Towards Slicing for Transport Networks: The Case of Flex-Ethernet in 5G

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***Abstract*—Current solutions for network virtualization in the transport network relies on Virtual Local Area Network (VLAN) and Virtual Private Network (VPN) technologies, which facilitate logically isolated connectivity, providing data traffic seperation. However, co-existing VLAN/VPNs on top of a common infrastructure may compete for the same physical resources and introduce performance degradation, especially in case of congestion. This paper introduces Flex-Ethernet (Flex-E) and investigates its use as candidate interface solution for facilitating "hard" slicing in transport networks. This study sheds light on how Flex-E together with newly developed techniques like Segment Routing (SR), can enable a dynamic path allocation with strict performance guarantees. The standardization gaps and open challenges are also elaborated.**

***Index Terms*—Flex-E, Network Slicing, 5G, transport networks, Segment Routing, SDN**

I. Introduction

The fifth generation of mobile communications (5G) is expected to facilitate an innovative business ecosystem in which verticals implement new services. Transport, energy, health care, home networks and smart manufacturing, are among the vertical segments that can benefit from 5G. However, such diverse landscape of services imposes conflicting performance requirements, which introduce the need for agile and programmable resource allocation. To realize practically a network of service specific capabilities, NGMN defined the notion of network slicing, as a logical self-contained network, which enables customized services with respect to different business requirements on the top of a common infrastructure [1][2]. Logical networks allow the support of diverse service performance with the appropriate isolation, network and cloud resources, topology, network functions, value added services, policy and operations.

Current transport networks support connectivity between the radio access and core networks for diverse technologies like GSM, UMTS, HSDPA and LTE [3]. A unified architecture for a converged backhaul transport network relies on MPLS and/or Ethernet with encapsulations over Multi-Protocol Label Switching (MPLS), consolidating TDM, HDLC, ATM and IP/Ethernet backhaul technologies [4]. However, the configuration of the transport network is static, while VPN based networking provides no performance guarantees, only traffic separation. LTE Quality of Service (QoS) is applied through bearers establishment and mapping of GPRS Tunnelling Protocol (GTP) tunnels with Differentiated Services Code Point (DSCP) tags on the IP layer. DSCP is used for priority scheduling, nevertheless no absolute guarantees for metrics like throughput or delay can be provided.

This paper introduces the notion of "hard" slicing in the transport network layer and presents Flex-E interface technology as a means to realize the concept of logically isolated Ethernet flows operating on common links that avoid influencing negatively the performance of each other in case of congestion. Flex-E adopts the "all-IP, all-Ethernet" design paradigm leveraging the benefits of Ethernet as the data link layer technology of choice, independently of the PHY. Flex-E can utilize fully the capacity of Network Processing Units (NPU) without waiting for future Ethernet rates to be standardized, while it supports a variety of Ethernet MAC rates independently of the Ethernet PHY rate being utilized.

Slicing on the interface level can practically be combined with overlay network techniques that facilitate routing and traffic management. Flex-E can then be used to bundle or divide physical Ethernet interfaces into multiple Ethernet hard pipes based on timeslot scheduling, while Segment Routing (SR) [5] and/or Deterministic Networks (DetNet) [6] can flexibly steer traffic towards specific routes assuring latency, while providing also the means for selecting a particular link and queue with respect to each slice. An enhanced control plane and orchestration/management plane is needed to coordinate Flex-E pipes and SR decisions, while aligning slice allocations in the mobile network with the underlying transport layer.

The contributions of this paper are the following:

- We analyze Flex-E in the light of network slicing for facilitating flexible “hard” pipes with capacity guarantees on the interface level. Flex-E appears as a promising solution for slicing the transport layer. It can exploit high multiplexing gains and increase network utilization efficiency, while at the same time guarantees isolation through an exclusive use of timeslots.
- We elaborate an integrated solution that exploits Flex-E “hard” pipes and SR for providing traffic steering of overlay tunnels. SR can also influence the traffic management process inside a router by enabling a queue selection with respect to a particular slice.
- We shed light into the control plane aspects of Flex-E that are currently in an early standardization state and explore the interfaces for interacting with the orchestration/management plane.

