Translucent Optical Network Planning With Heterogeneous Signal Modulation Formats

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***Abstract*—We investigate the design and planning of translucent optical networks with heterogeneous signal modulation formats. By employing multiple signal modulation formats of different optical reaches in the network, the required number of optical regenerators can be minimized. Hence, the overall network deployment capital cost and operational cost are much reduced. By building auxiliary graphs, a novel integer linear programming (ILP) is formulated to minimize the overall weighted network cost. Also, an effective heuristic is proposed to tackle networks of much larger scales. Numerical simulation studies indicate that our approach can achieve significant savings in overall network costs.**

***Index Terms*—Modulation formats, network costs, optical regenerator, translucent optical network.**

I. Introduction

THE wavelength-division-multiplexed (WDM) optical network is widely recognized as the most promising technology to realize future high-capacity backbone network deployment. In general, an optical network is referred as transparent if all the network nodes are equipped with all-optical cross connects (OXCs) or reconfigurable optical add-drop multiplexers (ROADMs) without any optical-electronic-optical (OEO) conversion [1]. Each light-path is routed from its source to its destination without any OEO conversion at intermediate nodes along the route. A transparent optical network possesses the advantage of modulation format transparency, bit-rate transparency and protocol transparency [2]. Despite these great advantages, a transparent optical network, however, suffers from accumulation of physical layer impairments induced by the underlying fiber transmission, such as chromatic dispersion, polarization mode dispersion, nonlinear effects, and crosstalks [3], especially when the data rate increases to 10 Gbps, 40 Gbps, and even 100 Gbps. These impose severe limit on the route span and network flexibility. In contrast, in an opaque optical network, all data channels are converted to electrical signals at each network node for possible signal regeneration and channel switching. However, the tremendous cost incurred to deploy fully-capable electronic switching of the high-speed data channels at each node prohibits large scale network rollout. To seek a graceful balance between the network design cost and the service provisioning performance, translucent optical network architecture has been proposed [4]. Generally, it sparsely but strategically places the electronic regeneration resources in a sub-set of the network nodes, to provide 3R functions, namely, re-amplify, re-shape, and re-time, to the optical signals, so that the optical signals can travel for another long span before next regeneration resource is available. Thus, a translucent optical network is a compromise between all-optical switching and all-electronic switching, showing the inherent cost-effectiveness, together with the ability to alleviate the limitations imposed by the physical impairments.

Most of the recent investigations on translucent optical network design focus on the regeneration site number minimization, which is commonly referred as regeneration node placement problem. The work in [5] presented the detailed node structure with regeneration capability, and several heuristics were proposed to place the regeneration sites, specifically for the network with topological information and forecast traffic information. The work in [6] tried to maximize the transparency benefit of the optical networks by modeling the regeneration placement problem as the search of the minimal connected dominating set (CDS) of a virtual graph. This award-winning solution was later verified [7] and the regenerator placement problem has proved to be NP-complete. In [8], a complete integer linear programming (ILP) formulation was presented to address the regeneration site selection and the routing and wavelength assignment (RWA), simultaneously, by introducing a graph transformation scheme. The work in [9] proposed a heuristic, named Cross Optimization for RWA and Regenerator Placement (COR2P), to tackle the problems separately and procedurally.

With the recent advances in the optical fiber transmission technology, various robust advanced signal modulation formats have been proposed and characterized to achieve longer optical reach, which is defined as the maximum distance that an optical signal can travel without any O-E-O regeneration, than the conventional non-return-to zero (NRZ) signal format. Such longer optical reach achieved may reduce the required number of expensive regeneration sites in the network, although it may also incur higher complexity in the respective transponder. In this paper, unlike the conventional way of network design with homogeneous signal modulation format throughout the network, we propose a cost-effective approach to reduce the required network deployment cost in translucent optical networks by employing two different signal modulation formats, each offers different optical reach. By properly and strategically assigning one of the two signal formats to the optical signal running between any two adjacent regenerator sites in the network, the total required number of regenerator sites in the network can be reduced, hence, substantial network capital cost can be saved. Mixed data format and line rates for different lightpaths have been recently studied in the design of transparent optical networks [10], [11], so as to reduce the network costs. Nevertheless, in this paper, we considered optical translucent net-

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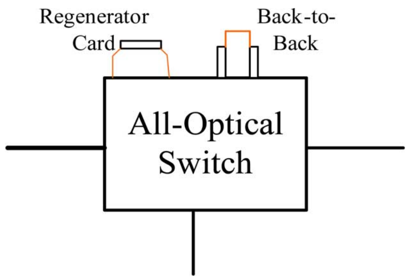

Fig. 1. Two implementation options for 3R regeneration.

works, instead, and investigated the benefit of employing heterogeneous signal formats with different optical reaches so as to realize better network resource allocation and planning. Here, to the best of our knowledge, this is the first attempt to employ heterogeneous data formats to reduce the required resources and costs in a translucent optical network.

