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# Cross-Layer Optimization of Network Resource Virtualization in IP Over O-OFDM Networks

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*Abstract*—**Optical orthogonal frequency division multiplexing (O-OFDM) is a promising transport technology for virtualization and bandwidth sharing over high-capacity optical fibers. In this paper, we propose an IP over O-OFDM optical network architecture utilizing network virtualization across IP and optical layers. A design goal of this architecture is to provide dynamicity and flexibility in addition to the high capacity required to support multirate traffic with various quality of service requirements. In this architecture, optimized allocation of optical resources to virtual optical networks that accommodate the traffic of IP networks is considered. O-OFDM is utilized to allocate a set of low-rate contiguous subcarriers to each traffic connection represented by a virtual optical link. In addition, we study virtualization of IP network resources (i.e., routers and bandwidth capacities of links) in order to compose several customized virtual IP networks. Furthermore, coordination between IP and optical network virtualization mechanisms is investigated in order to achieve the required optimization of network resource virtualization across the different domains. For this purpose, a novel replanning approach is proposed and is aimed to adapt the resources allocated for virtual optical networks based on the requirements of an IP layer.**

*Index Terms*—**Optical network virtualization; IP network virtualization; Virtual network composition.**

## I. INTRODUCTION

Nowadays, a key challenge for network operators is the deployment of dynamic network infrastructures capable of supporting many different types of applications. Network virtualization enables infrastructure providers to partition their physical network infrastructures into multiple-application/service-specific and customized virtual networks. Therefore, it aims to solve the current ossification in the Internet infrastructure and provide flexibility for the future Internet [1,2]. Network virtualization has been investigated over the different layers of networking stack [3]. Currently, most network services and applications are provided over the IP layer, which uses an optical layer underneath for high-bandwidth and high-performance

point-to-point connectivity [4]. In addition, dynamicity and flexibility in the network infrastructure are essential requirements to cope with the dynamic multirate IP traffic with various quality of service (QoS) demands [5,6]. To address these requirements, a dynamic IP over optical network architecture is essential. Introducing network virtualization, taking into account cross-layer virtualization across IP and optical layers, is the key to provide such dynamicity.

Optical network virtualization is defined as composition of isolated virtual optical networks (VONs) onto a shared optical infrastructure. Each VON is allocated a set of virtual optical resources that are created by partitioning/aggregating physical optical resources (i.e., optical nodes and optical spectrum of fibers) [7]. Similarly, network virtualization in the IP layer is proposed to virtualize IP network resources (i.e., routers and bandwidth capacities of links) and to compose several isolated virtual IP networks (VIPNs) with different bandwidth and QoS requirements on top of a shared physical IP network [6].

Despite the high capacity offered by existing wavelength division multiplexing (WDM), it provides coarse bandwidth granularity that restricts the ability to provide fully flexible multirate optical networks. Wavelength level granularity can lead to inefficient capacity utilization in an optical network for supporting heterogeneous bandwidth requirements [8]. Optical orthogonal frequency division multiplexing (O-OFDM) has been proposed as a bandwidth efficient optical transport technology. It provides fine bandwidth granularity and a physical layer aware transport mechanism, where a connection can be established by allocation of a number of contiguous subcarriers and modulation formats [9–11]. Different modulation formats can be used for each set of subcarriers [12,13]. Based on the aforementioned characteristics of O-OFDM, it is a promising technology for virtualization of optical links and providing efficient bandwidth sharing over high-capacity optical pipes. Therefore, it has been identified as a key enabler for optical network virtualization [8].

In this paper, we propose a new IP over O-OFDM optical network architecture supporting cross-layer network virtualization. In this architecture, a flexible and fine granular optical network virtualization utilizing O-OFDM and an IP network virtualization are proposed. As a basic functionality, the problem of virtual network composition/mapping on

top of the physical network substrate is investigated based on the functionality and characteristics of each layer. This problem deals with the efficient allocation of available network resources to virtual networks.

Furthermore, in order to optimize network resources allocation across the layers, we propose a coordination mechanism responsible for orchestrating the two virtualization mechanisms in IP and optical layers. This coordination is necessary to provide the efficient and optimized optical transport service that is adaptive to the demands of the IP layer. To achieve the coordination, a novel VON replanning algorithm is presented to flexibly adapt the allocation of virtual optical resources according to the change in the IP layer. Based on this adaptation, the capacities of IP networks sitting on top of the VONs can be flexibly adjusted according to the traffic load of VIPNs.

The rest of this paper is organized as follows. Section II provides an overview of related works. Section III describes the proposed IP over optical network architecture utilizing network virtualization. In Sections IV and V, optical and IP network virtualization are studied, respectively. In Section VI, our proposed coordination mechanism with VON replanning is introduced. Results and performance evaluation are presented in Section VII. Finally, Section VIII concludes this paper.

## II. RELATED WORK

Network virtualization has been an important research subject studied for different network layers in the past years. In optical networks, WDM-based VON composition approaches have been investigated by many research papers [7,14,15]. Some works [8,10,12,16] have studied O-OFDM for applying optical network virtualization and solving the routing and spectrum allocation problem, which is an alternative to the routing and wavelength allocation problem in WDM networks. Most previous papers address the offline version of the problem where all traffic or VON requests are known in advance. Recently, some research such as [17] and [18] have proposed heuristic algorithms to deal with the online composition of VON requests onto an elastic optical network.

