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Sparse Regeneration in Translucent Wavelength-Routed Optical Networks: Architecture, Network Design and Wavelength Routing*†

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Abstract. In this paper we study an alternate network architecture, called translucent network, to the fully transparent and fully opaque network architectures. In a translucent wavelength-routed optical network, a technique called sparse regeneration is used to overcome the severe lightpath blocking due to signal quality degradation and wavelength contention in a fully transparent network while using much less regenerators than in a fully opaque network. In this paper, we present a node model and a network model that perform sparse regeneration. We address the problem of translucent network design by proposing several regenerator placement algorithms based on different knowledge of future network traffic patterns. We also address the problem of wavelength routing under sparse regeneration by incorporating two regenerator allocation strategies with heuristic wavelength routing algorithms. We compare the performance of different regenerator placement algorithms and wavelength routing schemes through simulation experiments. The benefit of sparse regeneration is quantitatively measured under different network settings.

Keywords: translucent optical network, network design, sparse regeneration, physical impairments, signal quality, bit error rate (BER), regenerator placement, regenerator allocation, routing and wavelength assignment (RWA), wavelength-division multiplexing (WDM)

1 Introduction

Due to the advent of new applications, such as the real-time data, voice and video, e-Business, and multimedia, today's computer and telecommunication networks, particularly the Internet, will continue to see an ever-increasing demand for network bandwidth. Wavelength division multiplexing (WDM) is a promising technique to accommodate such a demand by utilizing the huge bandwidth of optical fibers. With the advances in optical switching technologies, WDM wavelength routed networks (WRN) emerge as promising candidates for future Internet backbones. WRN differs from conventional networks in that its traffic has a coarser granularity, i.e., at a wavelength level, and that it uses optical signals for both transmission and switching.

In previous studies, a WRN is mostly referred to as an all-optical network, where a lightpath is routed from the source node to destination node without undergoing optical-electrical-optical (O/E/O) conversion at any intermediate node [1,2]. Although there are many practical reasons supporting the deployment of all-optical networks, in the current phase these networks must face the technical difficulties in overcoming the physical impairments introduced by long-haul fibers and

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cascading optical components such as erbium-doped fiber amplifiers (EDFA) and optical cross-connects (OXC) [3,4]. Physical impairments impose a fundamental limitation on the reach distance of signals in WDM optical networks. Wavelength continuity is another constraint that makes the design and operation of an all-optical network more complicated. A national-scale all-optical network will not appear in the near future before these technical obstacles are cleared.

An all-optical network is also called a *transparent* optical network [5]. The opposite of a transparent optical network is the *opaque* optical network [6]. An opaque optical network employs 3R regeneration (reamplification, reshaping and retiming) at every intermediate node of a lightpath to regenerate the signal and improve transmission quality. Currently, 3R regeneration can only be realized through O/E/O conversion. In the near future, 3R regeneration will remain the main method to extend the reach distance of signals, while O/E/O conversion will still be indispensable for a 3R regeneration-capable optical network. Most of today's optical networks are fully opaque, where O/E/O conversions take a major fraction of network cost. When such networks scale up, the cost to regenerate every wavelength at every intermediate node will be prohibitively high.

This paper investigates an alternate method to both fully transparent and fully opaque networks and terms it as *translucent* optical network [6]. In a translucent optical network, a signal is made to traverse as long as possible before its quality falls below a threshold value. Because a signal is regenerated only if necessary, we need much fewer regeneration resources. We call this technique *sparse regeneration*, which we will describe in detail in later sections.

Other ongoing research also supports the idea of sparse regeneration in large-scale wavelength-routed optical networks. As surveyed by [7], the ordinarily used 600 km reach distance for transparent optical signals is far from the requirement for today's Internet traffic. Even a reach distance of 3000 km can only satisfy 60% of the connections. However, current technologies have difficulty in extending the reach distance to more than 2000 km [8]. In [9], the authors suggested using "islands of transparency" to establish sub-connections between regeneration sites. In [10], the authors addressed the problem of maximizing the transparency advantage by following our research in [11].

This paper addresses the network design and wavelength routing problems in translucent optical networks. We referred to the translucent network design problem as the regenerator placement problem in [11,12]. Following our earlier work in [6,11,12], some recent work also addressed the translucent network design problem [13,14]. In [15], the authors addressed this problem under the polarization mode dispersion (PMD) impairment. In [16], the authors addressed the network design problem with path-based protection requirements under the optical signal-to-noise ratio (OSNR) constraints. The wavelength routing problem in translucent networks was addressed in [14,17]. In [18,19], the authors addressed similar wavelength routing problems under physical impairments, e.g., amplified spontaneous emission (ASE) and non-linear effects. This paper is extended from our work in [6,11,12], and presents a more systematic study on the architecture, network design, and wavelength routing issues of a translucent wavelength-routed optical network.

