How Much can Flexible Ethernet and Elastic Optical Networking Benefit Mutually?

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***Abstract*—In this paper, we explore how much flexible Ethernet (FlexE) and elastic optical network (EON) can mutually benefit each other, given their flexibilities in managing Ethernet channels and optical spectra. Specifically, we consider three FlexE architectures, *i.e.*, FlexE-unaware, FlexE-aware and FlexE-terminal, explain how to integrate them with EON, and formulate an mixed integer linear programming mode (MILP) to optimize the corresponding network design of each integration. The exact solutions provided by the MILP models confirm that FlexE and EON can mutually benefit each other when the FlexE-aware and FlexE-terminal architectures are considered, and the more flexible the FlexE architecture is, the more benefits the integration can get. Meanwhile, the solutions also show that fixed-grid wavelength-division multiplexing (WDM) networks cannot fully explore the advantages of the FlexE architectures due to the rigid transmission scheme. Hence, our results suggest that integrating FlexE and EON would be necessary in the future.**

***Index Terms*—Flexible Ethernet (FlexE), Elastic optical networks (EONs), Traffic grooming.**

I. Introduction

Recently, the rapid development of world-wide datacenter networks [1] and the stringent requirements from 5G initiatives have imposed great pressure on Ethernet technologies to make revolutionary changes. As an important innovation to respond to the challenges, the standard of flexible Ethernet (FlexE) has been published by the Optical Internetworking Forum (OIF) [2]. FlexE leverages time-division multiplexing (TDM) to divide the transmission opportunity in a fixed-rate physical channel (PHY) into a series of calendar slots (CS'), which can be allocated to carry traffic generated by various applications in a flexible but isolated manner [2]. Hence, FlexE can ensure the stringent quality-of-service (QoS) requirements of applications with improved network resource utilization.

Specifically, FlexE inserts a shim layer in between the media access control (MAC) and physical layers to facilitate the aforementioned flexible mapping between the traffic flows from MAC clients and the CS' in PHYs. The mapping supports three capacities, *i.e.*, bonding, sub-rating and channelization. The bonding lets FlexE combine multiple PHYs to carry a flow when its data-rate is higher than the capacity of a single PHY. For example, in Fig. 1(a), the FlexE system combines three PHYs of 100 GbE to carry a flow of 300 Gbps. On the contrary, the sub-rating handles the cases in which the flow' data-rate is lower than the capacity of a PHY, and leaves some CS' unused. For instance, the system in Fig. 1(b) transmits a 150 Gbps flow with two 100 GbE PHYs, each of which carries a subflow of 75 Gbps. The channelization provides the flexibility to groom multiple flows on PHYs, for making full utilization of their capacities, *e.g.*, the system in Fig. 1(c).

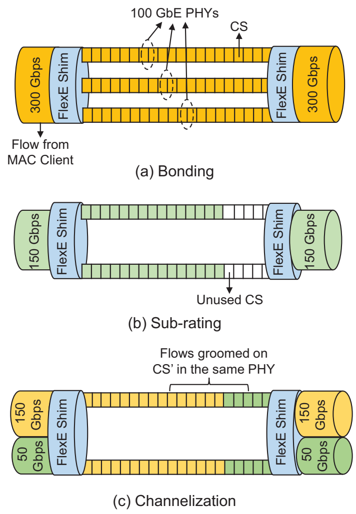

Fig. 1. Three capacities of FlexE to map traffic flows to CS' in PHYs.

Note that, for realizing long distance transmissions, FlexE needs to work together with the transport boxes (T-Boxes) in an optical transport network (OTN). Depending on whether the T-Boxes are FlexE-aware or not, FlexE can cooperate with the OTN in three architectures, *i.e.*, FlexE-unaware, FlexE-aware and FlexE-terminal, respectively [3]. A T-Box in the FlexE-unaware architecture maps PHYs to the transponders in it in a fixed manner, and thus once a FlexE group is created with some selected PHYs the related T-Box(es) and transponder(s) are determined as well. Meanwhile, the T-Box cannot determine whether a CS is used or not or recognize the flows from different clients in the PHYs. These limitations would have adverse affects on the utilizations of the PHYs in the FlexE, and the T-Boxes and optical spectra in the OTN. In the FlexE-aware architecture, a T-Box can compress the rate of a PHY by discarding unused CS' and leverage a switch fabric to map PHYs to the transponders in it more flexibly. Nevertheless, the T-Box still cannot identify the client flows in PHYs, and thus flow-level routing is still not feasible for it. Flow-level routing can be realized in the FlexE-terminal architecture, where each T-Box equips a FlexE shim to recognize the flows in PHYs and utilizes a switch fabric to map flows to transponders freely.