In this paper, we utilize an integer linear programming (ILP) formulation for VON composition in an O-OFDM-based optical network. This ILP is an extension of the ILP presented in our previous paper [19]. It supports node mapping and link mapping in a single stage where the entire solution space is utilized. This is more efficient than mapping node and links in two separate stages, which leads to restriction in the solution space. Therefore, the ILP optimizes the selection of best candidate physical nodes with the selection of best lightpaths connecting them in order to map the entire VON request with the least amount of allocated resources. To the best of our knowledge, this ILP formulation for the first time deals with the problem of online VON requests allocation utilizing O-OFDM by mapping each VON at the time it arrives and with no need to know all VON requests in advance.

Many studies such as [20–22] have proposed approaches, including ILP formulations for virtual network mapping/embedding, which can be applied on packet networks such as IP networks. Very few papers such as [20] and [21] apply coordinated mapping of nodes and links, which is more efficient than mapping nodes and links in two different stages as followed in many papers such as [22]. In this paper, we utilize an ILP approach for single-stage composition of a virtual network in an IP over O-OFDM network. This work extends our previous work on the ILP model for IP network virtualization presented in [23]. In this approach, a single-stage coordinated mapping of nodes and links is applied so that solution space is fully utilized and optimal solutions under specified constraints can be obtained.

Because a multilayer network architecture composed of an IP over optical transport layer is a fundamental part of Internet infrastructure, architectures for IP over an optical network are investigated in many research papers. WDM is mostly considered as the transport technology used to establish lightpaths for carrying IP traffic. For instance, in [24], the authors investigate mechanisms to design and optimize the VON topologies, which accommodate the traffic of IP networks. Methods of converging IP and WDM optical domains for the goal of supporting QoS and traffic engineering are investigated in [25] and [26].

Utilizing O-OFDM as an optical transport technology in IP/optical network architectures is studied by very few papers. For instance, the authors of [27] propose an adaptive mechanism for IP/optical networks to support dynamic IP traffic flows. This mechanism utilizes O-OFDM technology to build a full mesh logical topology of virtual pipes between IP routers. To the best of our knowledge, studying coordinated IP network virtualization and optical network virtualization in IP over optical network architecture is still missing. This paper, for the first time, addresses cross-layer optimization of network resource virtualization in IP over an OFDM-based network and studies composition of VIPNs on top of VONs in a coordinated manner that enables flexible and adjustable network resource allocation across the layers.

## III. IP OVER OPTICAL NETWORK ARCHITECTURE UTILIZING NETWORK VIRTUALIZATION

The proposed IP over optical network architecture utilizing network virtualization is depicted in Fig. 1. In this architecture, both IP and optical layers utilize their own network virtualization mechanism. By applying network virtualization in an optical layer, several isolated VONs over shared optical infrastructure can be composed. Each VON is dedicated to a portion of the optical spectrum of fibers, on which the traffic of the IP network is accommodated. As shown in Fig. 1, each IP network is mapped onto a single VON. In addition, IP network resources can be virtualized, and several isolated VIPNs, each composed of a set of virtual IP network resources, can coexist on top of each IP network, as shown in Fig. 1.

Network virtualization in the IP layer can provide the required isolation between the traffic of different IP

Fig. 1.   Network virtualization in an IP over optical network.

applications by dedicating a VIPN for each IP application or service. As a result, efficient bandwidth sharing and traffic isolation in each layer can be achieved through network virtualization technology. In addition, network virtualization can support heterogeneity by allowing virtual networks in both layers to have different network topology and protocols. As a result, diverse networks can coexist on top of a shared substrate. In order to optimize resource allocation across the layers and to achieve the required flexibility and dynamicity, the virtualization mechanisms are coordinated in the proposed architecture. This coordination aims to flexibly update the optical resources allocated to a VON based on IP layer traffic requirements. For instance, an IP network might need extra capacities to accommodate increased traffic; therefore, an extra optical spectrum needs to be allocated for the corresponding VON. The extra spectrum might be added to the lightpaths already allocated to a VON, or new lightpaths with reserved optical spectrum might be required. On the other hand, IP network links might become underutilized, and free capacities can be released on time so that part of the optical spectrum allocated for the corresponding VON can be released. To provide these functionalities, a VON replanning approach is proposed. This approach aims to efficiently upscale/downscale the optical capacities allocated to VONs, so that optical resource allocation can be optimized and IP layer traffic requirements are satisfied. A detailed explanation of mechanisms applied in the proposed architecture is presented in the next sections.

## IV. OPTICAL NETWORK VIRTUALIZATION

### A. Definition

In this paper, we propose an optical network virtualization mechanism based on the slicing approach where

virtualization can be implemented by slicing the optical spectrum and sharing it between several virtual links as well as slicing the optical node resources such as optical ports and sharing them between several virtual optical nodes. In each VON, a set of virtual optical nodes (e.g., virtual optical cross connect [VOXC]) are interconnected by virtual optical links. VON composition comprises two main actions: virtual optical node mapping, where an appropriate slice of physical optical nodes must be reserved, and virtual optical link mapping, where virtual optical links must be assigned to a suitable slice of physical optical paths.

