OPTIMISATION OF PHYSICAL LAYER PARAMETERS FOR AN ALL-OPTICAL NETWORK TESTBED

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ABSTRACT

The capacity and high flexibility potentials of all-optical networks (AONs) have already been realized. While keeping the signal in the optical domain, an AON is limited by performance degrading effects. Therefore, the link budget has to take into account both noise and distortion related impairments. In this paper a simulation environment is used to analyse wavelength division multiplexing (WDM) transmission links at the physical layer of an AON testbed. The primary focus of the numerical modelling was the characterisation of signal degradation levels, link power budget and end-to-end physical connection for a typical metro environment. For the required end-to-end performance ($Q \geq 7.5\, dB$), the reachable transmission distance at both 2.5 Gbps and 10 Gbps data rate is investigated. The simulation results show that it is feasible to implement an AON connecting several research facilities in the same city. The outcome was applied to provide technical options for those facilities to connect together. The users can choose from two options: using directly a modulated laser at 2.5 Gbps or an external modulator at 10 Gbps, based on their bandwidth demands, cost constraints, and the distance to the access point. The results presented in this paper are also applicable for more general cases.

Key words

Wavelength division multiplexing (WDM), physical layer, end-to-end lightpath, numerical simulation, signal impairments, bit-error rate.

I. Introduction

Along with the growth of bandwidth demands, all-optical networks (AONs) using wavelength-division multiplexing (WDM) techniques became more attractive recently because they provide tremendous capacity for data transport links at effective costs. Furthermore, AONs present a cost-efficient way of managing bits via wavelength routing and bandwidth provisioning without converting optical signals into the electrical domain [1].

However, while AONs offer numerous advantages, they are also subject to some constraints. To guarantee an overall quality of service (QoS) for network users, the most important thing is to maintain the end-to-end quality of transmitted signals, i.e. guarantee a low bit error ratio (BER) or equivalent high Q-factor. Thus an AON design and optimization must take into account both noise and distortion impairments [2], especially when the channel speed goes to 10 Gbps and above. Upon such impairments, the signal quality degradation accumulates along the transmission path. Although signal regeneration (optical and/or electrical) can boost the signal quality, it is costly, and should therefore be avoided in optical network design and planning. Furthermore the amount of degradation is diversified while the optical signals experience various paths. Therefore, transmission path provisioning in the physical layer is critical to achieve the advantages of AONs.

This work presents a research project involving the investigation of parameter optimization for end-to-end lightpath provisioning at the physical layer through an AON testbed. The simulation environment is used to analyze the WDM physical layer transmission links for the testbed. The primary focus of numerical modelling is the characterization of signal degradation levels, link budget and end-to-end physical connection in a typical metro environment. The simulation outcome and optimization are applied to provide various options for connecting research facilities within a 60-km distance. The overall performance of the WDM system is also characterized by the BER and Q-factor.

This paper is organized into sections. The design specification of the testbed is listed based on the required overall network functionality (Section 2), and optimization of system and component parameters (Section 3). It is followed by the analyses of the numerical results, discussion of their applicability and conclusions regarding the potential real network application (Section 4). Prospective work is also outlined.

II. System specification

The testbed design requires the AON functionality to be implemented involving key building blocks for an all-optical end-to-end WDM network [3][4]. These key building blocks include: photonic cross-connect (PXC), multiplexer (MUX), de-multiplexer (Demux), transmitter,

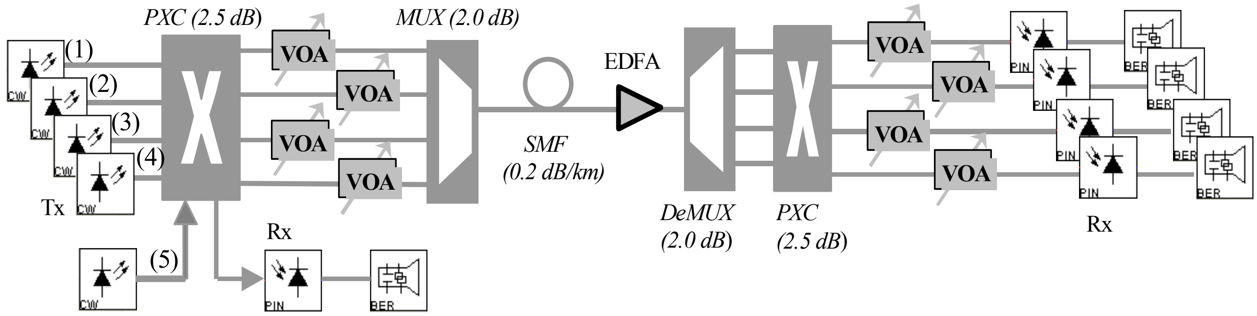


Figure 1. Node and link configuration in Optical Network Lab (ONL) facilities

receiver, and optical amplifier [6]. The requirements for the testbed are as follows,

