Plug and play optical nodes: network functionalities and built-in fiber characterization techniques

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Plug and play optical (PPO) nodes may be used to facilitate the deployment of optical networks. PPO nodes must be able to learn about the signal propagation properties of the surrounding optical fibers and make their wavelength-routing decisions based on the collected data. We discuss what are the open challenges that must be overcome to provide optical networking solutions based on cost-effective PPO nodes. Three possible PPO node hardware architectures with trade-offs in complexity, cost, and functionality are presented along with their built-in fiber characterization techniques. © 2007 Optical Society of America

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1. Introduction

The latest advances in optics demonstrate that today's technologies have the potential to enable end-to-end user communications in the gigabit transmission range [1–3]. Advantages of wavelength-routed networks include the possibility to benefit from a higher degree of transparency by setting up end-to-end optical circuits, or *lightpaths* [4]. Higher transparency, in turn, reduces the amount of electronic processing that is required in the network and provides a cost-effective way to support high volumes of traffic, e.g., by reducing the number of required transceivers/transponders [5–7]. However, the deployment of optical networks is mainly delayed by two factors: the excessive cost of optical nodes and the highly complex procedures for the design, installation, and maintenance of the overall network.

The high cost of an optical node is partially due to the small-scale production and the lack of integrated solutions at this time. Meanwhile, the network design complexity originates from the fact that a large number of measurements must be taken in the laboratory to make sure that the network planning phase is correctly carried out by trained engineers. These measurements mainly relate to the quality of the optical signals, e.g., optical signal-to-noise ratio (OSNR) and signal waveform distortion, during their propagation across the fibers and the optical nodes. In conventional (first-generation) optical networks, the signal propagation is limited within two physically adjacent nodes, which greatly limits the number of measurements that need to be performed. However, in transparent (second-generation) optical networks with a large number of nodes, the network installation may be complex, because many in-service measurements are required to verify the proper installation of the equipment. Another factor adding to the network complexity is network management: a continuous monitoring of the optical signal quality must be performed to detect malfunctions, and, where possible, to anticipate element failures. In addition to the above burdens, the entire process must be repeated whenever an upgrade is needed in the network, as newly added nodes may affect existing nodes and the way optical circuits are established.

To circumvent the complex and costly design of extant optical networks, we propose to investigate an unconventional approach. The enabling component of the proposed

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approach is a cost-effective, self-configurable plug and play optical (PPO) node. A PPO node consists of (i) an optical cross-connect for optical circuit switching, (ii) a miniature optical transmission laboratory (minilab) module for signal quality monitoring and processing, and (iii) a (low-rate) service channel interface for network management and control. Once plugged into the network and with the help of the minilab module, the PPO node automatically learns about the optical propagation properties of its neighboring fibers and nodes. It then offers on-demand optical circuit switching capabilities to its connected client nodes, e.g., routers.

With the envisioned PPO node functionalities, design, installation, and management of fiber-based optical networks will be simple due to the PPO nodes' built-in capabilities of topology autodiscovery, node self-configuration, and fiber parameters monitoring. There is no need for complex network planning, nor is a team of engineers required in the field to check correct installation of equipment and to monitor network functions. These tasks will be automatically performed by the PPO nodes in a cooperative manner, by using the measured fiber parameters and the on-board signal processing features.

If the PPO node approach is proven to be feasible, the network operational costs are going to be considerably reduced: i.e., minimal training is required to install, operate, and maintain the PPO nodes. In addition, PPO node enabled networks come with the ability to increase the (client) router connectivity thanks to the transport and transparency service they enable at the optical layer. In turn, this translates into a reduction of the capital investment, i.e., fewer routers and/or smaller packet forwarding engines may suffice to support the applications. In summary, PPO nodes may be easily deployed to create wavelength-routed networks in access/metro, local, and possibly even wide areas. Such networks are able to self-maintain, configure, protect, and recover from failures with minimal human intervention.

The paper depicts the potentialities, functionalities, and open challenges envisioned for the PPO node enabled networks, or PPO networks. It describes three key modules in the PPO network: the PPO network management and control module, the client network management and control module, and the PPO node on-board minilab. It then discusses three alternative solutions for the minilab module and analyzes their trade-off between complexity and capabilities.

2. Envisioned PPO Network Scenario

The envisioned PPO network scenario is based on the assumption that a few years from now, end users will have access to low-cost, high-speed interfaces offering transmission rates in the gigabit range. Whether these interfaces are gigabit Ethernet cards and/or next-generation last mile passive optical networks, the amount of traffic handled by the access/metro portion of the network is expected to grow significantly. Routers and transport solutions in the access/metro network will require frequent upgrades to keep up with the traffic growth, significantly augmenting the network capital and operational costs.