In the proposed IP over optical network architecture, each router is physically connected to a physical optical node. By applying the proposed optical network virtualization, each router is logically connected to a virtual optical node. For instance, in Fig. 1, R1 and R2 are connected to OXC1. With partitioning OXC1 into VOXC1 and VOXC7, R1 and R2 are logically connected to VOXC1 and VOXC7, respectively, and they are located in two different IP networks that sit on two different VONs. The IP link that connects between two routers is a logical link and realized by a virtual optical link (i.e., an optical path) connecting the two VOXCs connected to these routers. For instance, the link between R1 and R7 is mapped to a virtual optical path between VOXC1 and VOXC3.

### B. O-OFDM-Based Optical Network Virtualization

O-OFDM enables optical link virtualization by mapping each virtual optical link onto a set of O-OFDM subcarriers in an end-to-end optical path. Hence, several virtual optical links that might belong to different VONs can be allocated onto the frequency band of optical links. The required number of subcarriers and their modulation format can be

determined by the bandwidth and QoT requirements as well as physical layer impairments of optical paths. In an O-OFDM network, switching and cross connections are realized using bandwidth variable optical cross connects (BV-OXC) [10]. Virtualization of an optical node can be achieved by partitioning of BV-OXC nodes based on their ports and/or the supported frequency range (e.g., a virtual BV-OXC can be mapped into a subset of ports and/or specific bandwidth/frequency slot range of a physical BV-OXC) [18].

## C. ILP Formulation of VON Composition

In this section, we formulate the VON composition as an integer linear programming (ILP) problem. The proposed ILP deals with the problem of online VON requests allocation by mapping each VON on demand at the time it is required. The VON request describes the required VON topology, including number and locations of virtual optical nodes and required capacities of virtual optical links. It is assumed that each virtual optical node might have several candidate physical optical nodes that can be used for mapping, and the ILP selects one of them to host the virtual optical node.

To achieve a coordinated node and link mapping in a single stage, the graph of the physical optical network is extended and provided as an input to the ILP. The extension includes adding a meta-node representing each virtual node and a meta-link (with zero distance) to connect each meta-node to a candidate physical node that can be used to map the corresponding virtual node. Therefore, each meta-node is only connected to the physical nodes that can be used to host the corresponding virtual node. This mechanism is used to ensure that the two end points of each virtual link (i.e., the two virtual nodes) have to be mapped onto the two end points of the path selected to map their interconnecting virtual link. A virtual link can be seen as a logical link between two meta-nodes. An example of extended network graph construction is shown in Fig. 2. In this example, meta-nodes $a$, $b$, and $c$ represent the virtual nodes $a'$, $b'$, and $c'$ of a VON request. Physical optical nodes $A$ and $B$ are candidate nodes for mapping the virtual

node $a'$ that is represented by the meta-node $a$. Therefore, there are two meta-links connecting meta-node $a$ to nodes $A$ and $B$. The optical paths that connect $a$ and $b$ in the extended graph are candidates for mapping the virtual link $a' - b'$. For instance, if the path $a - A - C - D - b$ is selected, this means at the same time that nodes $A$ and $D$ are selected to map the virtual nodes $a'$ and $b'$, respectively.

The candidate optical nodes for each virtual optical node are selected based on matching between the required location and switching capability of the virtual node to the location and available switching capability of the physical optical nodes.

The proposed ILP is path-based where the paths that are candidates for mapping virtual links and supported modulation formats are inputs of the ILP. We use $G_O = \{N_O, L_O\}$ to denote the extended graph of an optical network where $N_O$ is a set of optical nodes (including meta-nodes) and $L_O$ is a set of optical links (including meta-links). Let $P(n, m)$ denote a set of paths between source and destination meta-nodes $n$ and $m$, where a physical path in this set is $p : p \in P(n, m)$. Let $src(n)$ and $dst(m)$ denote the physical source and destination optical nodes of path $p \in P(n, m)$; $src(n)$ and $dst(m)$ are connected by meta-links with $n$ and $m$, respectively, so these nodes are candidate physical nodes to map the virtual nodes represented by meta-nodes $n$ and $m$. $L(p)$ denotes the set of optical links included in a physical path $p$. A physical optical link in the path $p$ is denoted by $l : l \in L(p)$. Let $F = \{f1, f2, ..., f|F|\}$ be an ordered set of subcarriers (frequency slots) per physical optical link. If the subcarrier that has the index $i$ is available, then $fi = 1$; otherwise $fi = 0$.

We use $G'_O = \{N'_O, L'_O\}$ to denote the graph of VON, where $N'_O$ is a set of virtual optical nodes and $L'_O$ is a set of virtual optical links. A virtual link between source virtual node $n'$ and destination virtual node $m'$ is denoted by $l'(n', m')$. We use $meta(n')$ to denote the meta-node corresponding to the virtual node $n'$. The function $num(l'(n', m'), p)$ is used to return the required number of subcarriers based on the required capacity of $l'(n', m')$ and the modulation format used in the path $p$.

