Dynamic Physical Impairment-Aware Routing and Wavelength Assignment in 10/40/100 Gbps Mixed Line Rate Optical Networks

Filippos BALASIS *, Xin WANG *, Sugang XU *, and Yoshiaki TANAKA *, **
* Global Information and Telecommunication Institute, Waseda University, Japan
** Research Institute for Science and Engineering, Waseda University, Japan
fbalasis@akane.waseda.jp, xinwang@ruri.waseda.jp, xusugang@m.ieice.org, ytanaka@waseda.jp

Abstract—**The growing global Internet traffic will inevitably lead to a serious upgrade of the current optical networks' capacity. Instead of upgrading the data rate of each wavelength in every fibre link across the entire optical WDM network infrastructure, it is more efficient and cost-effective to support different data rates within one fibre link (e.g., 10, 40 and 100 Gbps). This is called optical network with mixed line rates (MLR). Moving to higher than 10Gbps data rates that can be used within the same fibre requires the implementation of phase modulation schemes. Nevertheless, the co-existing OOK channels cause a critical physical impairment to the phase modulated channels, namely cross-phase modulation (XPM), that limits the network's performance. In order to mitigate this type of impairment a more sophisticated physical impairment aware routing and wavelength assignment scheme needs to be adopted. In this paper, the critical impairment for each data rate and the way it affects quality of transmission (QoT) is presented. Secondly, QoT aware RWA schemes for a MLR optical network are presented and evaluated in terms of performance through simulations.**

Keywords—**Mixed Line Rate, Optical Network, XPM, ASE, Physical Impairment, RWA**

I. INTRODUCTION

The emergence and establishment of bandwidth intensive applications such as IPTV, cloud computing, has led to an explosive growth of the heterogeneous internet traffic. Many technologies have been proposed as candidates for the upgrade of the network's capacity and the greater utilisation of optical fibre's limited bandwidth. However, the concept of MLR optical network has recently drawn the academic community's attention due to its cost and energy efficiency [1]-[3]. Other advantages of mixing different rates within the same fibre link are the more gradual and cost-effective upgrade of the capacity and the fact that it is possible to apply into the current WDM network infrastructure without many modifications [4]. Some early experiments from Nokia Siemens and Alcatel [5],[6] have shown the industry's interest as well.

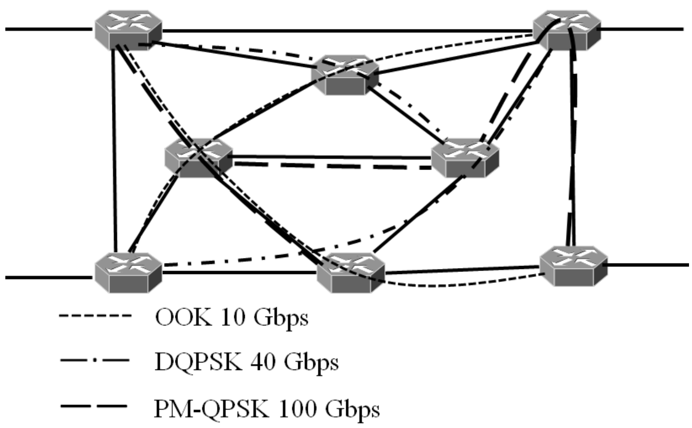

Fig. 1. A wavelength switched optical network with mixed line rates and multiple modulation formats.

Until recently, the highest data rate available in a wavelength channel was 10 Gbps achieved through on-off keying (OOK) modulation format within the standard ITU grid of 50 GHz. In order to migrate to higher data rates with the same spectral separation more advanced and spectral efficient phase modulation schemes are needed. The most promising candidates, in terms of noise resiliency, for 40 Gbps and 100 Gbps transmission have been DQPSK and PM-QPSK respectively and are the ones that are considered in our study. Fig. 1 depicts such an optical network with mixed line rate and multiple modulation formats. Nevertheless, the biggest obstacle for the realisation of a MLR optical network is XPM occurred to the xPSK channels by the adjacent 10 Gbps OOK channels. This non-linear impairment is caused by the Kerr effect [7]. The high optical intensity of the propagated OOK pulses generates oscillations in the refractive index of the

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Filippos BALASIS is with the Global Information and Telecommunication Institute, Waseda University, Tokyo, 169-0051, Japan (Tel: +81 3 3203 9450; fax: +81 3 3203 9450; e-mail: fbalasis@akane.waseda.jp).
Xin WANG is with the Global Information and Telecommunication Institute, Waseda University, Tokyo, 169-0051, Japan (Tel: +81 3 3203 9450; fax: +81 3 3203 9450; e-mail: xinwang@ruri.waseda.jp).
Sugang XU is with the Global Information and Telecommunication Institute, Waseda University, Tokyo, 169-0051, Japan. (Tel: +81 3 3203 9450; fax: +81 3 3203 9450; e-mail: xusugang@m.ieice.org).
Yoshiaki TANAKA is with the Global Information and Telecommunication Institute, Waseda University, Tokyo, 169-0051 Japan. He is also with the Research Institute for Science and Engineering, Waseda University, Tokyo, 162-0044 Japan (Tel: +81 3 3209 5210; fax: +81 3 3209 5210; e-mail: ytanaka@waseda.jp).

fibre's material. The changes of the refractive index produce a non-linear phase shift to the adjacent xPSK channels and thus increase the bit error rate at the receiver. In order to overcome this impairment that affects performance a more sophisticated physical impairment (PI) aware routing and wavelength assignment (RWA) scheme that ensures quality of transmission (QoT) is needed.

