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Dynamic Multi-domain Virtual Optical Networks Deployment with Heterogeneous Control Domains

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(Invited Paper)

***Abstract*—We propose a multi-domain resource broker to dynamically provision multi-domain Virtual Optical Networks (VON) across heterogeneous control domains (i.e., GMPLS and OpenFlow) and transport (i.e., Optical Packet Switching and Elastic Optical Networks) technologies. We have designed, implemented and experimentally evaluated the multi-domain resource broker in an international testbed across Spain, UK and Japan.**

***Index Terms*—optical network virtualization; resource allocation algorithms; GMPLS/PCE; OpenFlow; OPS; EON.**

I. Introduction

Data Center (DC) interconnection traffic stands for 7% of global DC traffic, while intra DC traffic stands for 76%. More than 350 Exabyte (EB) and 3970 EB per year are expected in 2015, respectively [1]. Current DC interconnections are based on Ethernet transport services, which are provided through the classical IP/MPLS stack [2]. In consequence, there is a clear need for the development of efficient and dynamic network technologies for Ethernet transport services.

In this context, Optical Packet Switching (OPS) technology is seen as an appealing packet transport solution for offering Ethernet services within the Data Center [3]. Elastic Optical Networks (EON) will provide long-reach optical transport for data rates beyond 100Gb/s [4]. Thus, EON will provide the required flexible transport capacity at the backbone networks, while OPS switches, used for intra-DC connections, will provide the benefits of statistical multiplexing and connection-oriented packet-based services.

Optical network virtualization enables physical infrastructure providers to partition, abstract and compose their physical resources into multiple independent slices (i.e., virtual networks) with each virtual resource results in the same functionality of the real physical resource, with an acceptable performance penalty [5].

In an optical network supporting network virtualization, each Virtual Optical Network (VON) requires a control plane for the provisioning of dynamic, adaptive and fault-tolerant network services. Two control plane architectures are active subjects of research, namely GMPLS and OpenFlow (OF). On one hand, the GMPLS architecture is based on a distributed control plane (i.e., signaling, routing and link management), and has been extended to support delegating the path computation function to a path computation element (PCE) [6]. On the other hand, OF allows operators to control the network using software running on a logically centralized controller [7]. OF defines an open protocol that allows configuring a network device remotely.

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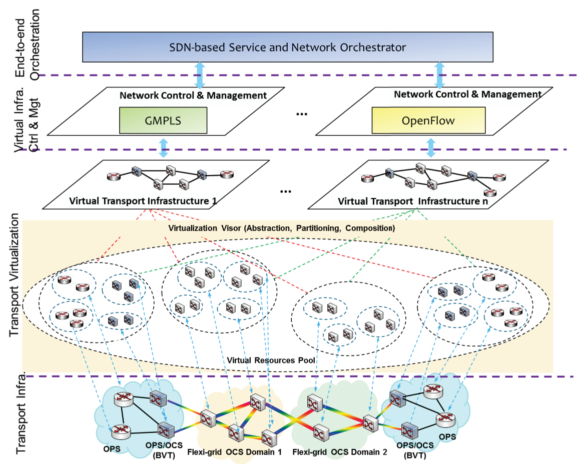

Fig. 1. Transport Virtualization Layer

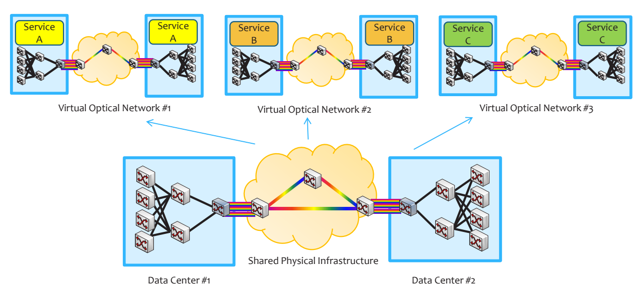

Fig. 2. Data Center interconnection by means of virtual optical networks

The proposed network architecture for a next-generation software defined optical Ethernet transport network is shown in Figure 1, which is composed of four layers: an optical infrastructure layer, a transport network virtualization layer, a control plane layer, employing both GMPLS and customized network control based on OF sits over each virtual transport infrastructure and a service and network orchestration layer, using SDN-based orchestrator to enable the seamless interworking between GMPLS and OF control domains. A network control domain is considered to be any collection of network elements under a given control mechanism, regardless of whether it encompasses one or more TE domains.

