Quasi-CWDM Optical Network: Cost Effective and Spectrum Efficient Architecture for Future Optical Networks (Invited)

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Abstract—Elastic optical network (EON) is a promising candidate for the next generation optical transport network because of its high spectrum efficiency and flexible spectrum allocation. However, to migrate from today’s dense wavelength division multiplexing (DWDM) network to EON, optical nodes such as reconfigurable optical add/drop multiplexers (ROADMs) should be replaced with the ones with expensive flexi-grid wavelength selective switches (WSSs). Thus, whether and how today’s optical network will be evolved to EON is still under debate. Meanwhile, with the technical maturity of optical super-channels that transmit bit rates at the level of 1 Tb/s, super-channels are expected to dominate the future optical transport network because of their attractiveness of high spectrum efficiency and superior cost effectiveness. In this paper, we propose a new quasi-coarse wavelength division multiplexing (Quasi-CWDM) optical network architecture that is compatible to today’s WDM network in spectrum operation, while still maintaining the flexibility of adaptation between the bit rate and the transparent reach of an optical super-channel, but not requiring expensive flexi-grid WSSs. Specifically, the Quasi-CWDM optical network employs large fixed frequency grids, whose spacing falls between the traditional CWDM and DWDM, e.g., 200 GHz or 400 GHz. To maintain the flexibility between the bit rate and the transparent reach of an optical super-channel, different modulation formats are chosen according to channel physical distances. To minimize network hardware cost and maximize carried user traffic demand, we develop a mixed integer linear programming (MILP) model and a heuristic algorithm that can efficiently groom upper-layer IP traffic onto the optical layer by optical super-channels. We compare the design based on the Quasi-CWDM network to those based on the DWDM network and the advanced EON. It is found that the proposed Quasi-CWDM network has a much lower hardware cost than the other two types of networks, while achieving spectrum efficiency close to EON.

Index Terms—Quasi-CWDM, traffic grooming, elastic optical network, cost effective, spectrally efficient

I. INTRODUCTION

The rapid growth of Internet traffic in the past decade requires the optical transmission technology to be continuously evolved. The optical transmission technology has been evolved from the past CWDM to today’s DWDM technology. To provide even higher transmission capacity, a more spectrally efficient transmission technique called elastic optical network (EON) [1] was also proposed and has received extensive research interest recently.

The EON improves spectrum utilization through reducing the granularity of each frequency slot (FS) and adding flexibility in spectrum allocation for an optical channel, which allows an optical channel to span multiple FSs as shown in Fig. 1(c). However, to build an EON, ROADMs should be upgraded to include costly flexi-grid WSSs, which can greatly increase the network hardware cost. In addition, though EON is flexible to allocate any bandwidth (in units of FS) to an optical channel, a question is often raised: considering the guard-band between any two neighboring channels, is it spectrally efficient to establish optical channels with very few FSs? Thus, these could be barriers for the migration from today’s DWDM network to EON, and it is still under debate whether the optical transport network would eventually migrate to EON.

Fig. 1. Optical channel spectrum layouts under different technologies.

Bearing in mind the above question and considering the maturity of optical super-channels that are expected to dominate the future optical transport network, in this paper we propose a new optical transport network architecture that operates based on the Quasi-CWDM technology. To simplify the spectrum operation in the optical layer, the Quasi-CWDM technique only establishes optical super-channels with fixed bandwidth. As shown in Fig. 1(d), its frequency spacing is generally much larger than that of DWDM, while smaller than CWDM. Within each fixed-bandwidth super-channel, the flexibility in adapting the bit rate of an optical channel depending on its physical layer conditions is still maintained through using different modulation formats. In addition, because of the removal of the requirement of arbitrary bandwidth allocation as in EON, the ROADM node in a Quasi-CWDM network does not contain expensive flexi-grid
WSSs, but needs much cheaper array waveguide gratings (AWGs) and fixed-grid WSSs. Note that these AWGs and WSSs could be even cheaper than those used in the DWDM network because the frequency spacing is even larger under the Quasi-CWDM technique. It should also be noted that though similar to the DWDM network with mixed line rates (MLRs), the proposed Quasi-CWDM is fundamentally innovative, motivated by the future dominance of optical super-channels, while the latter is based on non-super-channels.