The challenge of developing a PI-aware for such non-linear impairment is not only the more complex calculation of the accumulated phase noise along the candidate path but also the calculation of the distortion caused to the already established lightpaths. To the knowledge of this paper's authors, with the exception of [8] and [9], there are not many proposals in the literature for XPM-aware provisioning of MLR optical networks. In [8], the authors consider a design of such a network in the static scenario only and they propose an algorithm that adapts the optical reach of 40Gbps channels whenever they co-propagate with 10Gbps ones. However, they apply a fixed parameter to modify the length of a fibre link regardless of the number of co-existing 10Gbps channels or their spectral separation with the 40Gbps ones and thus, they do not accurately estimate the XPM impairment. In [9], the authors consider a MLR optical network where each lightpath is set up dynamically and its QoT metrics are calculated based on analytical models. They also consider the worst case scenario for XPM impairment whenever a xPSK lightpath is established and the use of guard bands between xPSK and OOK channels. However, the overestimation of XPM impairment can cause unnecessary blocking of xPSK lightpath requests and the use of guard bands may lead to inefficient use of wavelength resources in order to secure QoT for xPSK connections.

In this paper, we study the case of dynamically set up lightpaths in a MLR optical network realised by transceivers that can be either tuned or not on a fixed data rate and modulation format. For that case, we present and compare two novel PI-aware RWA schemes that take into account the presence of XPM impairment and optimises performance and resource utilisation. The rest of this paper is organized as follows. In section II, we describe the types of impairment and their calculation method for OOK, DQPSK and PM-QPSK channels respectively. In section III, we present the concepts behind the proposed algorithms. In section IV, our methods are compared to the shortest path and minimum hop routing schemes. For the comparison, the case study via simulation and its results are shown. Finally, section V concludes this paper.

II. Physical Impairments in OOK, DQPSK and PM-QPSK Wavelength Channels

A. OOK

In optical transmission that uses OOK scheme amplified spontaneous emission noise (ASE) and chromatic dispersion (CD) are the most critical impairments. Since CD can be managed through dispersion compensation fibres (DCF), our study focuses on ASE noise only. For future work however, we intend to include other types of impairment as well, such as polarization mode dispersion (PMD) and switching crosstalk. ASE noise is due to the spontaneously emitted photons by the fibre's material. This radiation cannot be distinguished by the optical amplifier and therefore is amplified along with the propagating optical pulse and added as noise to the signal [7]. If erbium-doped fibre amplifiers (EDFA) are considered then the ASE noise power at the output of the amplifier is calculated as Eq.(1) [7]:

$$P_{\mathrm{ASE}} = 2 n_{\mathrm{sp}} h f_{\mathrm{o}} (G-1) B_{\mathrm{o}} \tag{1}$$

where n_{sp} is the spontaneous emission factor, h the Planck constant, f_{o} the frequency of the propagating signal, G the gain of the amplifier and B_{o} the optical bandwidth of the receiver. In the case of distributed amplification across the fibre links, then after N_i spans in a fibre link i the total accumulated ASE noise power is Eq.(2) [7]:

$$P_{\mathrm{ASE},i} = 2 n_{\mathrm{sp}} h f_{\mathrm{o}} N_i (G-1) B_{\mathrm{o}}\ ,\ N_i = L_i / l_{\mathrm{s}} \tag{2}$$

where L_i is the length of the link i and l_{s} the length of the span. The optical SNR is calculated as Eq.(3) [7]:

$$\mathrm{SNR_o} = P_{\mathrm{in}} / P_{\mathrm{ASE}} \tag{3}$$

where P_{in} is the average power of the optical signal that due to the distributed amplifing is considered constant. From the $\mathrm{SNR_o}$ it is possible to calculate the BER of the OOK signals by the following Eqs.(4) and (5) [7]:

$$\mathrm{BER_{OOK}} \approx \frac{1}{2}\mathrm{erfc}\left(Q/\sqrt{2}\right) \approx \frac{\exp\left(-Q^2\right)}{Q\sqrt{2\pi}} \tag{4}$$

$$Q = \frac{\mathrm{SNR_o}\sqrt{M}}{\sqrt{\mathrm{SNR_o}+1}+1} \tag{5}$$

where $M=2B_{\mathrm{o}}T$, B_{o}=50GHz the optical bandwidth of the receiver and T the symbol duration (100ps for OOK channels).

B. DQPSK

The calculation of impairment for the DQPSK channels is more rigorous since, in addition to the XPM, ASE noise also causes a non-linear phase shift to the propagating signal. Moreover, the XPM impairment induced in fibre link i by an adjacent OOK channel j depends on its power level and spectral distance. The variance of non linear phase noise caused by XPM is shown as Eq.(6) – Eq.(8) [9]:

$$\sigma_{i,j}^2 = \frac{\varphi_{i,j}^2 \tau_{i,j}}{T_j}\left\{2c_1 - c_2 \exp\left(-\frac{T}{\tau_{i,j}}\right)\right\} \tag{6}$$

$$\varphi_{i,j} = \frac{2\gamma_i P_{i,j}}{a_i},\quad \tau_{i,j} = \frac{|D_i \Delta\lambda_i|}{\alpha_i} \tag{7}$$

$$c_1 = \exp\left(-\frac{T_j}{\tau_{i,j}}\right) + \frac{T_j}{\tau_{i,j}} - 1\,, c_2 = \cosh\left(\frac{T_j}{\tau_{i,j}}\right) - 1 \quad (8)$$

where α_i , D_i and γ_i are the attenuation, dispersion parameter, and nonlinear Kerr coefficient of fibre, respectively. T_j, $\Delta\lambda_j$ and $P_{i,j}$ are the bit-time of the interfering OOK channel, its spectral separation with respect to the DQPSK channel, and its average power at the input of the fibre, respectively.

The total variance of the non-linear phase noise in a link i and a route r can be calculated with Eq.(9), (10) [9] [10]:

$$\sigma^2_{\mathrm{XPM}} = \sum_{i\in r} \sigma^2_{\mathrm{XPM},i} \quad (9)$$
$$\sigma^2_{\mathrm{XPM},i} = \sum_{j=1}^{n} \mu_j \sigma^2_{i,j} \quad (10)$$

where the parameter μ_j = 0, 1 indicates whether the OOK channel j is active or not, and n is the number of the wavelength channels of the link with OOK modulation.

