# Dynamic quality of transmission optimization and global impairments control in reconfigurable transparent WDM networks: schemes and demonstrations

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Two novel dynamical quality of transmission (QoT) optimization schemes with explicit optimization targets and accurate end-to-end QoT estimation are proposed for reconfigurable transparent wavelength-division multiplexing (WDM) networks. Numerical simulations show that the scheme of quality ($Q$) best has the best $Q$ factor improvement with large attenuation adjustment. The scheme of $Q$ allowable can achieve minimized number of tuning sites and attenuation adjustment and also improve the $Q$ factor of light path to the required value. In addition, the idea of dynamic QoT optimization and global impairment control has been experimentally demonstrated on a simple mesh network by the cooperation of a control plane and tunable devices.

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Optical-bypass core wavelength-division multiplexing (WDM) networks appear to be evolving from traditional fixed point-to-point connection to agile and transparent mesh networks by eliminating some expensive electronic regenerators and introducing more intelligence in the control plane (CP), which can lower the capital expenditure (CAPEX) and operating expenditure (OPEX) considerably[1]. However, due to immature optical reamplification, reshaping, and retiming (3R) technology and lack of optical-electrical-optical (OEO) conversion in transparent networks, physical layer impairment (PLI) will accumulate along light paths, and vary dynamically as the result of fast re-route, restoration, etc. To solve the problem, recent studies on physical impairments aware networks (PIAN) incorporating PLI in the connection establishment have received great attention, both from the research communities and the industry worlds[2−7]. These studies on PIAN, nevertheless, suppose that the light path performance of physical layer is fixed and cannot be controlled dynamically[2−7]. Actually, the light path performance can be adjusted dynamically with universal deployment of many kinds of tunable devices and impairment compensators such as optical amplifiers, wavelength selective switches (WSSs), and tunable dispersion compensators (TDCs). However, traditionally, these tunable devices cannot be aware of the states of each other and thus only tune work states separately by local monitoring. This may result in disordered performance adjustments along the light path, which will usually cause large time delays, transients, and increasing operating expenditures of operators[8]. To overcome the shortcomings metioned above, we have proposed the basic idea of dynamical quality of transmission (QoT) optimization by incorporation of extended CP and tunable devices[9]. However, the QoT performance estimation in Ref. [9] is based on separated physical constraints and cannot accurately express the end-to-end quality of transmission (such as quality ($Q$) factor, etc.). Moreover, the simple heuristics in Ref. [9] have no explicit optimization objects since it obtains feasible solution only if all the constraints are met.

In this letter, we apply a novel semi-analytical QoT estimator introduced by Ref. [4], which can accurately estimate the $Q$ factor of an end-to-end light path in presence of self-phase modulation (SPM), inter-channel nonlinear effects such as cross-phase modulation (XPM) and four-wave mixing (FWM), dispersion, and amplified spontaneous emission (ASE) noise. Based on the QoT estimator, we propose two nonlinear programming problem (NLP) optimization schemes with explicit optimization targets. We apply the two QoT optimization schemes on a 1600-km transmission system with 17 attenuation tunable WSS nodes and compare their QoT improvements and distribution of attenuation adjustment by numerical simulations.

In addition, based on the adaptive multi-service optical network (AMSON) testbed with reconfigurable optical add/drop multiplexing (ROADM) nodes[10], the idea of dynamic QoT optimization and global impairment control has been successfully demonstrated. To the best of our knowledge, this is the first demonstration of global control of light path QoT at the level of CP.

We consider the realistic wavelength switched networking scenario, where the compensation adjustment should not affect neighboring channels with different routes. Thus the tunable devices in our studies only include tunable dispersor compensator and WSS attenuator, both of which are embedded in ROADM nodes and can be tuned on a channel-by-channel basis. As shown in Fig. 1, the attenuation of each wavelength at the output/drop port of all the ROADM nodes can be dynamically tuned in the range of 0–30 dB. Also an insertion loss randomly distributed in the range of 0–10 dB will be introduced for each ROADM node to incorporate the different port connections. The output signal at each node is further amplified by optical amplifier (OA) with fixed gain of 20 dB and launched into fiber span comprised of 100-km standard single-mode fiber (SSMF) and dispersion-compensating fiber (DCFs). To incorporate nonlinear phase effects in the QoT estimation, fixed inline dispersion compensation is considered and the dispersion compensation can only be tuned at transmitter and receiver nodes. For all of our simulations, the residual dispersion per span is 100 ps/nm. The precompensation and the post-compensation are optimized according to the techniques introduced by Ref. [11], then the nonlinear phase shift can accurately reflect interplay effect of dispersion and nonlinear effects (SPM, XPM, and FWM)[5].