The remainder of this paper is organized as follows. Section II, presents basic background information on slicing and all-Ethernet. Section III elaborates on the primitives of Flex-E technology, whereas Section IV devises a SDN solution aligned with network slicing orchestration concepts. Section V describes challenges and open issues related with the deployment of Flex-E, while section VI concludes this work.

II. Motivation & Background

A. Slicing the Transport Network

In principle, a 5G network slice supports a communication service type with specific requirements and configurations for handling the control and data plane. For each slice, although traffic is separated, the desired bandwidth is not guaranteed in software or through packet classification and traffic shaping at ingress and egress points. Physical layer virtualization approaches considering optical networks [7], [8], focus on the attributes of optical link elements like the number of wavelengths per fibre, while the supported granularities drive the virtualization approach. Adaptive transponders over Wavelength Division Multiplexing (WDM), spectrum fragmentation and Optical Cross-Connect (OXC), and Reconfigurable Optical Add-Drop Multiplexer (ROADM) are optical network virtualization techniques that can be exploited for network slicing.

In the light of 5G network slicing, the Metro Ethernet Forum (MEF) suggests that a new transport network should take into account the following main attributes: it must be Ethernet-based, agile, assured and orchestrated with dynamic and automatic service management for the entire life-cycle of connectivity services [9]. Flex-E is a choice for enabling network slicing for the transport network using a hardware means to guarantee QoS on the interface level [10].

Table I: Ethernet/Packet-based Transport Networks

Ethernet over MPLS (EoMPLS) is a tunneling mechanism for Ethernet traffic through an MPLS-enabled layer 3 network.
Ethernet over SONET/SDH (EoS), SONET/SDH transfers multiple digital bit streams synchronously over optical fiber. EoS Ethernet frames sent on the optical link are encapsulated by a Generic Framing Procedure (GFP) to create a synchronous stream of data from the asynchronous Ethernet packets.
Packet over SONET (PoS) [RFC 2615] can be used to map any packet technology including ATM. Under POS, PPP encapsulated IP packets are framed using high-Level Data Link Control (HDLC) protocol and mapped into the SONET SPE or SDH VC
Ethernet over DWDM [ITU-T G.872] combines packet-processing and optical-wavelength assignment into a single system.
Ethernet over OTN [ITU-T G.709] (OTN is the successor of SONET/SDH) requires the mapping of ingress frames at a UNI (ingress port) to a specific container called an Optical Channel Data Unit (ODU).
Flexible OTN (FlexO) [ITU-T G.709.1/Y.1331.1] provides for OTN interfaces a similar functionality to that of Flex-E for Ethernet ones. It offers an interoperable system interface for OTUCn transport signals, while it enables higher capacity ODUflex and OTUCn, by means of bonding m standard-rate interfaces.
Flex-E [IA-OIF-FLEXE-01.0] is running on top of OTN-WDM providing Ethernet services, where the multiplexing of users is performed in time. Such time multiplexing between client groups takes place in a layer between the MAC and the Physical Coding Sublayer (PCS).

B. The all-Ethernet Movement

In the last fifteen years there is a clear movement towards packet-based services, which drives packet-aware capabilities in both the mobile and transport networks. For the mobile network, the all-IP, all-Ethernet design paradigm led to a complete redesign of the core network from a connection-oriented 3G core to a 4G IP-based Evolved Packet Core, while for the transport network the main effort concentrated on exploiting the benefits of using Ethernet technologies as the data link layer independently of the PHY. A flat-network design greatly simplifies the control and management procedures, improves performance and promotes network efficiency. An all-IP, all Ethernet flat network design offers the ideal ground over which the concept of network slices can be realized.

