Technologies and Architectures to Enable SDN in Converged 5G/Optical Access Networks

(Invited)

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Abstract—**The challenging performance targets of future 5G networks will require a radical change in the network design with a much closer interaction between wireless and optical systems. Dynamically reconfigurable time-division multiplexing (TDM) dense wavelength division multiplexing (DWDM) long-reach passive optical networks (PONs) provide a promising platform to enable the convergence of residential broadband, enterprise connectivity and wireless data traffic onto a single network architecture by exploiting the dynamic allocation of DWDM channels. In this paper we describe the architectural choices and the specific technologies that are required by these designs. We also demonstrate the co-existence of heterogeneous services and modulation formats, i.e. residential 10G PON channels, business 100G dedicated channel and wireless fronthaul on long reach TDM-DWDM PON systems. Two different TDM-DWDM PON designs are demonstrated: the first one for densely populated urban areas; and the second one better suited for rural deployment. Two service use cases are also demonstrated by implementing end-to-end software defined networking (SDN) management of the access and core network elements: a fast protection mechanism with end-to-end service restoration in the case of a primary link failure; and dynamic wavelength allocation (DWA) in response to an increased traffic demand.**

Keywords—Optimal fiber communication, passive optical networks, dense wavelength division multiplexing, access protocols, software defined networking, fast protection, dynamic wavelength allocation

I. INTRODUCTION

Fifth generation (5G) wireless networks are aiming to deliver an unprecedented level of service to the end user in term of experience, which will inevitably require larger mobile broadband bandwidth with ubiquitous availability, a faster response time, higher reliability and security[1,2]. In order to be able to meet the challenging performance targets, 5G networks will require a paradigm shift in the network design with a much closer interaction between wireless and optical

systems [3,4] and in this context the terminology 5G networks is being adopted to identify this novel highly integrated wireless/optical network. The challenge faced by both fixed network and mobile operators in order to deliver these advanced wireless services while continuing to reduce the cost-per-bit will inevitably lead to a consolidation of the network infrastructure. Residential broadband, enterprise connectivity and wireless data traffic, which are today carried by separate networks, must converge onto a single network architecture able to provide flexibly and economically the performances required by these different services [5]. The metro-access (or regional) network segment of the future 5G network in particular will require an evolution from the physical layer point of view due to the convergence of different traffic types and the strict requirements imposed by the wireless services. Fibre-to-the-x (FTTx, with x being home, building or cabinet) networks and in particular passive optical networks (PONs) are the most promising candidates to enable the convergence of these different services on a single metro-access architecture. Dynamically reconfigurable time-division multiplexing (TDM) dense wavelength division multiplexing (DWDM) PONs coupled with software defined networking (SDN) control plane can also enable highly dynamic service and capacity provision.

This paper reports on the major conclusions on the metro-access segment of the network architecture developed within the EU FP7 Integrated Project DISCUS [6]. The DISCUS access network architecture is first described including an overview of the specific technologies that are required by this design. The network test-beds that were developed to demonstrate the end-to-end DISCUS architecture, integrating multiple network layers, from the application down to the physical layer are then presented. The results of the physical layer characterization are reported for two different TDM-DWDM PON architectures: a single amplifier node (AN) tree-like design and a chain of ANs design. The physical layer, operating in burst mode in the upstream direction, includes the forward error correction (FEC) implementation, the use of a

10Gb/s linear burst-mode receiver (LBMRx) and ANs capable of carrying heterogeneous services and modulation formats such as a coherent 100G point-to-point (P2P) link. The demonstrator also presents the physical integration of an SDN controlled access and core network demonstrating two use cases: an SDN-enabled fast protection mechanism with end-to-end service restoration in case of a primary link failure; and an SDN-enabled dynamic wavelength allocation (DWA) in response to an increased traffic demand.

II. METRO-SCALE ACCESS NETWORK ARCHITECTURE

A consolidation of network resources can be achieved by growing the reach of PONs from today's 10-20km to a metro-scale of up to 100km. The architectural solution studied in DISCUS of using long reach passive optical networks (LR-PONs) connected to a small number of core nodes (CNs) can enable a further node consolidation in the core network where these CNs can be interconnected by a fully meshed set of optical light paths with no intermediate packet processing. This enables a reduction of the order of 50:1 in network traffic processing nodes addressing also the issue of network cost and energy consumption scalability [6].