The paper is organized as follows. In Section II, the network architecture considered and the problem of regenerator placement in such translucent optical networks are discussed. Section III presents the details of the ILP formulation for the regenerator placement and the data format assignment. A heuristic is also proposed to tackle the problem in networks of larger scale, and numerical simulation results are also presented. Section IV summarizes the paper.

II. Regeneration Site Architecture

A. Advanced Modulation Formats and Optical Reach

Optical reach refers to the physical distance that an optical signal can travel before its quality degrades to a level that requires regeneration in order to assure its performance. It is often limited by the physical layer impairments in the optical transmission links, including system noises, fiber dispersion and nonlinearities. In view of optical transmission, the modulation format of an optical signal has a significant impact on its achievable optical reach [12]. Different kinds of signal modulation formats have different intrinsic receiver sensitivities as well as varied robustness against different kinds of physical layer impairments in optical fiber transmission. Hence, they demonstrate different optical reaches. Recently, various advanced modulation formats have been proposed so as to extend the optical reach of the optical signal, as compared to the conventional NRZ format. However, they require more complicated optical transceivers for signal generation, thus probably incur higher transceiver costs.

B. Regeneration Site Architecture

Typically, two 3R regeneration options at the optical switching nodes are commonly adopted in the telecommunication industry [13], except that all-optical 3R regenerator, which it is still too expensive and impractical, is not considered. One is realized by employing a dedicated regenerator card, while the other is to construct a regenerator by connecting a pair of transponders back-to-back, via a patch cable, as depicted in Fig. 1. A transponder is an integrated transceiver for signal conversion between the client side and the WDM network channel side, in both directions. By interfacing two transponders of different signal modulation formats, signal format conversion is also achieved at the regeneration site. In this work, it is assumed the regeneration sites are sparsely placed in the network and at each regeneration site, back-to-back transponder approach is adopted, as it allows easier cost modeling and also provides true channel add-drop function, compared to the regenerator card approach [13], thus largely facilitates service provisioning. Fig. 2 shows how multiple transponders are arranged in the dedicated rack at the regeneration site. If a light-path is required to be regenerated, a pair of transponders is put into one slot of the rack, via back-to-back connection. In case of signal format conversion, two different types of transponders will be used.

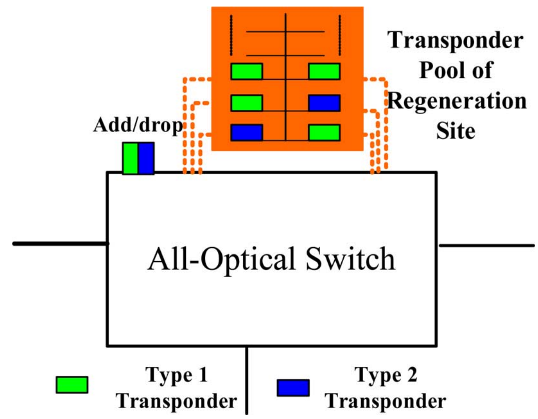

Fig. 2. Architecture of a regeneration site, including a pool of transponders.

III. ILP Formulation of Translucent Optical Network Planning Using Heterogeneous Modulation Format

A. Problem Statement and Input of ILP

In this work, two different signal modulation formats, each offers different optical reach, are employed throughout the network. Here, we present an ILP formulation to strategically assign one of the two signal formats to the optical signal running between any two adjacent regeneration sites in the network. Hence, the total required number of regeneration sites in the network can be reduced, and substantial network capital cost can be saved. First, the inputs of the problem are listed as follows:

- The network topology $\boldsymbol{G}(\boldsymbol{V}, \boldsymbol{E})$ is given as a weighted undirected graph. $\boldsymbol{V}$ is the set of network nodes, while $\boldsymbol{E}$ is the set of weighted links, with each weight representing the physical distance of the respective link.
- Two types of transponders, with respect to two signal modulation formats are employed. Type 1 transponder has optical reach $\boldsymbol{R_1}$ and cost $\boldsymbol{C_1}$, while Type 2 transponder has optical reach $\boldsymbol{R_2}$ and cost $\boldsymbol{C_2}$.
- The cost to deploy a regeneration site at any node is set to be $\boldsymbol{C_{\mathrm{site}}}$ as input. This parameter is used to balance the capital cost and the operation cost, as the latter would be higher when more regeneration sites are required.
- K is the set of static traffic demands, as given.
- N denotes the maximal number of transponders that could be deployed at a regeneration site.
- Ω is the set of wavelengths in each link.
- $py(u, v)$ is the link set in the physical layer topology comprising the virtual link (u, v).
- α is a constant with extremely small value.