The transmitter consists of nine 10-Gb/s non-return-to-zero (NRZ) on-off keying (OOK) channels spaced 50-GHz apart, centered around 1550 nm, with the same polarization. Each channel is modulated by 128 bit pseudo-random binary-sequence (PRBS), decorrelated with that of other channels by introducing a random delay. Only the QoTs of central channels will be evaluated to consider the worst degradation caused by XPM. At the receiver, a second order super Gaussian optical filter with 18-GHz bandwidth and a fifth Bessel electrical optical filter with 7.5-GHz bandwidth are used. We evaluate the relation between nonlinear phase shift and optical signal-to-noise ratio (OSNR) penalty by changing the number of transmission span from 4 to 16 and the power launched into SSMF from −3 to 6 dBm with a 1 dBm step. The gain of inline amplifier after SSMF and DCF are always fixed so that the power launched into DCF is always 10 dB less than that of SSMF. The details of fiber and erbium-doped fiber amplifier (EDFA) parameters are shown in Table 1.

We evaluate the OSNR penalty at the bit error rate (BER) of $10^{-5}$, and the relation between nonlinear phase shift and OSNR penalty is shown in Fig. 2.
According to Ref. [4], the $Q$ factor of a light path can be expressed as

$$Q = Q_{\mathrm{ref}} + \zeta(D_{\mathrm{res}}, \varphi_{\mathrm{nl}}) \times \left(\mathrm{OSNR}_{\mathrm{req}}^{Q_{\mathrm{ref}}} - \mathrm{OSNR}_{\mathrm{BtB}} - P_{Q\mathrm{ref}}(\varphi_{\mathrm{nl}})\right) \quad (1)$$

where $\mathrm{OSNR}_{\mathrm{req}}^{Q_{\mathrm{ref}}}$ corresponds to a required OSNR after transmission to guarantee a $Q$ factor equal to $Q_{\mathrm{ref}}$. The function $\zeta(D_{\mathrm{res}}, \varphi_{\mathrm{nl}})$ is related to the observation that $Q$ factor (in dB) generally scales proportionally with OSNR (in dB) with a slope $\zeta$, near to 1 in usual cases. We obtain the function $P_{Q\mathrm{ref}}(\varphi_{\mathrm{nl}})$ by approximating OSNR penalty curve shown in Fig. 2 by a quadratic polynomial.

**Table 1. Transmission Line Parameters**

| Fiber | SSMF | Inline DCF |
|---|---|---|
| Length (km) | 100 (per span) | 18.8 |
| Attenuation (dB/km) | 0.2 | 0.6 |
| Dispersion (ps/(km·nm)) | 17 | −85 |
| Effective Area ($\mu$m$^2$) | 80 | 20 |
| EDFA Gain after the Fiber (dB) | 10 | 21.3 |

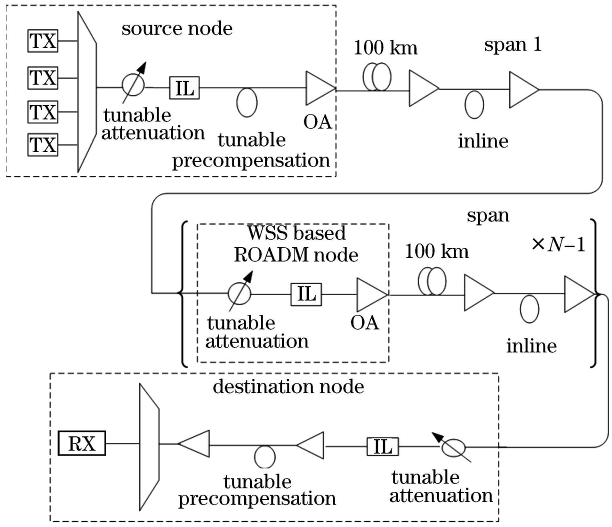


Fig. 1. QoT optimization model and constraints. IL: insertion loss; TX: transmitter; RX: receiver.