In this context, the concept of Virtual Data Centers (VDC), comprising both virtual networks (interconnecting the distributed DC) and virtual IT resources (compute and storage within DCs), have been proposed for supporting multi-tenancy and application-specific requirements of DC [8]. Figure 2 shows how different applications and services can be run on top of different VDC, each providing the necessary QoS requirements.

While IT resources can be easily virtualized, the provisioning of a VON for DC interconnection remains a research challenge, due to the fact that a DC interconnection usually comprises heterogeneous optical transport and control plane technologies, which do not naturally interoperate. The authors in [9] have proposed VON services across multiple domains, but this work did not take into account the inherent heterogeneousness of multiple control domains. This paper proposes a Multi-domain Resource Broker (MRB) which takes into account this heterogeneity. Also an orchestration mechanism is presented, which allows the composition of end-to-end virtual transport infrastructures across different transport technologies as well as end-to-end network service provisioning across multiple VONs comprising different transport and control plane technologies.

The proposed MRB shall not be understood as a broker within the classical understanding (e.g., buy/sell, negotiate), but as a network entity able to satisfy different network virtualization requirements, within the heterogeneous network control domains.

This paper extends the work presented in [10] and it is organized as follows: firstly, the architecture for a multi-domain resource broker is presented; secondly, we focus on the deployment of GMPLS-controlled VONS; thirdly, OF-controlled VONs are detailled; fourthly, a multi-domain resource allocation algorithms is presented; finally, we present the experimental assessment of the proposed multi-domain resource broker and we conclude.

II. Multi-domain VON System Architecture

The proposed MRB system architecture provides a mechanism for virtualizing optical transport nodes and links (Fig. 3). The partitioning of the resources is technology dependent, and to this end, the proposed system architecture incorporates a generic network slicing abstraction mechanism for the different transport infrastructure resources (i.e., OPS and EON).

We propose three different implementations of the network slicing abstraction mechanism, with the purpose to provide a virtualization mechanism in:

- GMPLS-controlled EON,
- OF-controlled EON,
- OF-controlled OPS.

The virtualization of a GMPLS-controlled EON and of an OF-controlled EON have been addressed in [11] and [7], respectively. In next sections, the proposed virtualization architectures are detailed, including how these feet in the multi-domain resource broker architecture. To the best of our knowledge the virtualization of an OPS network has not been addressed previously. For simplicity, we assume a virtualization model of an OPS node based on port partitioning.

The MRB controls the VON deployment by means of the different Virtualization Visors (VV). These VV are responsible for the virtualization of technology-dependent optical infrastructure domains. Each proposed VV partitions each domain resources (i.e. links and nodes) into virtual optical resources. Later, the obtained virtual optical resources are composed into actual VON domains, controlled by either a GMPLS or an OF control plane, assigned by each VV.

The MRB is responsible for the setup of a multi-domain VON but not for its control, as either a GMPLS control plane or OF controller are responsible for each VON domain. An orchestration mechanism is needed in order to provision end-to-end connectivity within the VON. In order to provide this necessary orchestration, we propose the usage of a Hierarchical Stateful PCE (HS-PCE), as proposed in [12]. The usage of HS-PCE is detailed later.

The MRB consists of four main components: the request handler, the resource assignment module, the resource configurator module and the global network Traffic Engineering Database (TED) (Fig 4).

The request handler accepts VON requests from a client, using incoming TCP sessions for the reliable delivery, and handles these requests asynchronously and dynamically. A VON Request consists of a XML file, describing the requested virtual nodes, the requested virtual links between these nodes and the required minimum guaranteed bandwidth. For each VON setup request a VON identifier (VON-ID) is assigned. The VON-ID will be used by the MRB to map the assigned resources in each domain to the VON request.