On the radio side current efforts focus on eCPRI that is a packet based fronthaul interface developed by CPRI Forum and IEEE P1904.3 Radio over Ethernet (RoE). Carrier Ethernet enables service providers to offer premium Ethernet services on transport networks. According to ITU-T a migration from a legacy network to a new packet transport one is significant for telecom carriers [11]. ITU-T Recommendation G.709 proposes Optical Transport Network (OTN) that enables IP/Ethernet-oriented services as a replacement of legacy Synchronous Optical Networking/Synchronous Digital Hierarchy (SONET/SDH) networks. SONET/SDH supports fixed frame rates, whereas OTN supports a fixed

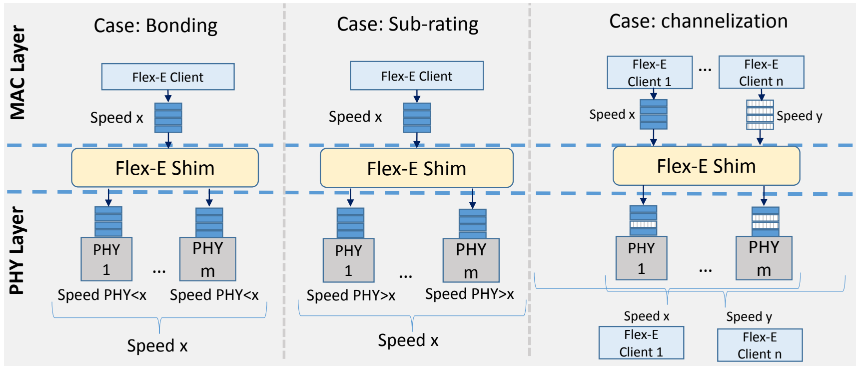

Fig. 1. Flex-E operational scenarios

frame size that facilitates the mapping of IP/Ethernet services over the carrier network. The ongoing *all-Ethernet* activities are summarized in Table I.

The industry consensus is that OTN/WDM will serve as one of the PHY underlay towards 5G, wherein Flex-E can run on top of OTN-WDM enabling Ethernet services. The multiplexing of users is performed over time with every Flex-E Ethernet client exploiting a "hard" pipe over bonds of PHYs with guaranteed performance.

III. Flex-E based Agile Resource Allocation

A. Flex-E Basic Operation & Concepts

Flex-E technology is introduced as a thin layer, known as Flex-Shim, being able to support data rates out of the conventional range offered by current Ethernet standards. The main idea behind Flex-E is to decouple the actual PHY layer speed from the MAC layer speed of a client. Flex-E is based on a time-division multiplexing mechanism that is able to drive the asynchronous Ethernet flows over a synchronous schedule over multiple PHY layers. The main operational components of Flex-E include the following:

- *Flex-E Client* is an Ethernet flow based on a MAC data rate that may or may not correspond to any Ethernet PHY rate. The MAC rates currently supported are 10, 40, and m x 25 Gb/s.
- *Flex-E Group* is a group of Ethernet PHYs that are bonded together. OIF supports Flex-E groups composed of one or more bonded 100GBASE-R PHYs. Higher rates like 400GbE are under development in the IEEE P802.3bs project and will be supported in future Flex-E releases.
- *Flex-E Shim* is the layer that maps or de-maps the Flex-E clients over a Flex-E group. This procedure relies on a calendar-based slot scheduling. Essentially a set of slots are assigned to each client, according to the MAC layer speed and group participation.

Currently there are three operational scenarios supported by Flex-E, which relate in a different way the MAC layer speed with the corresponding PHY speed (higher or lower), allowing a distinct manner for multiplexing clients in time (see Fig. 1):

- *Bonding*: allows a MAC layer speed higher than a single PHY by grouping multiple PHYs to serve a flow (e.g. support a 200G MAC over two bonded 100GBASE-R PHYs).
- *Sub-rating*: MAC layer speed is less than the actual PHY. Allows the MAC layer to use a portion of a PHY to serve a flow (e.g. support 50G MAC over a 100GBASE-R PHY).
- *Channelization*: enables multiple Flex-E clients over a shared single PHY or bounded PHY via the means of time division multiplexing in the Flex-Shim (e.g. support 150G and a 50 MAC over two bonded 100GBASE-R PHYs).

Hybrids of these scenarios are also possible, for instance a sub-rate of a bonded PHY supporting 250G MAC over three bonded 100GBASE-R PHYs. These options allow increased resource flexibility for 5G and fine-tuning the offered rate depending on the usage.