Previously, Eira *et al.* [3] conducted a comprehensive and thoughtful analysis on the pros and cons of applying the three aforementioned architectures in fixed-grid wavelength division multiplexing (WDM) based OTNs. However, the analysis did not consider the flexible-grid elastic optical networks (EONs) [4–6]. EONs have brought the bandwidth allocation granularity in the optical layer down to 12.5 GHz or even smaller, with the support of bandwidth-variable transponders (BV-Ts) and bandwidth-variable wavelength-selective switches (BV-WSS') [7]. Moreover, the technical advance on sliceable BV-Ts (SBV-Ts) [8] not only enables to change a transponder' data-rate with a fine granularity, but also makes it possible to realize the split-spectrum scheme [5, 9] with a single transponder. Hence, by getting rid of fixed-rate transponders, an EON-based OTN is expected to be more friendly toward FlexE, and a seamless integration might be achieved. Nevertheless, the open question is that how much exactly FlexE and EON can benefit mutually, when we consider the three "FlexE + OTN" architectures (*i.e.*, FlexE-unaware, FlexE-aware and FlexE-terminal).

In this paper, we first discuss how to integrate the FlexE architecture with EONs. Then, we design several mixed integer linear programming (MILP) models to explore the advantages of the flexibility provided by integrating FlexE and EON, for realizing cost-effective network design. With the exact solutions on network design from the MILP models, we analyze the differences between "FlexE + EON" and "FlexE + fixed-grid WDM" and show that FlexE and EON can mutually benefit each other when the FlexE-aware and FlexE-terminal architectures are considered, and the more flexible the FlexE architecture is, the more benefits the integration can get.

The rest of the paper is organized as follows. Section II explains how to integrate FlexE with EON. We design several MILP models to optimize the integrations of FlexE and EON in Section III, and the integrations' performance is compared in Section IV. Finally, Section V summarizes this paper.

II. Integration of FlexE and EON

Before elaborating on the integration of FlexE and EON, we first clarify the definition of "FlexE group" since it is a key concept for understanding the integration schemes.

Definition 1 (FlexE Group): A FlexE group is a group of PHYs, which is between a pair of FlexE shims that map/demap flows from MAC clients to/from CS' in the PHYs [2].
The FlexE shim in the destination node needs to compensate for the skew on client flows due to optical transmission, and therefore even though FlexE allows a FlexE group to be split over multiple BV-Ts in the T-Boxes that connect to a same router card, the lightpaths from these BV-Ts have to take the same routing path, *e.g.*, parallel lightpaths.

With Fig. 2 [3], we explain how to integrate FlexE and EON in the FlexE-unaware architecture, where only the router cards process FlexE shims while each BV-T in a T-Box is associated with pre-connected PHYs. Hence, as the T-Boxes are FlexE-unaware, the BV-Ts in them have to take a fixed data-rate (*i.e.*, the total capacity of the associated PHYs) no matter what the actual CS utilization is. This suggests that the FlexE-unaware architecture can hardly explore the benefits of EONs.

Fig. 3 illustrates the integration of FlexE and EON in the FlexE-aware architecture [3]. The T-Boxes have the capability

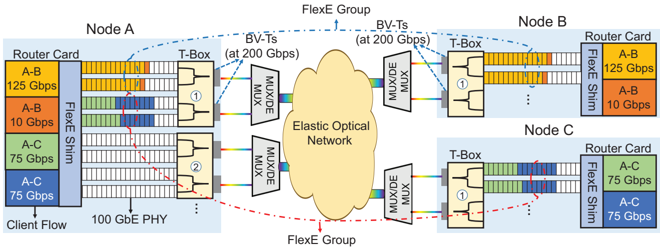

Fig. 2. Integration of FlexE and EON in FlexE-unaware architecture.

of checking the usage of the CS' in PHYs and adapting the data-rates of their BV-Ts accordingly. Furthermore, each T-Box is equipped with a switch fabric to facilitate flexible mapping between PHYs and BV-Ts. As BV-Ts are able to change their data-rates with a much finer granularity, *e.g.*, 12.5 Gbps [10], than the fixed-grid transponders, the integration of FlexE and EON in the FlexE-aware architecture can significantly improve the spectrum efficiency in the OTN. For instance, the two client flows for A-B, *i.e.*, 125 Gbps and 10 Gbps, respectively, can be carried by adjusting the BV-T's data rate to 137.5 Gbps (corresponding to 11 frequency slots (FS') at 12.5 Gbps in the EON) and only a capacity of 2.5 Gbps will be wasted. In contrast, as a fixed-grid transponder might only choose its data-rate from $\{50, 100, 150, 200\}$ Gbps [3], we in the best case have to use a transponder at 150 Gbps to carry the two flows and waste a capacity of 15 Gbps.