Resource assignment algorithms need to be introduced, focusing on the optimal planning (i.e., off-line) or the dynamic request allocation (i.e., on-line) of VON requests. We have developed an algorithm bundle (Fig. 7), including several algorithms designed for different scenarios (i.e., single/multi-domain flexi-grid, OPS). The algorithm bundle reads the information of physical networks (e.g., the network topology and the availability of physical resources of each domain, such as ports or spectrum slots, and the inter-domain connectivity) from the global network TED, which is the infrastructure resource database and contains all the necessary information on the virtualized resources, such as spectrum availability or virtual control resources, as well as the status of the inter-domain links, and is obtained from a local XML file, although a topology discovery mechanism for VV is expected (e.g., topology server, BGP-LS [13]).

The global TED contains a detailed network view of each domain. We have selected this approach to cover the use case where a single operator is responsible for the different domains and wants to offer a multi-domain VON. Domain topology abstraction should be investigated as further research.

Taking into account the above inputs and optical constraints (i.e., spectrum continuity), the algorithm bundle will compose a VON that can satisfy the user's request and optimize the physical resource utilization.

As a result of a VON request we obtain an optical network slice with several domains. These domains might be controlled by either a GMPLS or OF control plane. Once the multi-domain VON has been setup by the resource configurator module (at MRB) in cooperation with the different Virtualization Visors, the MRB does no longer participate in the control of the resulting VON.

To provide end-to-end control functions, it is necessary to have the interoperability and coordination provided by the an orchestrator. In Figure 3, the HS-PCE architecture is used to this end [12]. Our approach relies on a set of stateful PCEs