The phase shift variance caused by ASE noise is calculated as Eqs.(11) and (12) [10]:

$$\sigma^2_{\mathrm{ASE}} = 1/\rho, \quad (11)$$
$$\rho = n \cdot B_{\mathrm{REF}} T \mathrm{SNR_o} \quad (12)$$

where ρ is the SNR per symbol, n=2, B_{REF} is the reference bandwidth in which OSNR is measured (12.5 GHz) and T is the symbol duration (50 ps for 40 Gbps DQPSK channels). Finally, the BER due to phase noise for a DQPSK connection is calculated as Eqs.(13) and (14) [9],[10]:

$$\mathrm{BER} = \frac{3}{8} - \frac{\rho}{4}\exp(-\rho)\sum_{m=1}^{\infty}\left[I_{\frac{m-1}{2}}\left(\frac{\rho}{2}\right) + I_{\frac{m+1}{2}}\left(\frac{\rho}{2}\right)\right] \cdot \frac{\sin\left(\frac{m\pi}{4}\right)}{m}\exp(-m^2\sigma_T^2/2) \quad (13)$$

$$\sigma_T^2 = \sigma^2_{\mathrm{XPM}} + \sigma^2_{\mathrm{ASE}} \quad (14)$$

where is I_k(x) the k-order modified Bessel function of the first kind. The BER formula can be calculated with very good approximation within a finite number of terms.

C. PM-QPSK

In PM-QPSK modulation scheme, each wavelength channel carries two orthogonally polarised QPSK modulated bit streams. Therefore, in this case the QoT model is similar to that of DQPSK. However, there are some differences that need to be taken into account. First of all, since there are two polarisations of the signal, Eq.(13) will change into Eq.(15) [9]:

$$\rho = n' \cdot B_{\mathrm{REF}} T' \mathrm{SNR_o} \quad (15)$$

where n'=1 and T'=40 ps (because the symbol rate is equal to 25 Gbaud/sec).

Additionally, in PM-QPSK transmission, not differential but coherent detection technique is used instead in the receiver. The phase estimation algorithm takes into account K previously received symbols and this affects the method the XPM phase noise variance is calculated [9]. Particularly, Eq.(6) is modified as shown in Eq.(16) [9]:

$$\sigma^2_{i,j} = \frac{\varphi^2_{i,j}\tau_{i,j}}{T_j}\left\{\frac{K+1}{K}c_1 - \frac{c_2}{K^2}\sum_{n=1}^{K} n\exp\left(-\frac{nT}{\tau_{i,j}}\right)\right\} \quad (16)$$

where K is the number of past symbols. K=6 is assumed for optimal phase detection [10]. Finally, the BER for QPSK modulation is calculated as Eq.(17) [9], [10] :

$$\mathrm{BER} = \frac{3}{8} - \frac{1}{2}\frac{\sqrt{\rho}}{\pi}\exp(-\rho)\sum_{m=1}^{\infty}\left[I_{\frac{m-1}{2}}\left(\frac{\rho}{2}\right) + I_{\frac{m+1}{2}}\left(\frac{\rho}{2}\right)\right] \cdot \frac{\sin\left(\frac{m\pi}{4}\right)}{m}\exp(-m^2\sigma_T^2/2) \quad (17)$$

III. QoT-Aware Provisioning of the Lightpaths

A. Type of Transponders and Wavelength Selection Strategy

As shown in Eqs.(6)-(8), the XPM induced phase shift depends mainly on the spectral distance and power levels of the adjacent OOK channels. Due to the complexity of defining the optimal power level, especially in a dynamic scenario, power management is left for future work. Instead, this paper is mainly focusing on provisioning the lightpaths in such way so that the xPSK channels have the maximum as possible spectral separation from the OOK channels. This requires a specific placement of the channels in the fibre's spectrum and a particular wavelength selection scheme as well. In addition to the wavelength selection strategy that will prevent the xPSK channels to entangle with the OOK channels in the fibre's spectrum, another factor that should be taken into account when planning MLR optical networks is the type of the used transponders. The transponders can be either fixed, namely, tuned on a specific wavelength and bit rate, or fully tunable where the wavelength, the bit rate and the modulation format can be configured dynamically on request. A tunable optical transponder has the obvious advantage of greater flexibility and efficiency in the usage of wavelength resources and thus, for the same traffic demands, a network with tunable transponders is expected to perform better than a network with fixed ones. In Fig. 2 the architecture of an optical add-drop multiplexer (OADM) node is shown where the optical transponders are assumed to be tunable.

Although multirate transponders have become recently available, the range of the variable bit rate is still limited and is achieved through the same modulation scheme. An optical transceiver with adaptive modulation format is needed in

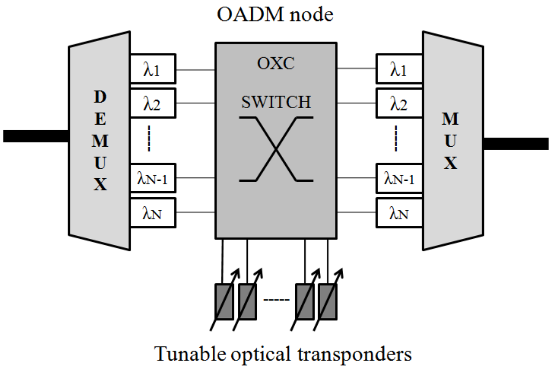

Fig. 2. A node with an optical add-drop multiplexer (OADM) and tunable optical transponders.