The rest of this paper is organized as follows. In Section 2, we describe the translucent network architecture with sparse regeneration. In Section 3, we address the regenerator placement problem. In Section 4, we address the wavelength routing problem under sparse regeneration. In Section 5, we present the numerical results. We conclude this paper in Section 6.

2 Translucent Network Architecture with Sparse Regeneration

2.1 Regeneration Demands

The translucent network architecture addresses two kinds of demands for regeneration. The first kind of demands arises from the signal quality requirements. This is the most common reason for regeneration. When a lightpath traverses several fiber links and optical components through wavelength routing, its signal quality degrades. Each component at an intermediate node may introduce insertion loss. The optical fiber amplifiers, e.g., EDFAs, may compensate for some loss but introduce noise at the same time. In addition, the OXCs and (de)multiplexers introduce crosstalk among different wavelength channels. To overcome these impairments, a long-distance lightpath may resort to regeneration in the electronic domain to regenerate the signal. In this paper, we use the bit error rate (BER) to evaluate the signal quality and as a criterion for generating the regeneration demands. BER can be measured by tapping a portion of the signal on a lightpath using taps [20]. If the BER of a lightpath exceeds some threshold value, e.g., 10^{-12}, a regeneration demand is generated.

Wavelength contention generates the other kind of demands for regeneration. Wavelength contention occurs when two lightpaths using the same wavelength are transmitted onto the same fiber. In a large-scale WDM network, the probability that several lightpaths compete for the same wavelength on the same fiber may be quite high and hence may cause a significant amount of blocking. We usually resort to wavelength conversion [21] to resolve wavelength contention. However, optical wavelength converters are still immature. Therefore, O/E/O wavelength conversion becomes a viable alternative, which converts one wavelength into an electronic signal and then converts it back onto another wavelength. In a translucent network, it is natural to use the O/E/O regenerators to do wavelength conversion.

2.2 Node Model

The network element that performs 3R O/E/O regeneration and wavelength conversion is called a wavelength-convertible 3R O/E/O regenerator. As shown in Fig. 1, a regenerator consists of a pair of transmitter and receiver, called a T-R pair, and an electronic processing module. We refer to such T-R pairs and electronic processing modules as regeneration resources in the remainder of this paper. The electronic module can regenerate the optical signal in the electronic domain through 3R processing. Both the transmitter and receiver are full-range tunable components, which means that the regenerator can carry out wavelength conversion from any input wavelength (λ_1) to any output wavelength (λ_2). Note that a fixed receiver and a tunable transmitter may also form a wavelength-convertible regenerator, if the input wavelength is fixed.

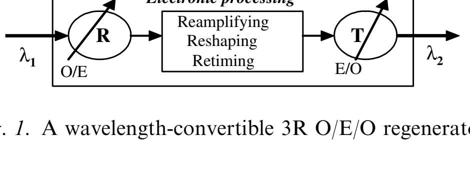

Fig. 1. A wavelength-convertible 3R O/E/O regenerator.

Sparse regeneration makes use of the regeneration resources sparsely distributed in the network rather than assigning a regenerator to each input wavelength at each network node. A node can be modeled as an OXC, which consists of a number of wavelength routed switches (WRS), plus an access unit that adds/drops some wavelengths from/to the electronic branches. In a translucent network, some nodes are assigned a certain number of optional electronic processing modules, each of which plus a T-R pair forms an embedded regenerator (see Fig. 1). The sparse regeneration node model shown in Fig. 2 can be used to model any node in translucent WRN (with or without regenerators depending on the availability of the electronic processing modules). We call the node with regenerators a regeneration capable node, and call the node without regenerators a transparent node.

At each node, the wavelengths on the incoming fiber links are demultiplexed and switched by the WRS modules in the OXC, and then are multiplexed onto the outgoing fiber links. Each WRS can switch a certain wavelength in a non-blocking manner. We assume that a node can add and drop any wavelength when it has sufficient transmitters and receivers in the access station. At a regeneration capable node, the whole transmitter and receiver arrays, T_X and R_X, can be assigned into three sets, T_A, R_A and T_R-R_R, where the sets T_A and R_A represent the transmitter array and the receiver array used for the access function respectively, and the set T_R-R_R represents the T-R pair array dedicated for the regeneration function. If a lightpath is at its source, it enters into the set T_A. If the lightpath is at its destination, it enters the set R_A. If the lightpath is regenerated at an intermediate node, a T-R pair in the set T_R-R_R is allocated.