Densely populated areas can be efficiently connected by deploying a simple LR-PON architecture with a single optical amplifier node (AN) served by the backhaul fibers. The AN connects to a totally passive optical distribution network (ODN), supporting up to 512 or 1024 users and reaches of 20km, forming a tree-like structure (the left section of Fig. 1) [7]. On the other hand, in sparsely populated rural areas, the communities to be served can be much smaller than the total LR-PON split which would mean that the conventional tree-like design, would be considerably underutilized, directly increasing the cost per customer. The utilization and efficiency of rural deployment can be improved by an alternative LR-PON structure that utilizes a chain of ANs [8]. The right section of Fig. 1 presents this LR-PON concept using a chain of ANs dual parented on two geographically separated nodes of a flat optical core network, which directly reuses the ring fiber topologies deployed in today's metro networks.

The choice of the optical amplifier technology in these architectures is mainly determined by the wavelength plan and also by considerations regarding cost and components integration. Erbium-doped fiber amplifiers (EDFAs), for example, are very strong candidates due to their overall good performance in terms of low noise figure, high gain and high output power and the ability to provide these characteristics in a system with a large number of channels in the C-band and L-band. When used in the upstream direction, EDFAs could be susceptible to gain transients induced by the burst traffic, particularly if a large number of DWDM channels are deployed. The chain of ANs is also more susceptible to gain transients due to the concatenation of several EDFAs. In order to reduce the impact of the burst traffic EDFAs employing fast gain stabilization should be used in the AN [8].

Dynamically reconfigurable TDM DWDM LR-PONs could deliver all foreseen and future services with either fixed access customer premises equipment (CPE) or wireless and mobile devices. By exploiting the dynamic allocation of DWDM channels, the LR-PON can support both residential users and business users sharing 10G PON channels, with options to rent dedicated 10G PON channels or high capacity 100G P2P links for those users requiring very high capacity connections. The long reach architecture can introduce transmission round trip times of up to ~1ms which is generally not compatible with the ultra-low latency required by some wireless architectures and by some future services discussed for 5G. However, such low latencies could also be supported by placing small active nodes with an optical networking unit (ONU) and the necessary processing equipment in the amplifier node (AN) and allocating a dedicated wavelength, which could carry for example a common public radio interface (CPRI) channel, from the AN to the remote site over the LR-PON fiber infrastructure. This configuration could also support midhaul links with split processing [4], which, taking advantage from statistical multiplexing of user traffic dynamics, would benefit from a lower required capacity that could be carried by TDM-PON channels.

The ODNs and the ANs are transparent to the PON traffic and do not provide any wavelength routing. The wavelength selection and reconfiguration is performed only at the user end, in the ONU, and at the head end, in the CN. In the ONU the downstream wavelength selection is performed by a tuneable bandpass filter in front of the receiver, while a tuneable laser enables the wavelength reconfiguration of the upstream transmitter. In the CN the wavelength routing and reconfiguration of the various upstream PON channels is obtained using a wavelength multiplexer with a 50GHz channel spacing followed by optical switch matrix. The optical switch routes the output ports of the wavelength multiplexer to the
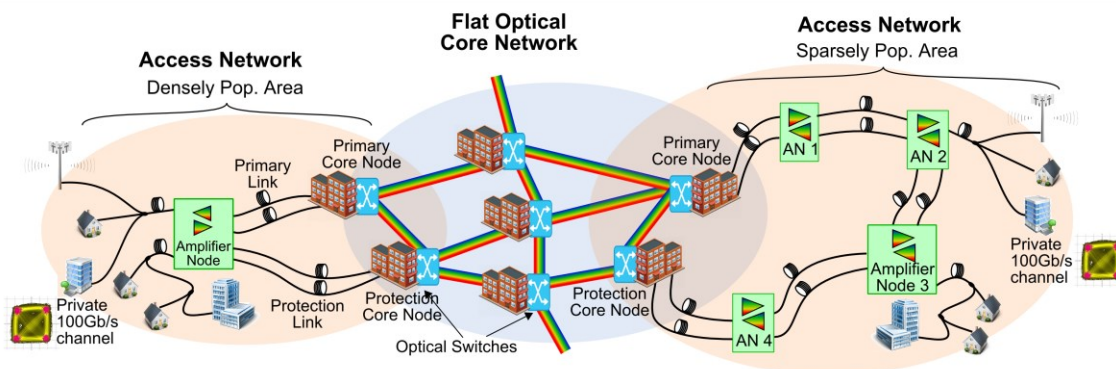