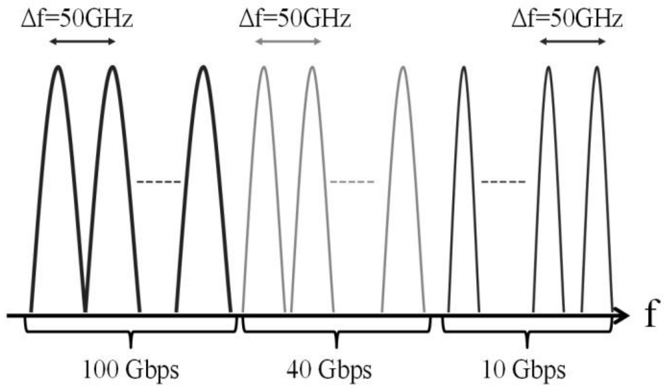

Fig. 3. Tuning of the fixed rate optical transponders in the fibre's spectrum according to their data rate.

order to scale from 10Gbps up to 100Gbps because OOK modulation is still preferred for lower data rates due to its longer optical reach and lower energy consumption [3],[11]. Currently, there are no transponders commercially available that employ different modulation formats and when they get released it is almost certain that the implementation cost will be high. Furthermore, in the case of a MLR optical network the probability of xPSK channels intermingling with OOK ones is higher and hence some wavelength channels need to be inactive in order to guarantee QoT for 40G and 100G transmission. In other words, the complexity of the QoT model increases. On the other hand, fixed rate transponders, are more affordable and more realistic in terms of implementation. In addition to their cost effectiveness, the problem of optimising the provisioning of the lightpaths is simplified. For the sake of a more complete research scope, both scenarios of a MLR network with tunable and fixed rate transponders are examined separately. Moreover, in the case where fixed rate transponders are considered, various combinations of data rates are examined.

Either way, a wavelength selection strategy that considers the XPM physical impairment can be proven quite beneficial to network's performance. In the case of a MLR network with fully tunable transponders, the first-fit (FF) for xPSK lightpaths and last-fit (LF) for OOK ones becomes the obvious optimal choice. This is so as to maximise the spectral separation among these two types of lightpaths. Furthermore, when fixed rate transponders are only available, in addition to the FF-LF strategy, a specific tuning of the transceivers is required. Particularly, the optimal placement of the wavelength channels in the fibre's spectrum is shown in Fig. 3, where the channels of the same data rate (or modulation scheme) are grouped in line. Whether there can be a fixed number of inactive wavelengths between the xPSK and the OOK channels or not, is left to the operators' judgement which will based on real world measurements. In this paper however, no guard-band is considered for the purpose of maximising spectral efficiency (e.g., the possibility of an xPSK connection next to an OOK one satisfying the BER threshold due to link's short distance). Besides the wavelength selection strategy and the tuning of the transceivers, as it is presented in the following part of this section, for the case of xPSK lightpaths, knowing in advance which wavelength is going to be assigned is required for the choice of the optimal path. This is why in our proposed method, when a connection request arrives, the FF wavelength is assigned first and then the route with the minimum XPM impairment is calculated.

B. *QoT Estimation Model*

In a MLR optical network, the provisioning of the lightpaths requires different treatment for OOK and xPSK requests respectively. For the 10 Gbps connections, the path with the shortest length or minimum number of hops remains the optimal choice, since ASE noise is the main impairment. Nevertheless, this cannot be applied to the xPSK lightpaths since besides ASE noise, XPM is a nonlinear impairment that depends on the number and spectral distance of the already existing 10Gbps lightpaths and must also be taken into account. What is more, when searching an optimal route for an OOK lightpath, it should be investigated whether its set up can lead to a serious XPM impairment to the already established xPSK lightpaths. Therefore, an efficient RWA scheme should be able to adapt on the data rate of an incoming connection request. Next, the routing methods for xPSK and OOK lightpaths are separately described and then the PI-aware schemes are presented in steps.

DQPSK and PM-QPSK Lightpaths

Regarding the xPSK lightpaths (40Gbps and 100Gbps connections), a physical impairment-aware routing and wavelength assignment algorithm is proposed to calculate the path that offers the minimum BER for a source-destination pair. To achieve this, to every link, a weight is assigned that equals to the phase noise variance of that link. Since the phase variances per link can be added linearly, as shown in Eqs.(9) and (14), it is possible, by finding the "shortest" path in terms of weights, to ensure that the least OOK congested links will be selected and that this path will offer low BER. At this point, it should be noted that, besides the XPM noise variance, the ASE induced noise variance can also be added linearly per link. If the distributed amplification through EDFA modules is considered, then for a link i the ASE phase noise variance is calculated as shown in Eq.(18):

$$\sigma^2_{\text{ASE},i} = \frac{1}{\rho} = 1/(n \cdot B_{\text{REF}} T \text{SNR}_o) = P_{\text{ASE},i} / n \cdot B_{\text{REF}} T \cdot P_{\text{in}} \quad (18)$$

where $P_{\text{ASE},i}$ is the ASE noise in link i. And as it is shown in Eq.(3) the ASE noise can be added linearly in every route. Therefore, we can define as weight W_i for every link i its total phase noise variance, Eq.(19):

$$\boldsymbol{W_i} = \sigma^2_{\text{XPM},i} + \sigma^2_{\text{ASE},i} \quad (19)$$

The benefit of this method compared to other XPM-aware RWA schemes is that it is less XPM-biased and more accurate in the estimation of QoT. To be more specific, if the avoidance of links with established OOK lightpaths is the only criterion in the lightpath provisioning, then this may lead to a miscalculation of the optimal path since the ASE induced phase noise of a much longer route can outweigh the XPM impairment of other candidate paths.