The PPO nodes have the potential to contain some of these costs by offering a simple way to deploy optical transport capabilities over the (dark) fibers already existing in the access/metro. A large number of PPO nodes could be deployed to create optical topologies on demand. Once connected, each PPO node would cooperate with the already existing nodes and make efficient use of the available optical resources, such as lit fibers and wavelengths to provide high speed optical circuits to the connected clients. In a more remote future (e.g., 20–50 years from now), advances in the field of integrated optics may further lower the PPO node cost, possibly making it a key player even in "the last mile" portion of the network.

An example of the envisioned optical fiber network is shown in Fig. 1. In the figure, only a subset of PPO nodes is connected to electronic client nodes. An end user may request the creation of a lightpath for transmitting data directly to another end user (single-hop transmission). Alternatively, an end user may request a lightpath to reach a preferred router. With the latter option, the router performs electronic forwarding of the received packets toward the intended final destinations (multihop transmission). Additionally, the router can statistically multiplex connections from multiple users on a single lightpath. Routers too can request lightpaths to be created to reach other routers or desired end users. With all these lightpath creation alternatives, a tech-

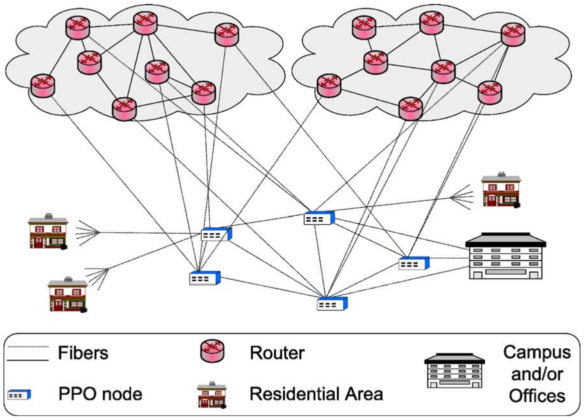

Fig. 1. PPO node and network concept.

nique similar to the one used by modem technology is envisioned, in which a lightpath (the equivalent of the phone circuit) is requested, and the transmission rate is selected based on the channel quality.

In the PPO network, a distributed and automatic procedure determines: (1) which client must connect to which client and (2) which route, wavelength, and transmission rate ought to be used to achieve good performance, e.g., minimize network congestion and blocking of user connection requests. Due to the large number of optical circuit alternatives provided by the PPO nodes and the numerous phenomena affecting the quality of the optical circuits, chromatic dispersion and polarization mode dispersion (PMD) to mention a few, the resulting optimization problem is much more complex than the one already solved for the modem technology. A dedicated (low-speed) service channel is used to implement the user-to-network interface (UNI) between the clients (e.g., routers) and the PPO network. Viable options for the UNI that are already available in today's control plane technologie, include generalized multiprotocol label switching [8] and automatically switched optical network [9]. The PPO network may act as the server for various clients besides routers and end users. For example, gigabit passive optical network, synchronous optical network/synchronous digital hierarchy, Ethernet, frame relay, and asynchronous transfer mode are all possible higher layer solutions that may run on the lightpaths provided by the PPO nodes at the optical layer.

Upon request, PPO nodes must be able to provide clients with lightpaths that may span across multiple PPO nodes. Due to the network status and various transmission impairments it might not be always possible to connect two clients with a lightpath at the desired transmission rate. An exhaustive trial-and-error approach is not practical here as the number of possible lightpath alternatives grows exponentially with the number of PPO nodes, client nodes, and wavelengths. For this reason, the PPO node must be equipped with the processing capability to solve accurate models of the fiber transmission impairment to predict *a priori* the quality of any given lightpath [10], as well as the effects that multiple lightpaths, sharing the same fiber on spectrally adjacent wavelengths, may have on the quality of the optical signals. Predicted transmission rates can then be verified *a posteriori* using the minilab available at the PPO nodes once the lightpath is created, thus providing feedback for model corrections and tune up. The result of this transmission analysis performed at the PPO node indicates which clients can be connected, and which transmission rates can be used without significant signal degradation of the lightpath under consideration and of the spectrally adjacent lightpaths.