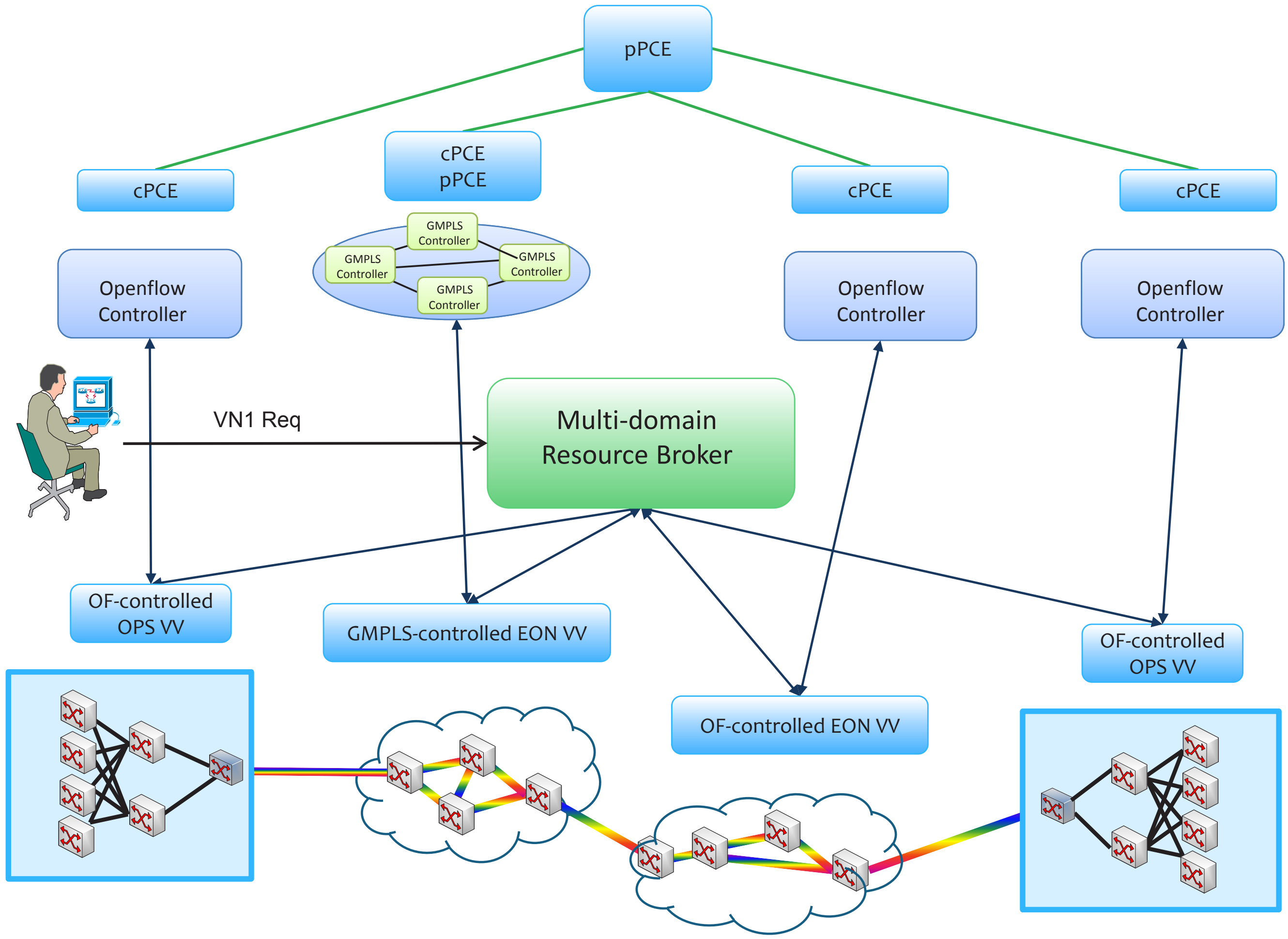

Fig. 3. Multi-domain Optical Network Virtualization architecture

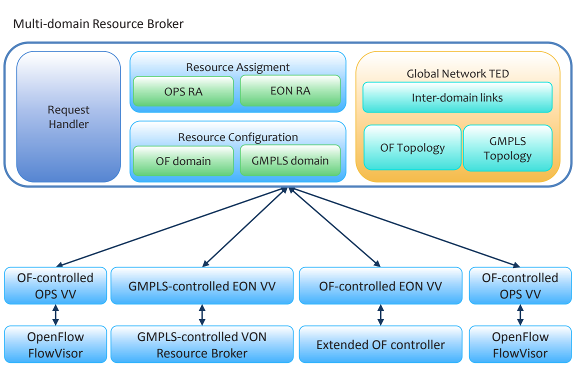

Fig. 4. Multi-domain Resource Broker

arranged in a hierarchical PCE (H-PCE) manner. Thus, the parent PCE (pPCE) orchestrates the provisioning of services with generalized identifiers and each child PCE (cPCE) acts as a middleware for each virtual domain control layer. Each cPCE controls its domain either integrated with an OpenFlow controller, or delegating the actual establishment and release of connections to an underlying GMPLS control plane.

III. GMPLS-controlled EON Virtualization Visor

Fig. 5 shows the proposed system architecture for a VV responsible for GMPLS-controlled EONs. A virtualizable GMPLS/PCE-controlled EON network is managed by a Resource Broker, which interfaces with the VV. The Resource Broker is responsible for managing the incoming asynchronous and dynamic requests. Each request is modeled as a graph that describes a set of virtual optical switches and links for the virtual transport plane, specifying for each one the number of requested input and output optical ports, and the required spectrum, respectively. The request also includes some requirements and constraints for the virtual control plane, such as the needed capacities for the virtual GMPLS controllers, or the selected values for configuring the parameters/attributes of the control processes running on the virtual GMPLS controllers, which can be later modified by the service provider.