The regeneration process at a regeneration capable node is described as follows. If a lightpath generates a regeneration demand at the regeneration capable node, its input wavelength, say λ_1, is dropped at the OXC, and is directed to an available receiver in R_R. The receiver is tuned to the wavelength λ_1, performs O/E conversion, and sends the signal to an electronic processing module. Then the electronic processing module carries

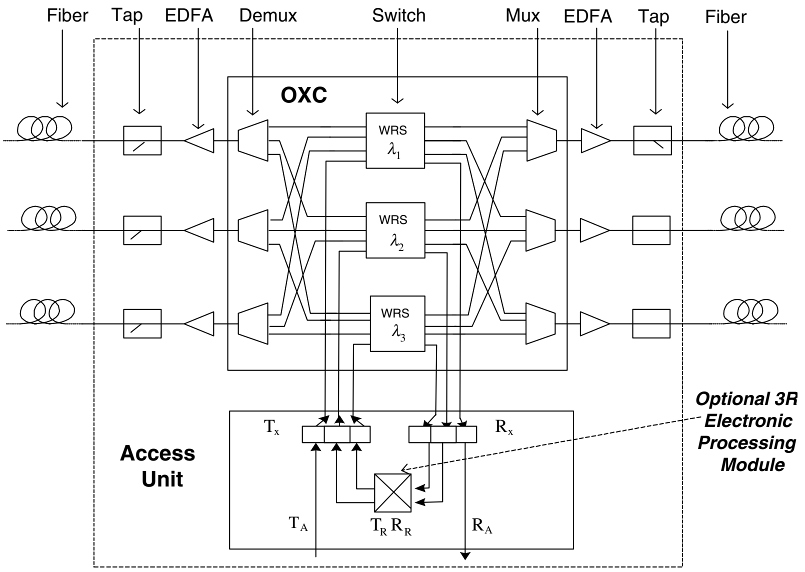

Fig. 2. Sparse regeneration node model.

out 3R processing on the electronic signal, and sends it to a corresponding transmitter in T_R, which performs the E/O conversion. The transmitter is tuned to the output wavelength λ_2 ($\lambda_2 \neq \lambda_1$, if wavelength conversion is needed), and transmits the regenerated optical signal with full power onto the outgoing fiber.

2.3 Network Model

A translucent wavelength-routed network is modeled as follows. We use an undirected graph $G=(V, E)$ to represent the network topology. Each link represents a pair of fibers in opposite directions. Each fiber has W wavelengths. By Set_R, we denote the set of regeneration capable nodes, where $Set_R \subseteq V$. By R_i, we denote a predefined number of regenerators assigned to the regeneration capable node i. In this paper, we assume uniform digital format on all wavelength channels and at all electronic processing modules. Therefore, we do not need to consider the compatibility of digital formats when regenerating a lightpath.

A lightpath starts from a transmitter in T_A at the source node and terminates at a receiver in R_A at the destination node. The sparse regeneration node model (described in Section 2.2) allows for both all-optical switching and O/E/O regeneration when regenerators are present at some intermediate regeneration capable nodes. When a lightpath is routed through the intermediate regenerators at these regeneration capable nodes, it is divided into several fragments by O/E/O regeneration. We define such a fragment as a regeneration segment. As a special case, we consider a fully transparent lightpath as a single regeneration segment. Each regeneration segment consists of one or more consecutive fiber links, and is subject to the wavelength continuity constraint, i.e., all fiber links on the regeneration segment must use the same wavelength. Wavelengths on two regeneration segments may be different. In other words, after the regeneration process described in Section 2.2 is carried out, the lightpath will consist of two consecutive sub-lightpaths, i.e., two regeneration segments. This regeneration process can be carried out at more intermediate regeneration capable nodes to produce more regeneration segments.

3 Sparse Regenerator Placement

3.1 Problem Statement

In the design of translucent networks, we deal with the regenerator placement problem, which distinguishes a translucent network design problem from a conventional transparent network design problem. Therefore, we refer to the translucent network design problem as a regenerator placement problem. To focus on this problem, we assume that the network topology and optical-layer components (e.g., fibers, amplifiers, OXCs, and (de)multiplexers) have already been deployed. Our regenerator placement problem is defined as follows:

Given. An optical-layer network topology $G(V, E)$; N groups of regenerators, each having X regenerators; a BER threshold value B (upper bound); and a number LN_{MAX}, which denotes that a transparent optical signal can traverse at most LN_{MAX} links without having its BER exceed the BER threshold B under an average link length in the network (note that $\mathrm{LN}_{\mathrm{MAX}}$ is an estimate under worst-case physical impairments).

Objective. Find N nodes (i.e., $|Set_R| = N$) in V. Place the X regenerators at each node so that they can accommodate 3R O/E/O regeneration and wavelength conversion for as many lightpaths as possible.

Constraints. No specific constraints except that X should not exceed the size of the transmitter array T_x (as well as the size of the receiver array R_x).