Based on the transmission analysis results, each PPO node can identify its own *optical transparency island*, defined as the subset of PPO nodes that can be reached all-optically from that PPO node [10,11]. Notice that an optical transparency island is individually defined for each PPO node and may partially overlap with the transparency island of other PPO nodes. The island's size is strongly dependent on the transmission rate considered (Fig. 2) and it might vary over time due to changes of physical parameters (e.g., temperature) and distribution of the existing lightpaths. The PPO node can detect and react to such changes by processing the measurements produced

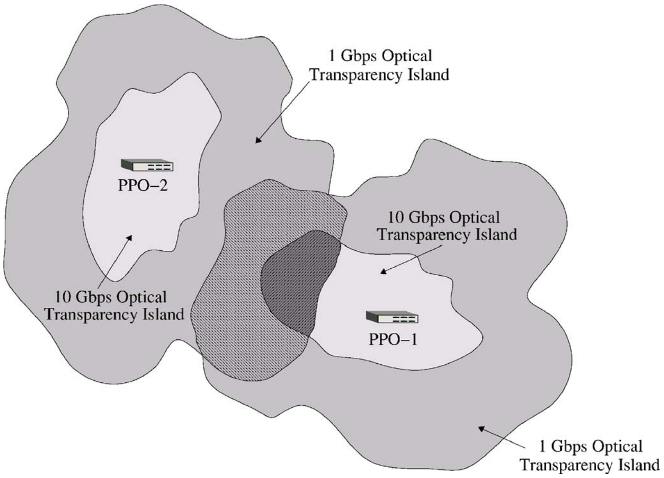

Fig. 2. Optical transparency island.

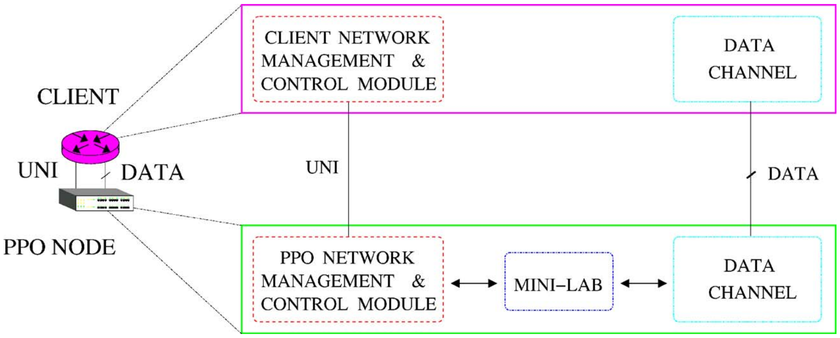

Fig. 3. PPO node and client modules.

by the on-board minilab. Three key modules that are required to carry out the PPO network distributed and automatic procedures are described next.

3. Three Key Modules in the PPO Network

As already indicated, the three key modules of the PPO network are: (i) the PPO network (server layer) management and control module, (ii) the client network management and control module, and (iii) the on-board minilab module. These three modules are connected as shown in Fig. 3. A description of their functionalities is provided next.

3.A. PPO Network Management and Control Module

This module is responsible for:

- setting up, tearing down, and reconfiguring lightpaths to fulfill client requests;
- advertising and autodiscovering of available resources within the optical transparency island;
- predicting the effect of transmission impairments using real-time transmission models, e.g., determining if a lightpath is feasible, at what transmission rates, and the impact it would have on the already existing lightpaths;
- monitoring the status of the network, e.g., detecting optical signal degradation of existing lightpaths, possibly malfunctioning client interfaces, changes in the transmission parameter values.

Management and control signaling is carried over low-speed service channels on a dedicated control wavelength (e.g., at 1.3 μm outside the amplifier window). Both PPO nodes and routers exchange control information over the service channels, whose transmission rate may be limited (compared with data channels) to reduce cost.

Due to the nature of the PPO network, scalability of the control plane to handle hundreds of PPO nodes is of paramount importance. Scalability may be enabled by leveraging the optical transparency island concept. For example, link state advertisement messages generated by a PPO node (e.g., in the form of IP packets) may be naturally constrained within the PPO node's optical transparency island, by the management and control protocol. The amount of flooding is thus reduced, without affecting the PPO node ability to compute the best path to reach any other PPO node within its own transparency island. Notice that although the PPO node's optical transparency island is similar to the concept of autonomous system in IP networks, it has some significant differences, e.g., the transparency island may change over time, must be automatically computed by the PPO node, and each PPO node may have its own optical transparency island that partially overlaps with other PPO nodes'.

With the exchange of link state advertisement messages, each PPO node maintains two distinct local databases. The first database is used to keep track of available resources within its own optical transparency island and to self-discover newly added/removed resources, e.g., newly plugged PPO nodes. The second database keeps track of both the measurements made by the minilab, both locally and at remote PPO nodes, and the (*a priori*) results acquired by running the real-time transmission models. In certain instances, it may be convenient to create temporary dummy lightpaths between PPO nodes to test transmission impairments, e.g., generate the (*a posteriori*) dispersion map, and provide more accurate estimates of the optical signal quality. Both databases can be updated using extensions of the OSPF-TE protocol [12].