B. The Role of Flex-E Shim

Flex-E introduces a Shim layer responsible for the mapping of Flex-E clients (i.e. Ethernet flows) to groups of PHYs. The Flex-E Shim layer is positioned between the Ethernet MAC and the Physical Coding Sublayer (PCS) of the PHY layer, as depicted in Fig. 2. Each layer supports:

- *Data Link Layer*: a) Logical Link Control (LLC) for multiplexing network protocols over the same MAC, b) MAC Sublayer for addressing and channel access control mechanisms, and c) Reconciliation Sublayer (RS) that processes PHY local/remote fault messages.
- *PHY Layer*: a) PCS performs auto-negotiation and coding, b) Physical Medium Attachment (PMA) sublayer performs framing, octet synchronization/detection, and scrambling/descrambling, and c)

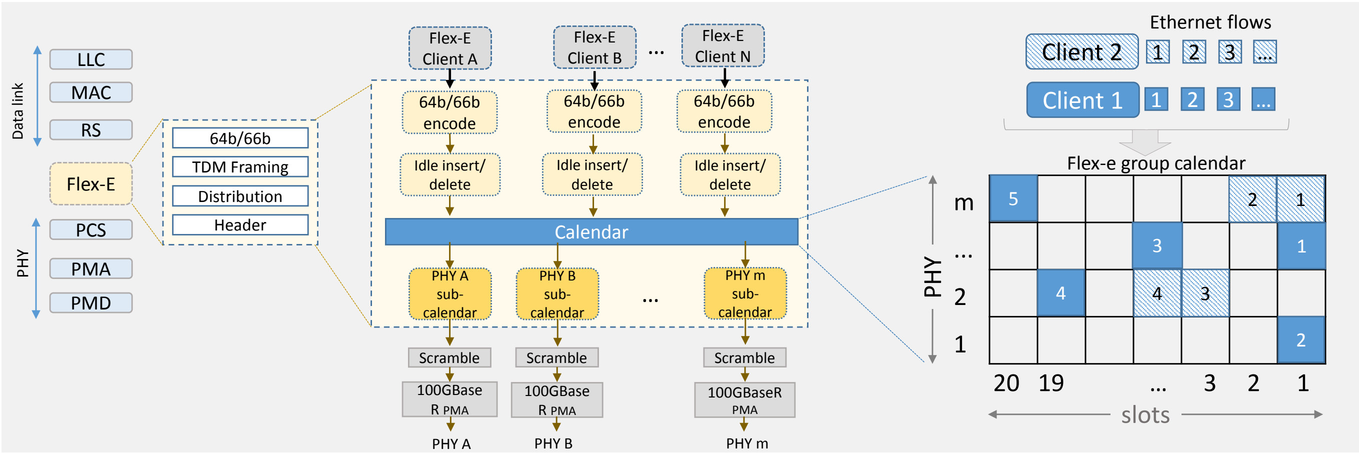

Fig. 2. Flex-E layer between Ethernet MAC and PCS showing the FlexE Shim distribute/aggregate sub-layer in PCS/PMD.

Physical Medium Dependent Sublayer (PMD) is the transceiver that is physical medium depended.

Each Flex-E client has its own separate MAC and RS above the Flex-E Shim, which operate at the client rate. The layers below the PCS are used intact as specified for Ethernet. As a first step in every Flex-E client flow, a 64b/66b encoding is performed to facilitate synchronization procedures and allow a clock recovery and alignment of the data stream at the receiver. Then a procedure of idle insert/delete is performed. This step is necessary for all Flex-E clients in order to be rate-adapted, matching the clock of the Flex-E group according to IEEE 802.3. The rate of the adapted signal is slightly less than the rate of the Flex-E client in order to allow alignment markers on the PHYs of the Flex-E group. Then all the 66b blocks from each Flex-E client are distributed sequentially into the Flex-E group calendar where the multiplexing is performed.

Flex-E calendar: For each Flex-E group, a calendar is responsible to assign 66b block positions on sub-calendars on each PHY, to each of the Flex-E clients. The calendar has a length of 20 slots per 100G of Flex-E group and a bandwidth allocation of 5 Gb/s granularity, where a client may have any combination of slots in a group. In order to facilitate the demux process, the calendar is communicated along with the data. There are two calendar configurations for each PHY of the Flex-E group: the A calendar configuration (encoded as 0) and the B calendar configuration (encoded as 1). The two calendars are used to facilitate reconfiguration. Calendar slot are logically interleaved. A link failure is generated towards all Flex-E clients in the group once any PHY of the group fails.