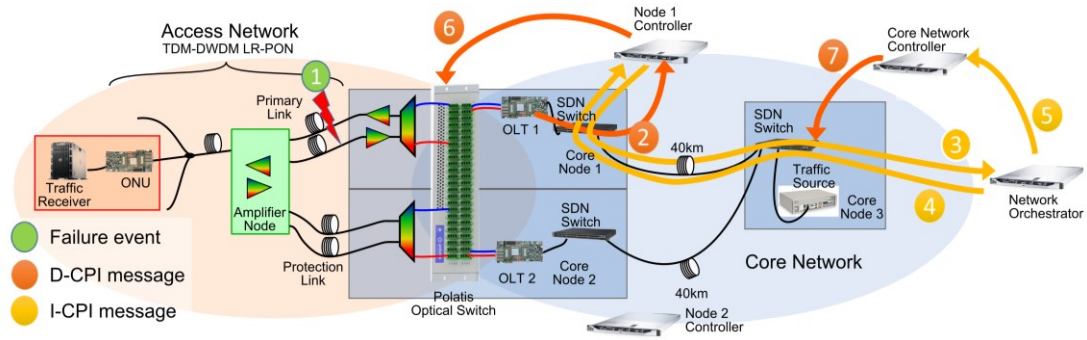Fig. 1. Proposed network concept applicable for both urban and rural deployment scenarios.

Fig. 2. Network level view and message exchange overview for the protection experiment.

optical line terminals (OLTs) assigned to the specific PON channels. On the other hand, the downstream channel would be configured by a tuneable transmitter in the OLT and routed to the correct input port of a wavelength multiplexer using the optical switch.

The introduction of an SDN control plane can enable highly dynamic service and capacity provision over the LR-PON in response to changing demand by implementing agents in the network elements [9]. Since in a LR-PON architecture, much of the currently protected metro network is replaced by the backhaul links, the ANs, which are serving hundreds of residential and potentially business users, would need to be dual parented for protection with a secondary backhaul link to a geographically separated CN. Fast protection of these links is required in order to fulfill user requirements, particularly for enterprise and mobile backhaul applications. Fast PON protection enabled by SDN control also allows the implementation of protection load balancing schemes, which allow substantial cost reduction in both IP and PON backup resources [10], by increasing the ability to share protection equipment across the network. Fig. 2 presents the network configuration used to demonstrate experimentally the fast PON protection and an overview of the messages exchanged.

The overall SDN architecture implemented in DISCUS follows the open network foundation (ONF) architecture using three main interfaces [11]: the application-controller plane interface (A-CPI) between the control plane and the application (a user portal in this case); the intermediate-controller plane interface (I-CPI) between the network orchestrator (NetO) [12] and the node controller (NC) and core network controller (OF); and the device-controller plane interface (D-CPI) between the controllers and the physical devices [9]. The D-CPI operates between the physical devices, i.e. OLT, optical switch and OpenFlow (OF) SDN switch, and the node controller. The OF SDN switch, a Pronto 3780 48x10G ports running release 2.4 (OF v1.4 compatible firmware) implements a native OF interface. Thus the communication to the controller is carried out over the OF v1.4 protocol through the Ryu OF controller application programming interfaces (APIs). The OLT and the optical switch do not implement a native OF v1.4 protocol, thus we have developed an OF agent collocated with the controller that emulates the OF protocol link. The controller sends OF-compatible commands to the OF agent, which then translates the messages into appropriate commands for the physical optical switch and OLT devices. The OF commands for the ONUs are sent to the agent in the OLT, which then generates a physical layer operation, administration and maintenance (PLOAM) message to communicate with the specific ONU.