$x(l', p, f) \in \{0, 1\}$ are problem variables, which are used to define the lowest allocated subcarrier index in the allocated path for each virtual link. $x(l', p, f) = 1$ if subcarrier $f$ in path $p$ has the lowest index between the subcarriers allocated to $p$ for $l'$. The allocated contiguous subcarriers in a selected path are defined by the variables $y(l', p, f) \in \{0, 1\}$. $y(l', p, f) = 1$ if subcarrier $f$ in path $p$ is allocated for $l'$. $z(n', n) \in \{0, 1\}$ are a set of variables to define the allocated physical node for each virtual node. $z(n', n) = 1$ if physical node $n$ is selected to map the virtual node $n'$.

The ILP formulation is stated below. It is considered in this formulation that $n = meta(n')$, $m = meta(m') : n$, $m \in N_O$, $n'$, and $m' \in N'_O$.



Fig. 2.   Construction of an extended optical network graph with meta-nodes and meta-links.

$$\textbf{\textit{Objective : Minimize}} \sum_{l'(n',m') \in L'} \sum_{p \in P(n,m)} \sum_{f \in F} (x(l'(n', m'), p, f)$$

$$\times \, num(l'(n', m'), p)) \times \sum_{l \in L(P)} 1,$$

$$\sum_{p \in P(n,m)} \sum_{f \in F} x(l'(n',m'),p,f) \le 1 : \forall \, l'(n',m') \in L'_O, \quad (1)$$

$$x(l'(n',m'),p,fi) \le y(l'(n',m'),p,fj):$$
$$\forall \, l'(n',m') \in L'_O, p \in P(n,m), fi, fj \in F, fj \ge fi, fj$$
$$\le fi + \text{num}(l'(n',m'),p) - 1, \quad (2)$$

$$x(l'(n',m'),p,f) \le \frac{\sum_{fi \le f + \text{num}(l'(n',m'),p) - 1}^{fi \in F, fi \ge f,} fi}{\text{num}(l'(n',m'),p)}:$$
$$\forall \, l'(n',m') \in L'_O, p \in P(n,m), f \in F, \quad (3)$$

$$\sum_{l'(n',m') \in L'_O} \sum_{p \in P(n,m): \, l \in L(p)} y(l'(n',m'),p,f) \le 1 : \forall \, l \in L_O, f \in F,$$
$$(4)$$

$$\sum_{p \in P(n,m)} \sum_{f \in F} y(l'(n',m'),p,f) \le \sum_{p \in P(n,m)} \sum_{f \in F} x(l'(n',m'),p,f)$$
$$\times \text{num}(l'(n',m'),p) : \forall \, l'(n',m') \in L'_O, \quad (5)$$

$$x(l'(n',m'),p,f) \le z(n', \text{src}(p)) : \forall \, l'(n',m') \in L'_O, p$$
$$\in P(n,m), f \in F, \quad (6)$$

$$x(l'(n',m'),p,f) \le z(m', \text{dst}(p)) : \forall \, l'(n',m') \in L'_O, p$$
$$\in P(n,m), f \in F, \quad (7)$$

$$\sum_{n \in N_O} z(n',n) = 1 : \forall \, n' \in N'_O, \quad (8)$$

$$\sum_{n' \in N'_O} z(n',n) <= 1 : \forall \, n \in N_O, \quad (9)$$

$$\sum_{l'(n',m') \in L'_O} \sum_{p \in P(n,m)} \sum_{f \in F} x(l'(n',m'),p,f) \ge |L'_O|. \quad (10)$$

The objective function is to minimize the total number of allocated subcarriers to a VON. Constraints (1) ensure that each virtual link is mapped onto a single optical path. Constraints (2) are the contiguous subcarrier allocation constraints. They ensure that, if subcarrier $fi$ is selected as the lowest index to a virtual link $l'$ in a path, then the required number of contiguous subcarriers starting from $fi$ are allocated to $l'$. Each path is allocated with the best modulation format that can be used based on its end-to-end distance and required rate, so that the required number of subcarriers is minimum. Constraints (3) are the subcarrier availability constraints, which ensure that the selected contiguous subcarriers for each virtual link in the selected optical path are available. Constraints (4) are the spectrum clashing constraints that are used to avoid allocation of the same subcarrier at the same optical link

to different virtual links. Constraints (5) ensure that only the required number of subcarriers is allocated for each virtual link in a selected optical path. Constraints (6)–(9) are used for node mapping. Constraints (6) and (7) set the node mapping based on the result of the path selection. The actual source and destination nodes of each path $p$ selected to map a virtual link $l'$ are set as the nodes used to map the end points (i.e., virtual nodes) of $l'$. Constraints (8) ensure that each virtual node is mapped onto a single physical node. Constraints (9) ensure that a physical node can map at most one virtual node from the same VON request, and these constraints do not restrict any physical node from accommodating several virtual nodes from different VON requests. Constraints (10) ensure that all virtual links must be mapped for a successful VON composition.