Furthermore, assuming distributed amplification across the network, we can consider the power of the optical signal to be stable. Therefore, the only parameter that changes in Eq.(6)-(8) is the one of spectral separation which has a unit of 50 GHz (ITU grid) [4]-[6]. When fixed rate transponders are used in the network the number and type of wavelengths (OOK or xPSK) supported in every link are known in advance. Therefore, it is possible for a specific xPSK wavelength, to pre-compute the XPM phase noise variance caused by every OOK wavelength independently (e.g. applying in Eq.(6) OOK wavelength j, j+1, j+2...). Then, by knowing which OOK wavelengths are currently being used in a link, the weight of that link is calculated by Eq.(10). This simplifies the procedure of finding the optimal path for an xPSK connection as well as the calculation of the distortion caused by a number of OOK lightpaths. Assuming that in a fibre link i there are m and n wavelengths carrying xPSK and OOK signals respectively and arranged as in Fig. 3, it is possible to express the above concept with the following formula Eq.(20):

$$W_i^{\text{T}} = A_i M^{\text{T}} + C^{\text{T}}_{\text{ASE},i} \quad (20)$$

where W_i is the 1xm row vector containing the weights of all xPSK wavelengths for link i, A_i is the mxn matrix that contains the phase noise variances for every combined pair between a xPSK and an OOK channel in link i, (e.g. element $a_{k,l}$ ($1 \le k \le m$, $1 \le l \le n$) is equal to the variance of the non-linear phase noise induced by OOK channel l to xPSK channel k, Eq.(9)), M is the row vector containing the μ parameter from Eq.(10) for every OOK wavelength in the link and $C_{\text{ASE},i}$ the row vector that contains all ASE induced phase noise variances for every xPSK wavelength in link i. The elements of matrix A_i and vector $C_{\text{ASE},i}$ can be pre-computed and considered constants while the elements of vector M, that show which OOK wavelengths are currently being used in the link, are the only variables that change in time.

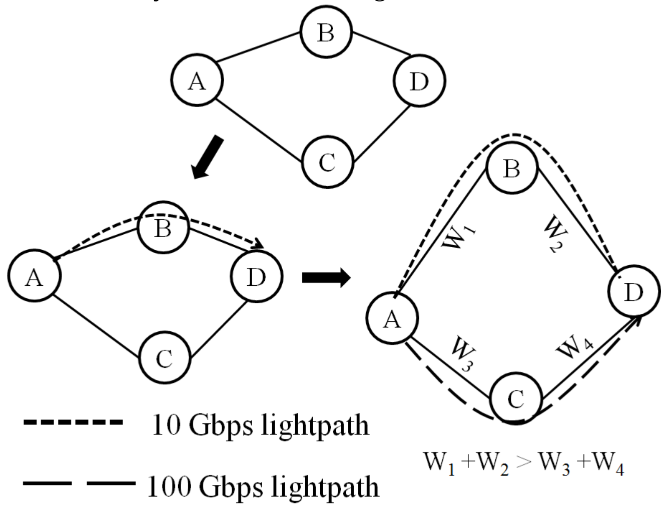

Fig. 4. When an xPSK lightpath is about to be set up, weights are applied to each link of the network's topology and their value depends on the number and spectral adjacency of the established OOK lightpaths.

When fully tunable transponders are considered, the complexity for the calculation of the phase noise variance increases along with the possible combinations of wavelengths in the available spectrum. Nevertheless, the same logic can be applied to reduce online calculation time. Assuming that there are n supported wavelengths in a fibre link, the number of possible XPM noise variances caused by one OOK lightpath is n-1. Again, by using Eq.(6) we can define the XPM noise variance caused by an OOK lightpath that is j wavelengths away as σ'^2_j, $1 \le j \le n-1$. Hence, by pre-computing all possible values of σ'^2_j the total XPM noise variance in link i for a xPSK lightpath that uses wavelength k is, Eq.(21) :

$$\sigma^2_{\text{XPM},i} = \sum_{l=1, l \neq k}^{n} m_l \cdot \sigma'^2_{|k-l|} \quad (21)$$

where index m_l={0,1} is 1 when wavelength l is used by an OOK lightpath.

A simple example of the proposed scheme can be seen in Fig. 4. When a request for a 10Gbps connection arrives between nodes A and D, the optimal path is the one with the shortest length A→B→D. Once it is established and a new 100Gbps request arrives between the same nodes, weights will be applied to the topology's links in order to find the optimal route as described above. The presence of the already established 10Gbps lightpath will result to larger weights for the route A→B→D and therefore A→C→D route is opted.

OOK Lightpaths

Regarding the 10Gbps lightpaths that make use of OOK scheme two methods can be applied: i) When a 10Gbps connection request arrives, the wavelength is assigned first according to FF-LF strategy and then the shortest path is established. ii) A route is found through the k-shortest fixed length path algorithm and then the wavelength is assigned. The first method sets as a priority the protection of xPSK lightpaths and the objective is to assign a wavelength to the OOK lightpath that is as distant as possible from the wavelengths of xPSK lightpaths. However, assigning the wavelength first might not lead to the shortest length or minimum hop route to the destination node. The second method on the other hand is more conventional and more beneficial to the QoT of OOK lightpaths but the risk of setting an OOK lightpath closer to a xPSK one is higher.

As a result, two schemes can be derived from the above analysis and their distinction lies on the way they handle the 10Gbps lightpaths: i) Minimum weight path for xPSK lightpaths and first wavelength then shortest length path for OOK lightpaths (MW-FW); ii) Minimum weight path for xPSK lightpaths and first shortest length path then wavelength assignment for OOK lihgtpaths (MW-FP). Both of the algorithms are presented in steps as follows:

MW-FW Algorithm steps

Step 1: When a new connection request arrives, select a wavelength according to the First-Fit/Last-Fit strategy described above. If no available wavelength is found then block the request;

Step 2: If a wavelength is available then select it as the candidate wavelength, and find the optimal route for this wavelength:
1) For xPSK requests a modified Dijkstra algorithm aforementioned is employed by setting a weight to each link, i.e., with the value of the phase noise variance of that link.
2) For OOK requests standard Dijkstra algorithm for shortest path calculation is employed.