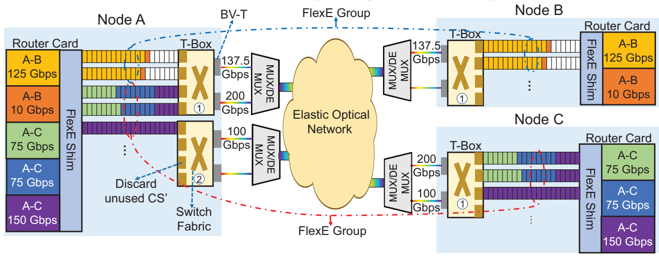

Fig. 3. Integration of FlexE and EON in FlexE-aware architecture.

We depict the integration of FlexE and EON in the FlexE-terminal architecture in Fig. 4 [3]. Here, the major difference from the FlexE-aware architecture is that the T-Boxes also possess FlexE shims. Hence, each FlexE group is between a router card and its T-Box(es), and flow-level routing can be realized in the T-Boxes. As a consequence, the restriction in the FlexE-unaware and FlexE-aware architectures, *i.e.*, flows to different destinations have to use different FlexE groups, can be removed. However, as each FlexE group terminates at one T-Box in this architecture, a client flow in the FlexE group would always be transmitted through one BV-T in the T-Box. In Fig. 4, we assume that the total capacity of the BV-Ts in a T-Box would not exceed 400 Gbps[1]. Then, after serving the A-B flows, the first T-Box in *Node* A only leaves a capacity of 262.5 Gbps for its second BV-T to carry the A-C flows. Hence, the 150 Gbps flow for A-C is put in the second FlexE group and gets transmitted in the second T-Box in *Node* A.

[1] In this work, we assume that the BV-Ts in each T-Box are SBV-Ts [8]. Specifically, the capacity of each BV-T is adjustable with a granularity of 12.5 Gpbs while the total capacity of the BV-Ts in a T-Box is fixed.

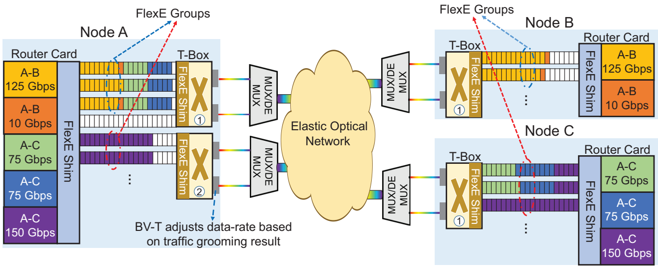

Fig. 4. Integration of FlexE and EON in FlexE-terminal architecture.

III. MILP Models for Optimizing Integrations of FlexE and EON

In this section, we formulate an MILP model to optimize the network design of each integration of FlexE and EON (*i.e.*, based on the three aforementioned architectures), under known client traffic patterns[2]. Then, based on the exact solutions provided by these MILP models, we can evaluate the mutual benefit of integrating FlexE and EON. Specifically, for each of the three architectures, we compare the network designs of "FlexE + fixed-grid WDM" and "FlexE + EON" and assess the network designs of "FlexE + EON" for the three architectures.

A. Integration in FlexE-Unaware Architecture

For the "FlexE + EON" in the FlexE-unaware architecture, each BV-T in a T-Box is assigned to carry the traffic in two pre-connected PHYs, *i.e.*, the BV-T's data-rate is fixed at 200 Gbps [3]. Due to the mapping between PHYs and BV-Ts are pre-determined, this architecture cannot explore the benefit of EONs, and the following MILP model can optimize the network designs of both "FlexE + WDM" and "FlexE + EON".

Parameters:

- $G(V, E)$: the network topology, where V is the node set and E is the fiber link set.
- F: the set of all the flows to be served, where each flow f_i has an unique index $i \in [1, |F|]$, a source-destination pair s_i-d_i, and a bandwidth demand b_i in Gbps.
- N: the number of PHYs that each router card has.
- T: the number of T-Boxes connecting to each router card.
- P: the number of BV-Ts that each T-Box has.
- R_v: the set of router cards on node $v \in V$, where $r \in R_v$ represents a router card on node v.
- $M_{v,u}$: the set of FlexE groups between nodes v and u, where $sr_m^{v,u}$ and $dr_m^{v,u}$ are the router cards associating with the m-th group in $M_{v,u}$, in v and u, respectively.
- C_p: the capacity of a PHY in Gbps, *i.e.*, $C_p = 100$ Gbps.
- C_t: the capacity of a BV-T, which is enough to carry the traffic in two pre-connected PHYs, *i.e.*, $C_t = 200$ Gbps.

