

SDN-based Network Orchestration of Variable-capacity Optical Packet Switching Network over Programmable Flexi-grid Elastic Optical Path Network

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Abstract—A multi-domain and multi-technology optical network orchestration is demonstrated in an international testbed located in Japan, the UK and Spain. The Application-Based Network Operations (ABNO) architecture is proposed as a carrier Software-Defined Network (SDN) solution for provisioning end-to-end optical transport services through a multi-domain multi-technology network scenario, consisting of a 4G-108 Gb/s variable-capacity OpenFlow-capable optical packet switching network and a programmable, flexi-grid elastic optical path network.

Index Terms— Optical packet switching, Discrete multi-tone, Flexi-grid WDM network, Software-defined network

I. INTRODUCTION

MULTI-DOMAIN and multi-technology network orchestration is a huge challenge for end-to-end service provisioning over future heterogeneous optical network

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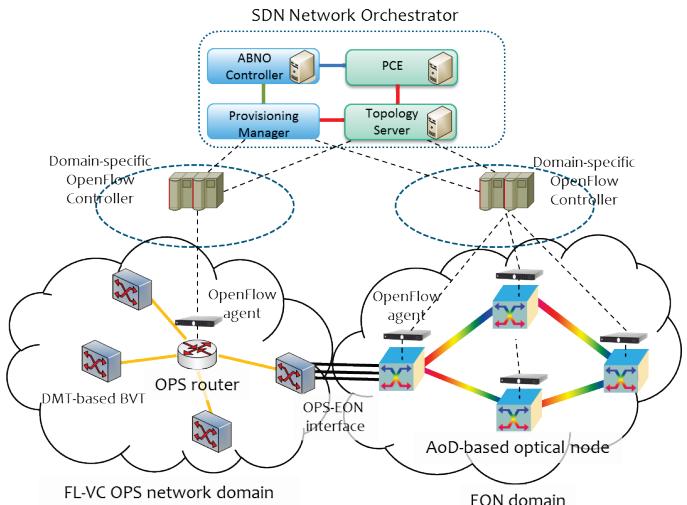


Fig.1 Multi-domain multi-technology orchestration in an OpenFlow-based OPS-EON network demonstrator

infrastructure. Such infrastructure may comprise different transport and control plane technologies, e.g., conventional Wavelength Division Multiplexing (WDM) Optical Circuit Switching (OCS) networks, flexible-grid dense WDM OCS networks for high-capacity long-haul connections such as for inter-datacenter networks, and Optical Packet Switching (OPS) networks for access, aggregation, and/or intra-datacenter networks as an alternative to energy-inefficient high-speed electrical packet switching networks [2].

Software-Defined Networking (SDN) technology, such as that based on OpenFlow [3], allows the decoupling of data and control planes and introduces a logically centralized entity that is responsible for network control, i.e., an SDN controller. The introduction of these centralized technology-dependent domain specific control entities is a key enabler for end-to-end service orchestration over such heterogeneous and often incompatible control plane and transport technologies. In addition, bandwidth variable transponders (BVT), such as those based on

optical orthogonal frequency division multiplexing (OFDM) technology, may play a key role in SDN-capable optical networks [4,5]. The programmability of BVT enables dynamic establishment of sub-wavelength granularity paths in each domain and helps SDN controllers create virtual slices of physical infrastructure with finer granularity.

So far, several SDN solutions have been introduced for end-to-end service provisioning over multi-layer networks. For example, in [6], an OpenFlow-based unified control plane for the multi-layer network, which consists of fixed (electrical) layer-2 packet switching networks and fixed/flexi-grid dense WDM networks has been proposed and demonstrated. Meanwhile, multi-technology and multi-domain network orchestration needs to be addressed in network scenarios where several specific SDN controllers are deployed on top of each single-technology optical network domain.