III. TEST-BED DESCRIPTION

Fig. 3 shows the details of the LR-PON physical layer of the two architectures demonstrated: logical tree-like for urban areas (a) and an active chain of ANs for rural deployment (b). Fig. 3(a) presents the tree-like design employing a single AN per LR-PON from where a totally passive ODN is connected. Part of the total split (4×4) is located in the AN, and this also provides access to a redundancy path in the backhaul link for resilience and protection. The second architecture is based on the structure of metro rings, where two fibers with counter-propagating traffic connect a chain of nodes. The ring is open and the two head-ends are the CNs, while the intermediate nodes are the ANs where the ODNs are optically aggregated into the LR-PON. A chain of 4 ANs, connected by fiber links between 0km (representing co-located ANs) and 40km, is demonstrated, which is easily adequate to cover the typical distances between today's local exchanges or central offices. Depending on the exact topology, a larger number of ANs could also be chained for a total network reach of >100km. Part of the total ODN split (4×4) is located in the ANs, which also provides access to the redundancy path while asymmetric 80/20 couplers are used to add and drop the traffic from the links of the open ring in both directions. In the event of a fiber cut or of a failure in the primary CN or in an AN, the traffic is routed to the protection CN, hence providing the same intrinsic resilience as metro rings. Red/blue filters are used to isolate the DS traffic which is to be transmitted to the ODN. Commercially available gain-stabilized erbium doped fiber amplifiers (EDFAs) are employed as in-line amplifiers in the AN to reduce the impact of gain transients caused by the bursty nature of the upstream traffic [8]. In the test-bed ANs 1 and 4 were fully implemented while ANs 2 and 3 were only partially implemented using optical attenuators to emulate the loss of the 80/20 couplers.

Fig. 3 also shows the details of the ODNs, of the backhaul links implemented and the details of the AN designs, such as amplifier gains and channel powers. Attenuators are added at various points in the systems to emulate end of life standard single mode fiber attenuation (0.3dB/km, taking account of potential maintenance splices etc.) and realistic splitter losses in the ODNs, including excess loss [13]. Throughout this work we consider in the ODN loss calculations a worst case loss of 3.5dB for each ×2 split. The protection link is implemented
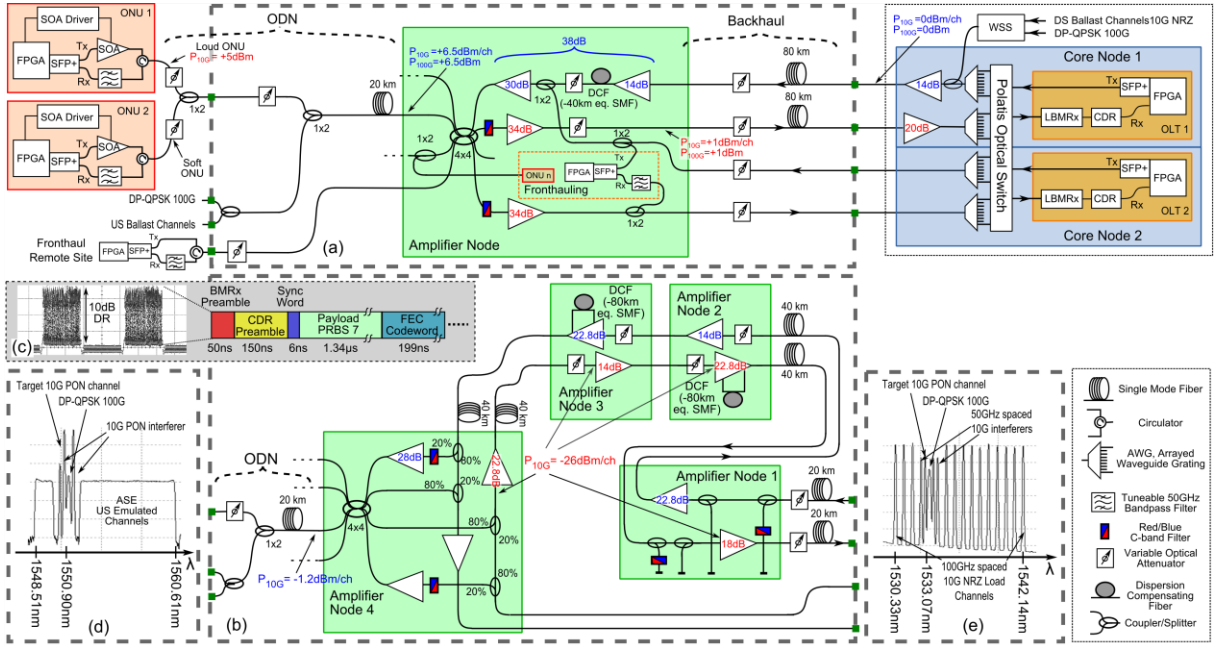
Fig. 3. Physical layer experimental setup for the single AN tree-like design (a) and the AN chain-based design (b); upstream burst structure (c); upstream (d) and downstream (e) spectra.

only for the tree-like design and consisted of just a few meters of fiber to achieve the maximum differential reach with the primary path.