Variables:

- $x_{i,m}$: the boolean variable that equals 1 if flow $f_i \in F$ gets assigned to the m-th FlexE group between its source s_i and destination d_i, and 0 otherwise.
- $w_m^{v,u}$: the nonnegative integer variable that represents the number of PHYs assigned to the m-th FlexE group between nodes v and u.
- $z_m^{v,u}$: the nonnegative integer variable that represents the number of BV-Ts that are assigned to the m-th FlexE group between nodes v and u.
- $y_{v,r}$: the boolean variable that equals 1 if router card r in node v is used, and 0 otherwise.
- $k_{v,r}$: the nonnegative integer variable that is the number of used T-Boxes connecting to router card r in node v.
- α_v: the nonnegative integer variable that represents the number of used router cards in node v.
- β_v: the nonnegative integer variable that represents the number of used T-Boxes in node v.
- γ_v: the nonnegative integer variable that represents the number of used BV-Ts in node v.

Objective:

The optimization objective is to minimize the used router cards, T-Boxes, and BV-Ts in the network planning as:

$$Minimize \sum_{v \in V} (P \cdot T \cdot \alpha_v + P \cdot \beta_v + \gamma_v), \quad (1)$$

where the weights assigned to the three terms ensure that the optimization reduces the numbers of used router cards, T-Boxes and BV-Ts in strictly descending priorities.

Constraints:

$$\sum_{m=1}^{|M_{s_i,d_i}|} x_{i,m} = 1, \ \forall f_i \in F. \quad (2)$$

$$\sum_{\substack{f_i \in F: \\ s_i = v, d_i = u}} x_{i,m} \cdot b_i \leq w_m^{v,u} \cdot C_p, \ \forall v \in V, u \in V, m \in M_{v,u}. \quad (3)$$

$$\sum_{\substack{u \in V: \\ u \neq v}} \sum_{\substack{m \in M_{v,u}: \\ sr_m^{v,u} = r}} w_m^{v,u} \leq y_{v,r} \cdot N, \ \forall v \in V, r \in R_v. \quad (4)$$

$$\sum_{r \in R_v} y_{v,r} \leq \alpha_v, \ \forall v \in V. \quad (5)$$

$$w_m^{v,u} \cdot C_p \leq z_m^{v,u} \cdot C_t, \ \forall v \in V, u \in V, m \in M_{v,u}. \quad (6)$$

$$\sum_{\substack{u \in V: \\ u \neq v}} \sum_{\substack{m \in M_{v,u}: \\ sr_m^{v,u} = r}} z_m^{v,u} \leq k_{v,r} \cdot P, \ \forall v \in V, r \in R_v. \quad (7)$$

$$\sum_{r \in R_v} k_{v,r} \leq \beta_v, \ \forall v \in V. \quad (8)$$

$$\sum_{\substack{u \in V: \\ u \neq v}} \sum_{m \in M_{v,u}} z_m^{v,u} \leq \gamma_v, \ \forall v \in V. \quad (9)$$

Eq. (2) ensures that each flow f_i gets assigned to one and only one FlexE group that is between its source s_i and destination d_i. Eq. (3) ensures that the total capacity of the PHYs assigned to the m-th FlexE group between nodes v and u is not less than the total bandwidth requirement of the flows included in the FlexE group. Eq. (4) ensures that the number of assigned PHYs in a router card r in node v should not exceed

[2]Note that, in order to limit the complexity of the ILP models such that for reasonably large networks, they can be solved within reasonable time, we assume that all the client flows are served all-optically end-to-end and the optical spectra on the fibers in the EON are always enough to support the lightpaths for the flows. Hence, the routing and spectrum assignment [11] of the lightpaths becomes trivial in the problem of network design.

the number of PHYs in the router card. Eq. (6) ensures that the total capacity of the BV-Ts assigned to the m-th FlexE group between nodes v and u is sufficient for carrying the PHYs in the FlexE group. Eqs. (5) and (7)-(9) ensure that the values of α_v, $k_{v,r}$, β_v and γ_v are correctly selected, respectively.