To evaluate the efficiency of the proposed Quasi-CWDM network from perspectives of cost and spectrum efficiency, we consider an IP over Quasi-CWDM optical network, in which IP traffic flows are aggregated or groomed onto super-channels in the optical layer. For the traffic grooming problem, we develop a mixed integer linear programing (MILP) model with the objective of minimizing total hardware cost and/or maximizing maximal served traffic demand. Different from the exiting approaches for traffic grooming in an DWDM network with MLRs, the optimization model is novel to optimally decide which layer to implement signal regeneration (IP layer or optical layer), or in other word, to incorporate the potential regenerator cost when establishing super-channels using different modulation formats. Also, to find a solution for a large network, we develop an efficient heuristic algorithm for the above traffic grooming problem that can perform close to the MILP model. Again, the algorithm is novel to incorporate the layer selection for signal regeneration or the regenerator cost when establishing new lightpath channels. We compare the performance of the Quasi-CWDM network with the DWDM network and the more advanced EON in the aspects of network hardware cost and spectrum efficiency. Simulation studies show that the Quasi-CWDM network is efficient to have a lower network hardware cost than those of the two other networks, while maintaining spectrum efficiency close to that of EON. The key contributions of this work include the following aspects.

1) We propose a new Quasi-CWDM network architecture that is promising with low hardware cost, but still maintains flexible adaptation between the bit rate and the transparent reach of an optical super-channel.

2) To verify the benefit of the proposed architecture, we evaluate its performance in the context of an IP over Quasi-CWDM network, for which an MILP model that incorporates the regenerator cost associated with each optical channel is developed.

3) Also, due to the computational difficulty of the MILP model, an efficient regenerator-aware heuristic algorithm that can balance the cost of optical transponders (or IP router ports) and optical regenerators is developed, which performs close to the MILP model.

A. Related Works

The problems on lightpath routing and spectrum assignment (RSA) in EON and IP over EON traffic grooming have been explored in the literature. For the RSA problem, Christodouloupolous et al. [2] presented an ILP optimization model to minimize the spectrum used to serve a traffic matrix and decomposes the RSA problem into two sub-problems for fast solution. In [3], Wang et al. looked into the RSA problem to show its NP-hardness, and developed ILP models and efficient algorithms to minimize the required number of sub-carriers. Other related works for the RSA problem can also be found in [4][5], etc. For the IP over EON traffic grooming problem, Cai et al. [6] developed an MILP model to evaluate the benefit of electronic traffic grooming in the IP over EON. Zhang et al. [7] studied the mixed-electrical-optical-grooming problem under dynamic traffic demand and proposed an auxiliary graph (AG)-based heuristic algorithm. In [8], they also studied an energy-efficient traffic grooming problem for IP over EON network with spectrally sliceable transponders.

Also, a DWDM optical network with MLRs is another effective method to reduce the cost and to improve network spectrum/energy efficiency. Nag et al. [9] proposed a design scheme for the MLR optical network, in which transceivers can use different modulation formats. Christodouloupolous et al. [10] developed a RWA algorithm that can adapt the transmission reach of an optical channel according to its modulation format. Other works in this direction can also be found in [11][12], etc.

II. IP OVER QUASI-CWDM NETWORK

A. Network Model

We employ the Quasi-CWDM network to accommodate its upper-layer IP traffic flows. Fig. 2 shows the architecture of an IP over Quasi-CWDM network, in which two network layers are included, namely, IP layer and Quasi-CWDM optical layer. Each node consists of a pair of core router and ROADM. The core router connects to the ROADM through short-reach optical interfaces that support Quasi-CWDM for super-channel establishment. The ROADM node has exactly the same architecture as that of a node in today’s DWDM network except that the contained AWGs and WSSs support Quasi-CWDM frequency spacing. Thus, they can be even cheaper since a smaller port count is required to cover the whole fiber spectrum. In Fig. 2, all the router nodes interconnected by lightpath virtual links make up the IP layer, and all the ROADM nodes interconnected by the fiber links make up the optical layer.