Upon receiving a request for a lightpath, the PPO node solves the routing and wavelength assignment (RWA) problem [13–15] by using both its local databases. In addition to solving the conventional RWA problem, the PPO node must determine a set of physical parameters that characterize the profile of the requested lightpath, e.g., range of acceptable transmitted power, transmission rate, maximum acceptable wavelength drift, etc. Transmission models are used by the PPO node to ensure that the profile of the newly created lightpath conforms to the client request, without negatively impacting the already created lightpaths in the network. Then, during the lifetime of the lightpath, the PPO node monitors the signal received from the client to ensure that it meets the assigned profile. In the case of violation, the PPO node could, for example, send a disconnect message and release the network resources to be used for other lightpath requests.

3.B. Client Network Management and Control Module

This module is responsible for handling end-to-end traffic flows at the client (electronic) layer. For the sake of a concise description, it is assumed that the client layer consists of routers. Routers handle client packets electronically and can operate at a much finer multiplexing granularity than the wavelength granularity of a lightpath. For example, multiprotocol label switching [16,17] may be used to provide traffic engineering at this layer.

Between client nodes, control messages are exchanged using inband signaling, i.e., routers exchange control messages using the available logical links. Notice that, logical links at the electronic layer may correspond to lightpaths in the optical layer (Fig. 4). Being clients, routers communicate with the underlying PPO nodes through the dedicated UNI. Using both the UNI and inband signaling, each router maintains two routing tables. The first one (T1) keeps track of the currently available resources, i.e., logical links, using extensions of standard IGP protocols [18], such as OSPF-TE [19]. The second routing table (T2) keeps track of the potential logical links (lightpaths not yet set up) that could be set up by the PPO nodes (Fig. 4) upon the routers' request. T2 may be updated using two different techniques, both requiring the use of the UNI. With the first technique, the PPO node provides the router with the list of routers that can be reached within the optical transparency island. The information collected in this way is then advertised to other routers using inband signaling over already existing lightpaths. The second technique makes use of dummy lightpaths that are created periodically by the PPO nodes to measure the transmission parameters of the optical layer. While a dummy lightpath is set up, the routers at the end of the dummy lightpath may exchange control messages and update table T2. The two techniques may coexist.

With the envisioned PPO network architecture, a client node, say router R1, has different options to choose from when it attempts to establish a data flow with another client. It may use the already existing lightpaths, i.e., using routing table T1

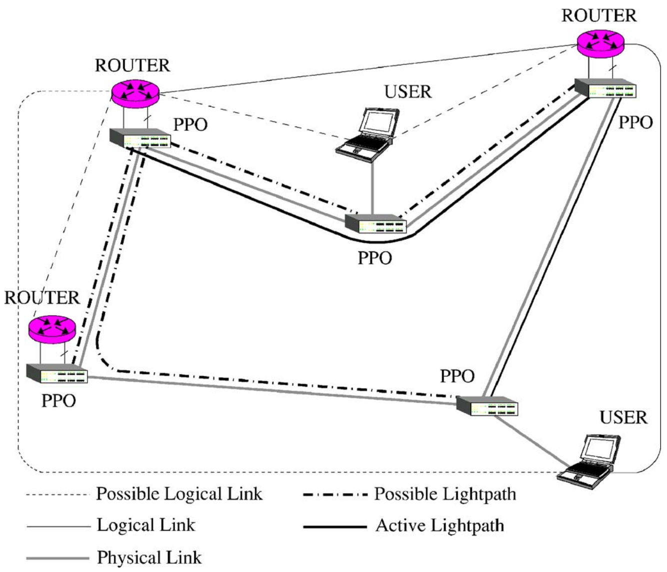

Fig. 4. Logical links and potential logical links.

to reach the destination, or create new lightpath(s) using routing table T2. In the latter case, R1 must request the underlying PPO node to create a lightpath to reach the intended destination client. If the PPO node determines that the required connection is possible within its optical transparency island, the new lightpath is created. If the requested lightpath cannot be set up, or its allowed transmission rate is not sufficient, R1 must select an intermediate router, say R2, which is within reach of the PPO node optical transparency island. R2 repeats the same procedure as R1. The multihopping procedure is repeated until the client destination node is reached.

With the above routing strategies, routers are provided with unconventional techniques to handle congestion, in addition to the conventional congestion avoidance procedure, e.g., random early discard strategy. For example, the router can request the underlying PPO node to increase the bandwidth on the outgoing logical links (lightpaths). The PPO node may fulfill the router request by either increasing, if possible, the transmission rate of the already existing outgoing lightpaths or creating additional lightpaths. An alternative solution available to a congested router is to reduce the traffic coming from the upstream neighboring routers by requesting them (via inband signaling) to create new lightpaths that bypass the congested router.