## V. IP Network Virtualization

### A. Definition

With IP network virtualization, several VIPNs can coexist on top of a single IP network and share its resources. A VIPN request describes the topology of the VIPN and the attributes (i.e., resource requirements) of its virtual routers and links. It is considered that location and packet processing capacity are attributes of virtual routers, while bandwidth and delay are attributes of virtual links. To compose a VIPN, each virtual router should be mapped onto a physical router, and each virtual link connecting two virtual routers should be mapped onto a physical path connecting the two corresponding physical routers. For instance, in Fig. 1, VR1, VR2, and VR3 are located at R1, R3, and R5, respectively. The virtual link connecting VR1 and VR3 is mapped onto a physical path between R1 and R5 (e.g., R1-R7-R5). The physical path should be assigned a specific bandwidth equal to the bandwidth requirement of the corresponding virtual link. In addition, the required transmission delay of a virtual link can be considered as a maximum packet transmission delay over the hosting physical path.

### B. ILP Formulation for VIPN Composition

In this section, we formulate the VIPN composition as an ILP problem. Mapping virtual links in packet networks is less complex than mapping virtual optical links because of the extra constraints on the optical spectrum. Therefore, a flow-based approach different from a path-based and extended network graph approach utilized for optical network virtualization is proposed in this section. In this approach, optimal physical paths are constructed and returned by the ILP for mapping virtual links, and flow conservation constraints in packet networks need to be satisfied in this regard.

The IP network is denoted by a graph $G_I = (N_I, L_I)$, where $N_I$ is the set of physical nodes (i.e., IP routers) and $L_I$ is the set of physical links. Similarly, the VIPN request is denoted by a graph $G'_I = \{N'_I, L'_I\}$, where $N'_I$ is the set of virtual routers and $L'_I$ is the set of virtual links. $C(n)$ denotes

the available packet processing capacity of a router $n$ ($n \in N_I$). $C(n')$ is the required processing capacity of a virtual router $n'$ ($n' \in N'_I$). $locX(n)$ and $locY(n)$ are $x$ and $y$ coordinates that represent the location of a router $n$. Similarly, $locX(n')$ and $locY(n')$ are $x$ and $y$ coordinates that represent the required location of a virtual router $n'$. $Dis(n')$ is used to define a distance range within which physical routers can be selected to host $n'$. $B(l)$ denotes the available bandwidth of a physical link $l$ ($l \in L_I$). $B(l')$ is the required bandwidth of a virtual link $l'$ ($l' \in L'_I$). $D(l)$ is the transmission delay over a physical link $l$. $D(l')$ is the required maximum delay over a virtual link $l'$. The two end points of a link are denoted by $E(l)$ in the case of physical link $l$ and $E(l')$ in the case of virtual link $l'$. $E(l) = n$ if $n$ is an end point of the physical link $l$. $E(l') = n'$ if $n'$ is an end point of the virtual link $l'$.

The proposed ILP formulation utilizes the decision variables $X(n', n) \in \{0, 1\}$, $n' \in N'_I$, $n \in N_I$ to indicate where each virtual router is located ($X(n', n) = 1$ means that $n'$ is located at $n$). The decision variables $Y(l', l) \in \{0, 1\}$, $l' \in L'_I$, $l \in L_I$ are used to indicate which physical links are used for mapping a virtual link. In addition, $Z(l', n) \in \{0, 1\}$ $l' \in L'_I$, and $n \in N_I$ indicate if a physical router is used for mapping a virtual link as a node included in the selected path.

The objective function of the presented ILP is to minimize the composition cost, which is equal to the amount of network resources (i.e., capacities of routers and links) that are allocated to a VIPN. The ILP formulation is stated below:

$$Objective : Minimize \sum_{n' \in N'_I} \sum_{n \in N_I} X(n', n)C(n')$$
$$+ \sum_{l' \in L'_I} \sum_{l \in L_I} Y(l', l)B(l'),$$

$$\sum_{n \in N_I} X(n', n) = 1: \forall\, n' \in N'_I, \tag{11}$$

$$\sum_{n' \in N'_I} X(n', n) <= 1: \forall\, n \in N_I, \tag{12}$$

$$X(E(l'), n) <= Z(l', n): \forall\, n \in N_I, l' \in L'_I, \tag{13}$$

$$X(E(l'), n) + \sum_{l \in L_I:\, n = E(l)} Y(l', l) \le 2Z(l', n): \forall\, n \in N_I, l' \in L'_I, \tag{14}$$

$$\sum_{n' \in N'_I} X(n', n)C(n') <= C(n): \forall\, n \in N_I, \tag{15}$$

$$X(n', n)abs(locX(n') - locX(n)) \le Dis(n'): \forall\, n' \in N'_I, n \in N_I, \tag{16}$$

$$X(n', n)abs(locY(n') - locY(n)) \le Dis(n'): \forall\, n' \in N'_I, n \in N_I, \tag{17}$$

$$\sum_{l' \in L'_I} Y(l', l)B(l') <= B(l): \forall\, l \in L_I, \tag{18}$$

$$\sum_{l \in L_I} Y(l', l)D(l) <= D(l'): \forall\, l' \in L'_I. \tag{19}$$

Constraints (11) ensure that each virtual router should be mapped onto a single physical router. Constraints (12) ensure that a physical router can accommodate at most one virtual router from a single VIPN request. These constraints do not restrict that a physical router can accommodate several virtual routers from different VIPN requests. Constraints (13) and (14) ensure that each virtual link is mapped onto a physical path, and they refer to flow conservation conditions. Constraints (15) represent the processing capacity bound of each physical router. Constraints (16) and (17) are the location constraints of each virtual router. Constraints (18) represent the bandwidth bound of each physical link. Constraints (19) represent the delay bound of each virtual link. When there is no feasible solution to satisfy all previous constraints, the VIPN request is rejected and VIPN composition is unsuccessful.