The links where the candidate wavelength is already occupied, are considered to have infinite weight/length. If no route to destination is found, then go back to Step 1 to select another candidate wavelength;

Step 3: If a route to destination is found then calculate the BER. If it is below threshold:
1) For xPSK requests establish the lightpath.
2) For OOK establish only if it does not violate the QoT of already existing xPSK lightpaths.

If the BER is not satisfied or there is violation to the existing lightpaths then go to Step 1 to select another candidate wavelength;

Step 4: If a new OOK lightpath is established or released update the XPM variances and BER of the affected xPSK lightpaths.

MW-FP Algorithm steps

Step 1: When a new connection request arrives:
If it is a xPSK lightpath request go to **Step 2**
else go to **Step 3**;

Step 2: Search for an available wavelength according to First-Fit strategy. If no wavelength is found block the request else use the modified Dijkstra where the weight of each link equals the phase noise variance of that link; The links where the candidate wavelength is already occupied, are considered to have infinite weight/length. If no route to destination is found, then select the next available wavelength and repeat **Step 2** else go to **Step 4**;

Step 3: In the shortest length path to the destination search for an available wavelength with Last-Fit strategy. If no wavelength is found proceed to the next path in the list of the k-shortest length paths and repeat the procedure. If no free wavelength is found for all k-shortest paths block the request, else go to **Step 4**;

Step 4: If a route to destination is found then calculate the BER:
1) For xPSK if it is below threshold establish the lightpath, else go to **Step 2**;
2) For OOK if it is below threshold and does not violate the QoT of already existing xPSK lightpaths establish the lightpath, else go to **Step 3**;

Step 5: If a new OOK lightpath is established or released update the XPM variances and BER of the affected xPSK lightpaths.

IV. Simulation and Results

A. Optical Transponder Considerations

Depending on whether fixed wavelength-rate or fully tunable transponders are implemented in the network, there is a difference in checking availability for a wavelength or transponder when a connection request arrives. In the case of fixed transponders, in order to set a lightpath with a specific wavelength and data rate, both concerned transponders in the source and destination nodes should be available, i.e. in idle state. Therefore, when a RWA algorithm is running, a candidate wavelength is considered available if the following conditions are satisfied: i) the wavelength continuity constraint along the route is not violated; ii) the transponders that are tuned on that specific wavelength in source-destination nodes are not currently used by other lightpaths. Hence, a connection request in a fixed transponder network might be blocked because no transponder of that rate is available or there is no "matching" pair of transponders in terms of wavelength and data rate between source and destination nodes. In the case of fully tunable transponders however, the latter limitations do not exist. Between any two transponders in two different nodes, it is possible to establish a lightpath at any data rate or wavelength as long as there is no violation of wavelength continuity constraint or QoT threshold. Thus, when a RWA scheme is searching for an available

TABLE I
PARAMETER CONFIGURATION EMPLOYED IN SIMULATIONS

Parameter	Value	Parameter	Value
B_o	50 GHz	Dispersion parameter	17ps/nm/km
P_{in}	1 mW		
ASE factor n_{sp}	1.5	Span length	60 km
Amplifier gain G	10 dB	Nonlinear Kerr coefficient	2.2(W·m)$^{-1}$
Channel spacing	50GHz		
BER threshold	10^{-9}	Fiber attenuation	0.2db/km

wavelength it will start examining from one end of the spectrum (first in order for an xPSK lightpath and last in order for OOK one) and will stop when it finds a wavelength that satisfies the conditions for the lightpath establishment or reaches the other end of the spectrum and blocks the connection request..

B. Simulation Conditions

To evaluate the proposed methods we compare them with the shortest path and minimum hop routing schemes. All of them will use the same FF-LF wavelength selection strategy and the QoT metrics presented in section II to define whether the incoming request will be blocked or not. The simulations use NSF network's topology with 14 nodes and 21 bidirectional links as depicted in Fig. 5. Every fibre link supports 40 wavelengths. In the current study the length of the network's links is downsized by a factor of 10, instead of thousand kilometres per link, hundreds are considered in the simulations. As mentioned in Section III-A both scenarios of a MLR network with fixed rate as well as tunable transponders are examined separately. For a network that uses fixed rate transponders four different combinations are investigated: i) 20 OOK 10Gbps — 20 DQPSK 40Gbps wavelength channels in every link (Fig. 6) ii) 20 OOK 10Gbps — 20 PM-QPSK 100Gbps wavelengths (Fig. 7) iii) 20 OOK 10 Gbps — 10 DQPSK 40Gbps — 10 PM-QPSK 100Gbps wavelengths (Fig. 8) and iv) 14 OOK 10 Gbps — 13 DQPSK 40Gbps — 13 PM-QPSK 100Gbps wavelengths (Fig. 9). In any case, the transponders are assumed to be tuned as explained in Section II-A (Fig. 3). Moreover, the results for the MLR network with tunable transponders (scenario v) are shown in Fig. 10. For all scenarios the number of transponders in every node is assumed to be 40. The lightpath requests arrive in Poisson process and are uniformly distributed among all source-destination pairs and the available data rates. That means in the scenarios i) and ii) the probabilities of a 10Gbps lightpath request and a 40/100 Gbps request, P_{10G} P_{40G} and P_{100G} respectively, are the same and equal to 0.5. Similarly, in the scenario iii) it is P_{40G}= P_{100G}=0.25 and P_{10G}=0.5 and in scenario iv) it is P_{40G}= P_{100G}= P_{10G}≈0.33. The probability condition of requests of scenario iv) are also applied to the scenario v) where tunable transponders are assumed. The holding time of the lightpaths is exponentially distributed. Other parameters of the simulations are shown in Table 1.