3.C. PPO Node On-Board Minilab Module

The on-board minilab is a unique module of the PPO node. Groups of PPO nodes may jointly perform coordinated measurements by using their respective minilabs in a distributed manner. By processing the measurements produced by the minilab module the PPO node may (frequently) update its local information about the optical physical layer. As already mentioned, this information is crucial for the correct operation of the PPO network management and control.

The minilab module assists the PPO node in accomplishing a number of tasks. For example, a newly plugged PPO node must gather information about the surrounding fiber parameter values. Already plugged PPO nodes continuously gather fiber transmission parameter values to detect critical changes, e.g., deterioration of the optical signal due to fiber damage. Another task is to monitor the optical signal quality when newly requested lightpaths are set up and the network is in operation. All these measurements are then used by the PPO network management and control module to reoptimize existing lightpaths and optimally set up additional ones.

The minilab module requires simplicity of configuration and easy integration of its components. On the other hand, to self-determine the network connectivity and transmission characteristics, this module needs to provide sufficient functionalities at a limited cost. In Section 4, the trade-off between the minilab module complexity and the offered functionalities is discussed considering three possible architectures.

4. Three Possible Solutions for the Minilab Module

This section discusses three alternative hardware configurations for the minilab module and their built-in techniques to characterize linear and nonlinear properties of the PPO node input/output optical fibers. The principle is to measure and collect various fiber parameter values that are then used to perform on-board fast analytical evaluation of the optical signal quality.

For cost effectiveness, the complexity of a PPO node needs to be consistent with the data rate the system is carrying. In low-speed optical systems with data rates lower than 2.5 Gbits/s, fiber nonlinearity and PMD may not be significant concerns and, therefore, a low-cost PPO node may be sufficient. On the other hand, in high-speed optical systems (10 Gbits/s or higher), nonlinearity and PMD are important concerns, and more sophisticated PPO nodes may have to be designed for that reason.

4.A. Basic Configuration for Low-Speed Networks

The basic hardware configuration for the minilab module is shown in Fig. 5. Each outgoing wavelength channel is paired with a low-cost light-emitting diode (LED). The optical power of each LED is regulated, and each output wavelength channel is modulated using a low-speed (kilobit per second) data stream. The modulated data stream carries the output power level information and both the PPO node and the channel identification information.

Each incoming wavelength channel is connected to a photodiode. The photodiode converts the incoming optical signal into the electrical domain. The converted signal is then processed to retrieve the channel identification information, the identification of the connected PPO node, and the optical power level of the transmitter. The optical loss (or gain) of the fiber can then be estimated by comparing the power level of the emitter with the average optical power received. Optionally, a PPO node may be equipped with a global positioning system used to specify the geographical location of the PPO node. This information may be useful, for example, to estimate the signal propagation delay.

This basic configuration represents a low-cost minilab solution, which enables PPO nodes to discover adjacencies and estimate the optical signal loss of each optical fiber link. This configuration is ideal for networks operating at low data rates. High-speed networks may require additional information on the optical fiber links, e.g., OSNR, chromatic dispersion and PMD, which cannot be estimated by this basic configuration.

4.B. Configuration for Linear Impairment Measurements

To measure fiber chromatic dispersion, wavelength-dependent propagation delay must be evaluated by the PPO node. This can be achieved using a wideband superluminescent LED (SLED) as the light source and a tunable optical filter at the receiver.

Commercially available SLEDs are able to guarantee 50 nm (or more) of spectral width at 10 dBm (or more) of optical power. Depending on both the number of transmitters required at the PPO node and the cost of a SLED, possible PPO node hardware configurations may include: (i) one SLED at each transmitter or (ii) one SLED at each PPO node. In the latter solution, the SLED is combined with an optical switch to deliver power to different output fibers in a round-robin fashion. Figure 6 shows an example of the hardware configuration of a PPO node with one SLED and an optical switch. Using this architecture, a PPO node is able to accomplish a number of fiber characterization functionalities.

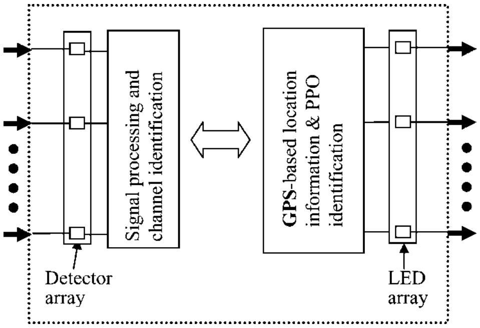

Fig. 5. Minilab hardware configuration using LEDs.