In this paper, we demonstrate the orchestration of different technology/domain-specific SDN controllers in an international OPS-OCS testbed located in Japan, the UK, and Spain. (Fig. 1). The ABNO architecture [7] is introduced for the provisioning of end-to-end transport services through the technology-specific SDN controllers in a Fixed-Length Variable-Capacity (FL-VC) OPS network [8] and an Elastic optical Path Network (EON) [9] testbed. In the OPS domain, a Discrete Multi-Tone (DMT), i.e., a direct-detection OFDM, transmitter [10] is employed as a cost-effective 100 Gb/s-class BVT and is adopted for distance-adaptive (2–40 km) variable-capacity packet transport up to 108 Gb/s. In the EON domain, an EON is setup with four Architecture-On-Demand (AoD) [11] based optical nodes. A Tb/s-class reconfigurable optical superchannel (SC) signal is employed to provide high-capacity flexible link. The received packets at the edge OPS node are aggregated and groomed into the SC by a high capacity OPS-EON interface and are transported over 200 km through a flexi-grid WDM link. Each domain is controlled by a specific extended OpenFlow controller, and the controllers are orchestrated via an ABNO controller to demonstrate end-to-end service provisioning. To the best of our knowledge, orchestration of end-to-end transport services through SDN control on an OPS-EON coexisting data plane has not yet been demonstrated.

The remainder of this paper is organized as follows. Section 2 describes the DMT-based OPS network testbed and shows its OpenFlow capability. The EON testbed with the OPS-EON interface is presented in Section 3. Section 4 shows the result of the end-to-end orchestration based on the ABNO architecture. We then conclude the paper in Section 5.

II. OPS DATA TRANSPORT PLANE: DISTANCE-ADAPTIVE OPTICAL DMT PAYLOAD PACKET

In the OPS network domain, we employ a concept called FL-VC OPS [8], wherein optical payloads have a fixed length to ease optical buffer implementation and scheduling while their modulation formats and bandwidths are adapted to bandwidth demands and/or network architectures to maximize network resource usage. The key elements are BVTs with fine-granularity, high-speed optical switches (OSWs), which

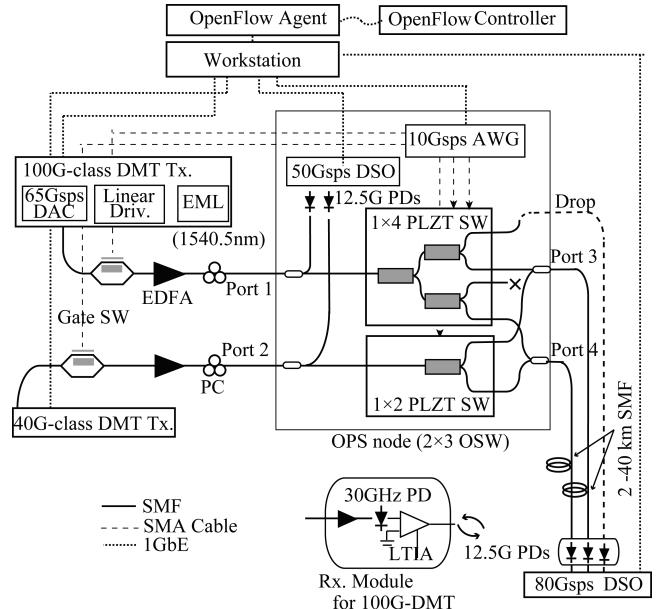


Fig. 2. Experimental setup for DMT-based OPS network with OpenFlow control

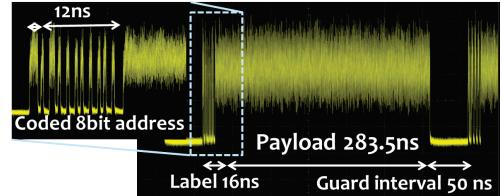


Fig. 3. Electrical waveform of the DMT-based optical packet

are transparent for multiple payload formats generated by the BVTs, and a sophisticated network controller that manages the OPS network resource and the modulation format of each optical payload. In particular, in this demonstration, a 100 Gb/s-class DMT transmitter (DMT-Tx) [10] is employed as a cost-effective intensity-modulated direct-detection (IM-DD) BVT. The flexibility of the DMT-Tx is exploited to generate fixed-length distance-adaptive payload packets, i.e., the packet length is fixed while >1000 subcarriers in each payload are modulated adaptively to maximize payload capacity according to the transmission distance [12].