The Resource Manager module of the Resource Broker handles the virtual control resources. It manages the available IP subnetworks that shall be used to establish the virtual IP Control Channel (IPCC) to later deploy dedicated Data Communication Network (DCN) for each virtual transport plane. It is also responsible for managing the number and location of the available virtual GMPLS controllers that each physical GMPLS controller supports (static partition-

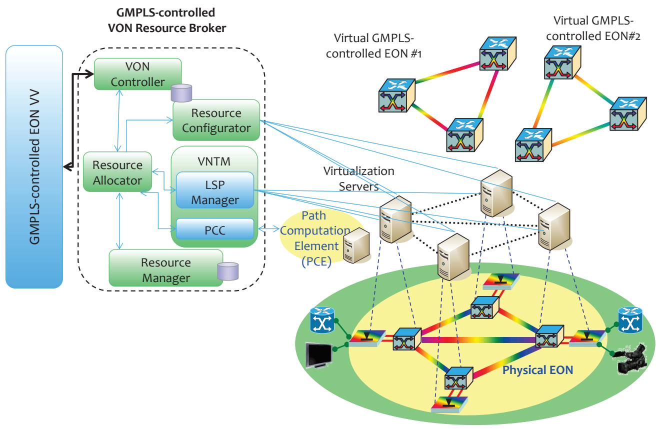

Fig. 5. GMPLS-controlled EON VV

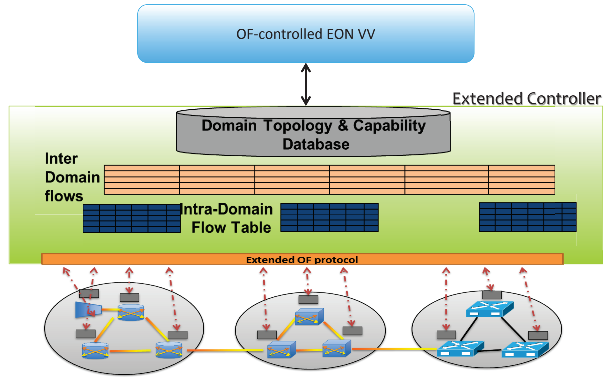

Fig. 6. OF-controlled EON VV

ing), as well as their configuration information (including the management IP address, the amount of CPU power and the available RAM). It also stores all the information required to configure the processes (e.g., routing, signaling, etc.) running in the virtual GMPLS controllers.

The VON Controller module accepts incoming TCP sessions, used to reliably transport VON requests, and handles these requests asynchronously and dynamically. Once the VON identifier is assigned, or found, the VON controller triggers the resource allocator in order to process the VON request.

The Resource Allocator module assigns the virtual transport and control resources to the requested VON. For the virtual control plane, it allocates the virtual GMPLS controllers, and assigns the GMPLS router address. It also assigns IP addresses and Generic Routing Encapsulation (GRE) tunnels for the required IPCC. For the transport resources, the virtual optical links are requested through the VNT Manager.

The VNT Manager module is composed of a Path Computation Client (PCC) and a LSP Manager. For each requested Virtual Optical Link, the PCC issues to the PCE a Path Computation Request. The PCE will reply with a Path Computation Reply, which includes the Explicit Route Object (ERO). This information is used by the Connection Controller to request a LSP through the RSVP-TE signaling process that is running on the source node. Once the LSP has been established, the RSVP-TE protocol answers with a Record Route Object (RRO) including the allocated frequency slot. This information is parsed and used to conduct the necessary control plane configuration.

The Resource Configurator module generates the virtual transport and control plane configuration XML file, which describes a VON scenario model that can be set up, modified or torn down by means of ADRENALINE Network Configurator (ADNETCONF). This is a proprietary software tool in charge of scenario model management in ADRENALINE testbed.

IV. OF-controlled EON Virtualization Visor

Figure 6 shows the architectural block diagram of the OF-controlled EON VV. Central to the proposed architecture are extensions to the OF protocol. While the existing OF circuit switch addendum extends OF from the packet domain to TDM circuits and wavelengths, it does not support flexible DWDM grid technology, so the flow specification for fixed and flexible grid optical networks has been extended in [7].

In a flexible grid optical network, a flow is identified by a flexible flow identifier comprising port, center frequency (CF), frequency slot bandwidth (FSB) and type of signal fields associated with that switch. The authors have presented an extended SDN Controller which supports flexible DWDM grid flows. For optical Network Elements (NE), an action is defined as a cross connection associated with one or more flow identifiers. For a flexible grid NE, the action also includes CF and FSB.