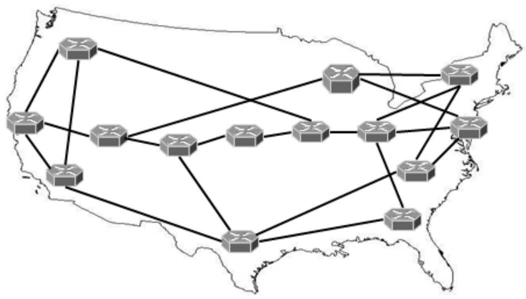

Fig. 5. NSF network topology used in the simulations.

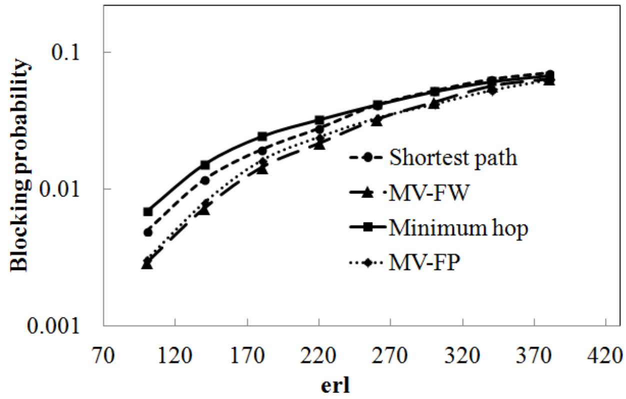

Fig. 6. Blocking Probability in the 10-40 Gbps scenario i).

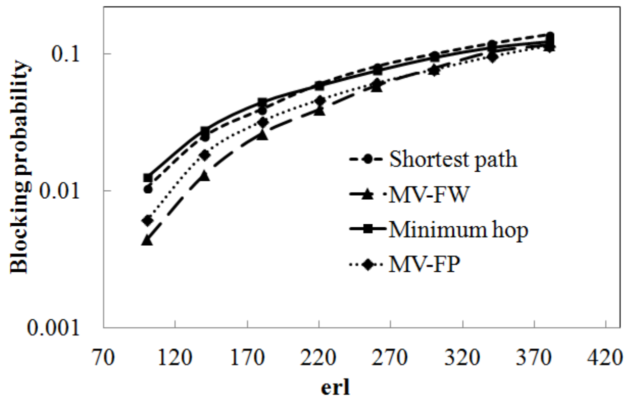

Fig. 7. Blocking probability in the 10-100 Gbps scenario ii).

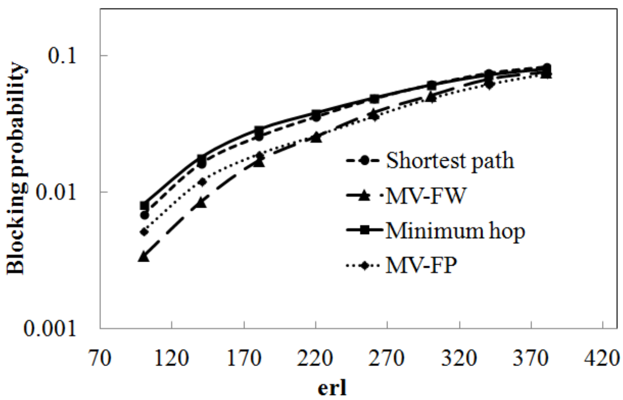

Fig. 8. Blocking probability in the 10-40-100 Gbps scenario iii).

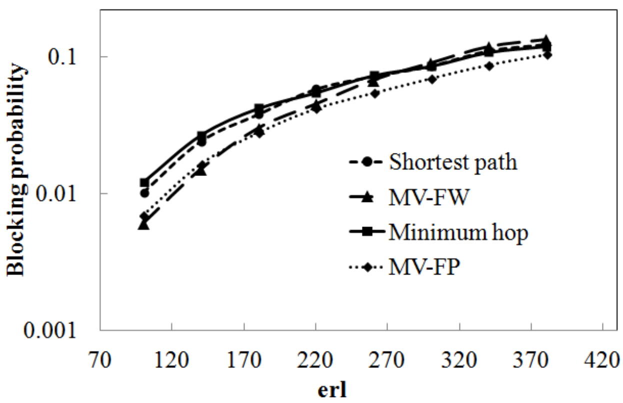

Fig. 9. Blocking probability in the 10-40-100 Gbps scenario iv).

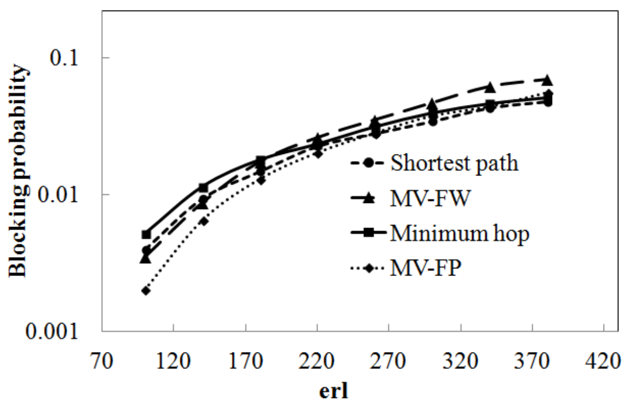

Fig. 10. Blocking probability in the 10-40-100 Gbps scenario v) with tunable transponders.