- Overall system performance: $BER \le 10^{-12}$, i.e. $Q \ge 7.5\ dB$.
- Transmission distance: 10 – 100 km, typical for metro WDM applications,
- 4 bi-directional channels at either 2.5 or 10 Gbps/channel,
- 200 GHz channel spacing,
- AON functionality in place (signal transmission, transport, photonic switching with add/drop channels, end-to-end transmissions, amplification, system control and signal reception),
- No signal regeneration along the transmission stage, no impairment compensation/control.

The node and link configuration of the testbed is shown in Figure 1 [7]. It has 4 WDM channels in addition to a pair of add/drop channels. At the transmitters, the source signals (pseudo-random bit sequences) are modulated at either 2.5 Gbps or 10 Gbps by directly modulated lasers (DML) or external modulators (Mach-Zehnder) respectively. The modulated signals pass through a PXC with a pair of add/drop channels, and then they are multiplexed and coupled into a standard single-mode fibre (with loss of 0.2 dB/km [8]). The output power of the transmitter is –3 dBm. Such a low power level can avoid penalties introduced by fibre non-linearity. Finally the signals are de-multiplexed and pass through another PXC before they are detected with PIN receivers. The receiver sensitivity is –17 dBm. Optical power ripple generated at an earlier stage in the network can be equalized by variable optical attenuators (VOA) before the multiplexer and receivers respectively. An optical amplifier is optional in the testbed, e.g. an erbium doped fibre amplifier (EDFA) with the gain of 10-dB and noise figure of 6.0 dB. The testbed specifications are summarised in table 1.

The PXCs in our testbed are based on micro electro-mechanical system (MEMS) technology to provide strictly non-blocking photonic switching of fibre-optic traffic. The operational wavelength ranges of our 8×8 PXC are 1290-1330 nm (1.3-µm band), 1530-1570 nm (C-band) and 1570-1610 nm (L-band). The switching time is less than 12 ms and the crosstalk below -50 dB. These optical switches provide dynamic switching by using customer developed control software running on control workstations. The control can be either centralized or distributed. A control workstation is connected to the switch via an RS-232C interface. Such configuration demonstrates the dynamic wavelength switching.

Table 1. Summary of Testbed Specification

Data rate per channel	(1) 2.5 Gbps using DML
	(2) 10 Gbps using EML
Channel spacing	200 GHz
Tx output power	-3 dBm
PXC insertion loss	2.5 dB
Mux/Dem insertion loss	2.0 dB
Receiver sensitivity	-17 dBm
Extinction ratio of EML	10 dB
EDFA noise figure	6.0 dB
Fibre loss	0.2 dB/km

In the transmission stage, optical signals inevitably suffer from impairments that lead to system performance degradation. There are two groups of signal impairments: noise- and distortion-based. The noise includes amplifier spontaneous emission (ASE), receiver noise (shot-, thermal-, etc.), laser noise, etc. The primary sources of distortion are fibre and component chromatic dispersion, polarisation mode dispersion, non-linearity such as self-phase modulation, cross-phase modulation, four wave mixing, laser frequency chirp, filter concatenation, crosstalk, etc. These noise and distortion effects on system performance, including causes, behaviours and remedies, have been extensively studied in the literatures, e.g. [2][9]. In a typical metro environment, such effects of signal impairments (both noise and distortion) for the 2.5 Gbps/channel with 200 GHz channel spacing WDM networks (4 channels) are quite small and could be negligible. The same conclusion also holds for 10 Gbps under the same constraints if the external modulators (with higher costs than a DML) are deployed. The simulation results also validate the above conclusion. Thus there is no need of impairment compensation or control for our testbed. Note that the DML is not considered for 10 Gbps channel speed in our work due to the well-known chirping effects, although it is more cost-efficient than an EML.