A control function manages the calendar slot allocation for each Flex-E client and inserts/extracts the Flex-E overhead on each Flex-E PHY in the transmit/receive direction. Calendar scheduling between the PHYs is currently performed on a RoundRobin fashion. The calendar scheduling mechanism and the ability to adjust the slot allocation for guaranteed user performance, enables Flex-E to precisely “slice” the transport network.

C. Mapping Mechanisms to Transport Networks

The IA OIF-FLEXE-01.0 is not explicitly describing the transport network PHY. It implicitly however describes OTN networks as a potential underlay technology. From the deployment perspective three mappings have been identified:

- *Case A (Flex-E unaware of the transport network)*: A legacy underlay transport network (e.g. OTN) provides no special support for Flex-E. Flex-E frames are transparently transported, while Flex-E Shim will need to tolerate and accommodate considerably more skew. All PHYs of the Flex-E group are carried independently over the same fiber route.
- *Case B (Flex-E decoupled from the transport network)*: Flex-E terminates in transport network equipment, before entering the transport network. Traffic traversing the transport network is independent of Flex-E.
- *Case C (Flex-E aware of the transport network)*: The transport layer is aware of carrying Flex-E frames and can be used in cases where the Ethernet PHY rate is greater than the wavelength rate or when the wavelength rate is not an integral multiple of the PHY rate. All PHYs of the Flex-E group are carried independently over the same fiber route. Special mapping processes are needed so that the frame can be terminated and aligned correctly.

D. Control and Management Plane information

Currently, the control plane for the end-to-end provisioning of a Flex-E pipe is an open issue, yet to be specified. A GMPLS signaling through RSVP-TE approach is proposed in [12], while a software defined network (SDN) control with out-of-band signaling can be a potential alternative candidate. In both GMPLS and SDN cases, new data models need to be devised that expose the Flex-E information and functionalities to the control plane. Although the design of YANG models is possible over RSVP [1], new YANG models are expected to emerge specialized for Flex-E. As in all control plane models, the design primitives for the Flex-E control plane are security, scalability and fast convergence. The following basic functionalities need to be supported:

1) *Flex-E Group provisioning, configuration and instantiation*: Routers must advertise the type of Flex-E support that they offer, the current calendar allocation and information like link delay and node delay. Regarding capabilities exposure auto-negotiation procedures also need to be defined.
2) *Flex-E calendar scheduling*: The control plane must be able to provide an efficient mechanism for the optimal assignment of PHYs to a specific group, while also consider for the optimal slot allocation in the group calendar for each Flex-E client.
3) *Establishment of Flex-E multi-hop paths with end-to-end synchronization:* Existing solutions consider a pre-configured Command-Line Interface (CLI) based Flex-E group configuration and client assignment. Note that the most important functionality in order to have a functional Flex-E setup is that for each PHY the mux and demux share the same sub-calendar. Otherwise, it would be impossible to decode the slot information to a specific Flex-E client. In a multi-hop setup this information sharing can be challenging.
4) *Dynamic calendar switching configurations:* Control plane must support dynamic switching between calendar configurations (A or B) and allow to modify the configuration of Flex-E clients into calendar slots, based on SLAs and performance criteria.
5) *Handshake messaging for calendar switch:* The control plane must be able to efficiently support a handshake messaging mechanism for calendar switch, between the mux and demux. This can be achieved through control plane coordination of calendar request and calendar acknowledge messages between the mux and demux.

[1]https://tools.ietf.org/html/draft-ietf-teas-yang-rsvp-07
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The Flex-E management channel is used to exchange configuration and OAM messages regarding the Flex-E Shim-to-Shim connections. Each PHY of the Flex-E group can carry its own management channels. Existing specification defines one 64/66 bit overhead block to be inserted in 1023x20 blocks run in each PHY for each Flex-E group. Functionalities that need to be supported by the management plane are related to fault management, e.g. when the intra-PHY skew exceeds the skew tolerance (local Flex-E demux fault), or dealing with remote PHY failures.