Each lightpath channel between a pair of source and destination nodes ends at two IP router ports and in the middle there could be zero or multiple signal regenerators. IP router ports belong to the IP layer, while the signal regenerators are the components in the optical layer. Their hardware complexity and costs are different. Table I shows the relative costs of regenerators and IP router ports with different modulation formats, where the cost of a BPSK regenerator is normalized to 1.0 unit. Due to the higher complexity of a router port, we also assume the cost of a router port to be double of a regenerator.
when they are in the same modulation format.

<table>
<thead>
<tr>
<th>Modulation format</th>
<th>Spectrum efficiency</th>
<th>Cost of regenerator</th>
<th>Cost of IP router port</th>
<th>Transparent reach (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4000</td>
</tr>
<tr>
<td>QPSK</td>
<td>1.3</td>
<td>2.6</td>
<td>3</td>
<td>2000</td>
</tr>
<tr>
<td>8-QAM</td>
<td>1.5</td>
<td>3</td>
<td>1</td>
<td>1000</td>
</tr>
</tbody>
</table>

### B. Modulation Formats versus Transparent Reaches

Different modulation formats have different transparent reaches, thereby requiring different numbers of regenerators for a certain lightpath distance. Table I also shows the relationship between transparent reaches and modulation formats [13]. Fig. 3 shows an example of the tradeoff between transparent reaches and modulation formats. Assume there is 500-Gb/s traffic demand between node pair (N₁, N₂) and wavelength spacing is 200 GHz, among which a 25-GHz guard-band is required. With the transparent reach information in Table I, BPSK does not require any regenerates, but it provides the lowest channel capacity (i.e., 175 Gb/s). In contrast, 8-QAM provides the highest channel capacity (i.e., 525 Gb/s), but needs the most signal regenerators, thereby the most expensive. Table II compares the required number of IP router ports, regenerators, and total costs for different modulation formats, from which we see that it is important to optimally balance the channel capacity efficiency and the hardware cost.

[Fig. 3. Tradeoff between modulation formats and transparent reaches.]

<p>| Table II Required Numbers of IP Router Ports, Regenerators, and Total Costs for Different Modulation Formats |
|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|</p>
<table>
<thead>
<tr>
<th>Modulation format</th>
<th># of regens</th>
<th># of IP router ports</th>
<th># of channels (bidirectional)</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>0</td>
<td>6</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>QPSK</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>10.4</td>
</tr>
<tr>
<td>8-QAM</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>9</td>
</tr>
</tbody>
</table>

### C. Signal Regeneration: in IP Layer or Optical Layer?

For the IP over Quasi-CWDM network, there are two ways to carry out signal regeneration for an optical channel, i.e., in the IP layer or in the optical layer. As shown in Fig. 4(a), signal regeneration may be implemented in the IP layer through interrupting an optical channel by a router. Its advantage is that more IP traffic demand can be added to the optical channel, which is very efficient if the channel is not fully filled. Considering the high capacity of an optical super-channel in the Quasi-CWDM network, this can be very attractive as a big super-channel pipe in general cannot be fully filled by the traffic demand between a single node pair, but needs to aggregate other traffic demand at the regeneration node. However, this option is often more expensive as it needs two additional IP router ports at the regeneration node.

Signal regeneration may also be implemented in the optical layer to let an optical channel be relayed by a signal regenerator (which can be an OEO regenerator) as shown in Fig. 4(b). This implementation is generally cheaper as it only brings in a pair of signal regenerators in the optical layer, instead of a pair of additional router ports. However, it loses the opportunity of inserting new IP traffic at the regeneration node, which has low efficiency if the capacity of a super-channel is not fully used.

Based on the above example, it is clear to see that choosing signal regeneration in the IP layer or in the optical layer is an important optimization issue in the traffic grooming problem of the IP over Quasi-CWDM network. Whether it is successfully addressed can directly impact the traffic grooming performance of the IP over Quasi-CWDM network.