The following extended OF messages are used: the Switch_Feature and CFlow_Mod. The Switch_Feature extension message supports optical NE capabilities including: central frequency, spectrum range, and granularity of BVT and BV OXC; number of ports and wavelength channels of WDM OXC; peering connectivity inside and across multiple domains.

The CFlow_Mod message supports a flexible grid domain based on the ITU-T G.694.1 recommendation. The equation 193.1 + n0.00625 (THz) is used to calculate the central frequency of a frequency slot, while 12.5 GHzm yields the slot width where n is an integer and m is a positive integer. The allowable granularity of m and n for flexible grid equipment can be determined using the Switch_Feature messages. To control a BVT or BV OXC only m and n values are exchanged between the controller and a NE via CFlow_Mod messages.

V. Multi-Domain Virtualization Algorithm

As previously explained, the physical substrate is a multi-domain multi-technology network comprising heterogeneous transport technologies (e.g. Flexi-grid EON, OPS). In order to create multiple coexisting but isolated VONs across such a multi-domain multi-technology scenario, the VON resource allocation algorithms need to consider the information of physical networks (e.g. the network topology, the inter-domain connectivity, and the availability of physical resources such as switch ports or spectrum slots of each domain) as well as technology domain specific attributes and constraints (e.g. spectrum continuity and impairments). The information will be stored in and retrieved from the Global Network TED module in the MRB.

When a VON request is received from a client, indicating the requested virtual topology comprising virtual nodes and virtual links and also specifying the required capabilities

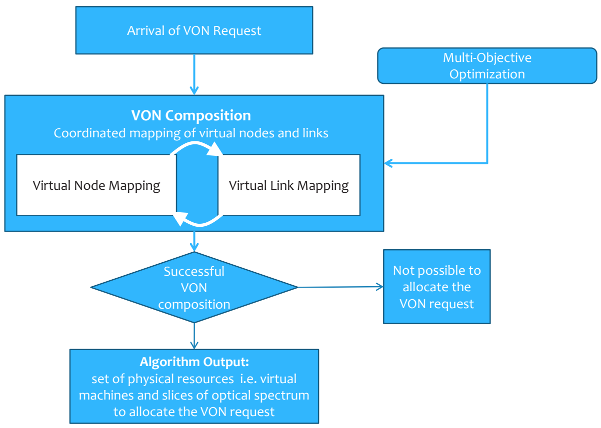

Fig. 7. Virtualization testbed architecture

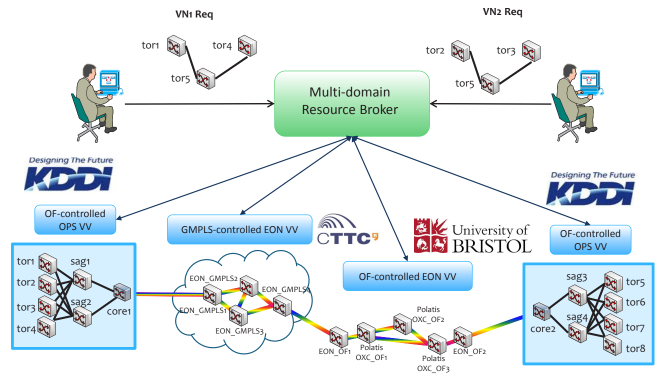

Fig. 8. International Experimental Scenario

and capacities (e.g. virtual node switching capabilities and virtual link bandwidth), the Resource Assignment module in the MRB will be called, which contains an algorithm bundle composed of multiple algorithms designed for different scenarios (e.g. single domain/multi-domain Flexi-grid EON, OPS). After the required capabilities and capacities of the VON request are analyzed, the suitable algorithm in the bundle will be executed to allocate the resources in the targeted domain scenario, taking into account the physical resource availability information and optical layer constraints. In the Flexi-grid domain, the virtual nodes are mapped to the physical nodes, while the virtual links are mapped to the physical light-path calculated by routing algorithms such as Shortest Path and Load Balancing. The required number of frequency slots (6.25GHz or 12.5GHz each) for each virtual link can be calculated using the formula m=BW/6.25 (or 12.5), where BW is the requested bandwidth of the virtual link. In order to set up an end-to-end feasible light-path, the spectrum continuity needs to be specially taken into account. Finally, an end-to-end "bandwidth corridor" with m frequency slots and central frequency 193.1 + n0.00625 (THz) will be established.

