x8 GR-OXC is presented in Fig. 2.

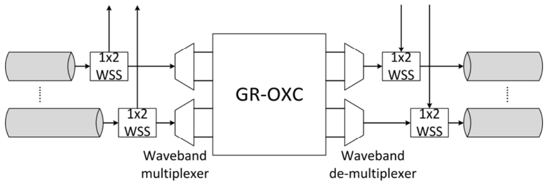

Fig. 1. Network node architecture.

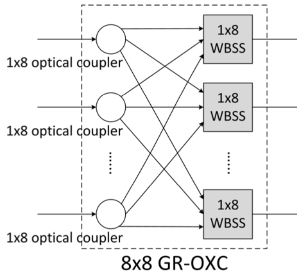

Fig. 2. 8x8 GR-OXC.

Fig. 3 presents the model of the considered transmission link. It consists of a sequence of single mode fiber (SMF) spans. Their number may vary according to the physical distance between the nodes. Erbium-doped fiber amplifiers (EDFAs) are inserted after each fiber span in order to compensate for the power loss in the fiber. A booster EDFA is also used right after the node to compensate for the power loss within the node itself. Moreover, the dispersion accumulated in each span is compensated by a dispersion compensating fiber (DCF) placed after each in-line amplifier.

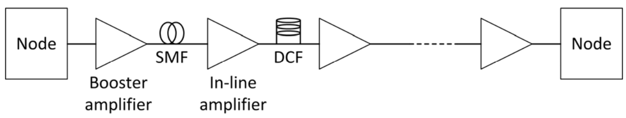

Fig. 3. Network link architecture.

These node and link models are then used to compute the Q-factor of an optical path (assumed to be a sequence of network links) as explained in the next section.

B. Impairment Model

In this work, the effect of physical-layer impairments is quantified by using the quality factor Q, modified from [7]. The Q-factor includes the effects of: Polarization Mode Dispersion (PMD); Amplified Spontaneous Emission (ASE) noise; crosstalk at multiplexers/de-multiplexers and switches; and filter concatenation. The power penalty due to PMD is calculated based on the length of optical path, the bit rate, and the PMD parameter. ASE and crosstalk are calculated assuming that they follow a Gaussian distribution. The filter concatenation effect is quantified through an eye closure penalty. The Q-factor of an optical path can be expressed as,

$$Q = \frac{pen_{FC} \cdot P_{transmitter}}{pen_{PMD} \cdot \sqrt{\sigma_{ASE}^2 + \sigma_{XT}^2}}, \quad (1)$$

where $P_{transmitter}$ is the transmitted signal power, pen_{FC} is the eye closure penalty due to the effect of filter concatenation, pen_{PMD} denotes the power penalty due to PMD, σ_{ASE}^2 represents the electrical variance of ASE noise, and σ_{XT}^2 is the electrical variance of crosstalk induced in multiplexers/de-multiplexers and switches. The BER value of an optical path can be derived from (1) as follows,

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right). \quad (2)$$

A detailed equation for each parameter in (1) is provided next.

1) PMD: the power penalty due to PMD of an optical path can be obtained by using the following expression [8],

$$pen_{PMD} = 10.2 B^2 D_{PMD}^2 L, \quad (3)$$

where B is the signal bit rate, D_{PMD} denotes the fiber PMD parameter, and L is the length of optical path.

2) Filter concatenation: the eye closure penalty due to the effect of filter concatenation can be calculated as [9][10],

$$pen_{FC} = h(t) * E_s(t), \quad (4)$$

$$h(t) = \mathcal{F}^{-1}\left[\prod_{i=1}^{N} H_i(f)\right],$$

where $h(t)$ denotes the impulse response of the cascade of filters (including multiplexers/de-multiplexers, switches, and the receiver's filter), $E_s(t)$ is the input signal, N is the total number of filters, and $H_i(f)$ represents the transfer function of the *i*th filter.

3) ASE noise: the electrical variance of the ASE noise [11] can be calculated from,

$$\sigma_{ASE}^2 = 4R^2 P_{avg} P_{ASE} \cdot \frac{B_e}{B_o}, \quad (5)$$

where R is the responsivity of a receiver, P_{avg} represents the average signal power at a receiver, P_{ASE} is the ASE power of amplifiers [11], B_e and B_o are the electrical and the optical bandwidth of a receiver, respectively.