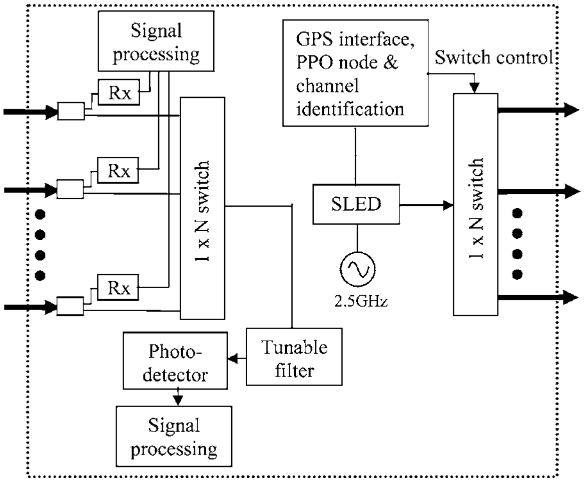

Fig. 6. Minilab hardware configuration using SLEDs.

To transmit the PPO node and channel identification, node location, and output power level, the SLED signal is modulated by an electrical signal and sent to the output fiber, as already described for the basic configuration in Subsection 4.A. In the receiver part of the PPO node, a low-cost and low-speed receiver at the input fiber interface suffices to detect and decode the incoming optical signal and to measure its average optical power level. These are the same functionalities provided by the basic PPO node configuration. In addition, the combination of the SLED and a tunable optical filter enables an additional set of functionalities, i.e., the measurement of the fiber chromatic dispersion and the evaluation of the OSNR when optical amplifiers are in place.

To characterize the fiber chromatic dispersion, the signal from the SLED is modulated by a sinusoidal wave. The chromatic dispersion of the fiber creates a differential group delay, causing the different wavelength components of the SLED spectrum to propagate at different speeds. At the receiver, the relative phase delay of the modulating sinusoidal signal can be detected by varying the wavelength selected by the tunable optical filter. Chromatic dispersion of the optical fiber can then be evaluated using conventional techniques. For example, the accumulated dispersion of the fiber link can be evaluated as

$$D(\lambda)L=\frac{\mathrm{d}(\Delta\tau_g(\lambda))}{\mathrm{d}\lambda}=\frac{1}{360^\circ f_m}\frac{\mathrm{d}\phi(\lambda)}{\mathrm{d}\lambda}, \tag{1}$$

where $\Delta\tau_g(\lambda)$ is the differential time delay, $\phi(\lambda)$ is the phase delay as the function of the wavelength, and f_m is the modulation frequency. Because of the periodic nature of this differential phase delay method, high modulation frequency will result in a small measurable chromatic dispersion while low modulation frequency will reduce the measurement accuracy. Here two different modulation frequencies may be required to work over a large range of frequencies, while maintaining good accuracy. When the lightpaths are set up and carry data traffic, the tunable optical filter may also be used as an optical spectrum analyzer, thus allowing the real-time monitoring of the channel OSNR. With this configuration, the PPO node is not able to measure nonlinear impairments and PMD of the optical fiber.

4.C. Configuration for Linear and Nonlinear Impairment Measurements

To estimate the nonlinearity and PMD of the optical fibers, an advanced hardware configuration of the minilab module is required. The configuration is shown in Fig. 7 and makes use of a tunable laser diode shared by the transmitter and the receiver, by means of a 1×2 switch. Coherent detection is used to estimate chromatic dispersion, nonlinearity, and PMD of the fiber pair between two PPO nodes. Depending on the state of the optical switch, the tunable laser can be used as either a transmitter or a local oscillator to achieve coherent detection at the receiver.

The PPO node identification and power level information are modulated into the optical signal and sent to the receiving part of the PPO node at the other end of the

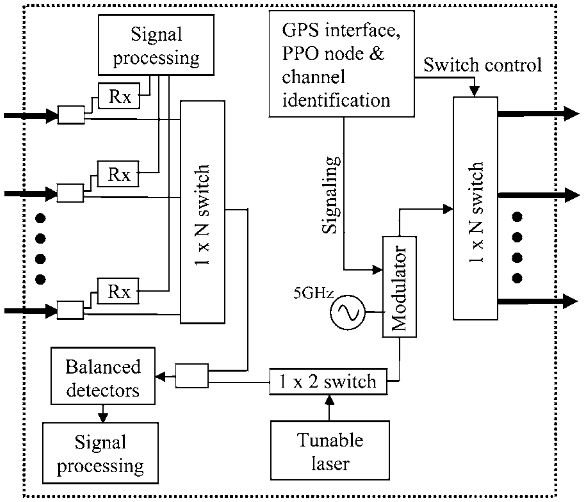

Fig. 7. Minilab hardware configuration using a tunable laser.

fiber link. To measure the fiber parameter values, a linearly swept radio frequency source is used to drive the modulator. The frequency response of the system represented by a fiber, or fiber system, can then be measured by the coherent detection optical receiver. Synchronization is not required for the measurement as the modulation frequency can be found at the receiver by evaluating the modulation sidebands with the local oscillator performing coherent spectrum analysis.