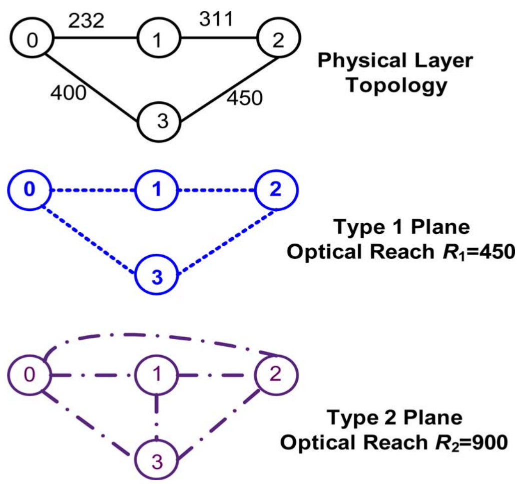

Fig. 3. Example of constructing two auxiliary graphs (Type 1 plane and Type 2 plane).

B. Auxiliary Graph for ILP Formulation

Our approach is similar to the graph transformation in [8], while ours also includes the property of multiple optical reaches available. With the network physical topology $\boldsymbol{G}(\boldsymbol{V}, \boldsymbol{E})$ and optical reaches $\boldsymbol{R_1}, \boldsymbol{R_2}$, the shortest path algorithm is executed to get the distance matrix of all the node pairs in the network. Then, two new virtual topologies, where the node set $\boldsymbol{V}$ is the same as that in the physical topology, are created, with the consideration of two possible optical reaches achievable by employing two different signal modulation formats. In the first virtual topology, denoted as Type 1 plane, if the distance of a node pair is not greater than optical reach $\boldsymbol{R_1}$, one direct edge is created, between this node pair. Using the same criteria, the second virtual topology, denoted as Type 2 plane, is formed based on another optical reach constraint $(\boldsymbol{R_2})$. A simple example is illustrated in Fig. 3, where $\boldsymbol{R_1} = 450, \boldsymbol{R_2} = 900$.

C. ILP Formulation

The variables for the ILP are defined as follows:

- Boolean variable $R(u)$ indicates whether node $u \in \boldsymbol{V}$ is selected to have regeneration site.
- Integer variable $n_1(u)$ denotes the number of Type 1 transponder in node u.
- Integer variable $n_2(u)$ denotes the number of Type 2 transponder in node u.
- Boolean variable F_1^k indicates whether request k use transponder Type 1 $(=1)$ or not $(=0)$ at the source.
- Boolean variable F_2^k indicates whether request k use transponder Type 1 $(=1)$ or not $(=0)$ at the destination.
- Boolean variable $f_{u,v,w}^{k,1}$ indicates whether wavelength w on the link from node u to node v, which are on Type 1 plane, is occupied by request $k(=1)$ or not $(=0)$.
- Boolean variable $f_{u',v',w}^{k,2}$ indicates whether wavelength w on the link from node u' to node v', which are on Type 2 plane, is occupied by request $k(=1)$ or not $(=0)$.
- Boolean variable $f_{m,n,w}^{k}$ indicates whether wavelength w on the link from node m to node n, which are on physical layer topology, is occupied by request $k(=1)$ or not $(=0)$.

The objective of the ILP is

$$\begin{aligned}&\text{Minimize :}\\&\sum_{u\in V}[C_{\text{site}}R(u) + C_1 n_1(u) + C_2 n_2(u)]\\&\quad + \sum_{k\in K}\left[C_2\left(1 - F_1^k\right)\right.\\&\quad \left.+ C_1 F_1^k + C_2\left(1 - F_2^k\right) + C_1 F_2^k\right]\end{aligned}$$

subject to

Regeneration site capacity constraints:

$$\forall u \in V, \quad 0 \le n_1(u) \tag{1}$$

$$\forall u \in V, \quad 0 \le n_2(u) \tag{2}$$

$$\forall u \in V, \quad n_1(u) + n_2(u) \le N. \tag{3}$$

Commodity flow constraints:

$\mathrm{src}(k)$ and $\mathrm{dst}(k)$ denote the source node and the destination node of request k, respectively. In addition, $\mathrm{out}(u)$ and $\mathrm{out}(u')$ denote the outgoing adjacent node sets of u on Type 1 plane and Type 2 plane, respectively, while $\mathrm{int}(u)$ and $\mathrm{int}(u')$ represent the incoming adjacent node sets of u on Type 1 plane and Type 2 plane, respectively:

$$\forall\, k \in K, \quad s = \mathrm{src}(k), \sum_{w\in\Omega}\sum_{v\in\mathrm{out}(s)} f_{s,v,w}^{k,1} = F_1^k \tag{4}$$

$$\forall\, k \in K, \quad s' = \mathrm{src}(k), \sum_{w\in\Omega}\sum_{v'\in\mathrm{out}(s')} f_{s',v',w}^{k,2} = 1 - F_1^k \tag{5}$$

$$\forall\, k \in K, \quad t = \mathrm{dst}(k), \sum_{w\in\Omega}\sum_{v\in\mathrm{int}(t)} f_{v,t,w}^{k,1} = F_2^k \tag{6}$$

$$\forall\, k \in K, \quad t' = \mathrm{dst}(k), \sum_{w\in\Omega}\sum_{v'\in\mathrm{int}(t')} f_{v',t',w}^{k,2} = 1 - F_2^k \tag{7}$$

$$\begin{aligned}&\forall\, k \in K, \quad \forall u = u' \in V(\ne \mathrm{src}(k), \ne \mathrm{dst}(k))\\&\sum_{w\in\Omega}\left[\sum_{v\in\mathrm{out}(u)} f_{u,v,w}^{k,1} + \sum_{v'\in\mathrm{out}(u')} f_{u',v',w}^{k,2}\right]\\&\quad = \sum_{w\in\Omega}\left[\sum_{v\in\mathrm{int}(u)} f_{u,v,w}^{k,1} + \sum_{v'\in\mathrm{int}(u')} f_{u',v',w}^{k,2}\right].\end{aligned} \tag{8}$$

Virtual topology and physical topology mapping constraints:

$$\begin{aligned}&\forall\, k \in K,\ \forall u \in V,\ \forall w \in \Omega\\&f_{u,v,w}^{k,1} \le \alpha\left[\sum_{(m,n)\in py(u,v)} f_{m,n,w}^{k,1} - |py(u,v)|\right] + 1\end{aligned} \tag{9}$$

$$\begin{aligned}&\forall k \in K,\ \forall u' \in V,\ \forall w \in \Omega\\&f_{u',v',w}^{k,2} \le \alpha\left[\sum_{(m,n)\in py(u',v')} f_{m,n,w}^{k,2} - |py(u',v')|\right] + 1.\end{aligned} \tag{10}$$

Wavelength usage constraints:

$$\begin{aligned}&\forall k \in K,\ \forall m,n \in V,\ \forall w \in \Omega\\&f_{m,n,w}^{k} = f_{n,m,w}^{k}\end{aligned} \tag{11}$$

$$\begin{aligned}&\forall\, k \in K,\ \forall m,n \in V,\ \forall w \in \Omega\\&\sum_{k\in K} f_{m,n,w}^{k} \le 1.\end{aligned} \tag{12}$$

Regeneration site specification constraint:

$$\forall u = u' \in V(\neq \mathrm{src}(k), \neq \mathrm{dst}(k))$$
$$\alpha \sum_{k\in K} \left\{ \sum_{w\in\Omega} \left[\sum_{v\in \mathrm{out}(u)} f^{k,1}_{u,v,w} + \sum_{v'\in \mathrm{out}(u')} f^{k,2}_{u',v',w} \right] \right\} \leq R(u) \quad (13)$$

$$\forall u \in V(\neq \mathrm{src}(k), \neq dst(k))$$
$$\sum_{k\in K} \left\{ \sum_{w\in\Omega} \left[\sum_{v\in \mathrm{out}(u)} f^{k,1}_{u,v,w} + \sum_{v\in \mathrm{int}(u)} f^{k,1}_{v,u,w} \right] \right\} = n_1(u) \quad (14)$$

$$\forall u = u' \in V(\neq \mathrm{src}(k), \neq \mathrm{dst}(k))$$
$$\sum_{k\in K} \left\{ \sum_{w\in\Omega} \left[\sum_{v'\in \mathrm{out}(u')} f^{k,2}_{u',v',w} + \sum_{v'\in \mathrm{int}(u')} f^{k,2}_{v',u',w} \right] \right\} = n_2(u). \quad (15)$$

The objective function minimizes the total cost to serve all the light-paths in set K, consisting of the regeneration site cost and the transponder cost. Specifically, the first term of the objective function determines the overall cost within those sparsely placed regeneration sites, while the second term quantifies the necessary investment at those source and destination nodes.