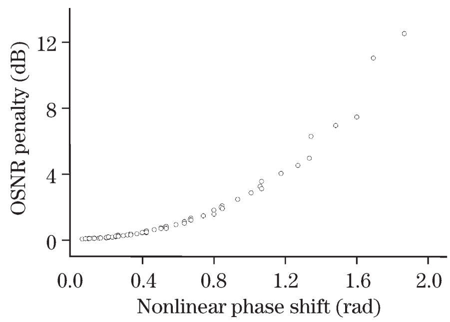


Fig. 2. Estimation of OSNR penalty.

Once the OSNR at receiver is calculated, the $Q$ factor can be estimated. The OSNR is calculated by the following functions[6].

$$\mathrm{OSNR}_{\mathrm{recv}} = -10\lg \left(10^{-\left(\frac{P_{\mathrm{in1}}+58}{10}\right)} + 10^{-\left(\frac{P_{\mathrm{in2}}-\mathrm{NF}_2+58}{10}\right)} + \cdots\right), \quad (2)$$

where $P_{\mathrm{in}}$ is the channel powers (in dBm) at the inputs of the amplifiers, and NF is the noise figure (in dB) of the amplifier. In this letter, the noise figure of each amplifier is 6 dB. Since the OSNR penalty caused by nonlinear effects and dispersion decreases while the OSNR increases as the increasing of channel power, the end-to-end QoT can be improved by power controlling.

Based on the QoT estimator above, we propose two NLP optimization schemes with different optimization targets. Recall the light path with $N+1$ nodes including source node and destination node connected by $N$ fiber spans. Given the launch power of transmitter $P_{\mathrm{tx}}=$ 1 mW. The original attenuation value of WSS for current wavelength channel at node $i$ is $V_{i,\mathrm{original}}$. The attenuation value of WSS at node $i$ after QoT optimization is $V_{i,\mathrm{opt}}$. Then the problems can be posed by the following optimization.

1) $Q$ best Scheme:

The target is to maximize $Q$ under the following constraints: $V_i \in [0, 30\ \mathrm{dB}]$, which defines the attenuation of

WSS to be limited in a special range; $-5 < P_{\text{rec}} < 0$ dBm, which defines the received power range.

All of the transitional variables such as $\text{OSNR}_{\text{recv}}$ and $P_{Q\text{ref}}(\varphi_{\text{nl}})$ can be calculated by using Eqs. (1), (2) and the quadratic polynomial derived from Fig. 2.

2) $Q$ allowable scheme:

The target is to minimize $\sum_{i=1}^{N+1} |V_{i,\text{opt}} - V_{i,\text{original}}|$, i.e., to minimize the attenuation adjustment value along the light paths. In addition to attenuation range and received power range constraints, the $Q$ factor after optimization should also be above the requirement. Thus the following constraints should be qualified: $Q \geq Q_{\text{req}}$; $V_i \in [0, 30 \text{ dB}]$; $-5 < P_{\text{rec}} < 0$ dBm.

We solved both schemes by a commercial tool LINGO[13]. Even for light path with 16 spans and 17 attenuation variables, it costs only 1 s for $Q$ best and $Q$ allowable. Compare to other online impairment aware routing and wavelength assignment (IA-RWA) which costs almost 2 s for evaluation XPM[3], the proposed QoT optimization and global impairment control method can be implemented with an online manner, to improve the QoT for each connection request under the dynamic traffic scenarios. For the original transmission, the attenuation of WSS at each node ($V_{i,\text{original}}$) is 15 dB. The randomly distributed insertion loss of all the 17 nodes is shown in Table 2. The desired $Q$ factor for the non blocking transmission is 12.6 dB (at a BER of $10^{-5}$).

The relative attenuation adjustments as a reference of original WSS states for both NLP optimizations are shown in Fig. 3. By choosing the minimized attenuation adjustment as optimization target, the $Q$ allowable scheme only tunes attenuation of three nodes (1, 7, 14), and the total adjustment of $Q$ allowable is only 2.98 dB which is much less than that of the $Q$ best scheme (50.6 dB). Moreover, the estimated $Q$ factors optimized by $Q$ best and $Q$ allowable are 16.5, and 12.6 dB, both of which reach the QoT requirement at a BER of $10^{-5}$ (12.6 dB $Q$ factor), better than that of original transmission without optimization (8.3 dB).