B. Integration in FlexE-Aware Architecture

The MILP model in the previous sub-section can be extended to consider the "FlexE + EON" in the FlexE-aware architecture, with the following specific modifications.

New Parameters:

- $T_{v,r}$: the set of T-Boxes associated with router card r in node v, where $t \in T_{v,r}$ is such a T-Box.
- P_v: the set of BV-Ts in node v, where $p \in P_v$ is such a BV-T whose T-Box and router card are denoted as $t_{v,p}$ and $r_{v,p}$, respectively.
- $P_{v,t}$: the set of BV-Ts in T-Box t of node v.
- C_{max}: the maximum capacity of a BV-T, *i.e.*, 400 Gbps.
- C_g: the granularity of capacity adjustment on each BV-T, *i.e.*, $C_g = 12.5$ Gbps.

New Variables:

- $y^{v,u}_{m,p}$: the boolean variable that equals 1 if BV-T p in node v is used for the m-th FlexE group between nodes v and u, and 0 otherwise.
- $z^{v,u}_{m,p}$: the nonnegative integer variable that represents the number of PHYs assigned to BV-T p for the m-th FlexE group between nodes v and u.
- $y_{v,p}$: the boolean variable that equals 1 if BV-T p in node v is used, and 0 otherwise.
- $n^{v,u}_{m,p}$: the nonnegative integer variable that represents the actual assigned capacity of BV-T p for the m-th FlexE group between nodes v and u, in number of C_g.
- $y_{v,t}$: the boolean variable that equals 1 if T-Box t in node v is used, and 0 otherwise.
- η: the nonnegative real variable that represents the normalized total wasted BV-T capacity.

Objective:

Note that, in the FlexE-aware architecture, each BV-T can take different capacities and we should try to minimize the total wasted BV-T capacity in the network design. Hence, we modify the optimization objective as follows.

$$Minimize \quad \eta + \sum_{v \in V} \left(P \cdot T \cdot \alpha_v + P \cdot \beta_v + \gamma_v \right), \tag{10}$$

Constraints:

We reuse the constraints in Eqs. (2)-(5) in the MILP in Section III-A, and the following new constraints are introduced.

$$w^{v,u}_m \leq \sum_{\substack{t \in T_{v,sr^{v,u}_m}, \\ p \in P_{v,t}}} z^{v,u}_{m,p}, \ \forall v \in V, u \in V, m \in M_{v,u}. \tag{11}$$

$$\sum_{p \in P_{v,t}} \sum_{\substack{u \in V: \\ u \neq v}} \sum_{\substack{m \in M_{v,u}: \\ sr^{v,u}_m = r}} z^{v,u}_{m,p} \leq \frac{N}{T}, \ \forall v \in V, r \in R_v, t \in T_{v,r}. \tag{12}$$

$$\sum_{\substack{u \in V: \\ u \neq v}} \sum_{m \in M_{v,u}} y^{v,u}_{m,p} \leq 1, \ \forall v \in V, p \in P_v. \tag{13}$$

$$z^{v,u}_{m,p} \leq y^{v,u}_{m,p} \cdot \frac{N}{T}, \ \forall v \in V, u \in V, m \in M_{v,u}, p \in P_v. \tag{14}$$

$$y^{v,u}_{m,p} \leq y_{v,p}, \ \forall v \in V, u \in V, m \in M_{v,u}, p \in P_v. \tag{15}$$

$$\sum_{p \in P_{v,t}} y_{v,p} \leq y_{v,t} \cdot P, \ \forall v \in V, r \in R_v, t \in T_{v,r}. \tag{16}$$

$$\sum_{r \in R_v} \sum_{t \in T_{v,r}} y_{v,t} \leq \beta_v, \ \forall v \in V. \tag{17}$$

$$\sum_{p \in P_v} y_{v,p} \leq \gamma_v, \ \forall v \in V. \tag{18}$$

$$\begin{aligned} (z^{v,u}_{m,p} - 1) \leq & n^{v,u}_{m,p} \cdot \frac{C_g}{C_p} \leq z^{v,u}_{m,p}, \\ \sum_{\substack{f_i \in F: \\ s_i = v, d_i = u}} x_{i,m} \cdot b_i \leq & \sum_{p \in P_v} n^{v,u}_{m,p} \cdot C_g, \end{aligned} \ \forall v, u \in V, m \in M_{v,u}. \tag{19}$$

$$\eta = \frac{\sum_{\substack{v,u \in V: \\ v \neq u}} \sum_{m=1}^{|M_{v,u}|} \left(\sum_{p \in P_v} n^{v,u}_{m,p} \cdot C_g - \sum_{\substack{f_i \in F: \\ s_i = v, d_i = u}} x_{i,m} \cdot b_i \right)}{C_{max} \cdot T \cdot \max_{v \in V}(|R_v|) \cdot |V|}. \tag{20}$$