4) Crosstalk: the electrical variance of crosstalk induced by multiplexers/de-multiplexers and switches can be expressed as [12],

$$\sigma_{XT}^2 = 2\xi_{pol} R^2 b P_{avg} P_{XT}, \quad (6)$$

where ξ_{pol} is the polarization mismatch factor between the signal and crosstalk, R denotes the responsivity of a receiver, b represents the multiplication factor of a receiver, P_{avg} is the average signal power at a receiver, and P_{XT} is the crosstalk power caused by multiplexers/de-multiplexers and switches [12].

Given a pre-defined signal quality threshold, the introduced impairment model can be used to estimate the maximum reach of a transparent optical path in terms of hop count. This information is used in the proposed GRE network design algorithm with 3R regenerator placement, as explained in the next section.

III. GRE Network Design Algorithm with 3R Regeneration Placement

This section is divided into two parts. First, it formally introduces the problem of GRE network design with 3R regeneration placement. Then, the section presents a detailed description of the proposed design strategy.

A. Problem Definition

For simplicity, in this paper it is assumed that each link in the network has the same length. The extension to the case in which the links have different length is straightforward. The inputs of the problem are: (*i*) the physical topology of the network, represented by a graph $G=(V,A)$, where V is the set of network nodes, and A is the set of network links; (*ii*) the number of wavelengths in a fiber W; (*iii*) the number of GRE pipes in a fiber W/B, where each pipe consists of B wavelengths; (*iv*) the ID of each GRE pipe in a fiber (i.e., the GRE index) which is an integer ranging from 1 to W/B; (*v*) set $T=\{t_1(s_1,d_1), t_2(s_2,d_2) \ldots, t_n(s_n,d_n)\}$ that defines the number of wavelength paths (t_i) from source node s_i to destination node d_i; (*vi*) the value of the optical transparent reach h (defined in terms of hop count), computed using the model introduced in Section II; and (*vii*) a hop slug parameter x that stands for the allowable increment of the hop count. The objective of the GRE network design with 3R regeneration placement problem is to find the location of a given number of regenerators in order to guarantee a 100% impairment satisfaction rate, with a minimum number of fibers used to provision all the demands in set *T*.

B. GRE Network Design Algorithm with 3R Regeneration Placement

Fig. 4 presents the flowchart of the proposed GRE network design algorithm with 3R regeneration placement. The algorithm starts with an initialization phase where a number of parameters are collected, i.e., $G(V,A)$, W, B, set T, x and h. The rest of the algorithm consists of three main steps as described below.

Step 1: all traffic demands in T are analyzed separately. If $t_i(s_i,d_i)$ can fill the entire capacity (B) of one or more GRE pipe(s), $\lfloor t_i(s_i,d_i)/B \rfloor$ GRE pipe(s) are reserved and $B\times\lfloor t_i(s_i,d_i)/B \rfloor$ wavelength paths are accommodated in this GRE pipe(s). The remaining traffic demands between s_i and d_i which cannot be accommodated are defined as $\overline{t_i(s_i,d_i)} = t_i(s_i,d_i) - \left(B\times\lfloor t_i(s_i,d_i)/B \rfloor\right)$. The value of $\overline{t_i(s_i,d_i)}$ is computed for all the elements in T and these "leftover" wavelength paths are examined in *Step 2*.