The flow control technique in OpenFlow naturally fits with such FL-VC OPS, e.g., the optical packets which have the same source and destination nodes are assigned to a flow. In addition, the optical packets with different QoS requirements may be modulated with different formats, and thus the packets are assigned to different flows even if they have the same source and destination set. An OpenFlow controller decides the modulation policy and the packet forwarding strategy based on the topology and/or traffic information and generates an action and instruction list for each flow. The resulting flow table distributed to each node and, if it is an intermediate node, the table may be translated into a switching matrix directly.

Figure 2 shows the experimental setup for the 100 Gb/s-class FL-VC OPS network demonstration. Two DMT-Txs are implemented as source nodes and a 2×3 PLZT $((\text{Pb},\text{La})(\text{Zr},\text{La})\text{O}_3)$ switch is used as an OPS router. For

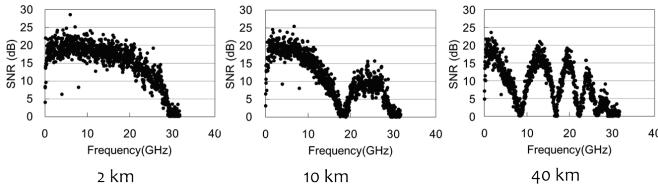


Fig. 4. Estimated SNR per subcarrier after 2, 10, and 40-km SSMF transmissions

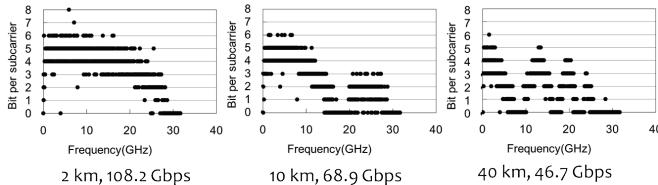


Fig. 5. Loaded bits per subcarrier for 2, 10, and 40-km SSMF transmissions

simplicity, no buffer is implemented. However the contention resolution for fixed-length packets can be performed by the fiber delay line buffers with simple scheduling algorithm [13]. One DMT-Tx consists of a 65-GS/s DAC and an electro-absorption modulated laser (EML) at 1540.5 nm, and the other contains a 12-GS/s DAC and is used to generate dummy packets. Each DMT-Tx output is *packetized* via a gate switch based on a 30-GHz LN modulator. The gate switch also appends a 2-Gbaud OOK-formatted label on top of the DMT payload. As in Fig. 3, the resulting packet consists of a 283.5-ns payload and 16-ns optical label that contains the repetition-coded 8-bit address.

Guard intervals are 50 ns and the rise and fall time of the OSW is approximately 10 ns. At the router, the labels are detected via the 50-GS/s digital storage oscilloscope (DSO) with 12.5-GHz Photo Detectors (PDs) and sent to an OpenFlow agent through the 1GbE. The agent is introduced to the OSW controller to support OpenFlow protocol. The agent translates the flow table into the SW table, which is uploaded to the memory of the 10-GS/s Arbitrary Waveform Generator (AWG). The 2×3 switch is used as a 2×2 crossbar switch with a dropping port. The extinction ratio is > 23 dB. The router output is then transmitted over 2-40km SMF links and received via the destination node, which is implemented by a 30-GHz PD with a linear TransImpedance Amplifier (TIA) and an 80-GS/s DSO. The received packets are demodulated in an offline manner, and the raw data are then uploaded to an Ethernet traffic generator at the OPS/EON interfacing demonstrator.