Generally, the regenerators can be placed under two lightpath establishment schemes [22,23]. The first is the static lightpath establishment (SLE) scheme. In SLE, all lightpath demands are fixed and should be provisioned at the same time. The other is the dynamic lightpath establish (DLE) scheme. In DLE, lightpath demands may arrive and leave in a dynamic manner. In this paper, we deal with the regenerator placement problem under the DLE scheme. Due to the difficulty in precisely describing future traffic patterns, regenerator placement under DLE has to be carried out based on some kind of prediction. Even if we have full knowledge of future traffic patterns, a placement optimal at one time may not remain optimal at another time, because the lightpaths are constantly being set up and torn down. Therefore, we resort to the heuristic approach. In the remainder of this section, we develop several heuristic regenerator placement algorithms based on different knowledge of future traffic patterns.

3.2 Network Topology Based Regenerator Placement

Without specific knowledge about future network traffic, the most useful information available for regenerator placement is the network topology. In many situations, the network topology reflects the estimate on the most possible traffic demands in this network. Regeneration demands are most likely to be generated at two categories of nodes. The first category consists of those nodes that are located at the ‘‘center’’ of a network. The second category consists of those nodes that have a higher nodal degree than other nodes. In our definition, a node is more ‘‘centered’’ than another node if it is traversed by a greater number of shortest hop-distance paths of all node pairs in the network. We develop two regenerator placement algorithms that favor these two categories of nodes respectively.

Algorithm 1. Nodal degree first (NDF) regenerator placement algorithm

Step 1. Assign each node a number equal to its in-degree.
Step 2. Select a node with the maximum assigned number as a regeneration capable node and place X regenerators at that node. If multiple such nodes exist, select one among them randomly. Remove this node and reduce the assigned number of each neighboring node by one.
Step 3. Repeat Step 2 until all N groups of regenerators are placed.

Algorithm 2. Centered node first (CNF) regenerator placement algorithm

Step 1. Assign a unique number between 1 and $|V|$ to each network node. The node that is more ‘‘centered’’ is assigned a larger number. The nodes equally ‘‘centered’’ are assigned numbers in random order.
Step 2. Select the first N nodes as the regeneration capable nodes and place X regenerators at each node.

3.3 Traffic Prediction Based Regenerator Placement

When certain information about future network traffic is available, we may use a traffic-prediction based regenerator placement algorithm. We employ a predefined wavelength routing algorithm on a large number of lightpath demands following a predicted traffic pattern and identify the nodes where regeneration demands are most likely generated. This method can be implemented with any wavelength routing algorithm, which we will address in Section 4. We propose two traffic-prediction based regenerator placement algorithms, which favor the nodes with heavier traffic loads and the nodes with more through lightpaths suffering signal quality degradation, respectively.

Algorithm 3. Traffic load prediction based (TLP) regenerator placement algorithm

Step 1. Assign each node i number C_i, initialized to be zero.
Step 2. Run a predefined wavelength routing algorithm on a number of randomly generated lightpath demands following a predicted traffic pattern.
Step 3. For each node along each lightpath computed by the wavelength routing algorithm, add one to the number C_i assigned to this node.
Step 4. Sort all nodes in non-increasing order of C_i.
Step 5. Select the first N nodes as regeneration capable nodes and place X regenerators at each node.

Although a higher traffic load does not necessarily mean worse signal quality for the lightpaths that traverse a node, it tends to increase the noise due to increased crosstalk. In addition, higher traffic load will more likely cause higher blocking due to wavelength contention at a node. Therefore, TLP selects those nodes that are predicted to have more through traffic.

Algorithm 4. Signal quality prediction based (SQP) regenerator placement algorithm

Step 1. Assign each node i number C_i, initialized to be zero.
Step 2. Run a predefined wavelength routing algorithm on a number of randomly generated lightpath demands following a predicted traffic pattern.
Step 3. For each lightpath computed by the wavelength routing algorithm, do the following: For the j-th node from the source along the lightpath, calculate the incremental value:

$$I_j = \begin{cases} 1, & \text{if } j \bmod LN_{\text{MAX}} = 0 \text{ or } \\ & (j\pm1) \bmod LN_{\text{MAX}} = 0 \\ 0, & \text{otherwise} \end{cases}$$

Add I_j to the number C_i assigned to this node.
Step 4. Sort all nodes in non-increasing order of C_i.
Step 5. Select the first N nodes as regeneration capable nodes and place X regenerators at each node.

Step 3 is designed to favor the nodes and their immediate neighbors after every LN_{MAX} links along a predicted lightpath. In addition to every LN_{MAX}-th node, considering its immediate neighboring nodes may compensate for the error due to estimation of LN_{MAX} based on average link length. LN_{MAX} is constant in a network, but may change for different networks.