The same ONUs and CNs are connected to the two LR-PON test-beds using an optical beam steering switch matrix from Polatis, which is used for experimental convenience to reliably interchange between the two network designs. Two OLTs and two ONUs are fully implemented, and additional traffic equivalent to a power of 40 channels in both up- and down-stream is added to fully load the network. As indicated in Fig. 3(e) the additional downstream channels are emulated using 10Gb/s on-off keying (OOK) externally modulated distributed feedback DFB lasers. Fig. 3(d) shows the upstream band, where the additional channels are emulated using amplified spontaneous emission (ASE), generated by a semiconductor optical amplifier (SOA) which is filtered and flattened using a wavelength selective switch (WSS) and modulated to mimic the typical burst mode power variations of upstream channels. Similar entry points allowed the insertion of the 100G P2P wavelength channel, which is realized using a commercial transponder to generate and receive a dual-polarization quadrature-phase-shift-keying signal (DP-QPSK). The OLT and ONU transmitters are commercial tunable 10G SFP+ transceivers, while the wavelength selection at the receivers is achieved by using a 50GHz tunable filter at the ONU and by routing the ports of a wavelength demux at the OLT using an Openflow-enabled Polatis optical switch, partitioned and shared by the two core nodes. The LBMRx at the OLT [14] is followed by a static electronic dispersion compensation-clock data recovery (CDR) module [15]. For the physical layer testing a simplified protocol, which controls the ONU burst timings, is implemented in the OLTs and ONUs using field programmable gate arrays (FPGAs). A FEC algorithm has also been implemented on FPGAs using standard Reed-Solomon (RS) encoders and decoders, based on

RS(248,216) both in upstream and downstream [7,15]. The structure of the upstream burst is shown in Fig. 3(c).

For the service level tests the LR-PON protocol is a partial implementation of the 10G symmetric XG-PON standard [16]. In addition the XG-PON protocol was adapted to support the longer PON logical distance, up to 125km as opposed to 60km, and the higher split ratio. The reader can refer to [15] for more details on the OLT and ONU protocol implementation. A simplified core network is also emulated using 2×40km fiber links and 3× Openflow bridges based on a Pronto 3780 switch with 10GbE interfaces.

IV. EXPERIMENTAL RESULTS

Fig. 4(a) presents the bit error rate (BER) before and after FEC measured as a function of the ODN loss for the downstream direction for both demonstrated architectures. The tree-like network design is able to support an ODN loss of at least 36dB, which corresponds to a 256 split plus 20km of fiber with a system margin of 2dB and to an overall split ratio of 1024 (256×4 due to the additional 4×4 AN split). The chained ANs design can support an ODN loss of at least 27dB after FEC, which corresponds to a 64 split plus 20km of fiber in the ODN and to an overall split ratio of 256 (64×4) per AN. Assuming a fully implemented network with 4× ANs this would correspond to a total split of 1024 (256×4). In both cases the two ONU's receiver sensitivities present a difference of less than 3dB, due to variations in the SFP+ performance.