### III. REGENERATOR-AWARE IP OVER QUASI-CWDM TRAFFIC GROOMING

We aim to design an IP over Quasi-CWDM network with the least cost that is made up of the costs of all the IP router ports and signal regenerators. The given inputs to the problem include: (1) The physical topology of a network $G_p = (N, E)$, where $N$ is the set of network nodes and $E$ is the set of network links. (2) The traffic demand matrix $[\lambda_{ij}^d]$, in which each element is the traffic demand in units of Gb/s between node pair $(s, d)$. (3) The cost of a regenerator $C_{\text{regen}}^f$ and the cost of an IP router port $C_{\text{ip}}^f$ with the $f^{th}$ modulation format, and the transparent reach of each modulation format. Their related information is shown in Table I. (4) The number of required regenerators $R_{ij}^f$ on an optical channel established on the shortest route between node pair $(i, j)$ when the $f^{th}$ modulation format is used. The constraints for the optimization problem mainly include: (1) All of the traffic demand between the node pairs must be served. (2) There is limited spectrum resource in each fiber link.

#### A. MILP Model

We use an MILP model to formulate the traffic grooming problem for the IP over Quasi-CWDM network. The indices, sets, parameters, and variables are given as follows.

**Indices:**
- $s$ and $d$ To index the source and destination nodes of end-to-end IP traffic demand. This demand is routed over the lightpath virtual topology.
- $i$ and $j$ To index the nodes in the lightpath virtual topology. A lightpath established between the two nodes connects a pair of router ports each at the nodes.

**Sets:**
- $N$ Set of network nodes.
- $N_i$ Set of the neighboring nodes of node $i$ in the physical topology $G_p$. 
\textbf{F} \quad \text{Set of modulation formats, which include BPSK, QPSK, and 8-QAM in this study.}

\textbf{W} \quad \text{Set of wavelengths in each fiber link.}

\textbf{Parameters:}

- $\lambda^{sd}$ \quad \text{Traffic demand in units of Gb/s between node pair.}
- $R_{ij}^f$ \quad \text{Number of required regenerators along the fixed shortest route of lightpath virtual link $(i,j)$ when the $f$th modulation format is applied. We assumed that each virtual link takes the shortest route.}
- $C_f^v$ \quad \text{Bit rate of a Quasi-CWDM optical channel with the $f$th modulation format.}
- $C_{\text{REGEN}}^f$ \quad \text{Cost of a signal regenerator with the $f$th modulation format.}
- $C_{\text{IP}}^f$ \quad \text{Cost of an IP router port with the $f$th modulation format in the Quasi-CWDM network.}
- $\theta_{mn}^f$ \quad \text{Equals one if physical link $(m,n)$ is traversed by the shortest route of lightpath virtual link $(i,j)$; zero, otherwise.}
- $\alpha$ \quad \text{A weight factor.}

\textbf{Variables:}

- $\lambda_{ij}^{sd}$ \quad \text{Traffic demand between node pair $(s,d)$ that traverses virtual link $(i,j)$.}
- $V_{ij}^f$ \quad \text{Number of Quasi-CWDM optical channels with the $f$th modulation format on virtual link $(i,j)$ (integer).}
- $N_{IP}^f$ \quad \text{Number of IP router ports with the $f$th modulation format at node $i$ (integer).}
- $N_{\text{REGEN}}^f$ \quad \text{Number of signal regenerators with the $f$th modulation format on virtual link $(i,j)$ (integer).}
- $\delta_{w}^{ij}$ \quad \text{A binary variable that equals one if an optical channel on virtual link $(i,j)$ uses the $f$th modulation format on wavelength $w$.}
- $C$ \quad \text{Maximum index of used wavelengths in all the fiber links (integer).}
- $u_w$ \quad \text{A binary variable that takes the value of one if wavelength $w$ is used.}
- $O_{w}^{mn}$ \quad \text{A binary variable that takes the value of one if wavelength $w$ is used in physical link $(m,n)$.}