4 Wavelength Routing under Sparse Regeneration

4.1 Problem Statement

A wavelength routing problem is also referred to as a routing and wavelength assignment (RWA) problem. Wavelength routing under sparse regeneration in a translucent network is concerned with every aspect of RWA in a transparent network in terms of allocation of optical-layer resources. In addition, wavelength routing under sparse regeneration must allocate regenerators at some intermediate nodes of a lightpath to accommodate 3R O/E/O regeneration and wavelength conversion. In this paper, we use wavelength-links to represent the optical-layer resources. A wavelength-link is a wavelength on an optical fiber link. A wavelength routing algorithm under sparse regeneration tries to minimize both the number of used regenerators and the number of used wavelength-links. When both objectives cannot be achieved, the former takes priority over the latter because regenerators are scarce and expensive resources in a translucent network.

Under the SLE scheme, a wavelength routing algorithm is performed on a set of fixed lightpath demands, and hence can minimize the allocation of regenerators simultaneously for all lightpaths. Some global optimization approaches, e.g., integer linear programming (ILP), can be applied to an SLE problem. In this paper, we consider wavelength routing under the DLE scheme, which should be performed on a single lightpath basis and quickly. A heuristic approach is more suitable for handling this problem than a global optimization approach. Our problem is described as follows.

Given. A translucent network topology *G (V, E)* with *N* regeneration capable nodes, each having *X* regenerators; a certain number of wavelength-links and regenerators have been allocated to previously established lightpaths across the network; an incoming lightpath demand from the source node *S* to the destination node *D*; a BER threshold value *B* (upper bound); and the models and methods for online estimation of BER.

Objective. Find a path for the new-coming lightpath demand by allocating a minimum number of regenerators and then a minimum number of wavelength-links.

Constraints:

- A transmitter in transmitter set T_A should be available at the node *S*, while a receiver in transmitter set R_A should be available at node *D*.
- The number of allocated regenerators at any intermediate regeneration capable node is not greater than the total number of regenerators at that node.
- The number of used wavelengths on a link is not greater than the total number of wavelengths on that link.
- Each regeneration segment along the lightpath should be assigned a continuous wavelength.
- The estimated BER value on each regeneration segment should not exceed its threshold value *B*.
- Existing lightpaths may not be dropped or rerouted.

4.2 Regenerator Allocation Strategies

The regeneration demands due to signal quality degradation and wavelength contention (described in Section 2.1) are generated by the constraint on wavelength continuity and the constraint on BER, (described in Section 4.1) respectively, which result in allocation of regenerators to a lightpath during wavelength routing. Jointly considering the regenerator allocation under these two constraints is too complex for a wavelength routing heuristic to run quickly. In this subsection, we propose two strategies that facilitate fast heuristics by satisfying these two constraints separately in different orders. We will incorporate them into a wavelength routing heuristic algorithm in Section 4.3.

4.2.1 Fragmentation

The fragmentation strategy first satisfies the constraint on BER. As the name suggests, fragmentation divides a lightpath into consecutive regeneration segments at some intermediate nodes and transmits them independently. A lightpath is fragmented if its BER value exceeds the predefined BER threshold *B*. A search is started from the LN_{MAX}-th node on a tested route of this lightpath to find a node with spare regenerators. LN_{MAX} has been defined in Section 3.3 as the maximum link number that a transparent optical signal can traverse without having its BER exceed the threshold value *B*. The search proceeds from the LN_{MAX}-th node to its immediate neighbors and so on until finding a node before which the regeneration segment has a BER value under the threshold value *B*. Then a predefined wavelength assignment algorithm (e.g., the first-fit algorithm) is executed to assign a wavelength to this regeneration segment. If the wavelength assignment succeeds, a regenerator at the node is allocated to this lightpath. Otherwise, the search continues until a regeneration segment (i.e., the first fragment) with both a satisfactory BER value and a continuous wavelength is created. The same fragmentation procedure is repeated on the remainder of this route until all the regeneration segments (i.e., fragments) from the source node to the destination node are created. If no feasible regenerator allocation exists on this tested route, all tentatively allocated resources should be released.

4.2.2 Trace-back

The trace-back strategy first satisfies the constraint on wavelength continuity. When a continuous wavelength cannot be assigned along a tested route of this lightpath, a search is started from the destination node in the reverse direction of the route to find a regenerator, which results in a regeneration segment with a continuous wavelength from the source node to the node that contains this regenerator. Then the signal quality requirement, i.e., BER, on this regeneration segment is verified. If the BER value is higher than the BER threshold value *B*, the search continues to find another regenerator until the regeneration segment before the found regenerator has a satisfactory BER value. Then, this selected regenerator is allocated to the lightpath, and the node with the allocated regenerator is treated as a new source node. The same trace-back procedure described above is executed iteratively until all the regeneration segments from the original source node to the destination node are created. If no feasible regenerator allocation exists on this tested route, all tentatively allocated resources should be released.