In the upstream direction the BER was measured at the OLT in burst mode operation on 2μs burst with the loud burst from ONU 1 acting as a worst case interferer for ONU 2 in terms of the LBMRx operation. The burst power of ONU 1 was maintained constant at close to the LBMRx overload power (loud ONU) with an ODN loss of 16dB and 15dB, respectively for the tree-like and the chain networks. The ODN
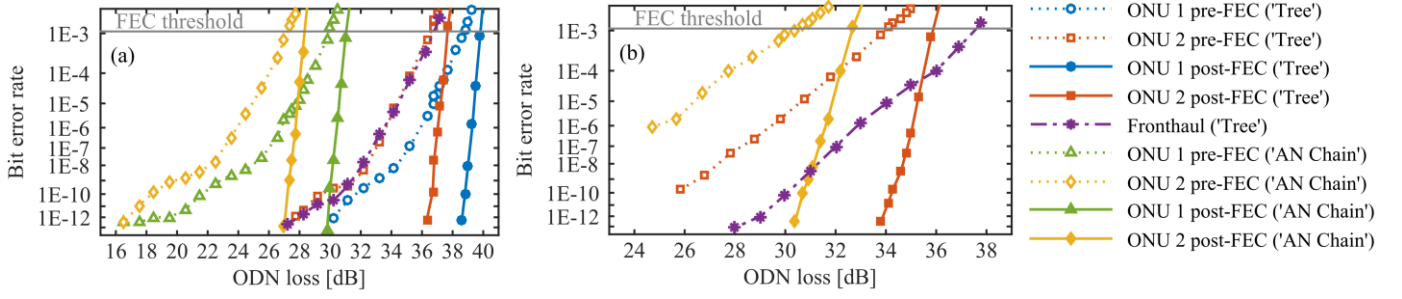
Fig. 4. BER vs ODN loss: a) Downstream, b) Upstream.

loss was varied from 15 to 35dB only for ONU 2, effectively varying the dynamic range (DR) of the burst powers reaching the LBMRx. In both cases the post-FEC BER is always below 1e-12 for ONU 1 and hence it is not reported in Fig 4(b). The ONU 2 BER shows that the tree-like design can support ODN losses of up to 34dB, corresponding to dynamic range of 18dB and to a 256 split plus 20km of fiber with no system margin and to an overall split ratio of 1024 (256×4). In the case of the AN chain design ONU 2 operates post-FEC with BER<1e-12 for ODN losses of up to 30dB, corresponding to a dynamic range of 15dB and to an overall split ratio of 256 (64×4) per AN with margin and to a total network split of 1024 (256×4). The measured FEC performance closely follows the theoretical threshold of 1.1e-3 for a post-FEC error rate of 1e-12 both in downstream and upstream link.

The impact of the burst traffic on EDFAs located in the chained ANs, was also characterised in [8] by modulating the amplitude of the ASE used to emulate the upstream channels. The post-FEC BER presents only a marginal impact of the residual EDFA transient compared to the results in Fig. 4. The accumulated residual EDFA gain transient is dependent on the period of the ASE modulation and the corresponding peak-to-peak power variation observed by a continuous-wave probe channel is presented in Table 1, while Fig. 5 shows the profile of the transient induced by a 100µs add/drop period.

The fronthaul channel can operate error free without FEC (BER<1e-12) in both directions for an ODN loss of up to 28dB (Fig. 4). While the downstream is effectively showing the same performance as the downstream PON channel, in the upstream direction the fronthaul channel shows better performance than

the PON upstream channel because it is not transmitted through the link towards the CN and hence maintains a higher OSNR. Moreover it should be noted that the fronthaul channel is a continuous mode link and hence does not require the use of a burst-mode receiver.

Standard commercial solutions to implement high capacity 100G link use coherent modulation formats such as DP-QPSK, which are potentially highly susceptible to linear and non-linear impairments caused by co-propagation with on-off-keying (OOK) channels. The performance of the 100G P2P downstream link was hence characterized in the presence of the emulated traffic for a system fully loaded with 10G OOK PON channels as shown in the spectra in Fig. 2(e) and in particular with two interfering channels 50GHz on each side of the 100G channel. Fig. 6(a) presents the pre-FEC BER of the 100G downstream link as a function of the ODN loss using an EDFA pre-amplifier at the receiver with 5.5dB noise figure (NF). The tree-like and chain designs can both support the 100G channel with ODN loss higher than 36 and 30dB respectively (equivalent overall to 1024 network users). Fig. 6(a) also shows the BER measured as a function of the ODN loss in back-to-back (B2B), where the 100G transmitter is connected directly to the EDFA pre-amplifier at the receiver and the ODN loss is emulated by a variable optical attenuator at the input of