- Equations (1) and (2) ensure that the number of two types of transponders at a regeneration site could not be less than zero.
- Equation (3) ensures that the total number of transponders allowed in a regeneration site does not exceed N.
- Equations (4) and (5) ensure either Type 1 or Type 2 transponder is used at the source node of request $k, \forall k \in K$.
- Equations (6) and (7) ensure that either Type 1 or Type 2 transponder is used at the destination node of request $k, \forall k \in K$.
- Equation (8) ensures that the incoming flow is the same as the outgoing flow for every node, which is neither a source nor a destination of request $k, \forall k \in K$.
- On Type 1 plane, the source and the destination nodes are denoted as u and v, respectively. $py(u,v)$ refers to the set of physical links on Type 1 plane that consist virtual link (u,v). Equation (9) ensures that if the wavelength w of a virtual link (u,v) on Type 1 plane is used, the wavelength w on those physical links covered by virtual link (u,v) should be assigned to (u,v) $((m,n) \in py\ (u,v$ Similarly, on Type 2 plane, the source and the destination nodes are denoted as u' and v', respectively. $py(u',v')$ refers to the set of physical links on Type 2 plane that consist virtual link (u',v'). Equation (10) ensures that if the wavelength w of a virtual link (u',v') on Type 2 plane is used, the wavelength w on those physical links covered by (u',v') should be assigned to (u',v') $((m,n) \in py(u',v'))$.
- Equation (11) ensures that the light-path is bidirectional.
- Equation (12) ensures that a particular wavelength on any link can only be used for one light-path demand at most.
- Equation (13) ensures that for every node which is neither a source nor a destination for a certain request, it is selected to be a regeneration site as long as the request flow passed through it.
- Equation (14) and (15) calculate the number of Type 1 and Type 2 transponders in each regeneration site.

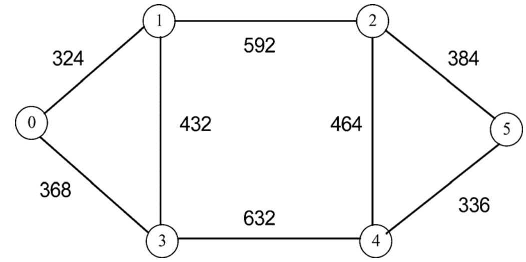

Fig. 4. Six-node eight-link network, used for illustration.

D. Illustrative Numerical Example

It is well known that ILP is a time-consuming computation task. Thus, we have employed a small network, specifically a six-node eight-link network [14], as shown in Fig. 4, with link distances attached, to illustrate our formulation and compare with two other cases, where only either one of the signal modulation formats, is used. All results were optimal.

With 9 wavelengths available on each link, we set the value of $\boldsymbol{R_1}$ to be the maximal link length within the network, i.e., 632 km, assuming that no in-line regeneration was needed. The value of $\boldsymbol{R_2}$ was set to be two possible ones, including $1.5 \times \boldsymbol{R_1}$ and $2 \times \boldsymbol{R_1}$, for sensitivity investigation. The traffic matrix included 15 light-path demands, meaning that every node pair has a light-path to be established. In addition, the cost of the Type 1 transponder $(\boldsymbol{C_1})$ associated with $\boldsymbol{R_1}$ was normalized to be 1, while Type 2 transponder $(\boldsymbol{C_2})$ had the cost of 1.5 [15]. The value of $\boldsymbol{C_{\mathrm{site}}}$ was set to be 20, which was set arbitrarily with a relatively high value, so as to minimize the required number of regeneration sites. The results of the simulations with the two different values of $\boldsymbol{R_2}$ were tabulated in Tables I and II, respectively. The overall network costs were computed directly from the outputs of the ILP. For instance, the overall network costs of the "Only Type 2 transponder" case in Table I was calculated as $(30 \times 1.5 + 8 \times 1.5 + 4 \times 1.5 + 2 \times 20) = 103$. Clearly, heterogeneous signal format design could always achieve good overall network cost savings, compared with the other two homogeneous signal format design cases. For instance, in Table II, the cost savings were 13.2% and 34.4%, with the cases of only Type 2 transponder and only Type 1 transponder, respectively. The cost savings came from either reducing the number of transponders used at each regeneration site (see Table I) or reducing the required number of regeneration sites (see Table II). As a result, the proposed heterogeneous signal format design offered more options when setting up new connections, and enabled more cost effective design to reduce the required number of transponders or regeneration sites, compared with the conventional homogeneous signal format design.

