Candidate Paths for Impairment-Aware PCE in 10-100 Gb/s Optical Networks

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***Abstract*—Two impairment-aware path computation element (PCE) architectures, exploiting *candidate* paths, are presented. Novel PCE protocol extension is proposed to improve path computation in multi bit-rate optical networks affected by detrimental non-linear effects among 10 Gb/s and 100 Gb/s lightpaths. The PCE architectures have been successfully experimented on a real 10-100 Gb/s testbed.**

***Index Terms*—PCE, 100 Gbit/s, multi bit-rate, WSON, XPM.**

I. Introduction

THE recent advances in optical technologies and transmission techniques are rapidly enabling the evolution of wavelength switched optical networks (WSONs) to support lightpaths operating at different bit-rates and modulation formats. Lightpaths at 10 Gb/s bit-rate with on-off keying (OOK) modulation will soon coexist in the same WSON with lightpaths operating at 100 Gb/s with dual polarization quadrature phase shift keying (DP-QPSK). In multi bit-rate WSONs, traffic dependent physical effects have to be carefully considered being more detrimental than in single bit-rate/modulation WSONs. In particular, intensity-modulated 10 Gb/s OOK lightpaths may induce a detrimental cross-phase modulation (XPM) on phase-modulated 100 Gb/s DP-QPSK lightpaths [2], [3]. However, because of the walk-off between channels, the larger the spectral distance between QPSK and OOK signals, the less detrimental the effects of XPM. These effects might significantly impact the impairment-aware routing and wavelength assignment (IA-RWA) performance and the overall network resource utilization. In [4], the path computation element (PCE) architecture is considered to address IA-RWA. In particular, a solution called *IV-candidates+RWA*, or simply *IV+RWA*, is proposed. In IV+RWA, impairment validation (IV) is first performed by an IV PCE and a set of (feasible) candidate paths is identified for the subsequent (impairment-unaware) RWA, performed by an RWA PCE. The IV+RWA architecture has been proposed to address all implementation scenarios in which a single element performing combined evaluation of both IV and RWA is not considered adequate to retrieve, store and handle a large amount of both physical and networking information (e.g., because of scalability reasons). In this study, differently from other relevant experiments on impairment-aware PCEs [5]–[7], we consider and experimentally show the performance of the IV+RWA solution applied to the case of multi bit-rate 10-100 Gb/s WSON. Then, differently from [1], we propose an *enhanced* IV+RWA PCE architecture (EIV+RWA) capable of improving the IV+RWA PCE path computation performance thanks to a novel lightweight PCE protocol (PCEP) extension.

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II. IV+RWA PCE Implementations

A. Impairment validation tools

The two considered IV+RWA and EIV+RWA implementations exploit the same set of IV tools to estimate bit error rate (BER) of either 10 Gb/s OOK or 100 Gb/s DP-QPSK. The tools and related equations are detailed in [3]. The IV tool for 10 Gb/s OOK implements an OSNR-based model accounting for amplified spontaneous emission (ASE), chromatic dispersion (CD), first-order polarization mode dispersion (PMD), and self phase modulation (SPM) through non-linear phase shift ϕ_{NL}. Effects of CD and ϕ_{NL} are computed as penalty to the OSNR. Then, BER is derived from the final OSNR [3]. The IV tool for 100 Gb/s DP-QPSK with coherent detection accounts for ASE, SPM, and XPM, and estimates BER through the Gaussian approximation in [3]. In the case of 100 Gb/s, CD and PMD are not considered since coherent detection enables an electronic post processing which compensates the effects of dispersion. XPM is particularly detrimental (thus, accounted for) on 100 Gb/s lightpaths if induced by 10 Gb/s lightpaths [3]. The IV tool for 100 Gb/s considers XPM in two ways: in the *worst-case scenario* or with *guard band (GB)* [3]. The worst-case scenario for 100 Gb/s occurs when the central wavelength is occupied by the 100 Gb/s lightpath surrounded by 10 Gb/s lightpaths. If a 100 Gb/s lightpath has acceptable BER in the worst-case scenario, its BER is acceptable with any traffic condition and any wavelength along the path is *admitted* (i.e., it can be selected since it guarantees the BER requirements). Alternatively, 10 and 100 Gb/s lightpaths can be spectrally separated by GB, where GB is defined as the number of free wavelengths guaranteeing a negligible XPM in any path. In this case, only a subset of wavelengths along these paths is *admitted*, i.e. guaranteeing a spectral separation of GB among 10 and 100 Gb/s lightpaths. The adoption of worst-case scenario or GB depends on the considered PCE architecture implementation, as described in the following.