## VI. ADAPTIVE COORDINATION OF VIRTUALIZATION

A mechanism for coordination between IP and optical network virtualization is proposed. The goal of this mechanism is to provide the communication between the virtualization mechanisms in different layers. The proposed mechanism aims to accommodate as many VIPNs as possible in the IP layer through an adaptive resource allocation in IP and optical layers. It adaptively and on request from the IP virtualization mechanism updates the reserved optical resources for VONs utilizing a VON replanning approach. The flow chart in Fig. 3 describes the procedures of this mechanism. Three main procedures are included in this flow chart: 1) VIPN composition (where the ILP presented in Section V is called), 2) mapping a subgraph of the VIPN topology in order to identify required extra IP link capacities, and 3) VON replanning. If composition fails



Fig. 3.   VIPN Composition coordinated with VON replanning.

because of node mapping failure, the VIPN request will be rejected because replanning cannot resolve this failure. Otherwise, in the case of failed composition because of link mapping failure, i.e., lack of bandwidth in IP links, the mechanism will try to upscale the optical capacities and therefore the IP capacities to accommodate the VIPN request. To identify the IP links that need extra capacities, the mechanism maps a subgraph of the VIPN topology by incrementally removing some virtual links until a subgraph is mapped successfully. Then, extra IP link capacities can be calculated in order to map the removed virtual links onto the shortest paths in the IP network.

After identifying the required IP link capacities, VON replanning is called to adapt the corresponding VON to the requirements. VON replanning (described in the flow chart in Fig. 4) aims to upscale the optical capacities of the virtual optical links accommodating the traffic of IP links that need extra capacities. This is done by allocating more subcarriers to the optical paths that host the virtual optical links. As shown in Fig. 4, after identifying a virtual optical link (VOL) hosting an IP link that needs extra capacity, VON replanning finds an optical path that has enough available contiguous subcarriers to satisfy the current VOL optical capacity plus the required extra capacity. The original path returned by VON composition can be allocated by more subcarriers if enough available optical spectrum exists. Otherwise, VON replanning searches for a new path utilizing a shortest path algorithm. A successful VON replanning results in the allocation of new subcarriers in the selected optical paths. In addition, the IP network mapped onto the replanned VON is updated by adding the extra capacities to the affected IP links (as shown in the flow chart in Fig. 3). VIPN composition is called again at this stage in order to map the entire VIPN.

A second case is when VON replanning is required in order to downscale the capacities of a VON. This is done by releasing extra capacities from the optical paths allocated to a VON when those capacities are not required by the IP layer. Periodic check of IP networks can be applied to record the IP links with extra free capacities. Then, VON replanning is triggered to release some of the subcarriers

allocated to the corresponding optical paths in the VON. In order to achieve this replanning, we propose to use a trigger condition for replanning. To trigger replanning, an IP network must have a pre-defined minimum number of IP links with unused capacities larger than a predefined threshold value.

## VII. SIMULATION STUDIES

The NSFNET network topology is used in the simulation as the physical optical network infrastructure [28]. Binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), and 8-quadrature amplitude modulation (8QAM) modulation formats with the maximum distances 3000, 1500, and 750 km, respectively, are chosen. A single subcarrier occupies 5 GHz with a data rate $R$ Gb/s, $2R$ Gb/s, and $3R$ Gb/s for BPSK, QPSK, and 8QAM, respectively, where $R$ is 2.5 Gb/s. Scalability studies of the used ILP formulations for optical and IP networks have been done in our previous works [19,23]. In the next two subsections, two simulation case studies are presented.

### A. Offline VON Composition and On-Demand VIPN Composition Coordinated With VON Replanning

In this simulation study, a set of VONs are first composed on top of the physical optical infrastructure taking into account infrastructure topology and available optical resources previously presented. Then, the on-demand composition of VIPNs is carried out on the resulting IP networks accommodated on the composed VONs. Five VONs with different topologies are assumed, and each VON has the size of eight virtual optical nodes. The virtual optical nodes are connected by virtual optical links (VOLs) with a 0.5 probability to connect each pair of virtual nodes. The initial capacity of each virtual optical link is $16R$ Gb/s = 40 Gb/s.

Five IP networks are accommodated in the IP layer, each supported by a VON. Each router in an IP network is connected to a virtual optical node in the corresponding VON. An IP link exists between two routers if there is a VOL connecting the two corresponding virtual optical nodes. The initial bandwidth capacity of each IP link is equal to the initial VOL capacity, which is 40 Gb/s. Two scenarios of initial router processing capacity $|C|$ of each router are assumed: $|C| = 100$ units and $|C| = 150$ units.