Figure 4 shows the received Signal-to-Noise power Ratio (SNR) per subcarrier for different distances. The link distance is changed by replacing the SMF connected at output port 3. The SNRs are estimated by sending probe packets. As can be seen in Fig. 4, more subcarriers exhibit deep fading over longer distances. Fading is induced by interplay between the chirp due to the fiber chromatic dispersion and the square law detection at the PD, which is a major capacity limiting issue in C-band IM-DD systems [12, 14]. DMT is known as a practical technique to achieve the capacity in such frequency-selective

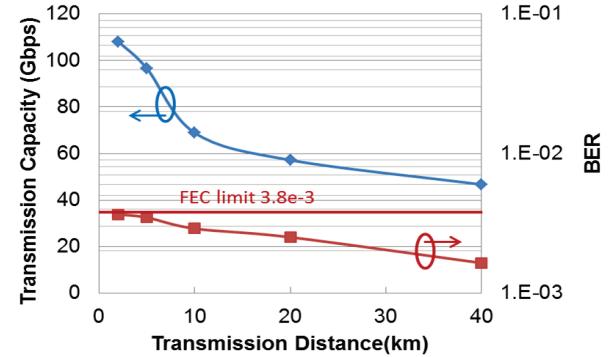


Fig. 6. Transmission distance versus achievable capacity within the 7% FEC limit

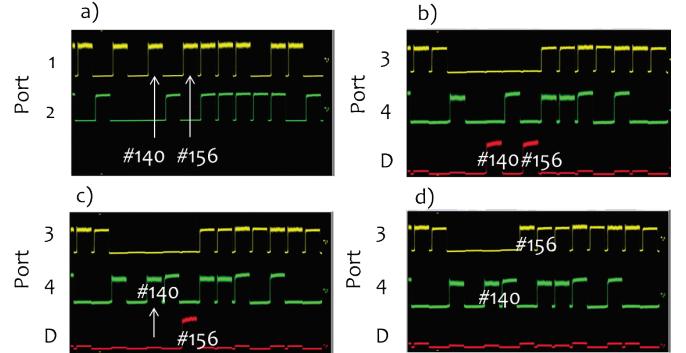


Fig. 7. Waveforms at a) input ports, b) output ports before the flow table update, c) after update for the flow labeled as 140, and d) after update for the flow labeled 156 (D = dropped)

Time	Source	Destination	Protocol	Length	Info
REF	172.27.1.31	172.27.1.30	OFP	104	Packet In (AM) (38B)
0.001144	172.27.1.30	172.27.1.31	OFP	146	Flow Mod (CSM) (80B)
3.981244	172.27.1.31	172.27.1.30	OFP	104	Packet In (AM) (38B)
3.981808	172.27.1.30	172.27.1.31	OFP	146	Flow Mod (CSM) (80B)

Fig. 8. OpenFlow packets captured by Wireshark

fading channels based on a water-filling interpretation. Figure 5 shows the number of loaded bits per subcarrier after the adaptation, where the modulation level of each subcarrier is increased from BPSK to 256QAM on the basis of the SNR to maximize the capacity of the DMT payloads for a given distance. The Bit Error Rate (BER) performance and achievable raw bit rate within a 7% Forward Error Correction (FEC) limit ($\text{BER} = 3.8 \times 10^{-3}$) are shown in Fig. 6. We achieve 108.2 Gb/s for < 2 km and 46.7 Gb/s up to 40 km.

To show the OpenFlow capability of the FL-VC OPS setup, we demonstrate a flow table update, i.e., when incoming optical packets have an optical label that is not registered in the flow table, the OpenFlow controller determines an action and instruction list for the packets and updates the flow table to forward the packets. Figure 7 shows the waveforms at the input and output ports of the PLZT switch before and after the flow update. As can be seen in Fig. 7 a), there are two unknown optical packets, #140 and #156. Initially, the switch drops these packets as shown in Fig. 7 b), while the OpenFlow controller is informed of the arrival of these packets through the agent. Figure 8 shows a Wireshark capture of the OpenFlow packets between the controller and agent, where we extended the label