Therefore, the primary roles of numerical modelling are set as finding the reachable distance under given low-cost devices, investigating the overall system performance of the testbed, and providing some options for connecting 4 optical research facilities within a 60-km distance.

III. Numerical optimisation and discussion

In this section, the overall system performance of the testbed is evaluated by Q-factors (equivalent to BER). To accomplish the tasks of the testbed mentioned above, 4 simulation scenarios are setup as follows,

(1) Using directly modulated lasers (DML) as transmitters at 2.5 Gbps channel speed, without any optical amplifier,
(2) Using DML transmitters at 2.5 Gbps channel speed, with an optical amplifier (an EDFA, gain of 10 dB),
(3) Using external modulators (EML) as transmitters at 10 Gbps channel speed, without an optical amplifier,
(4) Using EML transmitters at 10 Gbps channel speed, with an optical amplifier (an EDFA, gain of 10 dB).

For each of the above four scenarios, the relationship between system performance (Q-factor) and transmission distance is numerically analyzed and thus the transmission distance is optimized under the given parameters of the low-cost commercial available components. Then the critical transmission distances while keeping an acceptable overall system performance ($Q \geq 7.5\ dB$) are determined from these analyses. Furthermore, the end-to-end performances of each WDM channel under different scenarios are compared. The simulation results are applied to help providing technical options for connecting four research facilities within a 60 km distance into an AON.

In the simulation channel 3 is the cut-through channel (dropped) and the corresponding Q-factor is therefore not simulated. The Q-factors of all other 4 WDM channels are to be analyzed.

3.1 Critical transmission distance

Figure 2 shows the relationship between the end-to-end Q-factors of each WDM channel and the transmission distance under all four scenarios described before. From Figures 2(a) and 2(b), to satisfy the end-to-end performance requirement, $Q \geq 7.5\ dB$, the critical distance for a DML at the data rate of 2.5 Gbps is around 32 km and 70 km, without and with an optical amplifier (an EDFA, gain of 10 dB) respectively.

While the channel speed going up to 10 Gbps and still satisfying the end-to-end performance requirement, $Q \geq 7.5\ dB$, the DML is not suitable due to the laser chirping. Instead the EML is deployed and the critical transmission distance can be determined in Figures 2(c) and (d), i.e. 42 km and 87 km for not using and using an optical amplifier respectively.

All critical distances are obtained from the worst channel in the corresponding scenario. The numerical simulations are based on the specifications listed in Table 1. The results of critical transmission distance are summarized in Table 2.

Table 2. Summary of Critical Transmission Distance

Modulator	Speed	EDFA	Critical Distance
DML	2.5 Gbps	N/A	32 km
DML	2.5 Gbps	10 dB	70 km
EML	10 Gbps	N/A	42 km
EML	10 Gbps	10 dB	87 km

3.2 Performance comparison of different scenarios

The end-to-end performances under four scenarios described above are compared for typical WDM channels. In Figure 3(a) the Q-factor of a typical channel (channel 2) is compared between using a DML at 2.5 Gbps channel speed and using an EML at 10 Gbps. The comparison is investigated when no optical amplifier is used. Figure 3 shows that the critical distance for EML at 10 Gbps is about 10 km more than DML, with a Q-factor of 7.5 dB. Additionally, at the critical distance for either DML or EML, the Q-factor for EML at 10 Gbps is about 3 dB better than DML at 2.5 Gbps.

Figure 3(b) shows the comparison of the same typical channel (channel 2), while using an optical amplifier, an EDFA with a 10 dB gain. All other conditions are the same as in Figure 3(a). The difference of critical distance between DML and EML is about 17 km, with a Q-factor of 7.5dB. At the critical distance for either DML or EML transmitters, the Q-factor in the case using an EML at 10 Gbps is at least 3 dB better than in the case using a DML at 2.5 Gbps.

The comparison among other channels under the conditions of both Figures 3(a) and (b) are very similar to the results presented in the picture.