Table 1. Analysis of accumulated EDFA transients

$T_{Add/Drop}$ [µs]	Peak-to-Peak [dB]
300	1.2
100	1.18
50	1.12
20	0.95
10	0.6
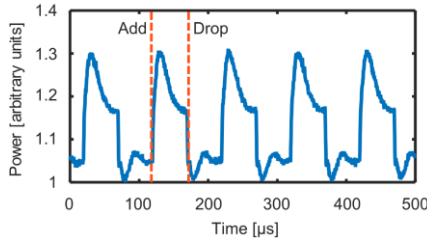
Fig. 5. Profile of the accumulated EDFA transient for a probe channel at 1551.72nm and $T_{Add/Drop}$ = 100µs
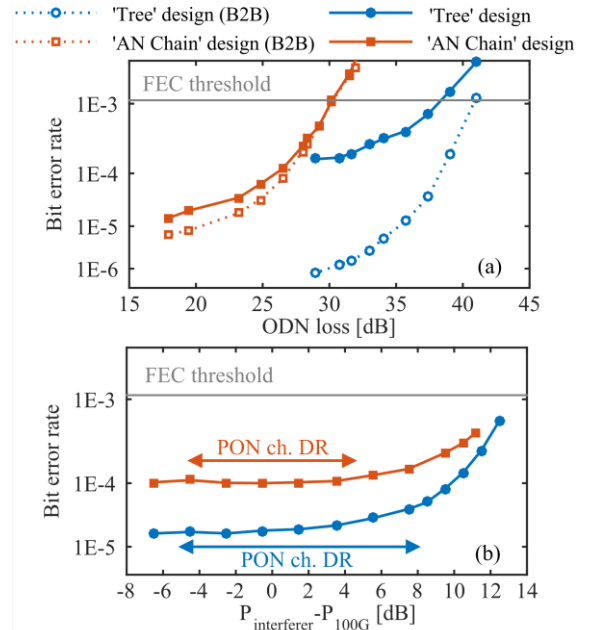

Fig. 6. Performance of the 100G link in downstream as a function of the ODN loss (a); performance of the 100G link in upstream as a function of the power of the neighboring NRZ PON channels (b).
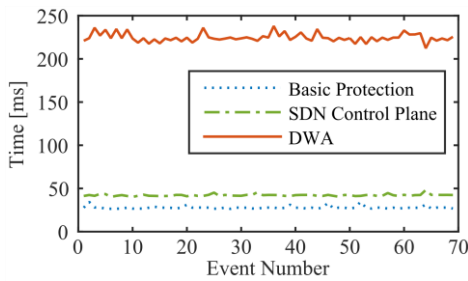
Fig. 7. Service restoration time for the protection mechanism and the DWA through the implemented SDN control plane.

the EDFA pre-amplifier. Assuming a negligible impact from other sources of impairments, such as chromatic dispersion, the effect of the non-linearities in the ODN and backhaul fibers can be clearly seen for both designs by comparing the B2B curve with the one obtained with the complete network. In the upstream direction the OOK PON traffic, which is interfering with the 100G channel, presents bursts with different power. The 100G channel was hence characterized in terms of penalty caused by the nonlinear crosstalk from the two neighboring 10Gb/s NRZ PON channels bursting with high power. The BER of the 100G upstream link was measured as a function of the power of two 50GHz-spaced interfering channels operated with 2µs bursts and 2µs gaps overlapped in time to provide also a worst case for the nonlinearity. The experimental results in Fig. 6(b) show that the 100G channel can work below FEC threshold even when the neighboring bursty channels present dynamic ranges larger than the 13dB (tree-like design) and 9dB (AN chain design) caused by the non-uniform ODN loss.

The ability to reconfigure the network resources using an SDN controlled access and core network was demonstrated in the DISCUS test-bed implementing two specific use cases: an SDN-enabled fast protection mechanism with end-to-end service restoration in case of a primary link failure; and an SDN-enabled DWA in response to an increased traffic demand. The SDN-enabled DWA is used for dynamic capacity provisioning and hence wavelength and service reconfiguration times of a few hundred ms are targeted.

The service restoration time in the case of a primary link failure has been measured for the SDN control plane based protection mechanism. The average restoration time over 70 consecutive measurements was 41ms (Fig. 7). In order to understand the effect of centralizing both the NetO and the NCs, we compared the above results with the case where orchestrator and controllers are collocated within the CN. This was accomplished by setting the emulated intra-control plane latencies at zero with the results shown in Fig. 7 as the basic protection. On average, basic protection can be accomplished within 27.8ms. The DWA results in Fig. 7 refer to the service restoration time when, in response to an increase in traffic demand, the NetO instructs the core and the NC to provision the new path according to its knowledge of the full end-to-end network topology and the ONU traffic is moved to a different PON channel. Using a custom implemented PLOAM message, the primary OLT requests the ONU to tune to a wavelength provisioned by the secondary OLT. We believe that the measured provisioning time of ~225ms could be reduced by an optimized design of communication interfaces between the ONU FPGA and the tunable components.