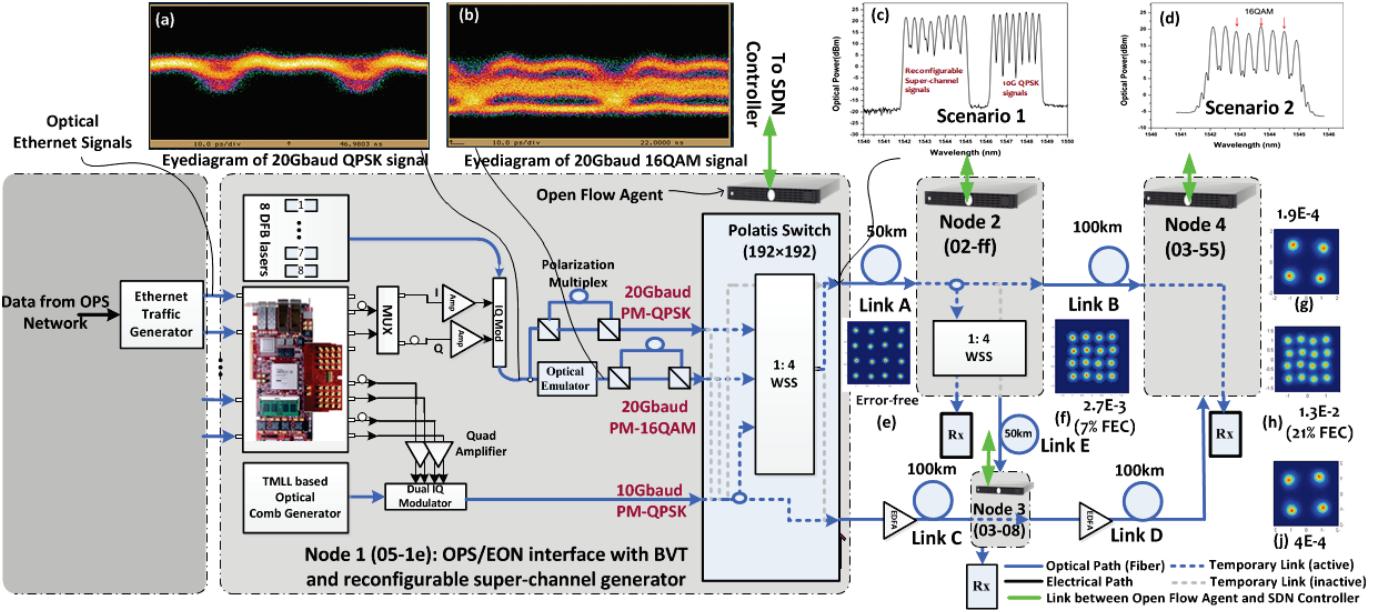


Fig. 9. Reconfigurable, programmable and flexi-grid EON with OPS/EON interface

flow control in OpenFlow 1.0 protocol, i.e., we extended *packet_in* and *flow_mod* messages, which include optical label information and an action message for controlling the OSW. These extensions have been detailed in [15]. The flow update time is 1.1 ms, with the exception of the AWG memory write time. After the flow update, each packet is forwarded to a proper output port, as in Figs. 7 c) and 7 d). The flow update demonstration shows OpenFlow capability over the FL-VC OPS network. The update takes a few milliseconds and can be longer when the size of the flow table increases and, packet length is >300 ns. Therefore, an efficient technique for a distributed OpenFlow implementation on the OPS routers is a future interest.

III. EON DATA TRANSPORT PLANE WITH OPS-EON INTERFACE

OPS networks and EON are inter-connected by an OPS-EON interface card. Figure 9 shows the transport plane of EON with the OPS-EON interface. The EON control plane, i.e., the SDN controller and agents, has been detailed in [16], including extensions to OpenFlow 1.0 protocol. An Ethernet traffic generator encapsulated the raw data from the OPS networks to optical Ethernet signals, to emulate the link between Japan and the UK. The OPS-EON interface card, which was implemented using a high-performance FPGA (HTG Xilinx V6 PCIE board), receives Ethernet traffic using multiple 10GE SPF+ modules. The interface then processes and grooms traffic to several 10-Gb/s data streams to drive a sliceable and programmable BVT through the SMA ports. To further increase the baud rate, two data streams are multiplexed to a 20-Gb/s data stream using a 2:1 multiplexer. Then, two transmitters attached to different egress ports can generate either QPSK or 16QAM signals with different baud rate for variable scenarios. The groomed data streams can be switched to different egress ports by the SDN interface, to adopt 10-Gbaud PM-QPSK, 20-Gbaud PM-QPSK or 20-Gbaud PM-16QAM signal formats for variable scenarios. Figure 10 shows the design of the OPS-EON interface. Each