4.3 Heuristic Wavelength Routing Algorithms

One of the simplest heuristics for wavelength routing is the hop distance based shortest path first routing (HD-SPF) heuristic, which assigns a weight of one to each link without considering the availability of regenerators and wavelengths, and then performs Dijkstra's SPF algorithm to find a shortest hop distance route. In addition to HD-SPF, we develop here a hybrid weighted shortest path first (HW-SPF) heuristic for wavelength routing under sparse regeneration. For each lightpath demand, we assign a weight $w(i, j)$ to each network link (i, j), which is defined below:

$$w(i,j) = \begin{cases} (1 - d \cdot r(j)/R_j) \cdot (1 - a(i,j)/W) \\ \cdot\, l(i,j), & R_j \neq 0 \\ (1 - a(i,j)/W) \cdot l(i,j), & R_j = 0, \end{cases}$$

where $r(j)$ and R_j denote the number of available and the number of total regenerators at the node j respectively, $a(i, j)$ and W denote the number of available and the number of total wavelengths on the link (i, j) respectively, and $l(i, j)$ is the link length. The factors $1-d \cdot r(j)/R_j$ and $1-a(i, j)/W$ are used to facilitate the SPF algorithm to select those links with more regenerators and more available wavelengths, respectively. The link length $l(i, j)$ is used as a factor to reduce the lightpath length. In the factor $1-d \cdot r(j)/R_j$, d is a parameter with a value in the range [0, 1]. The larger the parameter d is, the more the heuristic favors the routes with more regenerators. This heuristic algorithm is described as follows.

Algorithm 5. Hybrid weighted shortest path first (HW-SPF) wavelength routing algorithm

Input: A network topology $G(V, E)$ with the parameters W, R_j, and $l(i, j)$; the currently available network resources represented by (j) and $a(i, j)$; a lightpath demand from the source node S to the destination node D; a BER threshold value B; and a number M, which represents how many iterations the heuristic should execute (Initial $d = 0$).

Output: A route with a series of regeneration segments, each being assigned a wavelength; or a *Failure*.

Algorithm:

Step 1. Assign a weight $w(i, j)$ to each link (i, j) using the weight function described above.
Step 2. Use Dijkstra's shortest path algorithm to find a route in the weighted graph $G(V, E)$.
Step 3. Apply either the *Fragmentation* or *Trace-back* regenerator allocation strategy to the resultant route. The first-fit wavelength assignment is used by the regenerator allocation strategy (see Section 4.2).
Step 4. If a feasible regenerator allocation on the route exists, return this route with a series of regeneration segments corresponding to the regenerators allocated to the lightpath.
Step 5. Set $d = d + 1/M$. If $d \leq 1$, go to Step 1. Otherwise, return *Failure*.

This algorithm can implement both the fragmentation and trace-back regenerator allocation strategies proposed in Section 4.2. In addition, the parameter d provides a reasonable search space consisting of diversified routes with different number and distribution of regenerators. With a reasonable number of search iterations (M), the running time of this algorithm will be short enough to support dynamic establishment of lightpaths under sparse regeneration.

5 Numerical Results

5.1 Experiment Design

In this section, we conduct simulation experiments on three networks to measure the network performance under different settings. The first network is the 12-node ring network (see Fig. 3). The second is the 15-node/21-link medium-sized Pacific Bell mesh network (see Fig. 4). The third is the 53-node/68-link large-sized USA mesh network (see Fig. 5). In all these networks, each node contains a 128×128 OXC and an access station. Each access station is assigned 8 transmitters (T_A) and 8 receivers (R_A) to perform the access function. A link length in kilometers is labeled on each link. Each link has two fibers in opposite directions,

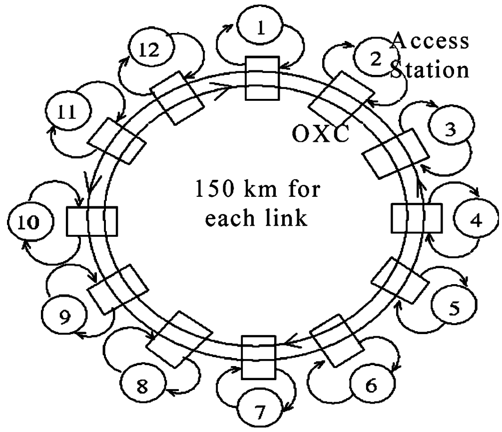

Fig. 3. The 12-node ring network.

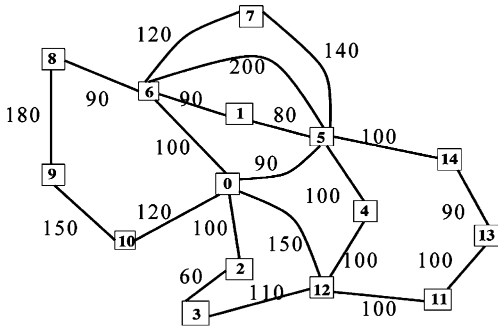

Fig. 4. The 15-node/21-link Pacific Bell network.

with each supporting 16 wavelengths. We assume that EDFAs are placed every 50 km along a fiber.