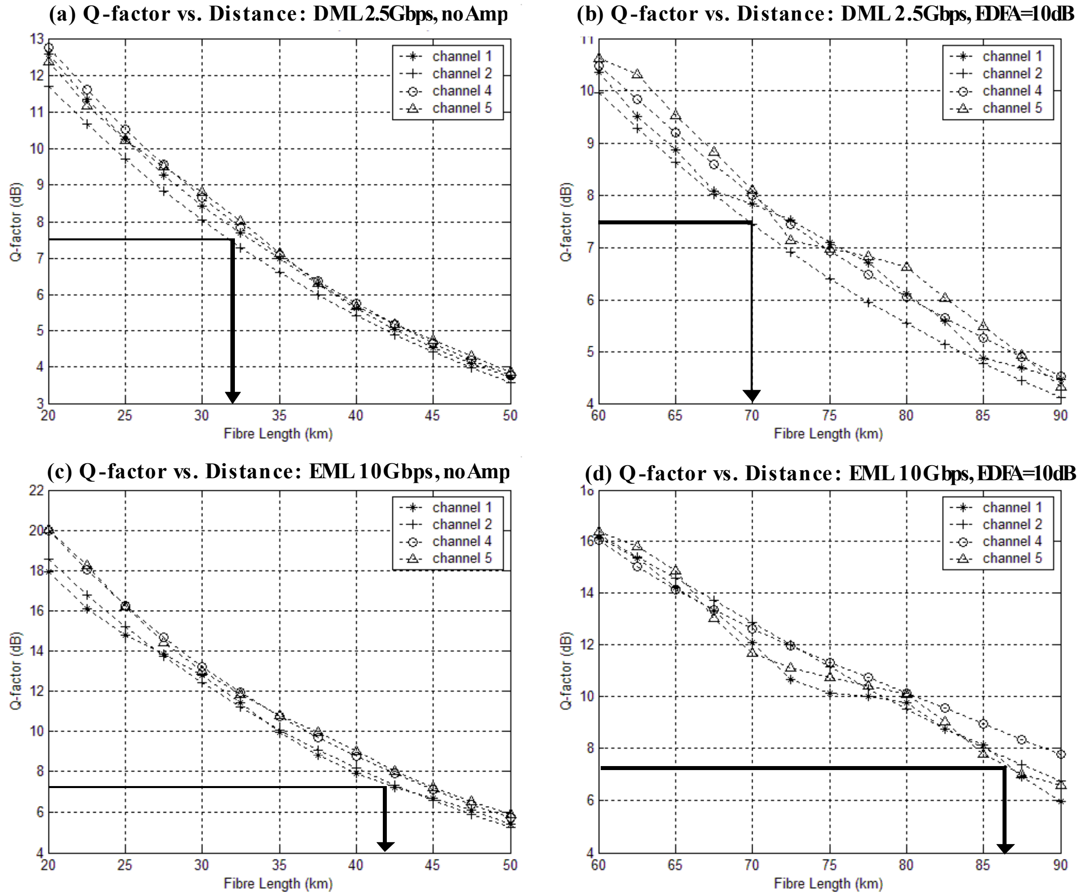


Figure 2. Critical Transmission Distance: Q-factor vs. fibre length

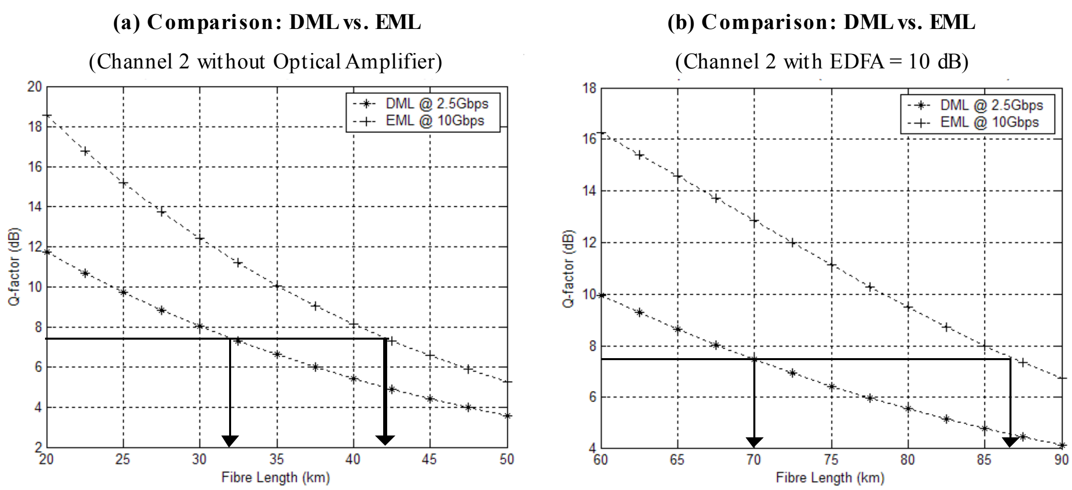


Figure 3. End-to-end Performance Comparison: DML vs. EML with/without Optical Amplifier