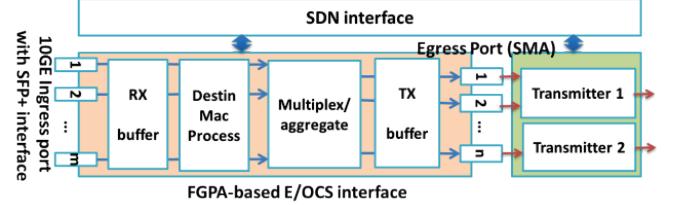


Fig. 10. Design of OPS-EON interface based on FPGA
OPS-EON interface provides links with variable capacity (40 Gb/s to 160 Gb/s).

SC signals can provide a large capacity transmission link for further Tbit/s Ethernet by grouping several carriers. SC signals show many advantages for flexigrid optical networks [17]. To support this feature, an 8-carrier SC signal is generated in a 50-GHz grid with the designed OPS-EON interface. Each carrier operates at 20 Gbaud. The flexibility of the OPS-EON interface provides modulation format programmability for each carrier. A 1:4 WSS (WaveShaper 4000s) assembles the signals to form SC signals. The total bandwidth of the generated SC signals can vary from 80 Gb/s to 1.28 Tb/s with a step of 80 Gb/s by configuring the used channel number and adopted modulation formats. Eye diagrams of the generated 20-Gbaud QPSK and 20-Gbaud 16QAM signals are shown in Fig.9 (a, b). Another 8-subcarrier programmable SC signal with 10-Gbaud PM-QPSK signals is generated in a 40-GHz grid for the long distance link. The tunable mode-locked laser (TMLL) -based optical comb generator provides the subcarriers with 40-GHz channel spacing.

As shown in Fig. 9, AoD-based Node 1, configures the launch signals for variable scenarios. For large capacity requirements (e.g., scenario 1), two SC signals are launched to the link in response to the large capacity request. The spectrum of the two SC signals is shown in Fig. 9 (c). In scenario 2, we use only 8-subcarrier SC signals with carriers 3, 5 and 7 using PM-16QAM to provide a bandwidth of 880 Gb/s (Fig. 9 (d)).

The EON consists of four AoD-based optical nodes with several beam-steering fiber switches (Polatis). The first SC

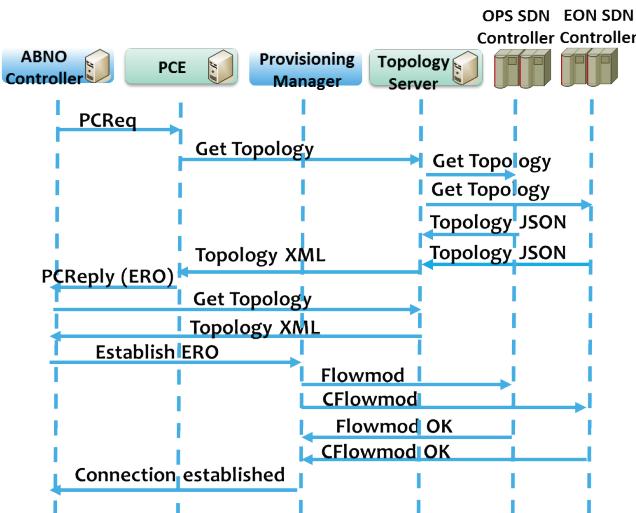


Fig. 11. ABNO controller message exchange

signals with modulation-format programmability can adopt a different modulation format for each carrier based on network request, link situation and can even adopt FEC coding in 16QAM signals. In scenario 2, the SC signals configure carriers 3, 5, and 7 to adopt 16QAM modulation and others with QPSK modulation. We test channel 7 (16QAM signals) in scenario 2. The received constellations are shown in Fig. 9 (e, f, h). An ECL is used to replace the DFB laser for the tested 16QAM channel. Due to the short link length, we decreased the launched OSNR to degraded performance. At Node 2, the dropped 16QAM signals show a BER of approximately 2.7×10^{-3} below the 7% FEC threshold. At Node 4, the BER increases up to 1.3×10^{-2} at Node 3 with more transmission length, which is below the 20% FEC threshold. By providing such a link configuration including FEC encoding, the data plane can provide more flexible service. For the QPSK subcarriers, all signals dropped at Node 4 show BERs around 4.0×10^{-4} and a recovered constellation is shown in Fig. 9 (g).