E. Implementation & Standardization Activities

Although Flex-E was introduced by OIF, potential use cases were considered within other organizations such as the Ethernet Alliance and described by certain industrial player like Google in [13]. Proprietary deployments considering an integrated approach of the control and management plane of Flex-E over OTN were also contributed by Huawei [14]. Regarding Flex-E implementation landscape Huawei incorporates Flex-E in PTN990 router series, Ixia presented a demo in OFC 2016 with FlexE 2x 100GbE and Ciena provides the Flex-E Liquid Spectrum solution.

Regarding the Flex-E standardization, the OIF is handling the Flex-E data plane, while IETF concentrates its efforts on the control plane. The OIF announced the initiation of a FlexE 2.0 project in December 2016, focusing on the management plane providing further details on the way to scale the calendar slot bandwidth, adding a skew management option, and supporting the transport of time or frequency. IETF is considering Flex-E within the context of network slicing in [15], with the main control plane work being carried out in the Common Control and Measurement Plane (CCAMP) Working Group. Flex-E can be viewed as a generalization of the Multi-Link Gearbox (OIF MLG 1.0 and OIF-MLG-02.0). The MLG interface multiplexes ten 10GBase-R PCS channels into a single 100Gbps link, compatible with the IEEE 802.3ba.

IV. An SDN-Based FLEX-E Solution for Network Slicing

In this section we devise an SDN approach that integrates Flex-E with overlay networks in support of network slicing. For carrier transport networks, SDN controllers like ONOS and OpenDayLight (ODL) offer plugins for traditional carrier network technologies like BGP, PCE and MPLS, enabling a technology-agnostic control in multi-domain environments. Our SDN architecture proposal is an extension of [11] in the following two directions: (i) Flex-E is embedded between the

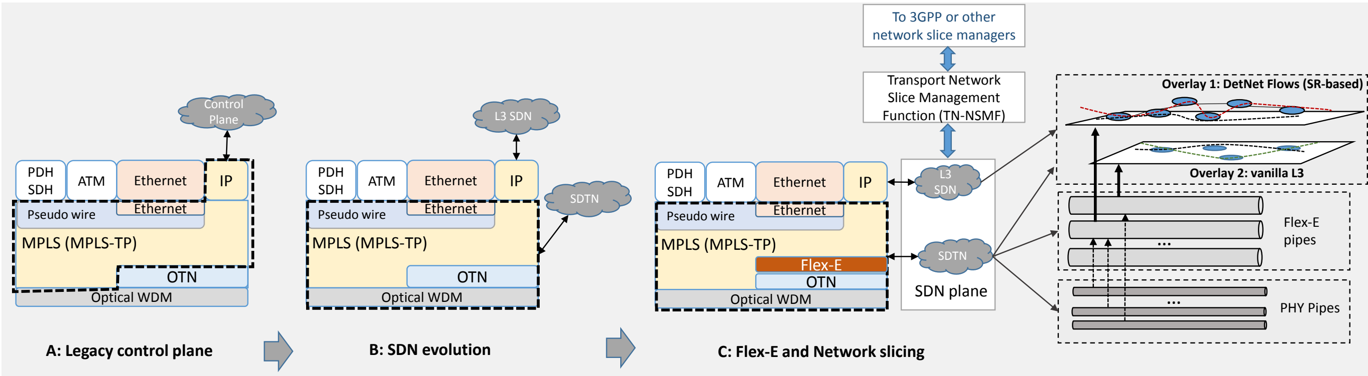

Fig. 3. An SDN-based solution for network slicing enabling isolation via the means of Flex-E

OTN and MPLS-TP, with the Software Defined Transport Networks (SDTN) integrated with a network slice management system and (ii) on top of the Flex-E pipes overlay network segments exploit the routing flexibility of SR and the performance guarantees of DetNet.