3.3 Applications of the simulation results

The simulation results are applied to assess the feasibility of connecting four research facilities located in the same city. The geographical topology and node/link configuration of these four nodes are shown in Figures 4 and 5 respectively. To connect with the adjacent neighbor node, two technical options based on the simulation results are provided for users: 1) using directly modulated lasers as transmitters with a data rate of 2.5 Gbps per channel; and 2) a data rate of 10 Gbps per channel with external modulator transmitters. The first option is more cost-efficient but at a lesser data rate. The selection of technical solutions depends on the users' data rate demands and the cost constraints.

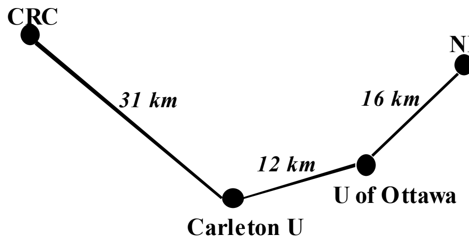
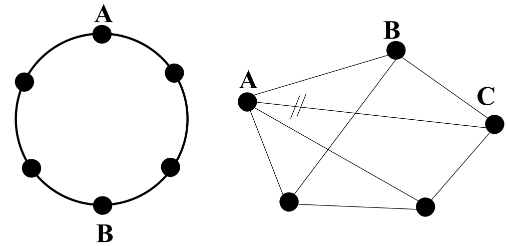