IV. END-TO-END ORCHESTRATION

The ABNO architecture [7] has been proposed as a carrier SDN solution that can operate in multi-layer, multi-technology and multi-domain network scenarios. This work extends a previous ABNO implementation [18], maintaining the ABNO architecture reference [7]. In this paper, we demonstrate the utilization of ABNO in the multi-domain scenarios, where each domain is controlled by its own technology-specific SDN controller. The presented ABNO architecture consists of four main components: ABNO controller, Path Computation Element (PCE), Topology Server, and Provisioning Manager.

The ABNO controller is the main component of the architecture and is responsible for controlling the workflows for end-to-end provisioning (Fig.11). The PCE handles the path computation across the network graph provided by the topology server and it has been extended to support OpenFlow [19]. Previously reported OpenFlow extensions for end-points and Explicit Route Objects (ERO) are shown in Fig. 12. For example, an end-to-end path computation request message

(PCReq) shall include source and destination data path ids, and path computation reply message shall include the ERO, indicating the requested path hop-by-hop. The topology server recovers the topology exposed by the North-Bound Interface (NBI) of each OpenFlow controller and is fed both to the PCE and the provisioning manager. The OPS and EON topologies are retrieved by each of the respective SDN controllers using a REST API. The topology server can serve a unified multi-layer topology to any ABNO component. The provisioning manager is responsible for the actual flow establishment request to the OpenFlow controllers through each specific controller's NBI. The provisioning manager translates the PCEP messages that it receives into the REST API for both OpenFlow-controlled OPS and EON domains, which are run by KDDI in Japan and the University of Bristol in the UK, respectively. The different messages exchanged are shown in Fig. 13. First, the EON SDN controller is contacted to establish an optical circuit, using a REST API to instantiate the required *CFLOW_MOD* messages [11]. The OPS SDN controller also offers a REST API to provision the required extended flow actions, which include an OPS label.

In Fig. 14, we show the PCE multi-layer network graph, including OPS and EON domains. We propose three different scenarios where an OPS node (00-01) is connected to EON through an OPS/EON edge node (05-1e) in which an OPS-EON interface card is placed. In the first scenario, a bit rate of 800 Gb/s for transporting aggregated OPS frames (each up to 108.2 Gb/s with a distance of 2 km) is requested end-to-end. The PCE computes a path from node 00-01 to the receiver at 02-ff. Then, the provisioning manager requests the required flow establishment towards each domain. Upon reception of the flow request, the OPS OpenFlow controller assigns OPS label 140 to the output port connected to the edge OPS/EON node. The

PCRequest Message objects		
END-POINT object		
	Source OpenFlow Address	dpid
	Destination OpenFlow Address	dpid
PCReply Message objects		
EXPLICIT ROUTE OBJECT (ERO)	OpenFlow Unnumbered Interface	dpid: interface
	OpenFlow Prefix	dpid

Fig. 12. Summary of PCEP extensions for OpenFlow [17->19]