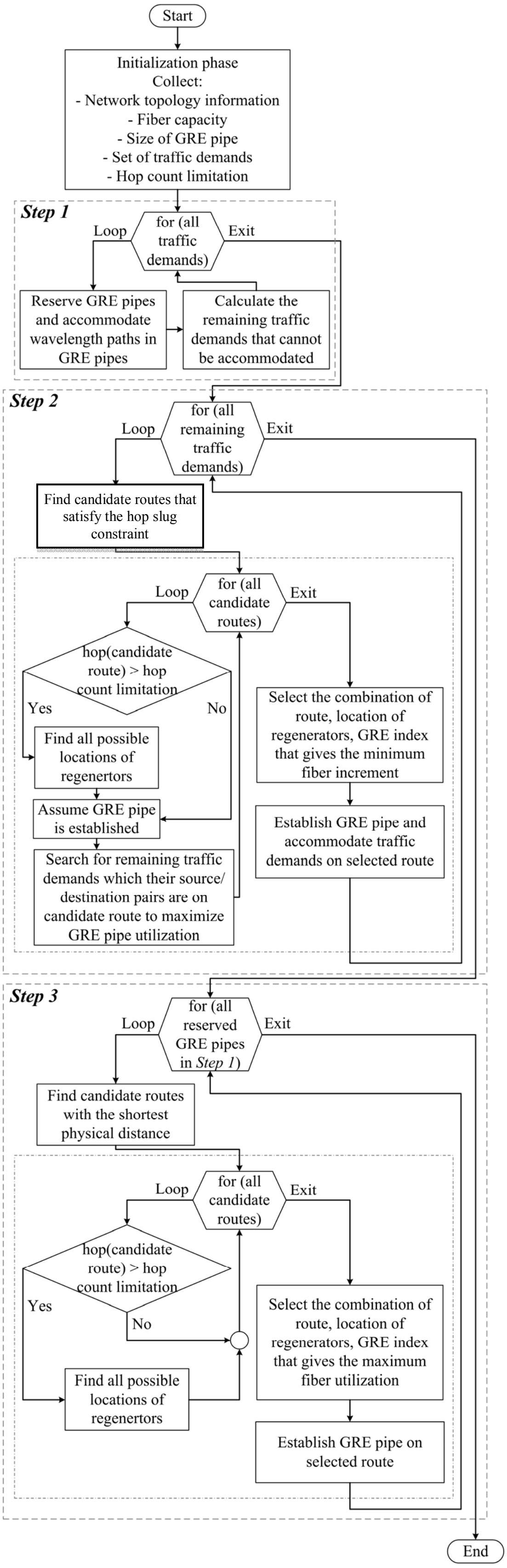

Fig. 4. Flowchart of the proposed GRE network design algorithm.

Step 2: for each $\overline{t_i(s_i,d_i)}$, the shortest (i.e., hop count) route between s_i and d_i is calculated. Then, $\overline{t_i(s_i,d_i)}$ are sorted in a descending order of the length of their respective shortest routes. For each sorted $\overline{t_i(s_i,d_i)}$, if the number of hops of the shortest route of $\overline{t_i(s_i,d_i)}$ is larger than h, the number of regenerators required for this route is $r = \lfloor (hop\ count\ shortest\ route - 1)/h \rfloor$, otherwise $r=0$. After that, all possible candidate routes in $G(V,A)$, whose hop counts are equal or less than $\min[hop\ count\ shortest\ route\ +\ x), (r+1)h]$ are computed. Next, for each candidate route, all possible locations of the r regenerators along the route are computed. This number is

$$\sum_{l=0}^{k} \frac{(\mathrm{r}+1)^l}{l!}, k = \min[(r+1)h\ -\ hop\ count\ shortest\ route,\ x]$$

This is an exhaustive search but, with realistic values of h and x it will be over within a reasonable amount of time. Under the assumption that a GRE pipe is established on the candidate route under exam, then all other "leftover" wavelength paths (i.e., $\forall\ \overline{t_j(s_j,d_j)}, j \neq i$) whose source/destination pairs are on the considered candidate route are checked to see if they can also be accommodated in the considered GRE pipe. After that, the GRE index and the location of the regenerators are chosen in such a way that the utilized capacity of the GRE pipe is maximized. Among all the candidate routes, the one with the regenerators' location and with a GRE index that requires the minimum addition of fibers is selected. The GRE pipe is then established on the selected route and $\overline{t_i(s_i,d_i)}$, plus all the "leftover" wavelength paths which could be accommodated on the selected route, are provisioned. After establishing all the remaining traffic demands, go to *Step 3*.