Figure 4. Geographical topology of four research facilities within a city



(a) Ring topology (b) Mesh topology

Figure 6. Applications of other topologies

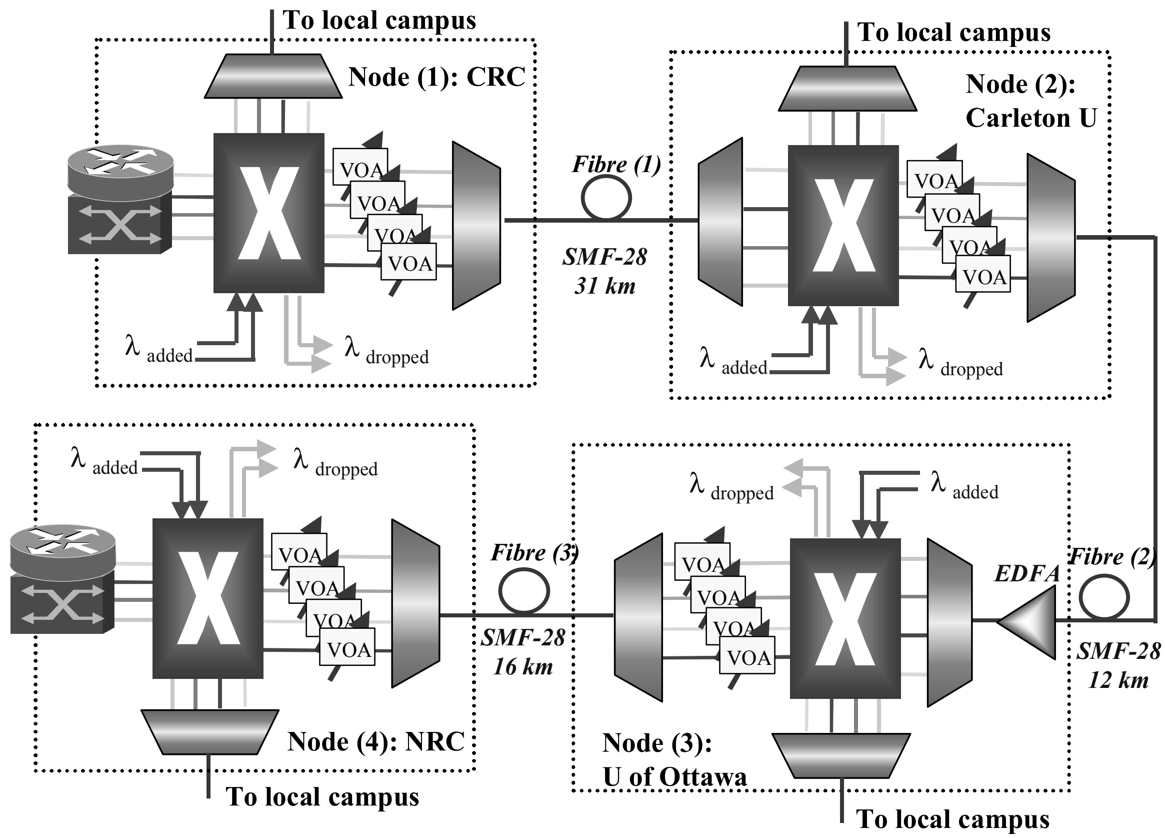


Figure 5. AON connecting research facilities within a city

A user can also connect to non-adjacent neighbours directly by provisioning a physical layer transmission path different to the geographical topology. In all-optical networks, such physical path provisioning is limited by the performance degrading effects. Based on the outcome in Section 3.1, for the low speed option without optical amplification, the path length is limited to 32 km. This path length can be extended to 70 km by using an EDFA with a 10 dB gain. If the path length is beyond this, more amplifiers or regenerators, and/or optical impairments control/compensation are needed. On the other hand, for the high speed option (10 Gbps) without optical amplification, the path length can be no more than 42 km. Similar to the low speed option, this length can also be extended to 87 km by using an EDFA with a 10 dB gain. Such length is far enough for typical metro networks.

The simulation results presented in this paper are obtained from the proposed linear topology, but they are also applicable to other topologies, e.g. ring and mesh, within the distance range analyzed in the linear topology case. For example, in a ring network shown in Figure 6(a), the furthest distance is between node A and B, say half of the ring circumference. Based on the results in Table 2, the supported ring circumference for DML is about 60 km and 140 km with and without the amplifier respectively. For EML the circumference could be extended to 80km and 170 km with and without the amplifier respectively. In meshed networks the supported transmission distance depends on the hops of the physical path. Figure 6(b) gives an example of meshed network. Similarly the supported transmission distance between each couple of adjacent nodes can be evaluated according to the simulation results in Table 2, for provisioning the end-to-end physical lightpath. Additionally, such calculation is also a guidance for provisioning backup path. In Figure 6(b), for example, if the distance summation of link AB and BC is within the supported transmission distance, then AB-BC could be set up as a backup path for AC.

For these topologies the distance limitation can be eliminated by adding optical amplifiers (e.g. EDFA) along the physical lightpath. The path length extension of each extra optical amplifier is described above. Furthermore, multiple optical amplifiers could extend the physical lightpath to longer length, nevertheless the amplifier cancatenation effects must be taken into account.

IV. Conclusions and future work

The parameter optimization in the physical layer is studied by applying link budget optimization and application of low-cost devices. The simulation results show that it is technically feasible to realize such an AON connecting several research facilities located within a 60-km distance. For the required end-to-end performance ($Q \geq 7.5\ dB$), the reachable transmission distance when using a DML at 2.5 Gbps is 70 km and 32 km, while using and not using an optical amplifier respectively. While using an EML at 10 Gbps, this distance is 87 km and 42 km for using and not using an optical amplifier respectively. These results lead to two technical options for each facility to connect with the testbed, either using a directly modulated laser at 2.5 Gbps or an external modulator at 10 Gbps. The selection of the technical options depends on the user's bandwidth demands, cost constraints, and the distance to the access point. The simulation results are obtained from the proposed linear topology but they are also applicable for other topology cases such as ring and meshed netwotks.

A testbed consisting of low-cost devices is already established. The device selection is based on the presented simulation results. In the next phase the simulation results will be compared with the real measurement of the testbed and therefore the simulation model will be validated.

The future research activities might also include the validation of protocols for dynamic end-to-end lightpath provisioning, the investigation of signal impairments and compensation schemes (10/40 Gbps), monitoring the optical performance (QoS), and fault management in all-optical networks. The AON testbed presented in this paper is open for collaborative activities and partnerships in research, development and applications.

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