The proposed SDN architecture is shown in Fig. 3. On the left (Fig. 3-A), the native control plane architecture is presented, where OTN technology exploits WDM services on the optical medium considering a MPLS control plane. In the center (Fig. 3-B), the ITU-T SDTN is presented, where not only the MPLS control is exposed to the SDN controller, but also the transport network functionalities from the OTN and WDM levels. Programmable data-planes through wavelength assignment and OTN fine tuning can be used, while an SDN control can be applied on the IP level. On the right (Fig. 3-C), a unified transport control plane is exposed to network service orchestrator. On top of OTN, Flex-E may exploit the MPLS services. The design is so generic that even direct SDN control can be applied to the Flex-E data plane or through the (G)MPLS stack. The network service orchestration can be driven by the 3GPP network slice manager. Our SDN-based architecture consists of the following fundamental elements:

- Flex-E over OTN is the dominant scenario aligned also with the OIF first implementation agreement. Although there is a proposal to adopt GMPLS as the Flex-E control plane, is not yet standardized. The adoption of SDN on top of MPLS/GMPLS is a mature technology, but requires standardization exensions related to Flex-E messaging related to calendar setup, update configuration and Flex-E grouping.
- A fully pluggable SDN control (like ODL) can be used to realize programmability on L3, L2 and L1 transport network. Such SDN solution can be applied to control Flex-E through extended MPLS plugins and vertically affect all L1, L2 and L3 parts of the transport network.
- With respect to network slicing 3GPP has defined the Network Slice Management Function that is responsible for the end-to-end management and orchestration of a Network Slice Instance (NSI) (TR 28.801). Currently there are the following gaps with respect to the transport network segment: (i) exposing the capabilities of the underlying transport network to the mobile one via the means of a data model and (ii) defining the procedures to configure and operate a NSI considering the parameters, e.g. latency, jitter, loss, etc., provided by the overlay mobile network.
- Network service orchestration of a NSI relates to a link or a path considering a complex topology structure, while assuring the required SLA. The network service orchestration drives the provisioning, configuration and instantiation as well as the running phase and decommissioning of a particular network service assuring the desired performance.

In current Flex-E deployments configurations are enforced statically via the means of CLI. SDN is expected to unleash the potential of Flex-E as an Ethernet-based solution for slicing the transport network.

V. Challenges & Open Issues

Although the initial standardization phase for Flex-E is completed, a number of challenges are still open. Flex-E needs to support automated service ordering offering on-demand transport connectivity within minutes. Automatic PHY allocation to groups, adding/removing Flex-E clients dynamically, or adding/removing Flex-E groups, are open issues that need to be investigated, while the procedures for switching calendar state updates can be further optimized. Flex-E needs flexibility when adding/removing a client to/from a corresponding group without affecting the traffic on other clients.

The goal of the control plane is to assist Flex-E in establishing an end-to-end “hard pipe” channel from a source node A to destination node B across multiple hops and to accomplish this there is a need for extensions on the control signaling mechanisms. In supporting efficiently port isolation via the means of Flex-E when SR or DetNet is adopted as an overlay solution there may be a need to specify new interfaces for archiving promptly coupled resource allocation. In this regard, control plane overhead analysis needs to be performed. Further extensions for Flex-E and SDN control are needed when considering user mobility within an SDN environment as introduced in [16] for optimizing the resource usage. A network slicing solution based on SDN integrating Flex-E with SR/DetNet can also assist in assuring the performance isolation for Fronthaul/Midhaul considering different base station functional splits for distinct services as elaborated in [17]. This would require an tight alignment and active interaction of the radio access with the transport layer.

The integration of Flex-E with Flex-O is an active field of research, while in FLEX-E aware OTN devices, Flex-Shim calendar mapping to an OTN schedule can be further optimized. Regarding SLA management, it is not obvious how Flex-E will be able to support an integrated solution with DiffServ, port based priorities, and VLAN 802.1p priorities. Furthermore besides throughput guarantees, other performance metrics like Excess Burst Size (EBS), delay or loss assurance need to be investigated further, while aligning the SDN control of Flex-E with the overlay SR and DetNet. Regarding OAM operations, Flex-E Group Discovery is under discussion in OIF to enable Flex-E neighbor and capability discovery. A new protocol needs to be devised or an alternative would be to rely on Link Layer Discovery Protocol (LLDP) extensions.