Step 3: for each GRE pipe reserved in *Step 1*, the shortest (i.e., hop count) route is computed. Similarly to *Step 2*, the reserved GRE pipes are then sorted in a descending order based on the length of their respective shortest routes. For each sorted GRE pipe, the set of all possible candidate routes, whose hop counts are equal or less than *hop count shortest route+x*, are calculated. If the number of hops of the shortest route of a specific GRE pipe is larger than h, the required number of regenerators (i.e., r) is computed as in *Step 2*. Then, on each candidate route, all the possible locations of the r regenerators are computed, and the route with the regenerators' location and a GRE index that guarantees the maximum fiber utilization is selected. *Step 3* is repeated until all the GRE pipes reserved in *Step 1* are established.

IV. PERFORMANCE EVALUATION

In this section, the impairment model presented in Section II is validated. Then, the performance of the GRE network design approach described in the previous section is evaluated.

A. Impairment Model Validation

To check the accuracy of the proposed impairment model, we first conduct a number of transmission experiments using the prototype of the 8x8 GR-OXC presented in [6]. The optical signal quality results obtained using the impairment model are compared with the experimental measurements obtained during the transmission experiments. The experimental setup is shown in Fig. 5. A distributed-feedback laser diode (DFB-LD) with 1550.116 nm signal wavelength is used as a light source. It is modulated by a 9.95328 Gb/s pseudorandom bit stream (PRBS) with word length of 2^{31}-1. Moreover, booster EDFAs are used to compensate for the power loss due to the GR-OXC. Finally, power and BER of the received signal are measured in a number of experiments where the number of traversed GR-OXCs is varied.

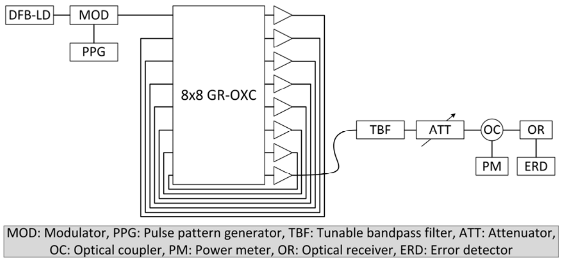

Fig. 5. Experimental setup.

Using Equations (1) and (2), and the same physical parameters setting as the experiment, the Q-factor and the BER of the signal are calculated. Note that during this validation process only the effects of ASE noise and filter concatenation are considered, as it was the case in [6]. Fig. 6 shows the BER values obtained using the proposed model and from the experiments. They are presented for different values of the average received signal power and the number of GR-OXCs traversed. The impairment model is able to accurately estimate the optical signal quality, i.e., a 97% accuracy can be achieved when computing the BER of the signal.

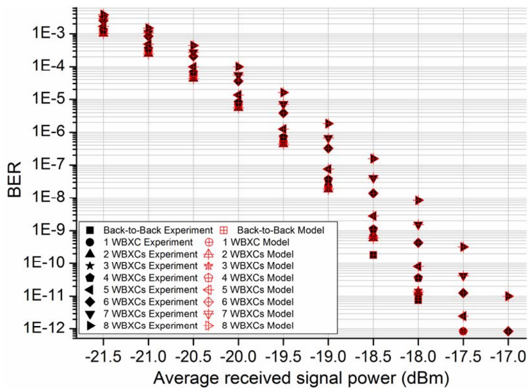

Fig. 6. BER versus average received signal power.

B. *Performance of the GRE network design algorithm with 3R regeneration placement*

In order to evaluate the performance of the proposed GRE network design algorithm, an optical transparent reach (in terms of hop count) is computed using the proposed impairment model. In this process it is assumed that W=80, and a wavelength occupancy worst-case scenario is considered while estimating crosstalk, i.e., each fiber is considered as fully occupied. The transmitted signals are assumed to be 10 Gb/s On-Off Keying (OOK) with 1 mW power and 50 GHz channel spacing. In order to understand whether or not the impact of the impairments induced at the node is higher than the one at the link, different link lengths are considered. Note that the SMF span is assumed to be 60 km.

Table I presents BER value of an optical path versus link distance. We can see that the value of the optical transparent reach is not affected too much by the link length. This is because the effects of the node impairments (especially, power loss) are much higher than the impact of impairments on the link. In particular, to be able to fully compensate for the node power loss, a booster amplifier with a high gain is required. This in turn results in high ASE noise level. Moreover, at the node crosstalk and filter concatenation effects also need to be accounted for.