B. PCE Architecture implementations

The first considered IV+RWA implementation follows the basic indications provided in [4]. The connection request generated by a path computation client (PCC) is handled by

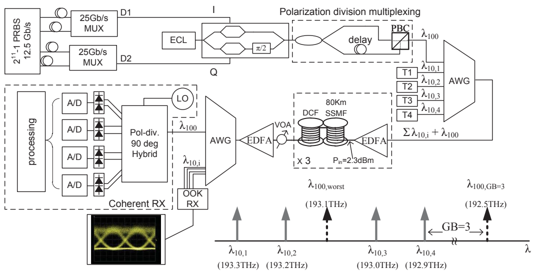

Fig. 1. Experimental testbed.

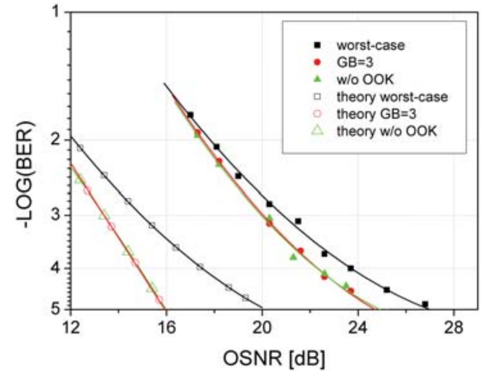

Fig. 2. BER vs. OSNR of the 100 Gb/s lightpath.

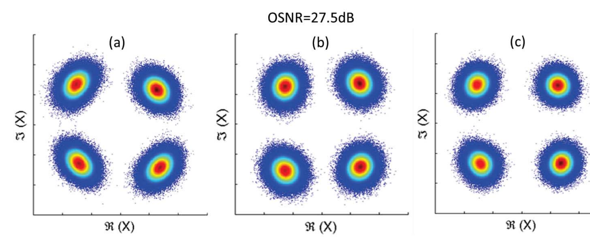

Fig. 3. Symbol constellation of a single 100 Gb/s DP-QPSK polarization: (a) in the worst-case scenario; (b) in the absence of OOK channels; (c) in the presence of OOK channels with GB=3.

the RWA PCE which forwards the PCEP `PCReq` message to the IV PCE. Such message includes, besides end-points and requested bit-rate, a `candidate` object specifying the number K of expected validated paths. The IV PCE runs impairment estimation tools on the basis of the physical information included in its traffic engineering database (TED) (e.g., provided and maintained by the network management system). IV PCE computes the set of feasible candidate paths, i.e. having acceptable BER ($\mathrm{BER} < \mathrm{BER}_{\mathrm{TH}}$). Since RWA is unknown at this stage, any wavelength has to guarantee acceptable BER, i.e. any available wavelength needs to be *admitted*. To this purpose, XPM due to 10 Gb/s is considered for 100 Gb/s only in the worst-case scenario. The set of computed candidate paths (i.e., the list of up to K explicit route objects – `ERO`s) is provided to RWA PCE within the PCEP `PCRep` message. The RWA PCE performs RWA on the basis of the network information (including detailed link wavelength availability) stored and dynamically updated in its TED. In our implementation we apply a typical RWA: first-fit WA on the least loaded (validated) path. The selected `ERO` and wavelength is finally returned to the requesting PCC through a PCEP `PCRep` message. If no path and wavelength is found, the request is rejected.

The second considered EIV+RWA implementation is derived from the previous IV+RWA. As in IV+RWA, a `PCReq` message is received by the IV PCE including end-points, bit-rate and `candidate` objects. Then, differently from the previous case, the `PCRep` message is extended with a novel optional object, called `GB` (here used for 100 Gb/s requests), to be possibly associated to each one of the returned paths. This object specifies the GB that needs to be accounted, among 100 and 10 Gb/s lightpaths, during RWA (if a path is acceptable in the worst-case scenario, GB is 0 and the `GB` object is omitted, otherwise `GB` is included). In this way, also paths not guaranteeing acceptable BER with the worst-case approach (but feasible with GB) can be considered for connection set up. The RWA PCE finally selects the least loaded path. To limit the usage of GB, 100 Gb/s lightpaths with GB indication are packed on neighbor wavelengths and last-fit WA is applied to those lightpaths, while first-fit to the others.