VI. Conclusions

This paper investigates the adoption of Flex-E as a means to realize hard isolation in provisioning network slicing for the transport network. The primitives of the Flex-E technology are described, providing the related background information and the current status of the standardization activities. An SDN-based architecture is presented elaborating on the interfaces for providing life-cycle management procedures and orchestration for network slicing. Such an architecture considers Flex-E as the underlying "hard pipe" solution, which enables flexibility and performance assurance for the associated overlay virtual network that can be controlled via the means of SR and/or DetNet. The current challenges and open issues are also discussed bringing light into the next research and standardization phase for Flex-E.

Acknowledgments

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References

[1] N. Alliance, "Description of Network Slicing concept," *NGMN 5G P*, vol. 1, 2016.

[2] I. Afolabi, T. Taleb, K. Samdanis, A. Ksentini, and H. Flinck, "Network slicing & softwarization: A survey on principles, enabling technologies & solutions," *IEEE Communications Surveys Tutorials*, vol. 20, no. 3, pp. 2429–2453, 3rd Quarter 2018.

[3] O. Tipmongkolsilp, S. Zaghloul, and A. Jukan, "The evolution of cellular backhaul technologies: Current issues and future trends," *IEEE Communications Surveys Tutorials*, vol. 13, no. 1, pp. 97–113, First 2011.

[4] BBF, "Technical specifications for mpls in mobile backhaul networks." TR-221, Issue: 1, Oct 2011.

[5] C. Filsfils, S. Previdi, L. Ginsberg, B. Decraene, S. Litkowski, and R. Shakir, "Segment routing architecture." IETF RFC8402, Jul 2018.

[6] N. Finn, P. Thubert, B. Varga, and J. Farkas, "Deterministic networking architecture," in *draft-ietf-detnet-architecture-08*. IETF-Draft, Sep 2018.

[7] M. Jinno, H. Takara, K. Yonenaga, and A. Hirano, "Virtualization in optical networks from network level to hardware level," *Journal of Optical Communications and Networking*, vol. 5, no. 10, pp. A46–A56, 2013.

[8] R. Nejabati, E. Escalona, S. Peng, and D. Simeonidou, "Optical network virtualization," in *Optical Network Design and Modeling (ONDM), 2011 15th International Conference on*. IEEE, 2011, pp. 1–5.

[9] MEF, "The third network: Vision and strategy based on network as a service principles," *White paper*, Nov. 2014.

[10] OIF, "Flex ethernet implementation agreement, ia oif-flexe-01.0," Mar. 2016.

[11] M. Murakami, H. Li, and J.-D. Ryoo, "Packet transport networks: Overview and future direction," *2nd APT/ITU Conformance and Interoperability Workshop (C&I-2)*, Aug. 2014.

[12] I. Hussain, R. Valiveti, Q. Wang, L. Andersson, M. Chen, and H. Zheng, "Gmpls routing and signaling framework for flexible ethernet (flexe)," in *draft-izh-camp-flexe-fwk-05*. IETF-Draft, Mar 2018.

[13] T. Hofmeister, V. Vusirikala, and B. Koley, "How can flexibility on the line side best be exploited on the client side?" in *Optical Fiber Communication Conference*. Optical Society of America, 2016, pp. W4G–4.

[14] R. Vilalta, R. Martnez, R. Casellas, R. Muoz, Y. Lee, L. Fei, P. Tang, and V. Lpez, "Network slicing using dynamic flex ethernet over transport networks," in *2017 European Conference on Optical Communication (ECOC)*, Sept 2017, pp. 1–3.

[15] L. Qiang, P. Martinez-Julia, L. Geng, J. Dong, K. Makhijani, A. Galis, S. Hares, and S. Kuklinski, "Gap analysis for transport network slicing," in *draft-qiang-netslices-gap-analysis-01*. IETF-Draft, Jul 2017.

[16] D. L. C. Dutra, M. Bagaa, T. Taleb, and K. Samdanis, "Ensuring end-to-end qos based on multi-paths routing using sdn technology." IEEE Globecom, Dec 2017.

[17] C.-Y. Chang, N. Nikaein, O. Arouk, K. Katsalis, A. Ksentini, T. Turletti, and K. Samdanis, "Slice orchestration for multi-service disaggregated ultra dense rans," vol. 56, no. 8. IEEE Communications Magazine, Aug 2018.