The normalized frequency response of a fiber system can be expressed as [20]:

$$H(f) \propto \cos\left(\frac{\pi\lambda_0^2 D f^2 L}{c} - \tan^{-1}(b)\right). \tag{2}$$

In Eq. (2), D represents the chromatic dispersion, L represents the fiber length, c represents the speed of light, λ_0 represents the wavelength, and $b=b_L+b_N$ is defined as an equivalent chirp parameter. Parameter b_L represents a linear chirp, which can be created by the optical modulator, while $b_N=\pm 2\gamma P/\alpha$ is a nonlinear chirp, which is caused by the fiber nonlinear coefficient γ, the attenuation coefficient α, and the signal optical power P. The ± option in b_N denotes the sign of fiber chromatic dispersion.

Figure 8 shows an example of measured frequency response in a dispersion compensating fiber (DCF). Note that the response notches move to lower frequencies when the input optical power is increased. The measurement of the dependency of the fiber system frequency response on the optical signal power can then be used to evaluate the nonlinearity of the fiber system as follows.

When the optical signal power is small enough, the frequency response of the fiber system is a function of the accumulated chromatic dispersion. Parameters b_L and D can then be expressed as

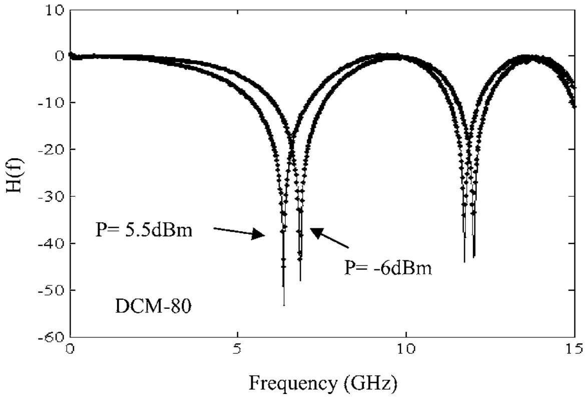

Fig. 8. Example of transfer function in a system with a dispersion compensating module (DCM-80).

$$b_L = \tan\left(\frac{\pi\nu_{0,l}^2}{\nu_{1,l}^2 - \nu_{0,l}^2} \mp \frac{\pi}{2}\right), \tag{3}$$

$$D = \frac{c}{L\lambda^2(\nu_{1,l}^2 - \nu_{0,l}^2)}, \tag{4}$$

respectively, where $\nu_{0,l}$ and $\nu_{1,l}$ are the 0th and the first order of the notch frequencies in the linear system. Therefore, the dispersion of the fiber system can be precisely evaluated. By increasing the signal optical power, the frequency response of the fiber system is modified compared with the linear condition, according to the fiber nonlinear parameter value. The first notch moves to $\nu_{0,f}$. Once the frequency shift is measured, the nonlinear chirp parameter can be found as

$$b_N = \frac{(1 + b_L^2)\tan(u)}{1 - b_L \tan(u)}, \tag{5}$$

where

$$u = \pi\left(\frac{\nu_{0,f}^2 - \nu_{0,l}^2}{\nu_{1,l}^2 - \nu_{0,l}^2}\right). \tag{6}$$

Figure 9 shows the measured value of b_N using both a standard single-mode fiber (SMF) (squares) and a DCF (circles) as a function of the signal power. The solid curves represent the calculated values when using the following parameter values: $L = 75.74$ km, $\alpha = 0.21$ dB/km, $D = 15.614$ ps/nm/km, and $\gamma = 1.2974\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$ for the SMF, and $L = 14.19$ km, $\alpha = 0.47$ dB/km, $D = -92.636$ ps/nm/km, and $\gamma = 3.534\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$ for the DCF. The values of dispersion, length, and attenuation are independently verified via an optical time-domain reflectometer (OTDR). In a system with N optical fiber spans, the nonlinear chirp effect has to be weighted by the dispersion of each span. The effective nonlinear chirp parameter can then be expressed as [21]:

$$b_N \approx \frac{2}{\sum_{i=1}^{N} D_i L_i} \sum_{i=1}^{N} \frac{\gamma_i P_i}{\alpha_i}\left(\sum_{k=i}^{N} D_k L_k\right). \tag{7}$$

Using the measurements on both linear and nonlinear parameter values, real-time modeling of the fiber link can be used to estimate the link performance at various data rates. This information is essential for identifying the lightpaths that can be successfully set up.