One thousand randomly generated requests for VIPNs in each IP network are simulated. The requests arrive in a Poisson process with an average arrival rate varied between two and 10 VIPN requests per 100 time units to test the effect of several traffic loads in the IP layer. The VIPN lifetime is selected by an exponential distribution with an average of 1000 time units. The number of virtual routers in each VIPN is randomly selected between three and four. Each pair of virtual routers is randomly connected with a probability of 0.5. The processing capacity requirements of virtual routers are uniformly distributed between 1 and 10 units. The required bandwidth capacity of each virtual link



Fig. 4.   Flow chart of VON replanning.

is a random number between $1R$ and $4R$ Gb/s using uniform distribution. Each virtual router is assigned randomly a required $x$ and $y$ location coordinate. Most of the previous parameters are used following similar setups in previous works [20–22].

Two scenarios are considered in this simulation study. In the first scenario, only the low-level modulation BPSK is used for transmission, while in the second scenario, the three modulation formats are supported so that modulation format is adaptively selected for each data transmission in the optical layer based on distance and quality of transmission. In addition, two different scenarios of total number of subcarriers ($|F|$) per optical link (i.e., optical spectrum capacity of fiber) are utilized to test the impact of different optical network capacities on the performance. These scenarios are $|F| = 256$ subcarriers and $|F| = 512$ subcarriers.

As shown in Fig. 5, VON replanning produces significant improvement in the average ratio of accepted VIPN requests in an IP layer for all average request arrival rates. This improvement is higher when $|C| = 150$ compared with the case of $|C| = 100$. In addition, when $|C| = 150$, the increase in the ratio when the total number of subcarriers is increased from 256 to 512 is higher on average when compared with the case of $|C| = 100$. This is due to the router's processing capacity constraints that lead to virtual router mapping failure. This failure cannot be resolved by VON replanning, and it is responsible for restricting the number of accommodated VIPNs. This can have a clear impact when the optical capacity is high where VON replanning can solve most of the IP link mapping failures, so node mapping failure becomes dominant. Therefore, relaxing these constraints by increasing $|C|$ to 150 units shows that VON replanning can perform better. It is also evident in Fig. 5 that the average ratio decreases as the average arrival rate increases. The increased demands on processing capacities of routers increase the probability of VIPN composition failure because of virtual router mapping failure. On the other hand, the increased demands on IP link bandwidth can be resolved using VON replanning.

In Fig. 6, the average percentage of virtual IP link mapping failure with respect to the total failure in VIPN composition is depicted. In this figure, it is evident that virtual link mapping failure is dominant when replanning is not applied. This figure shows the decrease in the percentage of link mapping failure on average when VON replanning is applied. Expanding the capacity of an optical network further decreases this percentage because higher optical capacity leads to more successful replanning. Changing the processing capacity of routers has no significant impact on the ratio when replanning is not applied. On the other hand, in each case of optical spectrum capacity, the percentage is higher when $|C| = 150$, and this is more evident for the high average arrival rates. The reason behind that is because node mapping failure is less likely to happen when $|C|$ is higher. Therefore, this makes link mapping failure more dominant. In Fig. 7, the replanning successful ratio increases when the total number of subcarriers is higher. This is because the optical network with higher capacity is better able to upscale the capacities of VONs through replanning. This ratio decreases as the average arrival rate



Fig. 6. Average percentage of link mapping failure for varied $|F|$ and $|C|$ values.



Fig. 5. Average VIPN request acceptance ratio for varied $|F|$ and $|C|$ values.



Fig. 7. VON replanning successful ratio for varied $|F|$ and $|C|$ values.

increases, which is an outcome of higher optical capacity consumption when serving increased bandwidth demands of more frequent VIPNs.

Figures 8–11 show the impact of varying the supported modulation formats (i.e., supporting high-level modulation formats or not) along with varying the total optical spectrum on the performance. In the scenarios depicted, the processing capacity $|C|$ of routers is 100 units. As shown in Fig. 8, supporting several modulations increases the average VIPN acceptance ratio. In the case of $|F| = 256$, supporting high-level modulation formats has more impact on saving the fiber optical spectrum that is more scarce in this case. Supporting high-level modulations decreases the percentage of link mapping failure on average when compared with using a single low-level modulation format, as shown in Fig. 9. Figure 10 shows that the VON replanning successful ratio is higher when high-level modulation formats are supported. This is due to the optical spectrum saving that can be achieved when using these formats. Figure 11 shows the savings in the optical spectrum resulting from using several modulation formats. The saving percentage is greater for higher optical capacity because,



Fig. 10.   VON replanning successful ratio for varied $|F|$ and different support modulations.



Fig. 11.   Average allocated optical spectrum for different $|F|$ and supported modulations.

in this case, the network provides more optical spectrum availability and therefore more flexibility in optimizing the shortest paths and selecting the best modulation formats.

### B. On-Demand VON Composition and On-Demand VIPN Composition Coordinated With VON Replanning

In this simulation study, on-demand allocation of VONs is considered where each VON is composed at the time it is required. When a VIPN request arrives, composition of the VIPN onto the existing IP networks will be examined, taking into account if any of the IP networks and therefore the corresponding VONs can be replanned. If composition cannot be done onto the existing IP networks, a new VON is composed; therefore, a new logical IP network results on top of the composed VON to be used to map the new VIPN request. Each new established IP network can be used to accommodate other future VIPN requests. If an IP network does not host any VIPN request (due to VIPN lifetime expiration), the optical resources allocated for the corresponding VON will be released.