Eq. (11) ensures that the PHYs assigned to the m-th FlexE group between nodes v and u have enough BV-Ts to support. Eq. (12) ensures that the total number of PHYs associated with the BV-Ts in T-Box t in node v would not exceed the number of PHYs that T-Box t has from router card r. Eq. (13) ensures that BV-T p can be assigned to one FlexE group at most. Eq. (14) ensures that the values of $z^{v,u}_{m,p}$ and $y^{v,u}_{m,p}$ are interdependent. Eqs. (15)-(16) ensure that the values of $y^{v,u}_{m,p}$, $y_{v,p}$ and $y_{v,t}$ are interdependent. Eqs. (17)-(19) ensure that the values of β_v, γ_v and $n^{v,u}_{m,p}$ are correctly selected, respectively. The value of η is calculated with Eq. (20).

The MILP above can be easily modified to solve the network design of "FlexE + WDM" in this architecture, *i.e.*, by changing the value of C_g to 50 Gbps and restricting the feasible values of $n^{v,u}_{m,p}$ as $\{0, 1, 2, 3, 4\}$.

C. Integration in FlexE-Terminal Architecture

As the FlexE groups in the FlexE-terminal architecture are all between a router card and its T-Boxes, we can only leverage the parameters and variables defined in the aforementioned MILP models but need to rewrite all the constraints. Here, the optimization objective is still same as that in Eq. (10).

New Variables:

- $x_{i,p}$: the boolean variable that equals 1 if flow $f_i \in F$ gets assigned to BV-T p in node s_i, and 0 otherwise.
- $n_{v,p}$: the nonnegative variable that represents the actual assigned capacity of BV-T p in node v, in number of C_g.

Constraints:

$$\sum_{p \in P_{s_i}} x_{i,p} = 1, \ \forall f_i \in F. \tag{21}$$

$$\begin{aligned} & x_{i,p} + x_{j,p} \leq y_{v,p}, \\ \forall v \in V, p \in P_v, & f_i \in F, f_j \in F, s_i = s_j = v, d_i \neq d_j. \end{aligned} \tag{22}$$

$$\sum_{\substack{f_i \in F: \\ s_i = v}} x_{i,p} \cdot b_i \leq n_{v,p} \cdot C_g, \ \forall v \in V, p \in P_v. \tag{23}$$

$$\sum_{p \in P_{v,t}} \sum_{\substack{f_i \in F: \\ s_i = v}} x_{i,p} \cdot b_i \leq \frac{C_p \cdot N}{T}, \; \forall v \in V, r \in R_v, t \in T_{v,r}. \quad (24)$$

$$y_{v,p} \leq y_{v,r_{v,p}}, \; \forall v \in V, p \in P_v. \quad (25)$$

$$y_{v,p} \leq y_{v,t_{v,p}}, \; \forall v \in V, p \in P_v. \quad (26)$$

$$\sum_{r \in R_v} y_{v,r} \leq \alpha_v, \; \forall v \in V. \quad (27)$$

$$\sum_{r \in R_v} \sum_{t \in T_t} y_{v,t} \leq \beta_v, \; \forall v \in V. \quad (28)$$

$$\sum_{p \in P_v} y_{v,p} \leq \gamma_v, \; \forall v \in V. \quad (29)$$

$$\eta = \frac{\sum_{v \in V} \sum_{p \in P_v} \left(n_{v,p} \cdot C_g - \sum_{\substack{f_i \in F: \\ s_i = v}} x_{i,p} \cdot b_i \right)}{C_{max} \cdot T \cdot \max_{v \in V}(|R_v|) \cdot |V|}. \quad (30)$$

Eq. (21) ensures that flow f_i gets assigned to one and only one BV-T in node s_i. Eq. (22) ensures that BV-T p in node v can only be used to serve flows to the same destination. Eq. (23) ensures that the capacity of BV-T p in node v is sufficient to serve the assigned flows. Eq. (24) ensures that the total capacity of the PHYs between router card r and T-Box t is enough to carry the flows between them. Eqs. (25)-(26) ensures that when BV-T p in node v is used, the related router card and T-Box are also marked as used. Eqs. (27)-(29) ensures that the values of α_v, β_v and γ_v are correctly selected, respectively. The value of η is calculated with Eq. (30).