In the OPS domain, the algorithm will select a specific label for each flow, and each label is used to identify the output port and the central frequency of the spectrum assigned for this flow at each intermediate node in the chosen path. The multi-domain algorithm will utilize the beneficial advantage of OPS, statistical multiplexing, by aggregating the traffic of several flows and mapping them onto the optical spectrum prior to the transmission in the Flexi-grid OCS core network. Efficient optical spectrum utilization will be a design goal.

Figure 7 shows a flowchart of the procedure of mapping a VON request. After a VON request is received from a user, this request is analyzed to obtain the resource requirements i.e. required capacities of virtual nodes and required bandwidths and latency of virtual links. Then, the VON composition is triggered. In the proposed composition algorithm design, coordinated mapping of virtual nodes and links are considered. This leads to utilize the entire solution space in order to produce efficient physical resource allocation, while mapping nodes and links in two separate stages restricts the solution space. With utilizing this coordinated mapping, the placement of virtual nodes can be done taking into account the status of the network when mapping the virtual links.

As shown in Figure 7, a multi-objective optimization will be utilized, and the algorithm design will be flexible to produce efficient resource allocation that suits the optimization objective. Mapping the virtual links will take into account which domains (i.e. OPS, Flexi-grid OCS domains) are included in the VON composition in order to find end-to-end paths with appropriate spectrum resources and modulation formats. The specific features of each domain should be carefully analyzed and included in the VON composition process in order to achieve the end-to-end optimal mapping.

The VON composition may be failed due to the lack of resources (spectrum) or optical layer constraints (e.g. spectrum continuity). In case of successful VON composition, the output of the algorithm will be a set of physical resources i.e. physical nodes to host the requested virtual nodes, and physical paths to support the virtual links.

The above mentioned methodology is adopted for the online dynamic VON requests, that is, the VON request is received and dealt with one by one. If multiple VON requests are received or scheduled to be processed at the same time, the off-line optimal planning methodology will be adopted. After the algorithm bundle is called, the suitable to-be-allocated resources for the VON request will be sent to the Resource Configuration module in the MRB for configuring equipment in corresponding domains.

VI. Experimental Assessment

To experimentally evaluate the proposed virtualization architecture, we built a heterogeneous multi-domain international testbed comprising an EON domain in the High Performance Networks group at University of Bristol (UK), a layer 2 optical packet switched domain in KDDI R&D Labs (Japan) and an EON domain in CTTC (Spain) as shown in Fig. 8.

The University of Bristol testbed is comprised of an in-house built 8x8 (4x4 bidirectional) BV-OXC utilizing two BV-WSS switches with internal recirculation fibre loops to emulate multiple nodes; a BV transponder (BV-TX & BV-RX) supporting C-band and 3 OF-enabled Polatis fibre switches. The CTTC GMPLS control plane platform of the ADRENALINE Testbed includes 14 nodes that run GMPLS Controllers with emulated EON hardware. Finally, a packet-based emulated network with a DC network topology (including ToR, aggregation and distribution layers) has been deployed in KDDI R&D Laboratories. The international connectivity between