TABLE I. BER VERSUS LINK LENGTH

#Hops / **BER**	2	3	4	5	6
150 km	4.01E-11	1.75E-06	7.27E-05	4.93E-04	1.59E-03
200 km	6.79E-11	2.17E-06	8.29E-05	5.42E-04	1.72E-03
250 km	1.12E-10	2.66E-06	9.41E-05	5.95E-04	1.85E-03
300 km	1.13E-10	2.67E-06	9.44E-05	5.97E-04	1.85E-03
350 km	1.82E-10	3.25E-06	1.07E-04	6.52E-04	1.99E-03
400 km	2.87E-10	3.93E-06	1.20E-04	7.12E-04	2.13E-03
450 km	4.45E-10	4.72E-06	1.35E-04	7.74E-04	2.28E-03
500 km	6.76E-10	5.64E-06	1.51E-04	8.41E-04	2.44E-03

The performance of the proposed GRE network design algorithm is evaluated through simulations using three regular mesh network topologies, i.e., 5x5, 6x6, and 7x7. For simplicity, it is assumed that the length of all links is 500 km. Furthermore, W equal to 80 is considered, while the GRE pipe size (B) is set to 10 wavelengths. Assuming that Forward Error Correction (FEC) is available, the signal quality threshold, i.e., the BER value below which a connection is deemed not acceptable, is set to 10^{-3}. Thus, the optical transparent reach (h) is set to 5 hops (Table I). Moreover, we assume randomly and uniformly distributed traffic demand values (i.e., t_i) expressed in terms of the average number of wavelength paths to be provisioned between each node pair. For each value of t_i, 20 different random traffic distributions are considered and the averaged results are plotted. For benchmarking purpose, two other network design algorithms are considered, namely *single-layer* scheme and *conventional GRE network design* approach. In the single-layer scheme, a conventional single layer optical path architecture is assumed, and wavelength paths are accommodated one by one so as to minimize the number of required fibers. The conventional GRE network design approach refers to the algorithm presented in [1] but without the implementation of the GRE pipe reallocation procedure used to increase the fiber utilization ratio. Therefore, for the all approaches in our evaluation, only the shortest (i.e., hop count) routes are considered as possible candidates to establish a GRE pipe.

For each of the considered topologies, it is found that, despite the use of shortest path candidates, it is not always possible to provision transparent connections with an acceptable signal quality for all possible node pairs. More specifically, setting a BER threshold of 10^{-3}, h=5, and with a link length of 500 km, it is found that only 90%, 77.78%, and 65.48% impairment satisfaction rates can be achieved in the case of 5x5, 6x6, and 7x7 network topologies, respectively, when a conventional GRE-based design approach is used. This is the reason why 3R regenerators need to be selectively placed at network nodes if a 100% impairment satisfaction rate for any connection between each node pair is mandatory in the network.

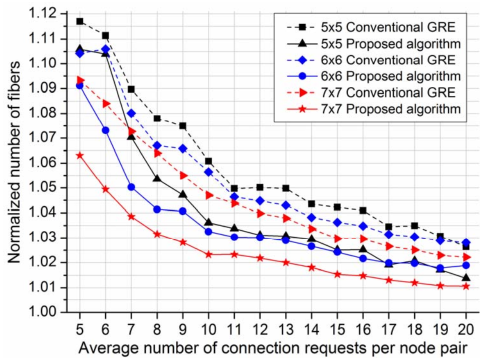

Fig. 7. Normalized number of fibers.

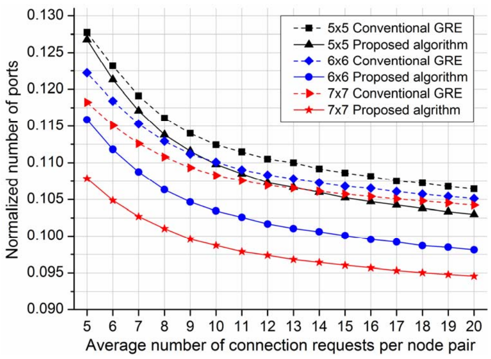

Fig. 8. Normalized number of ports.