\textbf{Objective:} \quad \text{Minimize} \quad \sum_{f \in F} C_{\text{IP}}^f \cdot N_{IP}^f + \sum_{f \in F} \sum_{i \in N, i \neq j} \sum_{f \in F} C_{\text{REGEN}}^f \cdot N_{\text{REGEN}}^f + \alpha C

\textbf{Constraints:}

\begin{align*}
\sum_{i \in N, i \neq j} \lambda_{ij}^{sd} - \sum_{j \in N, j \neq i} \lambda_{ij}^{sd} &= \begin{cases} 
\lambda^{sd} & i = s \\
-\lambda^{sd} & i = d \\
0 & \text{otherwise}
\end{cases} \\
& \forall s, d, i \in N: s \neq d (1)
\end{align*}

\begin{align*}
\sum_{s \in N, s \neq d} \lambda_{ij}^{sd} &= \sum_{d \in N, d \neq s} \lambda_{ij}^{sd} \\
& \forall s, d, i, j \in N: s \neq d, i \neq j (2)
\end{align*}

\begin{align*}
\sum_{i \in N} V_{ij}^f &= N_{IP}^f \\
& \forall i \in N, f \in F (3)
\end{align*}

\begin{align*}
\sum_{j \in N} V_{ij}^f &= N_{IP}^f \\
& \forall i \in N, f \in F (4)
\end{align*}

\begin{align*}
\sum_{f \in F, i \in N} \sum_{j \in N} \delta_{w}^{ij} \cdot \theta_{mn}^f &= \sum_{f \in F, i \in N} \sum_{j \in N} \sum_{w \in W} \sum_{m \in N} \sum_{n \in N} \sum_{i \in N} \sum_{j \in N} \sum_{f \in F} \theta_{mn}^f \cdot \delta_{w}^{ij} \leq 1 \\
& \forall w \in W, m \in N, n \in N (5)
\end{align*}

\begin{align*}
u_w &= 0_w \\
O_{w}^{mn} = \sum_{f \in F, i \in N} \sum_{j \in N} \sum_{w \in W} \sum_{m \in N} \sum_{n \in N} \sum_{i \in N} \sum_{j \in N} \sum_{f \in F} \theta_{mn}^f \cdot \delta_{w}^{ij} \\
& \forall w \in W, m \in N, n \in N (6)
\end{align*}

\textbf{The MILP model has two objectives. The first is to minimize the total cost of IP router ports and signal regenerators, and the second is to minimize the maximum index of used wavelengths in the whole network. However, the first objective has a higher priority by setting $\alpha$ to be a small value. We will not verbally explain each of the constraints due to the page limit. The MILP model has a total of $O(|N|^4)$ variables and a total of $O(|N|^3)$ constraints in computational complexity, where $|N|$ is the total number of nodes in the network.}

\textbf{IV. HEURISTIC ALGORITHM}

For large networks, we also propose an efficient heuristic algorithm for traffic grooming in the IP over Quasi-CWDM network. The algorithm is mainly extended from the traditional grooming algorithms used for the IP over DWDM network [14][15]. The algorithm mainly consists of two steps, i.e., the first step is to obtain an initial solution, and the second step focuses on re-optimization of the initial solution. Due to the page limit, we will simply describe these two steps below.

\textbf{Step one:} \quad \text{given a traffic demand list $D$ between different node pairs, we first find the shortest route between each node pair. We assume that lightpaths between node pairs are always established along their shortest routes. Then, create an empty virtual topology $G_v$, which is used to store lightpath virtual links. For each node pair in $D$, try to use the remaining capacity on virtual topology $G_v$ to serve its traffic demand. If not successful, establish a new lightpath channel with a suitable modulation format to serve the traffic demand on the channel, and meanwhile add the optical channel to $G_v$. Whether signal regeneration is required in the middle is also determined in this step based on the physical distance between the node pair. Then move to the second node pair in the list $D$ to repeat the same process until all the traffic demands are served. Eventually, we will obtain a virtual topology $G_v$ with many optical channels on the virtual links. We can calculate the total hardware cost based on the virtual topology $G_v$, which is the sum of the costs for the IP router ports and signal regenerators.}