ABNO_CONTR	PCE/TOPO_MGR	PCEP	PATH COMPUTATION REQUEST MESSAGE
PCE/TOPO_MGR	ABNO_CONTR	PCEP	PATH COMPUTATION REPLY MESSAGE
ABNO_CONTR	PCE/TOPO_MGR	HTTP	GET /get_topology_xml HTTP/1.1
ABNO_CONTR	BRISTOL_CTR	HTTP	PUT /cfollow_mod/ HTTP/1.1
ABNO_CONTR	BRISTOL_CTR	HTTP	PUT /cfollow_mod/ HTTP/1.1
ABNO_CONTR	BRISTOL_CTR	HTTP	PUT /cfollow_mod/ HTTP/1.1
ABNO_CONTR	KDDI_CTR	HTTP	POST /set_flow_action/ HTTP/1.1
KDDI_CTR	ABNO_CONTR	HTTP	HTTP/1.1 200 OK (text/plain)
BRISTOL_CTR	ABNO_CONTR	HTTP	HTTP/1.0 200 OK (application/json)
BRISTOL_CTR	ABNO_CONTR	HTTP	HTTP/1.0 200 OK (application/json)
BRISTOL_CTR	ABNO_CONTR	HTTP	HTTP/1.0 200 OK (application/json)

Fig. 13. Wireshark capture of ABNO Controller workflow

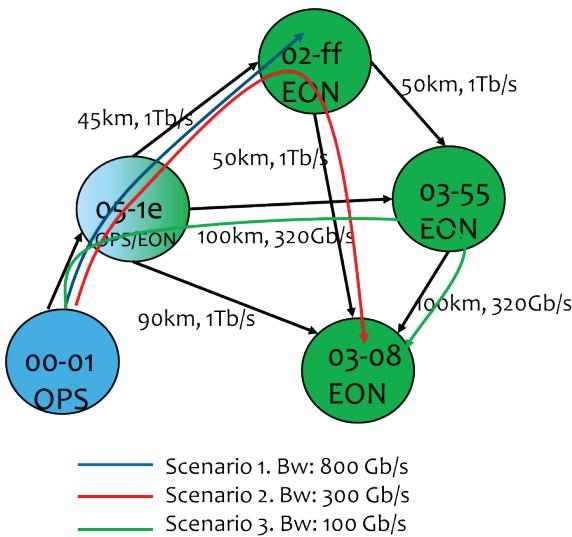


Fig. 14. PCE network graph including OPS and EON domains

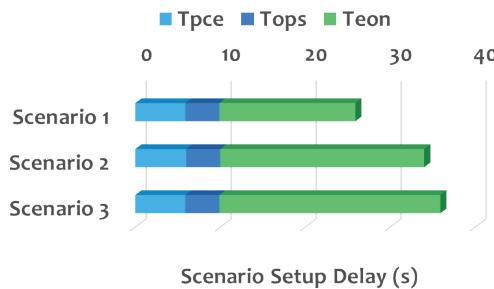


Fig. 15. Scenarios Setup Delay

EON OpenFlow controller estimates that 800 Gb/s requires two QPSK 4QAM sub-carriers which are setup at the BVT by selecting the spectrum range and slots (i.e., 193.627-194.027 THz with 50 GHz). The setup delay for this first scenario is approximately 26 s.

Figure 15 shows the measured end-to-end setup delays. The setup delay has been decoupled in path computation time (including topology request, Tpce), OPS flow (Tops) and EON flow (Teon) setup delays. The second scenario consists of an aggregated request of 300 Gb/s from 00-01 to the receiver at 03-08. In the second scenario, the behavior of the OPS OpenFlow controller is similar to the other three scenarios, while the EON OpenFlow controller assigns 2QAM sub-carriers, which are setup at BVT, with a global setup delay of 34 s. Finally, the third scenario requests 100 Gb/s, which requires 2 QPSK subcarriers. The setup delay is about 36 s.

V. CONCLUSIONS

46-108 Gb/s DMT-based FL-VC OPS over a programmable, flexi-grid EON orchestrated via multiple OpenFlow controllers in the framework of SDN has been demonstrated experimentally for the first time. In addition, the ABNO architecture has been demonstrated as a carrier SDN solution, which can operate in multi-layer, multi-technology and multi-domain network scenarios. Although further investigations are needed such as for the EON to OPS interfacing, and the real-time optical packet format adaptation based OpenFlow, the demonstrator could serve as a milestone

architecture for elastic-bandwidth slice provisioning with the finest data granularity over heterogeneous optical network architectures with domain-specific network controllers.

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