III. Experimental Demonstration

The two considered IV+RWA and EIV+RWA have been evaluated on the multi bit-rate testbed in Fig. 1 and through emulations on the network topology in [3]. The testbed implements DP-QPSK 100 Gb/s signal generation through a tunable external cavity laser (ECL) with a line width of about 100 KHz, modulated using an integrated LiNbO3 double nested Mach Zehender modulator. A 50 Gb/s QPSK optical signal is obtained by driving the in-phase (I) and the quadrature (Q) modulator branches with two 25 Gb/s pseudo random bit sequences (PRBS) of length $2^{11}-1$ (D1,D2). D1 and D2 are generated with a differential delay of 10 bit periods by properly multiplexing four 12.5 Gb/s PRBS. Finally, 100 Gb/s DP-QPSK transmission is obtained by emulating polarization multiplexing through a $50/50$ beam splitter, a delay line, and a polarization beam combiner (PBC) (Fig. 1). The 10 Gb/s OOK signals are generated by four transponders (T_i) at $\lambda_{10,i}$ (i=1,2,3,4). A 100 GHz spaced array waveguide grating (AWG) is used as multiplexer for the 10 Gb/s OOK and 100 Gb/s DP-QPSK signals. The link consists of three spans of 80 km standard single-mode fiber, each one followed by a dispersion compensating fiber. Finally, channels are dropped and received (coherent detection with digital post processing as in [8] is used for the 100 Gb/s). To show the impact of XPM in the testbed, the BER performance of the 100 Gb/s lightpath, depicted in Fig. 2, has been evaluated by varying the received OSNR. In a first experiment, the 100 Gb/s signal wavelength was set considering the worst-case scenario ($\lambda_{100,\mathrm{WORST}}$ in Fig. 1). In a second experiment, GB=3 is considered among the OOK and the DP-QPSK signals ($\lambda_{100,\mathrm{GB}}$). In a third experiment, with $\lambda_{100,\mathrm{WORST}}$, OOK signals were switched off. By comparing the measured BER obtained with GB=3 and OOK switched off, the experimental results confirm that (at least) three channels guarantee negligible XPM on 100 Gb/s DP-QPSK due to OOK signals. 8 dB penalty is the difference between experimental and theoretical performance, which is mainly due to front-end imperfections and narrow filtering from the receiver, while the error floors at high OSNR are due to electronic noise. Finally, XPM in the worst-case scenario corresponds to an OSNR penalty of about 1.5 dB at a BER

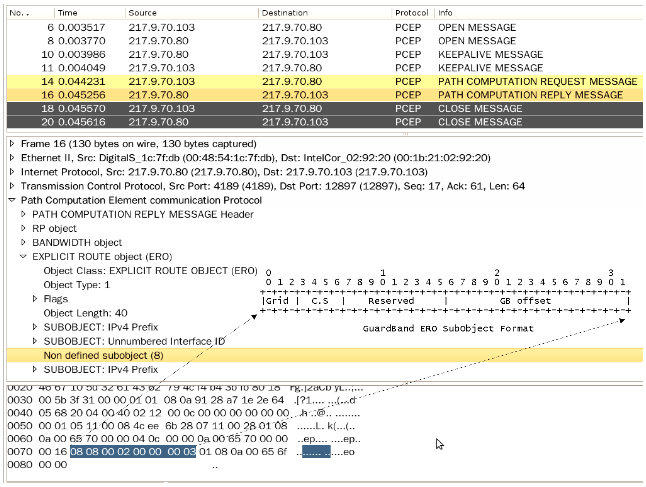

Fig. 4. PCEP capture.

of 10^{-3}. The effects of XPM on the 100 Gb/s signal are also visible in Fig. 3, which shows the received symbol constellation on a single polarization of the 100 Gb/s DP-QPSK in the presence and in the absence of the OOK signals. For each transmitted symbol, the corresponding distribution of the received samples has a circular symmetry in the absence of OOK channels in Fig. 3(b) or when GB=3 in Fig. 3(c), as expected for an additive white Gaussian noise channel, while it is bent around the origin in Fig. 3(a) due to XPM.