In addition, we have also tried to alter the value of $\boldsymbol{R_2}$ to a smaller value (say down to 1060) for the case considered in Table II, however, the optimized overall network cost did not change from the original value (say 59). This showed that the optical reach requirement of the transponders has a good tolerance in possible variations under our proposed heterogeneous signal format design. Such variation in optical reach might be attributed to possible performance variation in devices, packaging or other specifications, among transponders from different or even the same manufacturers. Hence, the good tolerance in transponders' specifications provides good design resilience under practical deployment.

TABLE I
TRANSPONDER MAP RESULT OF CASE 1: $\boldsymbol{R_1} = 632, \boldsymbol{R_2} = 948(= \times 1.5\boldsymbol{R_1})$; $\boldsymbol{C_1} = 1, \boldsymbol{C_2} = 1.5$

	No. of transponders placed at source and destination		No. of transponders placed at each regeneration site, if any			**Overall Network Costs**
	Type 1	Type 2	Regeneration Sites	Type 1	Type 2	
Only Type 1 transponder ($\boldsymbol{R_1}$) is used	30	-	Node 1	10	-	**90**
			Node 2	10	-	
Only Type 2 transponder ($\boldsymbol{R_2}$) is used	-	30	Node 2	-	8	**103**
			Node 4	-	4	
Both transponder types are used (heterogeneous design)	26	4	Node 2	6	2	**85**
			Node 4	4	0	

TABLE II
TRANSPONDER MAP RESULT OF CASE 2: $\boldsymbol{R_1} = 632, \boldsymbol{R_2} = 1264(= \times 2.0\boldsymbol{R_1})$; $\boldsymbol{C_1} = 1, \boldsymbol{C_2} = 1.5$

	No. of transponders placed at source and destination		No. of transponders placed at each regeneration site, if any			**Overall Network Costs**
	Type 1	Type 2	Regeneration Sites	Type 1	Type 2	
Only Type 1 transponder ($\boldsymbol{R_1}$) is used	30	-	Node 1	10	-	**90**
			Node 2	10	-	
Only Type 2 transponder ($\boldsymbol{R_2}$) is used	-	30	Node 1	-	2	**68**
			-	-		
Both transponder types are used (heterogeneous design)	17	13	Node 3	1	1	**59**
			-			

E. Heuristic

In this section, we present a simple, yet effective heuristic to tackle the larger-scale translucent optical network planning, employing our proposed heterogeneous signal format design. Similar to the work in [6], the proposed heuristic greedily chooses those regeneration site locations so as to maximize the usage of the current deployed network resource.

Given a set of traffic demands, K, two optical reaches $\boldsymbol{R_1}$ and $\boldsymbol{R_2}$, as well as network topology $\boldsymbol{G(V,E)}$, we first construct the auxiliary graphs, Type 1 plane and Type 2 plane, as discussed in Section III-B, as input. We should select the regeneration site subject to the constraint that there is an upper bound on the number of requests that can be regenerated at a specific node, in accordance to the capacity limit in the ILP formulation. The algorithm of the proposed heuristic is illustrated as follows, assuming $\boldsymbol{R_1} \ll \boldsymbol{R_2}$.

Greedy Translucent Optical Network Planning Algorithm

Step0:

For those requests in K, with the distance between the source and the destination smaller than $\boldsymbol{R_1}$, use Type 1 transponder at both ends, while deploying Type 2 transponder for requests when the distance between the source and the destination is larger than $\boldsymbol{R_1}$ but smaller than $\boldsymbol{R_2}$.

Step1:

Update K by eliminating those served requests in **Step0**.

If $K = \emptyset$ go to **Step4**

Else

In Type 2 plane, select the next regeneration site node to be the one that would make the most requests in K feasible, breaking the tie by choosing the node with larger node degree in Type 1 plane.

Update the set K and node information to reflect the newly selected regeneration site node and repeat the **Step1** until no more requests in$K$can be served through only one regeneration site

Step2:

If $K = \emptyset$go to **Step4**

Else

With the already deployed regeneration sites in the network after **Step1**, denoted as set $\boldsymbol{r}$, try to serve the maximal number of requests in K by allowing the corresponding demand to go through multiple regeneration sites in $\boldsymbol{r}$. We first sort the remaining demands with respect to their corresponding source and destination distances, and try to serve the demand with the shortest distance first, before serving the rest of the demands in ascending order.