V. CONCLUSIONS

Service convergence on the same infrastructure for future 5G networks can be enabled by dynamically reconfigurable TDM-DWDM LR-PON architectures. Some of the key technical aspects of these networks have been presented. The experimental results of the network demonstrators show that it is possible to support 1024 users and 40 channels over distances in the order of 100km with two different designs of LR-PON: a tree-like design for urban deployment and a chain of ANs for rural deployment. A fast protection mechanism with service restoration and the DWA of an ONU in response to increased traffic demand have also been demonstrated, enabled by SDN controlled access and core network elements.

REFERENCES

[1] M. Maier, M. Chowdhury, B. P. Rimal and D. P. Van, "The tactile internet: vision, recent progress, and open challenges," IEEE Communications Magazine, vol. 54, no. 5, pp. 138-145, May 2016

[2] P. Schulz et al., "Latency Critical IoT Applications in 5G: Perspective on the Design of Radio Interface and Network Architecture," in IEEE Communications Magazine, vol. 55, no. 2, pp. 70-78, February 2017.

[3] Xiang Liu and Frank Effenberger, "Emerging Optical Access Network Technologies for 5G Wireless [Invited]," J. Opt. Commun. Netw., vol 8, pp. B70-B79, 2016

[4] T. Pfeiffer, "Next Generation Mobile Fronthaul and Midhaul Architectures [Invited]," J. Opt. Comm. Netw. 7, B38-B45 (2015).

[5] M. Ruffini, "Multi-Dimensional Convergence in Future 5G Networks," Journal of Lightwave Technology, DOI: 10.1109/JLT.2016.2617896

[6] M. Ruffini et al., "DISCUS: an end-to-end solution for ubiquitous broadband optical access," IEEE Commun. Mag., vol. 52, pp. S24-S32, Feb. 2014.

[7] G. Talli et al., "SDN Enabled Dynamically Reconfigurable High Capacity Optical Access Architecture for Converged Services," Journal of Lightwave Technology, DOI 10.1109/JLT.2016.2604864.

[8] D. Carey et al., "Dynamically Reconfigurable TDM-DWDM PON Ring Architecture for Efficient Rural Deployment" ECOC 2016, W.3.E.4

[9] M. Ruffini, F. Slyne, C. Bluemm, N. Kitsuwan, and S. McGettrick., "Software defined networking for next generation converged metro-access networks," Optical Fiber Technology, Volume 26, Part A, Pages 31-41, Dec. 2015.

[10] S. McGettrick, F. Slyne, N. Kitsuwan, D. B. Payne, and M. Ruffini., "Experimental End-to-End Demonstration of Shared N:M Dual Homed Protection in SDN-controlled Long Reach PON and Pan-European Core," J. Lightw. Technol., vol. 34, no. 18, pp. 4205-4213, Sept. 2016..

[11] ONF, SDN architecture, TR-502, Issue 1, June 2014.

[12] R. Munoz et al., "Transport Network Orchestration for end-to-end Multi-layer Provisioning Across heterogeneous SDN/OpenFlow and GMPLS/PCE Control Domains," J. Lightw. Technol., vol. 33, pp. 1540-1548, April 2015.

[13] 40-Gigabit-Capable Passive Optical Networks 2 (NG-PON2): Physical Media Dependent (PMD) Layer Specification, ITU-T G989.2, 2015.

[14] S. Porto et al., "Demonstration of 10 Gbit/s burst-mode transmission using a linear burst-mode receiver and burst-mode electronic equalization [invited]," J. Opt. Commun. Netw, vol. 7, pp. A118-A125, Jan. 2015.

[15] C. Antony et al., "Demonstration of a carrier distributed, 8192-split hybrid DWDM-TDMA PON over 124km of field-installed fibres", Proc. OFC 2010, PDPD8.

[16] 10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification, ITU-T G.987.3, 2014.