Similarly, by changing the value of C_g to 50 Gbps and restricting the feasible values of $n_{v,p}$ as $\{0, 1, 2, 3, 4\}$, this MILP can also be easily modified to solve the network design of "FlexE + WDM" in this architecture.

TABLE I
SIMULATION PARAMETERS

Topology	14-node NSFNET
$\|F\|$, # of flows	[80, 100]
$\{b_i\}$, Flow bandwidth distribution	$\{10, 40, \tau \cdot 25\}$ Gbps
$\|R_v\|$, # of router cards on each node	2
N, # of 100 Gbps PHYs in each router card	8
T, # of T-boxes connecting to a router card	2
P, # of BV-Ts in each T-Box	2

IV. PERFORMANCE COMPARISONS

In this section, we run simulations to explore the mutual benefits of integrating FlexE with EON. Specifically, we solve the MILP models designed above to obtain the exact solutions of the network designs for both "FlexE + EON" and "FlexE + WDM". The MILP models are implemented with the GNU linear programming kit (GLPK), and they are solved in MATLAB R2017a. The computing environment is a computer with 2.93 GHz Intel Core i3 CPU and 6 GB RAM.

Table I shows the simulation parameters. The EON uses the 14-node NSFNET topology [12], where each fiber link is assumed to carry sufficient spectrum resources for the accommodating all the flows generated by the FlexE clients and the degree of the nodes is within $[3, 4]$. For the client flows, their bandwidth requirements (*i.e.*, $\{b_i\}$) can be selected from $\{10, 40, 25 \cdot \tau\}$ Gbps, where $\tau \in [1, 8]$ is the bit-rate upgrade multiplier of Ethernet interfaces [3]. To study the performance of "FlexE + EON" under different traffic conditions, the simulations consider three scenarios. In the first scenario, we assume that the client flows can take any of the feasible bandwidth requirements in $\{10, 40, 25 \cdot \tau\}$ Gbps randomly. The second scenario addresses the performance analysis of light and heavy traffic loads. Specifically, for the light load case, we set $\tau \in [1, 4]$, while the heavy load case has $\tau \in [5, 8]$. Finally, in the third scenario, we investigate the effect of the granularity of client bandwidth requirements and also consider two cases. In the light load case, the client flows select their bandwidth from $\{10, 40, 50, 100\}$ Gbps, while the heavy load case chooses the flow bandwidth from $\{100, 150, 200\}$ Gbps.

According to the aforementioned bandwidth distributions, we randomly generate $[80, 100]$ client flows in the NSFNET topology, and use the MILP models to obtain the exact network designs for serving them in the network built with different integrations. Note that, the complexity of the MILP models increases exponentially with the number of client flows. Therefore, we have to limit the number of flows such that the MILP models can be solved within a reasonable amount of time, *w.l.o.g.*, the network designs to accommodate the flows can already tell the performance difference among the integrations. For the integrations, we consider both "FlexE + EON" and "FlexE + WDM", and solve them in the FlexE-unaware, FlexE-aware and FlexE-terminal architectures.

The results for the first scenario are listed in Table II. Here, since there is no difference between "FlexE + EON" and "FlexE + WDM" in the FlexE-unaware architecture, we just perform a simulation to cover both of them. Meanwhile, for the FlexE-aware and FlexE-terminal architectures, we simulate "FlexE + EON" and "FlexE + WDM" separately. The obtained network designs are compared in terms of average used router cards, T-Boxes and transponders per node and the normalized total wasted transponder capacity (*i.e.*, η), respectively. We observe that when fixed-grid WDM is considered, the integrations with the three FlexE architectures perform the same in term of average used router cards, T-Boxes and transponders per node, while the results on η from the FlexE-aware and FlexE-terminal architectures are the same and they are smaller than that from the FlexE-unaware one. Hence, for "FlexE + WDM", the only advantage of FlexE-aware and FlexE-terminal over FlexE-unaware is that they can reduce the wasted capacity on transponders, but FlexE-aware and FlexE-terminal perform exactly the same. This suggests that the flexibility provided by FlexE-aware and FlexE-terminal can hardly be fully explored due to the fixed-grid transmission scheme.

On the other hand, when "FlexE + EON" is considered, FlexE-terminal performs better than FlexE-aware and they both outperform FlexE-unaware in terms of all the metrics in Table II. Moreover, if we fix the FlexE architecture and compare "FlexE + EON" with "FlexE + WDM", it can be seen that for both FlexE-aware and FlexE-terminal, "FlexE + EON" requires less router cards, T-boxes and transponders while largely reducing the wasted capacity on transponders as well. The results indicate that EON and FlexE can mutually benefit each other by maximizing their individual advantages, when FlexE-aware and FlexE-terminal are considered.