Fig. 8.   Average VIPN request acceptance ratio for different $|F|$ and support modulations.



Fig. 9.   Average percentage of link mapping failure for varied $|F|$ and different support modulation.

In this simulation study, the same simulation settings presented in the first simulation case study for the optical network topology, optical capacities, modulation formats, and VIPN requests are used. The required bandwidth of each virtual link is increased in this simulation to be a random value between $1R$ and $20R$ Gb/s. Each virtual optical node is used to host a single IP router. The number of IP routers connected with each optical node is defined by the value of a parameter router_num. This value therefore defines the maximum number of the virtual optical nodes that can be created in a single optical node. This value is varied during the simulation to test different scenarios.

Figure 12 shows that VON replanning leads to significant improvement in the average VIPN acceptance ratio in all the simulated scenarios. The main observations extracted from this figure are as follows:

The average acceptance ratio is higher when replanning is applied and when more optical capacity is available, i.e., $|F| = 512$.

The average acceptance ratio when replanning is not applied, router_num = 3 and $|F| = 256$, is similar to the average ratio when replanning is not applied, router_num = 3 and $|F| = 512$. This indicates that, in this scenario, increasing the capacity of the optical network does not affect the acceptance ratio. In this scenario, IP network constraints, i.e., number of routers, and their capacities are responsible for the failures in accepting more VIPN requests.

The average acceptance ratio when replanning is not applied, router_num = 6 and $|F| = 512$, is slightly higher than the average acceptance ratio when replanning is not applied, router_num = 6 and $|F| = 256$. This is therefore different from the previous scenario where router_num = 3, which is a result of the availability of more routers.



Fig. 13.   VON replanning successful ratio for varied router_num and $|F|$ values.

The average acceptance ratio when replanning is applied, and $|F| = 512$ is significantly higher than the average acceptance ratio when replanning is applied; $|F| = 256$ especially for the high average arrival rates. This is observed in both cases: router_num = 3 and router_num = 6. This indicates that replanning helps to mitigate the constraints in the IP layer by efficiently utilizing the existing VONs, IP networks, and available routers.

When replanning is not applied and in both cases of optical capacities, the average acceptance ratio when router_num = 6 is significantly higher than the average acceptance ratio when router_num = 3.

Figure 13 shows that the VON replanning successful ratio is higher when $|F| = 512$ compared with the successful ratio when $|F| = 256$. This figure also shows that the ratio is higher when router_num = 3 compared with the ratio when router_num = 6 in each case of optical capacity.

Figures 14 and 15 show comparison between the different cases of using VONs to compose the on-demand VIPNs.



Fig. 12.   Average VIPN request acceptance ratio for varied router_num and $|F|$ values.



Fig. 14.   Comparison of the utilization of VONs during the composition of VIPNs ($|F| = 256$).

Fig. 15.   Comparison of the utilization of VONs during the composition of VIPNs ($|F| = 512$).

These cases are 1) using an existing VON without replanning, 2) using an existing VON with replanning, and 3) composing a new VON. Figures 14 and 15 show the recorded number of occurrences of each case when $|F| = 256$ and $|F| = 512$, respectively. The main observations are as follows:

- Using existing VONs without replanning is dominant in all scenarios.
- Using VONs with replanning becomes slightly more frequent as the average arrival rate is increased.
- Composing new VONs happens less as the average arrival rate is increased.
- Using new VONs happens more when router_num = 6 compared with the case of router_num = 3.
- There is no significant difference between the number of occurrences of using existing VONs with replanning when router_num = 3 and router_num = 6.

## VIII. Conclusion

In this paper, we proposed an approach for cross-layer optimization of network resource virtualization in IP over O-OFDM optical network architecture. Optical network virtualization utilizing O-OFDM is studied, and an ILP formulation for online VON composition is proposed. In addition, IP network virtualization is introduced to provide IP network resource sharing and isolation. Furthermore, a mechanism for coordination between the virtualization approaches in IP and optical layers is introduced. This mechanism utilizes a VON replanning algorithm for adapting the resources of VON based on IP layer requirements.

Two simulation cases are studied with on-demand VIPN composition: 1) offline VON composition and 2) on-demand VON composition. Simulation results show the impact of VON replanning on increasing the number of accepted VIPNs in the IP layer in both simulation cases. This is done

through optimizing the allocated optical spectrum and therefore optimizing the available capacities of IP networks. Results show that IP layer constraints such as router processing capacity can play a role in restricting the number of accepted VIPNs when replanning is applied, especially in the offline VON composition case. Results also show that the on-demand VON composition and VON replanning can help to mitigate the IP network constraints by efficiently utilizing the existing VONs and accommodated IP networks. In addition, the simulation in the offline VON composition case shows that using high-level modulation formats can minimize the optical spectrum usage and lead to better performance in terms of more successful replanning and therefore more accepted VIPNs in the IP layer. The simulation in the on-demand VON composition shows the dominance of using existing VONs in composing VIPNs and the use of more new composed VONs when the VIPN arrival rate is lower and when the number of routers connected to each optical node is higher.

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