In the experimental demonstration, a 100 Gb/s request has been submitted to the PCE. Fig. 4 shows a capture of the PCEP messages exchanged between the IV PCE and the RWA PCE, both implemented in C++, when the PCE implementation is EIV+RWA. The IV PCE applies the IV tools considering also the experimental value of 8 dB penalty for the QoT estimation of 100 Gb/s lightpath. The PCEP session is first established through the initial handshake including `Open` and `Keepalive` messages (packets 6-11), then a PCEP `Request` is sent to the IV PCE (packet 14). In the considered case, the physical link operates at the OSNR value of 20.5 dB and $\mathrm{BER}_{\mathrm{TH}}=10^{-3}$. The PCE identifies as unacceptable the path in the worst-case scenario but as acceptable with GB=3 (i.e., 3.2 nm). The PCEP `Reply` (packet 16) includes the `ERO` and the `GB` object. The IV PCE path computation and validation time is about 200 μs. Also, a simulated Pan-European WSON [3] has been enforced within the PCE TED to assess the performance of the proposed PCE implementations in terms of computation time and number of exploited paths. The considered WSON, designed for 10 Gb/s, includes 17 nodes, 33 bi-directional links, 40 wavelengths, and physical parameters as in the testbed. Considering just the 10 Gb/s single bit-rate, XPM effects are negligible, and IV+RWA and EIV+RWA provide the same results. Indeed, they practically operate on the same set of paths (e.g., the set of feasible shortest paths in terms of hops is $P_{s,d}$, $|P_{s,d}| = 496$). Then, in the same WSON, a 10-100 Gb/s multi bit-rate scenario is considered. In this case, IV+RWA and EIV+RWA provide different results for 100 Gb/s since they consider different sets of paths. Tab. I shows that the set of candidate paths provided by IV+RWA corresponds to the 24% of $P_{s,d}$ for 100 Gb/s, while to 37% by EIV+RWA. Moreover, the exploitation of GB=3 does not negatively impact the average wavelength

TABLE I
PERCENTAGE OF ACCEPTABLE PATHS UTILIZED FOR ROUTING AND UTILIZED WAVELENGTHS PER LINK (@500 ERLANG)

	IV+RWA	EIV+RWA
acceptable paths	24.1%	37.5%
utilized wavelengths per link	25%	30%

utilization (shown for 500 Erlang considering Poisson traffic with uniform distribution of source-destination pairs and bit-rate requests), which is larger in the case of EIV+RWA with respect to IV+RWA, when 10 Gb/s lightpaths are active in the network. A slightly higher number of wavelengths is used with EIV+RWA than with IV+RWA since more paths are exploited with GB. With EIV+RWA, the maximum time experienced to communicate, for a single request, the `ERO` to the RWA PCE is 3.2 ms, including 2.3 ms for the EIV computation of K=6 candidate paths and the communication time for the PCEP message exchange (one `PCReq` and one `PCRep` with 6 `ERO`s, including 2 `ERO`s with the `GB` object). With IV+RWA on the same node pair, the time experienced to get the `ERO` at the RWA PCE is 2.7 ms, including 1.9 ms for the IV computation (one `PCReq` and one `PCRep` with just 4 `ERO`s).

IV. CONCLUSIONS

Two impairment-aware PCE architectures of type IV-candidates+RWA are presented for multi bit-rate 10-100 Gb/s WSON, where XPM is particularly a detrimental effect. Experimental results are provided to show their performance in terms of percentage of exploited paths and path delivery time. Computation and communication times result to be extremely fast (up to few milliseconds) for both transmission rates. A novel PCEP extension is also proposed to improve the overall effectiveness in network performance by enabling the usage of a larger set of candidate paths without significantly increasing the delivery time. In the long term, the proposed extension could also be exploited against the XPM induced by newly introduced lightpaths (e.g., at 400 Gb/s) using quadrature amplitude modulation (QAM), which exhibits both intensity and phase modulation.

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