The simulation experiments are conducted using a proven tool: the SIMulator for Optical Networks (SIMON) [24]. SIMON has embedded physical impairment models for a variety of components, including optical fiber, EDFA, OXC, and (de)multiplexer, and supports online computation of signal powers, noise powers and crosstalk powers, based on which BER values on any lightpaths and regeneration segments can be estimated using the established computation methods in [15,25,26]. In this paper, we consider the physical impairments due to PMD, ASE, crosstalk at mux/demultiplexers and cross-connects, power attenuation on fibers, and insertion loss of optical components. Relevant system parameters are listed in Table 1. The maximum link number for transparent optical signals(LN_{MAX}) under average link length in the three networks is estimated to be 4, 5, and 5, respectively. This estimate is obtained by the BER computation methods under worst-case physical impairments.

We denote the set of all experiment cases by $S = P \times A \times N \times X \times T \times L$. Furthermore, P = RDM, NDF, CNF, TLP, SQP is the set of regenerator placement algorithms, where RDM represents random selection of regeneration capable nodes, and the remaining four algorithms are as described in Section 3. The set of different wavelength routing schemes A = HD-SPF-Fragmentation, HD-SPF-Trace-back, HW-SPF-Fragmentation, HW-SPF-Trace-back. The schemes are the combinations of two regenerator allocation strategies, fragmentation and trace-back (see Sections 4.1 and 4.2), and two wavelength routing heuristics, HD-SPF and HW-SPF (see Section 4.3). N is the number of regeneration capable nodes sparsely placed in the

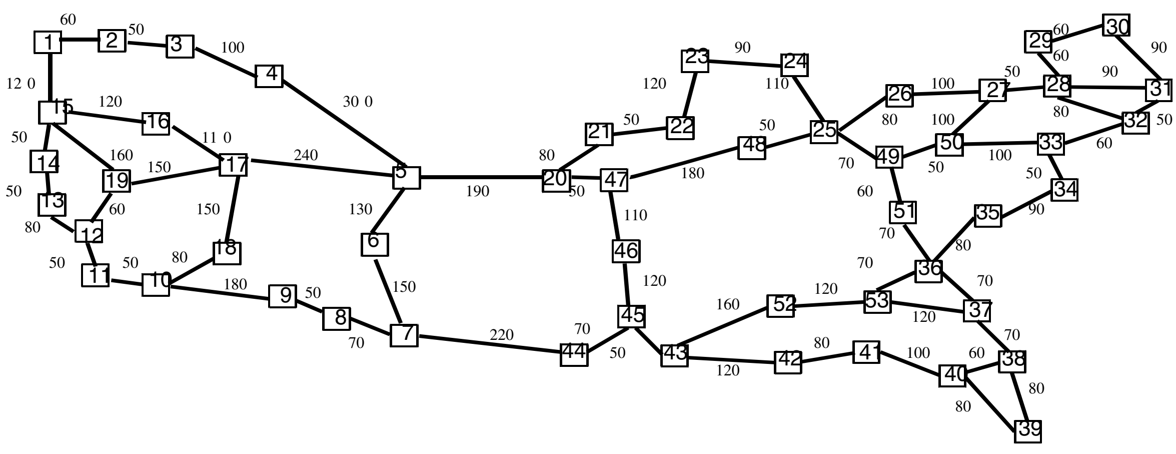

Fig. 5. The 53-node/68-link USA network.

Table 1. System parameters and their values used in the experiments.

Parameter	Value
Data rate	2.5 Gb/s
Wavelength range	1530–1565 nm
Fiber attenuation factor	0.2 dB/km
Fiber dispersion parameter	0.5
ASE factor	1.5
(De)multiplexer crosstalk ratio	−30 dB
OXC insertion loss	5 dB
Tap insertion loss	2 dB
BER threshold	10^{-12}
Wavelength spacing	100 GHz
Launched signal power	1 mW (0 dBm)
Optical bandwidth	50 GHz
EDFA saturated gain	18–25 dB
OXC crosstalk ratio	30 dB
(De)Multiplexer insertion loss	3 dB
EDFA insertion loss	2 dB

network. $N = \{0, 20\%|V|, 40\%|V|, 60\%|V|, |V|\}$, where $|V|$ is the total number of network nodes. X is the number of regenerators we assign to each regeneration capable node. Particularly, $X = \{2, 4, 8, 16, *\}$, where the asterisk represents the total number of wavelengths on all incoming links at a node. $N = |V|$ and $X = *$ results in a fully opaque network[1]. $T = \{$12-Node-Ring-Network, Pacific-Bell-Network, USA-Network$\}$ represents the set of network topologies. L is the set of traffic loads in Erlang. Experiments under different network topology uses a different set L.