In addition, when lightpaths are set up and data traffic is being carried, the same coherent detection monitoring configuration may be used to perform *in situ* monitoring of the fiber link or lightpath performance, e.g., the variation of OSNR and PMD. In particular, to evaluate PMD, the coherent detection receiver in the minilab module

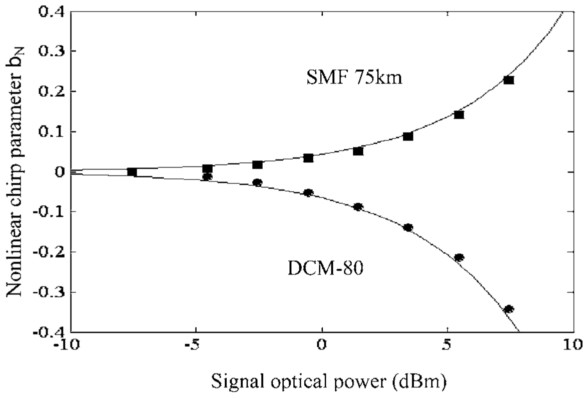

Fig. 9. Nonlinear chirp parameter b_N versus signal optical power for DCM-80 and a 75 km SMF.

downconverts the optical spectrum of the data channel to the radio frequency domain. Two different frequency components are then selected by bandpass radio frequency filters, and their relative polarization walk-off can be analyzed, which predicts the differential group delay (DGD) of the fiber system [22].

Although a PPO node is designed to collect as much information as possible about the physical (optical) layer characteristics of the network, the capability of a PPO node is limited by constraints on the cost and complexity. There will always be some system impairments that are not measured by the PPO node, e.g., the linear cross talk between WDM channels due to imperfect filtering in optical receivers and switches. If these impairments are not so critical, they may be taken into account as second-order factors for network performance optimization once the traffic streams are turned on.

5. Conclusion

The paper introduced the concept of self-configuring plug and play optical (PPO) nodes and discussed the potential impact that they may have on future network functionalities. Three possible solutions were proposed to realize the on-board minilab module, which enables the PPO node to self-characterize the optical properties of the neighboring fiber links.

If proven feasible, the PPO node enabled network will represent a self-configuring solution that continuously determines an efficient way to employ (optical) network resources throughout the lifetime of the network, i.e., (1) it determines the most cost-effective solution by using all-optical transmission and/or opto-electro-optic conversion (OEO) (through routers) at selected nodes on a per-flow basis, (2) it provides dynamic bandwidth provisioning that adjusts to traffic changes, i.e., as traffic patterns change, the network can set up new lightpaths, and tear down old ones, thus avoiding the problem of burning wavelengths (fixed reservation of wavelengths), (3) as new PPO nodes and fibers are added to the network, it discovers them automatically, without requiring the manual redesign of the network—similar to today's "plug and play" network nodes in LAN technology, (4) it provides timely monitoring of the signal quality on the optical circuit to inform the network management and control module, (5) it provides built-in optical signal processing methods to predict and monitor the performance of the optical circuits in the network. The self-configuration capability of the PPO node enabled network makes it possible to reduce the network design, installation, and maintenance costs, because no human intervention is required to perform complex tasks.

The success of the PPO node deployment highly depends on the possibility to build high performance, compact, and easy-to-install PPO nodes. Several are the open challenges that remain to be addressed when pursuing the PPO node concept. Self-handling of optical transmission impairment requires innovative approaches and protocols [12,23,24] that cannot be found in today's commercial solutions. Another challenge is represented by the fact that all-optical networks have been studied for more than a decade, and yet commercially viable solutions have not been found. Although optical/radio frequency signal-processing methods to predict and monitor fiber link performance have been proposed and demonstrated, optoelectronic integration will be necessary in the future to realize on-board low-cost minilab measurement modules. Once available, the measurement modules will require standardized interfaces.

Finally, it is interesting to note that some similarities exist between the proposed PPO node enabled fiber networks and the dynamic nature of *ad hoc* wireless networks. Numerous PPO nodes can be deployed as needed, and connected to existing fiber cables. A client/user interface may migrate physically from one PPO node to another. A client/user interface may migrate logically from one router to another, thus creating a new adjacency in the routing tables, by simply requesting a new lightpath. All these unknowns, combined with the complexity of handling optical signal quality at high transmission rates, constitute a set of challenging open problems that must be tackled.

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