Step3:

Update $K$by eliminating those served requests in **Setp2**.

If $K = \emptyset$go to **Step4**

Else

In Type 2 plane, select the next regeneration site node to be the one that would make the most requests in K feasible, breaking the tie by choosing the node with larger node degree in Type 1 plane until all the requests in K are served. The difference between this step and the operation in **Step1** arises from the idea that in this step the requests can be feasible by going through multiple regeneration sites while in **Step1** only one regeneration site can be used to perform regeneration

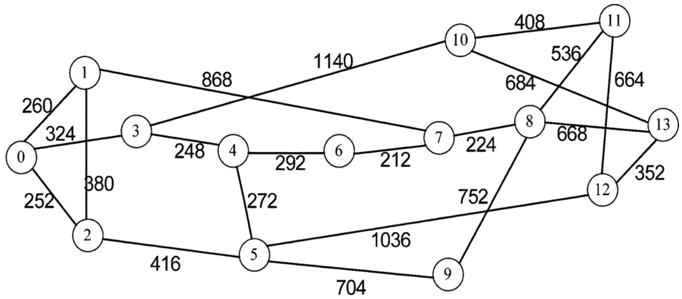

Fig. 5. 14-node 21-links NSFNET (link lengths km).

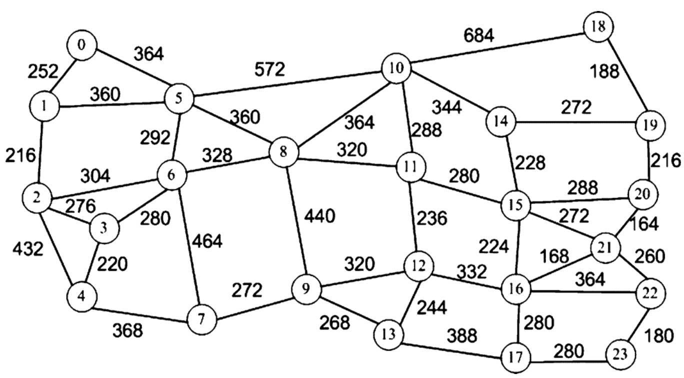

Fig. 6. 24-node 43-links USA backbone IP network (link lengths in km).

Step4:

For all the served requests, replace those end to end connections between which the distance is smaller than R_1 with Type 1 transponder, since we assume Type 2 transponder is used in all previous steps. Nevertheless, in fact, the lengths of many connections from the source or the destination to its corresponding regeneration site are not that long, thus providing us the opportunity to reduce the network cost.

END

F. Simulation Results

Given two optical reach parameters R_1 and R_2 (assuming $R_1 \ll R_2$), which correspond to the two types of transponders, we have tested the above heuristic over two network topologies, namely, 14-node 21-link NSFNET and 24-node 43-link USA IP network [14], as shown in Figs. 5 and 6, respectively. Similar to the Path-Improvement Heuristic [6], the spirit of selecting the next regenerator node to be the one that would make the most paths feasible if either one of the optical transponders was used. We set the R_1 to be the maximal link length within the NSFNET network, 1140 km, assuming no in-line regeneration was needed. For R_2, we initially set it to be 1500 km. The uniform traffic matrix ensured that every node pair had a light-path to be established. In addition, the cost of the Type 1 transponder (C_1) associated with R_1 was normalized to be 1; while Type 2 transponder (C_2) had the cost of 1.5. In order to minimize the number of regeneration sites, we set the value of C_{site} to be 20 and N to be 20. The simulation results under the two network topologies were shown in Tables III and IV, respectively. From Tables III and IV, we observed that our proposed heterogeneous design could achieve the most overall network cost savings in both network topologies, which could be attributed to reduced required number of regeneration sites when compared to the "Only Type 1 transponder" case, as well as the reduced required number of the costly Type 2 transponders when compared to the "Only Type 2 transponder" case.