TABLE II
RESULTS OF THE FIRST SCENARIO

$b_i \in \{10, 40, \tau \cdot 25\}$ Gbps, $\tau \in [1, 8]$					
Integration Scheme		Avg. Router Cards	Avg. T-Boxes	Avg. BV-Ts	η
FlexE-unaware	-	1.75	3.13	5.63	0.1879
FlexE-aware	WDM	1.75	3.13	5.63	0.0238
	EON	1.63	3	3.75	0.0053
FlexE-terminal	WDM	1.75	3.13	5.63	0.0238
	EON	1.50	2.25	3.75	0.0023

With the results in Tables III and IV, we explore the effect of the client flows' bandwidth distribution on the performance of the network designs. In both tables, we can see the similar trends observed in Table II, verifying that the mutual benefits of integrating FlexE-aware and FlexE-terminal with EON would not vanish due to traffic distribution changes. More importantly, the results in Tables II-IV show that when comparing "FlexE + EON" with "FlexE + WDM", the performance improvement achieved with FlexE-terminal is always larger than that with FlexE-aware. This suggests that the integration of FlexE-terminal and EON can mutually benefit each other the most. Meanwhile, by comparing the results on η in Tables III and IV, we observe that except for FlexE-unaware, η generally decreases with the bandwidth granularity of client flows when other conditions are the same. More specifically, in the heavy load case in Table IV, η can be zero for all the integrations related to FlexE-aware and FlexE-terminal, which means that when the client flows only take $\{100, 150, 200\}$ Gbps, our MILP models ensure that the capacity of all the allocated transponders are fully utilized.

TABLE III
RESULTS OF THE SECOND SCENARIO

Light Traffic Load: $b_i \in \{10, 40, \tau \cdot 25\}$ Gbps, $\tau \in [1, 4]$					
Integration Scheme		Avg. Router Cards	Avg. T-Boxes	Avg. BV-Ts	η
FlexE-unaware	-	1	2	3.5	0.1503
FlexE-aware	WDM	1	2	3.5	0.0409
	EON	1	2	2.8	0.0136
FlexE-terminal	WDM	1	2	3.5	0.0409
	EON	1	1.5	2.5	0.0066
Heavy Traffic Load: $b_i \in \{10, 40, \tau \cdot 25\}$ Gbps, $\tau \in [5, 8]$					
FlexE-unaware	-	2	3.5	6.3	0.1378
FlexE-aware	WDM	2	3.5	6.3	0.0659
	EON	2	3.5	4.3	0.0066
FlexE-terminal	WDM	2	3.5	6.3	0.0659
	EON	2	3	4.3	0.0066

V. CONCLUSION

In this paper, we explored the mutual benefits of integrating FlexE with EON and considered three FlexE architectures, *i.e.*, FlexE-unaware, FlexE-aware and FlexE-terminal. To optimize the integrations' network designs, we formulated three MILP models, which can be easily modified to consider fixed-grid WDM networks as well. Then, based on the exact solutions from the MILP models, we tried to clarify the differences between EONs and WDM networks in their integrations with FlexE, and evaluated "FlexE + EON" for the three architectures. Simulation results showed that EON and FlexE can mutually benefit each other when FlexE-aware and FlexE-terminal are considered, the advantages would not vanish due to traffic distribution changes, and integrating FlexE-terminal with EON would maximize their mutual benefits since it possesses the highest level of flexibility.

TABLE IV
RESULTS OF THE THIRD SCENARIO

Light Traffic Load: $b_i \in \{10, 40, 50, 100\}$ Gbps					
Integration Scheme		Avg. Router Cards	Avg. T-Boxes	Avg. BV-Ts	η
FlexE-unaware	-	1.73	2.73	5.09	0.2227
FlexE-aware	WDM	1.73	2.73	5.09	0.0097
	EON	1.36	2.36	3.18	0.0011
FlexE-terminal	WDM	1.73	2.73	5.09	0.0097
	EON	1	2	3.18	0.0011
Heavy Traffic Load: $b_i \in \{100, 150, 200\}$ Gbps					
FlexE-unaware	-	2	4	7.8	0.2375
FlexE-aware	WDM	2	4	7.8	0
	EON	2	4	4.8	0
FlexE-terminal	WDM	2	4	7.8	0
	EON	2	3.2	5.2	0

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