Fig. 7 and Fig. 8 present a performance comparison between the proposed design algorithm and the two benchmarking approaches (i.e., single-layer and conventional GRE design). The figures show the values of the number of fibers (Fig. 7) and the number of ports (Fig. 8) normalized with the values obtained for the single-layer approach. The number of fibers for both the conventional GRE design and the proposed algorithm (Fig. 7) is higher than for the single-layer approach. This is because both GRE-based cases have a coarse switching granularity (i.e., no wavelength switching is available). However, the normalized number of fibers obtained by the proposed algorithm is still lower than the one of the conventional GRE approach. On the other hand, the proposed design algorithm is able to achieve a significant port count reduction compared to the single-layer approach, i.e., up to 90% in the case of the 7x7 network topology (Fig. 8). Considering that the node cost plays an important role in the total network investment [2], a slightly increase in the number of fibers is entirely acceptable. Another essential aspect to consider is the impact of transmission impairments. As mentioned earlier, for the studied network topologies it is not possible to guarantee a 100% impairment satisfaction rate without 3R regenerators. On the other hand, our proposed design algorithm is not only able to provide 100% signal quality guarantee to all the connections, but also able to obtain lower number of fibers and ports, compared to the conventional GRE network design approach.

V. Conclusions

In this paper, the physical-layer impairment model for quantifying the impact on the signal quality of an optical path in a GRE-based optical network is proposed. The accuracy of the model is validated towards a number of transmission experiments, and it is shown that the proposed impairment model is able to estimate the signal quality of an optical path with 97% accuracy.

Furthermore, a GRE network design algorithm based on our impairment model is proposed. The algorithm offers 100% signal quality satisfaction rate by means of the use of optical signal regeneration. The location of regenerators is chosen with the purpose of minimizing the number of fibers needed to be deployed in the network. Simulation results show that with the proposed design approach the number of switch ports can be reduced by 87%, compared to a single layer optical path network, while the increase in the number of fibers can be limited to up to 10%.

Acknowledgment

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References

[1] Y. Taniguchi et al., “A Novel Optical Networking Scheme Utilizing Coarse Granular Optical Routing and Fine Granular Add/Drop”, in Proc. of IEEE/OSA OFC/NFOEC2012, Mar. 2012.

[2] Y. Taniguchi et al., “Hardware Scale Reduction in Large-Port Count OXCs Exploiting Selective Switch based Coarse Granular Routing”, in Proc. of PS2012, Sep. 2012.

[3] ITU-T Recommendation G.783, Digital transmission systems.

[4] A. Jirattigalachote et al., “Impairment-Aware Routing and Waveband Assignment for Efficient Optical Transport Networks”, in Proc. of IEEE/OSA OFC/NFOEC2012, Mar. 2012.

[5] S. Varma et al., “Regenerator Placement and Waveband Routing in Optical Networks with Impairment Constraints”,in Proc. IEEE ICC2011, Jun. 2011.

[6] K. Takaha et al., “Development of Ultra-Compact 8x8 Waveband Cross-connect”, in Proc. of OECC/PS 2013, July 2013.

[7] A. Jirattigalachote et al., “ICBR-Diff: an Impairment Constraint Based Routing Strategy with Quality of Signal Differentiation”, Journal of Networks, vol. 5, no. 11. pp. 1279-1289, Nov. 2010.

[8] C. D. Cantrell, “Transparent Optical Metropolitan-Area Networks”, LEOS 2003, The 16th Annual Meeting of the IEEE, Oct. 2003.

[9] I. Roudas et al., “Accurate Modeling of Optical Multiplexer/Demultiplexer Concatenation in Transparent Multiwavelength Optical Networks”, IEEE Journal of Lightwave Technology, vol. 20, no. 6, pp. 921-936, Jun. 2002.

[10] A. Nag et al., “Optical Network Design With Mixed Line Rates and Multiple Modulation Formats”, IEEE Journal of Lightwave Technology, vol. 28, no. 4, pp. 466-475, Feb. 2010.

[11] G. P. Agrawal, “Fiber-Optic Communication Systems”, 3rd edition, A John Wiley & Sons, INC., Publication, New York, 2002.

[12] B. Ramamurthy, “Impact of Transmission Impairments on the Teletraffic Performance of Wavelength-Routed Optical Networks”, IEEE Journal of Lightwave Technology, vol. 17, no. 10., pp. 1713-1723, Oct. 1999