C. Simulation Results

The blocking probability performances are plotted in Figs. 6 - 10. The figures show that when networks with fixed rate transponders are considered the proposed methods offers superior performance, especially under moderate traffic load. When the traffic load increases the advantage of the proposed scheme over the compared methods diminishes. This is probably due to the fact that along as the traffic is not large, our proposed schemes assign the lightpaths by efficiently utilizing the network's available wavelengths. While under heavy traffic load, the links are heavily congested and thus XPM noise and wavelength unavailability become unavoidable. The highest blocking probability is observed in Fig. 7. That is expected since 100 Gbps lightpaths are more vulnerable to XPM and ASE noise than the 40 Gbps lightpaths in scenario i). This can be seen by their BER formulas (Eq.(13) and (17)). Moreover, the results in Figs. 6 and 8 are similar because the wavelength channels placed in the first 10 places of the spectrum (10 number of 40Gbps channels in scenario i) and 10 number of 100Gbps channels in scenario iii) are fairly protected from the OOK channels (placed 21-40) since they are separated by at least 10 wavelengths. Therefore, the main reason of blocking for these wavelengths (places 1-10) in both scenarios is ASE noise and wavelength unavailability. In total, the proposed schemes are proven to be more beneficial in terms of performance in scenarios i)–iii). In scenario iv) (as shown in Fig. 9) the benefits are minor and this can be due to the fact that OOK wavelengths are only 33% of the available resources and thus, the network resembles one that has only xPSK wavelengths and no XPM noise. In the last scenario (as shown in Fig. 10) where any wavelength supports any data rate the conventional shortest length path and minimum hop routing schemes seem to scale better than MV-FW scheme. This is could be interpreted by the fact that a network with fully tunable transponders provides greater flexibility in finding an available wavelength for a specific route and subsequently the blocking probability is lower than the previous scenarios.

Finally, it is also shown that the MV-FP scheme is the most reliable in terms of performance. This can be attributed to having a "first shortest route then last-fit wavelength" for 10 Gbps lightpaths combined with a good impairment aware strategy for 40-100Gbps lightpaths which leads to a more efficient provisioning of the connections.

V. Conclusion

In this paper, two dynamic PI-Aware RWA schemes for MLR optical networks were presented and compared. A modified Dijkstra algorithm was introduced for 40-100 Gbps lightpaths that mitigates the XPM impairment by adjacent OOK channels and outperforms conventional shortest path and minimum hop routing schemes. It is shown that, in the case of a MLR optical network, QoT based provisioning of the lightpaths can have a strong impact on the network's performance. For future work, the proposed schemes can be extended to include more types of impairment as well as different scenarios of operation such as dynamic power management and implementation of 3R regeneration.

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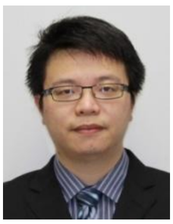
Filippos Balasis (B.E 2010) received his B.E. in electrical engineering and computer engineering from National Technical University of Athens, Greece, in 2010. Currently, he is a Master student in Global Information and Telecommunication Studies, Waseda University, Tokyo, Japan. His study emphasizes on physical impairment aware RWA schemes in translucent WDM optical networks. After fulfilling his military service he worked as an engineer in OTE, Greece's largest telecommunications provider, and he was part of the team responsible for the management and expansion of the company's access network. Mr. Balasis is a student member of IEICE.



Xin Wang (B.S. 2002–M.S. 2006) received the B.S. in computer science and engineering from Dalian University of Technology, Dalian, P.R.China, in 2002 and M.S. degree in computer science from Paris-sud 11 University, Paris, France, in 2006. Currently, he is a Ph.D student in Global Information and Telecommunication Studies, Waseda University, Tokyo, Japan. His research interests focus on planning and control issue in wavelength switched optical networks. He received the IEICE ICM English Session Award and IEICE Young Researcher's Award in 2012. Mr. Wang is a student member of IEICE.

Sugang Xu (B.E. 1994–M.E. 1997–Ph.D. 2002) received his B.E. and M.E. degrees in computer engineering from Beijing Polytechnic University, Beijing, China, in 1994 and 1997, respectively, and Ph.D. degree in information and communication engineering at the University of Tokyo, Tokyo, Japan, in 2002. He joined the Global Information and Telecommunication Institute (GITI), Waseda University in 2002, as a research associate. Since 2005, he joined National Institute of Information and Communications Technology (NICT), Japan, as an expert researcher. He is also a visiting researcher in GITI. His research interests include algorithms, network architectures, photonic network control, optical grid network systems, parallel and distributed processing. Dr. Xu is a member of IEEE and IEICE.

Yoshiaki Tanaka (B.E. 1974–M.E. 1976–Ph.D. 1979) received the B.E., M.E., and D.E. degrees in electrical engineering from the University of Tokyo, Tokyo, Japan, in 1974, 1976, and 1979, respectively. He became a staff at the Department of Electrical Engineering, the University of Tokyo, in 1979, and has been engaged in teaching and researching in the fields of telecommunication networks, switching systems, and network security. He was a guest professor at the Department of Communication Systems, Lund Institute of Technology, Sweden, from 1986 to 1987. He was also a visiting researcher at the Institute for Posts and Telecommunications Policy, from 1988 to 1991, and at the Institute for Monetary and Economic Studies, Bank of Japan, from 1994 to 1996. He is presently a professor at Global Information and Telecommunication Institute, Waseda University, and a visiting professor at National Institute of Informatics. He received the IEEE Outstanding Student Award in 1977, the Niwa Memorial Prize in 1980, the IEICE Achievements Award in 1980, the Okawa Publication Prize in 1994, the TAF Telecom System Technology Award in 1995 and in 2006, the IEICE Information Network Research Award in 1996, in 2001, in 2004, and in 2006, the IEICE Communications Society Activity Testimonial in 1997 and in 1998, the IEICE Switching System Research Award in 2001, the IEICE Best Paper Award in 2005, the IEICE Network System Research Award in 2006 and in 2008, the IEICE Communications Society Activity Award in 2008, the Commendation by Minister for Internal Affairs and Communications in 2009, the APNOMS Best Paper Award in 2009, and in 2012, and the IEICE Distinguished Achievement and Contributions Award in 2013. Professor Tanaka is a Fellow of IEICE.