\textbf{Step two:} \quad \text{based on the initial solution obtained in step one, a re-optimization process is carried out to further improve traffic grooming efficiency. The key idea is to try an optical channel with a higher modulation format (i.e., a higher bit rate) to replace multiple optical channels with lower level modulation formats (i.e., lower bit rates) if possible. If the replacement can lead to a reduced hardware cost and meanwhile all the traffic demands are served, we will do it. The attempt will be iteratively made for each virtual link in $G_v$ until no replacement can be further made.}

\textbf{V. TEST CONDITIONS AND PERFORMANCE ANALYSES}

\textbf{A. Test Conditions}

To evaluate the performance of the IP over Quasi-CWDM network, we considered three test networks: (1) a six-node,
nine-link (n6s9) network, (2) the 14-node, 21-link NSFNET network, and (3) the 24-node, 43-link USNET network. Due to the page limit, we do not show their topologies here. The Quasi-CWDM spectrum grid is assumed to be 200 GHz and the number of wavelengths in each fiber link is 20, which correspond to a 4000-GHz fiber spectrum. Meanwhile, there is a 25-GHz guard-band between any two neighboring optical channels. The traffic demand between each node pair is assumed to be randomly generated within the range of \((200, X)\) Gb/s for n6s9, \((100, X)\) Gb/s for NSFNET, and \((10, X)\) Gb/s for USNET, where \(X\) is the maximal traffic demand per node pair. The set of modulation formats includes BPSK, QPSK, and 8-QAM. The costs of IP router ports and signal regenerators with different modulation formats are shown in Table I.

**B. Cost Comparison for Different Approaches**

Fig. 5(a) compares the total hardware costs of the different approaches for the n6s9 network, in which legend “MILP” corresponds to the MILP model, and “Heu” corresponds to the heuristic algorithm. We can see that Quasi-CWDM has the lowest cost than all the other pure modulation cases. The results are reasonable as Quasi-CWDM is flexible to use different modulation formats according to each lightpath distance, and therefore the most efficient modulation format can always be chosen to best serve IP traffic demand. For the pure modulation cases, BPSK shows the highest network cost, and 8-QAM and QPSK has similar and lower costs than BPSK. This is because of the lower channel capacity provided by BPSK, which requires more BPSK IP router ports to accommodate all the traffic demand. Comparing the results of the MILP model and the heuristic algorithm, we see that they are close to each other for all the cases, thereby verifying the algorithm efficiency.

For the other two larger test networks, i.e., NSFNET and USNET, we employed the heuristic algorithm to evaluate the performance for the different cases. The results are shown in Figs. 5(b) and (c) which are similar to those of the n6s9 network. Quasi-CWDM can always achieve the lowest cost. However, we also notice that the total cost of BPSK is closer to Quasi-CWDM than QPSK and 8-QAM. This is because of the larger sizes of the two networks make BPSK more efficient. In addition to the cost difference, we also compare spectrum efficiency by summing the remaining capacity on all the established optical channels for the cases of Quasi-CWDM and BPSK (see the right \(y\)-axis in Figs. 5(b) and (c)). We can see that besides a lower hardware cost, Quasi-CWDM can provide much higher remaining capacity on the established optical channels. Specifically, there are up to 100% and 27% more capacity respectively remaining in NSFNET and USNET.

**C. Impact of Spectrum Grid Granularity**

We also evaluate how spectrum grid granularity can affect the performance of the Quasi-CWDM optical network. Assume that the total spectrum in each fiber is fixed, but the granularity of each channel can vary from 50 GHz, to 100 GHz, to 200 GHz, and to 400 GHz. The first two granularities essentially correspond to the standardized ITU-T DWDM networks. For comparison, the costs of IP router ports and signal regenerators under different modulation formats and fixed spectrum grids are assumed in Table III.