We also verified the effect of dynamic QoT optimization by numerical simulations using split-step Fourier method. The simulated eye diagrams of original transmission, $Q$ best and $Q$ allowable optimizations are shown in Fig. 4. For the numerical simulations, the $Q$ factors of original transmission, $Q$ best, and $Q$ allowable are 8.46, 16.9, and 12.42 dB respectively, which are very close to that of QoT estimation (8.3, 16.5, and 12.6 dB). It should be noted that although the QoT of $Q$ allowable is

**Table 2. Distribution of WSS Attenuation**

| Node | Attenuation | Node | Attenuation |
|---|---|---|---|
| 1 | 3 dB | 10 | 9 dB |
| 2 | 4 dB | 11 | 5 dB |
| 3 | 6 dB | 12 | 7 dB |
| 4 | 7 dB | 13 | 8 dB |
| 5 | 3 dB | 14 | 9 dB |
| 6 | 4 dB | 15 | 6 dB |
| 7 | 0 dB | 16 | 7 dB |
| 8 | 1 dB | 17 | 4 dB |
| 9 | 2 dB | | |

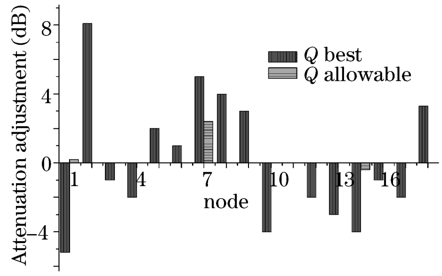


Fig. 3. WSS attenuation adjustment.

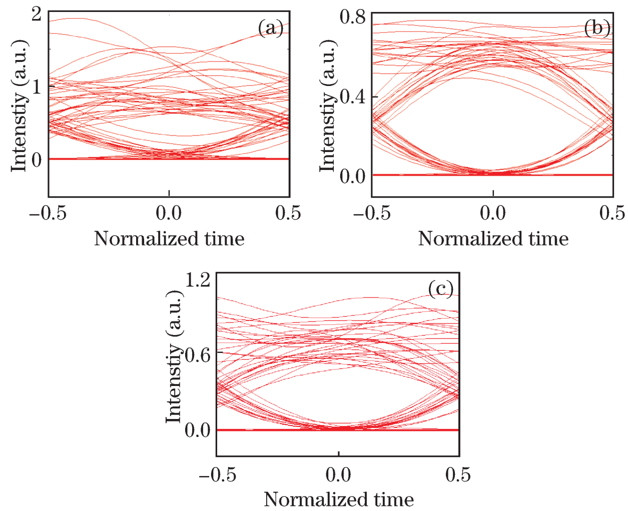


Fig. 4. Eye diagrams of (a) original transmission; (b) $Q$ best optimization; (c) $Q$ allowable optimization.

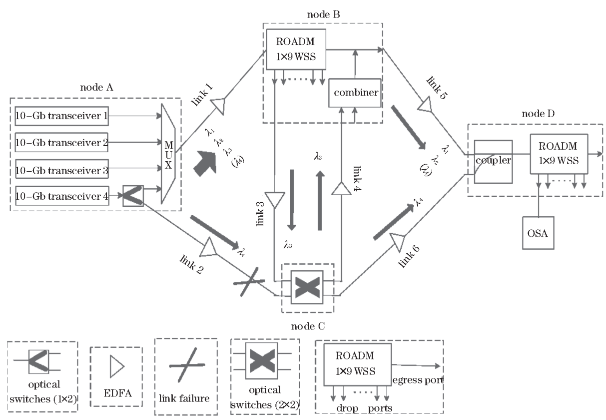


Fig. 5. Experimental setup of dynamic channel power level equalization. MUX: multiplexer.

not as good as that of $Q$ best, it achieves the minimized attenuation adjustment and improves the $Q$ factor to be above the required value. Since less tuning nodes and tuning quantity help to avoid transients and reduce time delay and network OPEXs, thus $Q$ allowable might be more applicable for dynamic reconfigurable networks, where large transients and large time delay caused by unnecessary attenuation adjustment should be avoided.

We also verified the feasibility of the proposed QoT optimization schemes by a channel power level equalization experiment on a simple mesh network, the transport plane (TP) of which is mainly comprised of two ROADM nodes based on WSS and two optical switches. The experimental setup is schematically shown in Fig. 5. Four

NRZ modulated 10-Gb/s Gigabit Ethernet (GE) channels with a 100-GHz spacing were transmitted from node A to D through different routes and finally watched by an optical spectrum analyzer (OSA) at node D. At node A, the first three channels modulated at 193.1–193.3 THz were multiplexed and transmitted by link 1, while the channel with modulation frequency at 193.4 THz was sent into a 1×2 switch. Nodes B and D were ROADM nodes consisting of two 1×9 WSSs, each of which had eight drop ports and one express port. All of the wavelengths can be assigned to each drop port and express port, with tunable attenuation value ranging from 0 to 15 dB. Node C consisted of a 2×2 optical switch. All of the four nodes were connected by short SSMF fiber spans with different attenuation. The attenuation was mainly due to different insertion loss of network elements and variable optical attenuators. At the CP level, each node run extended general multi-protocol label switch (GMPLS) protocol stacks separately.