TABLE III
NETWORK COSTS OVER 14-NODE 21-LINKS NSFNET

	No. of transponders		No. of Regeneration Sites	**Network Costs**
	Type 1	Type 2		
Only Type 1 transponder (***R₁***) is used	266	0	5	**366**
Only Type 2 transponder (***R₂***) is used	0	216	2	**364**
Both types are used ***(heterogeneous design)***	156	60	2	**286**

TABLE IV
NETWORK COSTS OVER 24-NODE 43-LINKS USA IP NETWORK

	No. of transponders		No. of Regeneration Sites	**Network Costs**
	Type 1	Type 2		
Only Type 1 transponder (R_1) is used	734	0	10	**934**
Only Type 2 transponder (R_2) is used	0	626	4	**1019**
Both types are used ***(heterogeneous design)***	450	176	4	**794**

TABLE V
COMPARISON BETWEEN ILP AND HEURISTIC OVER A SIX-NODE NETWORK

	Network Costs			
	15 Requests		**20 Requests**	
	ILP	**Heuristic**	**ILP**	**Heuristic**
C_{site}=20, N=20	85	85	106	106
C_{site}=20, N=15	85	85	106	106
C_{site}=20, N=10	85	85	124	127
C_{site}=15, N=15	75	75	96	96
C_{site}=15, N=10	75	75	109	112
C_{site}=10, N=10	65	65	94	97

Table V further shows the results of both ILP and our proposed heuristic over the six-node network, as in Fig. 4, with different combinations of the values of C_{site} and N, for comparison. Fifteen Requests were the any-to-any connectivity case, while the 20 Requests included another 5 different requests which require regeneration, in addition to the original 15 requests. The results shown in the ILP columns were the best solutions after the simulation was run for 8 h.

From Table V, it could be noticed that when the values of N were relatively high, our heuristic performed quite well, almost as good as the ILP, since it tried to put as much regenerators as possible at one regeneration site and the high-value of N allowed such greedy regenerator placement. Hence, its regenerator placement was close to optimal. Nevertheless, when the value of N was reduced, the greedy placement strategy used by the heuristic might not be able to consider the overall network requests and topology thoroughly, thus ILP would give more cost effective solutions, even though the results might not be optimal. On the other hand, when C_{site} was of high value, the number of regeneration site placed in ILP would be minimized.

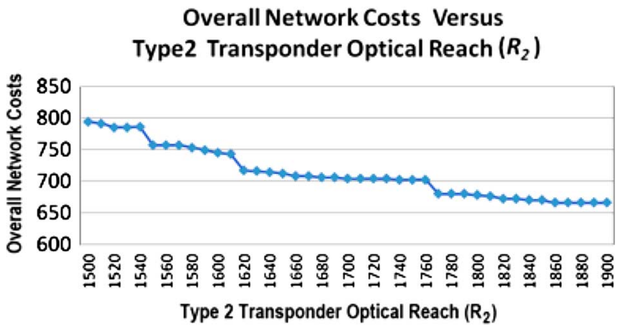

Fig. 7. Overall network costs of 24-node 43-link USA IP network topology by adjusting the values of $\boldsymbol{R_2}$, given $\boldsymbol{R_1} = 1140$.

The performance would be further enhanced if N was also of high value, as each regeneration site could accommodate more regenerators for the optimal placement in ILP.

In order to investigate the sensitivity of the proposed heuristic using the heterogeneous signal format design, we have also run the heuristic over the 24-node 43-link USA IP network topology by setting the value of $\boldsymbol{R_1}$ to be 1140 km, while varying the value of $\boldsymbol{R_2}$ from 1500 km to 1900 km, and the results were depicted in Fig. 7. Similar to the observation from the numerical study in Section III-D, the optimized overall network design cost would not change much if the value of $\boldsymbol{R_2}$ was within a certain range. Such characteristics implied that in the practical network deployment, a variety of transponders with their optical reaches falling within a certain range could also be employed such that the same target cost savings could still be achieved. This greatly relaxed the requirement in the transponder's specifications and facilitated the procurement of the transponder modules. Hence, flexible practical deployment could be realized.

IV. Summary

In this paper, we have proposed a novel design principle by employing heterogeneous signal modulations in translucent optical networks. A regeneration site architecture with a back-to-back transponder rack has been assumed and such architecture facilitates interoperability of transponder products offered from different vendors. With the recent proposals of many advanced optical modulation formats with extended optical reaches, strategic adoption of different signal formats to the optical signals running between any two adjacent regenerator sites in the network can possibly reduce the total required number of regenerator sites in the network. Hence, substantial network capital cost can be saved. We have presented a detailed formulation of a ILP for this heterogeneous signal format design, together with an efficient heuristic to tackle networks of much larger scale. Our numerical simulations showed that significant savings in the overall network costs could be achieved, compared with the conventional homogeneous signal format design.

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