<table>
<thead>
<tr>
<th>Modulation format</th>
<th>50 GHz</th>
<th>100 GHz</th>
<th>200 GHz</th>
<th>400 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>0.5</td>
<td>1.0</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td>QPSK</td>
<td>0.65</td>
<td>1.3</td>
<td>1.8</td>
<td>3.6</td>
</tr>
<tr>
<td>8-QAM</td>
<td>0.75</td>
<td>1.5</td>
<td>2.6</td>
<td>4.2</td>
</tr>
</tbody>
</table>

**Fig. 6. Total costs and served demand percentages under different modulation formats and fixed spectrum grids.**

Figs. 6(a) and (b) show the results of the heuristic algorithm for NSFNET and USNET, respectively. We can see that with the increase of the spectrum grid, the total cost is reduced for all
the modulation formats and Quasi-CWDM can always achieve the lowest cost. This observation is reasonable since a coarser spectrum grid requires fewer guard-bands given a limited fixed fiber spectrum (for example, a 200-GHz grid requires 20 guard-bands in a 4000-GHz fiber spectrum, while a 100-GHz grid requires 40 guard-bands), thereby improving the spectrum efficiency of the network. Besides a lower cost, Quasi-CWDM (or MLR for the DWDM cases under 50-GHz and 100-GHz spacing) can always serve 100% traffic demand, while BPSK and QPSK cannot guarantee to serve all the traffic demand.

D. Comparison with EON

We also compare the performance of the IP over Quasi-CWDM network with the most flexible IP over EON that can flexibly use multiple modulation formats (EON_MMF). For EON, assume there are 320 FSs in each fiber, of which each occupies 12.5-GHz spectrum. USNET is considered, in which between each node pair the traffic demand is randomly generated with the range of (10, 20) Gb/s. Each elastic optical channel can be assigned with a maximum 200-GHz channel bandwidth (i.e., 14 FSs plus a 2-FS guard-band) and a minimum number \( F_S^{\text{min}} \) of FSs. The purpose of setting \( F_S^{\text{min}} \) is to avoid spectrum wastage to assign guard-bands for channels with few FSs. Traffic grooming of IP over EON was based on the heuristic algorithm with multi-hop lightpath bypass, which similar to the algorithm for the Quasi-CWDM.

Because it is difficult to assume a relative cost for an elastic IP router port and signal regenerator, Fig. 7 compares the required numbers of IP router ports and regenerators for the USNET. We can see that the required numbers of IP router ports and regenerators for different modulation formats is reduced with the increase of minimal FS number \( F_S^{\text{min}} \) of an optical channel. It should be noted that EON is equivalent to the Quasi-CWDM network when the minimal number of FSs is 14 as \( F_S^{\text{min}} + 2 = 16 \) which corresponds to the upper bandwidth limit of an elastic channel, and therefore all the elastic channels have fixed 200-GHz bandwidth. This observation is important as it means that the Quasi-CWDM network requires smaller number of IP router ports and signal regenerators than EON, while both of them fully serve the same IP traffic demand. It should also be noted that the comparison has not considered the cost difference between an elastic router port (regenerator) and a quasi-CWDM router port (regenerator), of which the former is even more expensive due to its better flexibility.

![Fig. 7. Number of regenerators and IP router ports in EON with different minimal number of channel FSs, \( F_S^{\text{min}} \).](image)

IV. CONCLUSIONS

We proposed a new Quasi-CWDM network architecture, which has a low hardware cost and flexible adaptation capability between the bit rate and the transparent reach of an optical super-channel. We considered the traffic grooming problem for the IP over Quasi-CWDM network, for which an MILP model and efficient heuristic algorithm were developed to minimize the total hardware cost. The results show that the heuristic algorithm is efficient to perform close to the MILP model. The Quasi-CWDM network has the lowest hardware cost compared to the traditional DWDM network. Also, compared to EON, the Quasi-CWDM network shows to require fewer regenerators and IP router ports than EON when all the same traffic demands are served.

This work is a first exploration on new network architecture, Quasi-CWDM optical network. Considering its cost effectiveness and spectrum efficiency, and meanwhile, the expectation that optical super-channels will dominate the future optical transport network, we highly consider it as an important candidate for the next-generation optical transport network.

REFERENCES