We built the information interfaces between network elements at TP and CP protocol stacks. Through the interfaces, dynamic lightpath setup and attenuation adjustment of each wavelength can be controlled automatically by extended GMPLS stacks at the level of CP whenever the connection controller (CC) at CP receives connection requests.

When CC received the first two connection requests, two light paths carried by $\lambda_1$ and $\lambda_2$ will be set up through the route A-B-D. As for the third requests, $\lambda_3$ will be set up with the route through A-B-C-D. Then the fourth light path $\lambda_4$ will be set up through A-C-D. We recorded the optical spectrum of each wavelength at the output of node D. Since light paths with different routes experienced different attenuations, the optical power monitored by OSA will be of great differences if no power control strategy is adopted in the connection establishment (Fig. 6(a)). In the QoT optimization cases, with the knowledge of optical power information, link attenuation and tunable variables stored at the CP node, the end-to-end channel power equalization can be carried out on the fly. The optical spectrum of each light path with global power control is shown in Fig. 6(b), where the power levels of all the wavelengths are equalized. We also validated the adaptive QoT optimization in the reroute case. When link 2 failed intentionally (an extreme case that QoT cannot be satisfied), by monitoring the input optical power of $\lambda_4$ at node B, reroute operation will be triggered by CC adaptively. Then $\lambda_4$ will be restored by changing the working state of switch at node A. By optical power control, the channel power equalization can also be realized even if the routes before reroute (A-C-B-D) and after reroute (A-B-D) have different attenuations. The resulted optical spectrum of power level equalized channels after restoration is shown in Fig. 6(c). All of the operations of the light path establishment, power control, QoT monitoring and reroute were realized automatically at the level of CP, without any help of manually configuration. The experimental demonstration of channel power level equalization proves that the proposed dynamic QoT optimization and power control can be implement successfully in current reconfigurable transparent networks only with protocol and interface extensions.

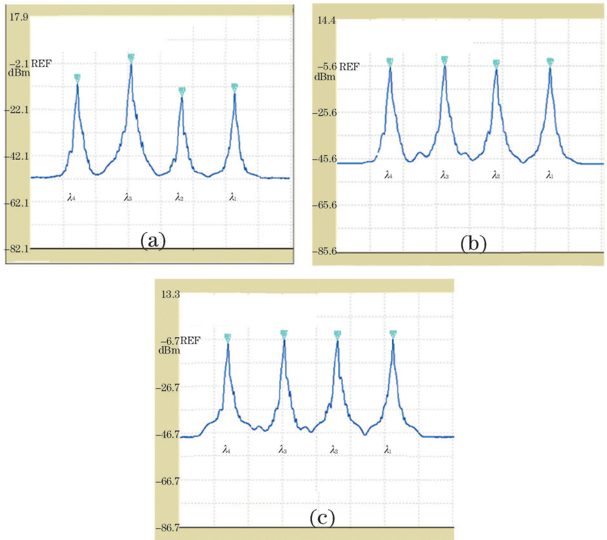


Fig. 6. Optical spectra of light paths (a) without dynamic QoT control, (b) with dynamic QoT control, and (c) adaptive QoT monitoring and reroute without QoT control.

In conclusion, we have proposed two NLP optimization schemes with explicit optimization targets by using end-to-end QoT estimation of physical impairments. The optimization results are verified by numerical simulations on a 1600-km transmission system with 17 WSS nodes. The results show that the $Q$ best scheme can reach the best $Q$ factor for the light path with large number of tuning sites and adjustment quantity, while the $Q$ allowable scheme presents much more less adjustment quantity and tuning nodes. Although the $Q$ factor of $Q$ allowable is not as high as that of $Q$ best, it still can improve the QoT to the predefined requirements. Thus $Q$ allowable may be more suitable for dynamically network scheme with fast connection requirements. We also experimentally demonstrate the idea of dynamic QoT optimization and global impairment control only with protocol and interface extensions at the level of CP.

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