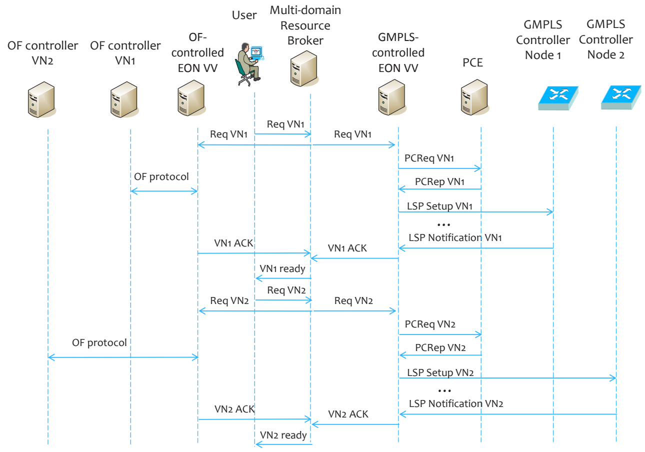

Fig. 9. Multi-domain resource broker message exchange

VN1	Assiged slice
tor1 – tor5	tor1-sag1-core1-eon_gmpls1-eon_gmpls2-eon_gmpls4-eon_of1-Polatis_OXC_OF1-Polatis_OXC_OF3-eon_of2-core2-sag3-tor5
tor5- tor4	tor5-sag3-core2-eon_of2-eon_of2-Polatis_OXC_OF3-Polatis_OXC_OF1-eon_of1-eon_gmpls4-eon_gmpls2-eon_gmpls1-core1-sag2-tor4

Fig. 10. Example of VN1 assigned slices

the MBR and the different VV running on each testbed is provisioned over VPN Tunnels over Internet.

The OF-controlled OPS VV corresponds to an OF Flowvisor, so its VV uses the XML-RPC API [14] to create the required slices through the definition of the required flowspaces for each slice. The OF-controlled EON VV is based on top of the extended SDN controller described in [7]. Finally, the GMPLS-controlled EON VV is requested via a proprietary interface which has been described in [15].

Figure 9 shows the message exchanges between the MRB and the different network elements responsible to setup a virtual network. A user creates a virtual network request (VN1) which might imply several domains, and sends it to the MRB via XML interface. The MRB runs the proposed algorithm (Fig. 7) and for each required domain contacts the required VV. In the example shown, an OF-controlled EON VV and a GMPLS-controlled EON VV are contacted.

Once the different VVs notify that the virtual resources for VN1 have been allocated (VN1 ACK), the user is notified with the assigned resources (VN1 ready).

Figures 10 and 11 show the results that were obtained to verify the functionalities of the proposed MRB architecture for different network domains (alternating CTTC, University of Bristol and KDDI domains). Figure 10 details the assigned slices for VN1. Please note that this is the view of assigned resources from the MRB perspective. The detailed partitioning of the resources within each domain is performed by each VV.

The VON Domain slice setup time is affected significantly

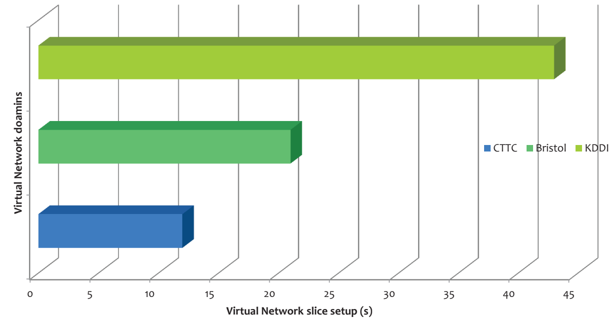

Fig. 11. Virtual Network Domains slice setup time (s)

by control plane VPN delay as well as the communication method between each OF agent or GMPLS controller and its corresponding NE. The different VON domain slice setup times can be easily explained by the fact that different VV using different technologies where used in each domain.

Also the different intra-domain network topologies explain the obtained results, which are tightly coupled with each intra-domain topology. It is also remarkable the need for a faster interface towards FlowVisor, where several requests for different flowspaces could be grouped allowing faster VON domains slice setup times.

VII. Conclusion

We have proposed a multi-domain resource broker for providing dynamic VONs as a service in heterogeneous control domains and transport technologies.

The proposed MRB design has been presented, and an experimental evaluation has been performed in an international testbed across Spain, UK and Japan.

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