We generate 100,000 lightpath demands randomly for each experiment case and distribute them uniformly among all source-destination pairs in the network. The lightpath demands arrive following a Poisson distribution with negative exponential holding times. By changing the ratio of holding time to inter-arrival time, the traffic load is increased from one Erlang to a value high enough to cause severe blocking in the network. We experiment on some representative subsets of S and present the numerical results in the following subsections. We use blocking probability as a metric to measure the network performance in the experiment cases.

5.2 Regenerator Placement Algorithms

We place eight regenerators at each of the $40\%|V|$ regeneration capable nodes selected by the regenerator placement algorithms. Among the five tested regenerator placement algorithms, the two traffic prediction based algorithms, TLP and SQP, need to use a predefined wavelength routing algorithm. We use the HD-SPF wavelength routing heuristic. After the placement, we use the HW-SPF wavelength routing heuristic under both the fragmentation and trace-back regenerator allocation strategies to test the network performance in terms of blocking probability. Under each level of traffic load, we select the better result (i.e., the lower blocking probability) between the results obtained by HW-SPF-Fragmentation and HW-SPF-Trace-back. The results for the five regenerator placement algorithms in three networks (the 12-node ring network, the 15-node/21-link Pacific Bell mesh network and the 53-node/68-link USA network) are shown in Figs. 6–8, respectively.

Fig. 6 shows that in the ring network, the blocking probability under the two topology based regenerator placement algorithms, NDF and CNF, are very close to that of the random placement algorithm (RDM). This is because a ring topology does not have any nodes more "centered" or having higher nodal degree than other nodes. The resultant placement is therefore similar to that obtained by random selection. The two traffic prediction based algorithms, TLP and SQP, have the same effect as the RDM under the prediction of uniform traffic distribution among all source-destination nodes. Nevertheless, they yield better results than the topology based algorithms, because they avoid the situation in which all selected regeneration capable nodes are so concentrated that there is no regenerator on a long segment of the ring.

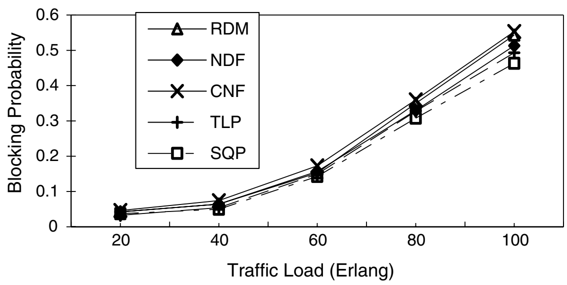

Fig. 6. Blocking probability vs. traffic load under different regenerator placement algorithms in the 12-node ring network.

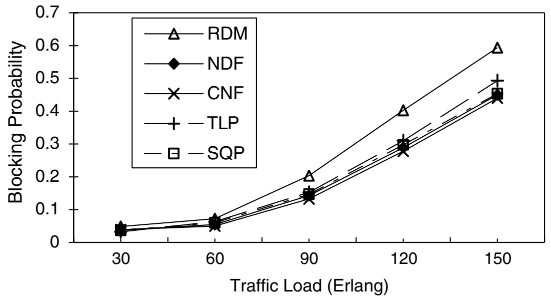

Fig. 7. Blocking probability vs. traffic load under different regenerator placement algorithms in the 15-node/21-link Pacific Bell mesh network.

Figs. 7 and 8 show that all the proposed regenerator placement algorithms outperform the RDM in the two mesh networks. In the medium-sized Pacific Bell network, the two topology based regenerator placement algorithms, NDF and CNF, yield better results, followed by SQP. However, the performance of CNF does not remain good in the large-sized USA network. This is because many lightpaths do not traverse the "centered" nodes in a large network, while many other lightpaths need more than one regenerator, which may not be located at the "center" of the network. In the USA network, SQP yields the best performance followed by NDF and TLP.

In summary, the signal quality prediction based regenerator placement algorithm (SQP) is a good choice for all kinds of network topologies. The two topology based regenerator placement algorithms, NDF and CNF, may generate the best results for some medium-sized irregular mesh topologies. NDF also works well for a large-sized irregular mesh topology.

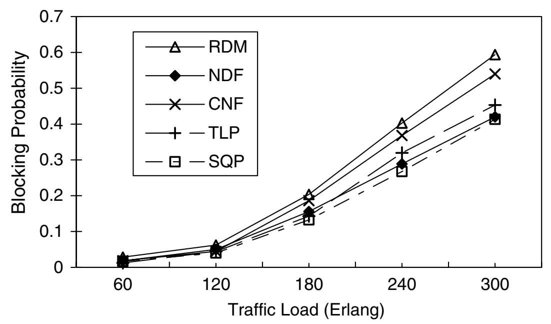

Fig. 8. Blocking probability vs. traffic load under different regenerator placement algorithms in the 53-node/68-link USA mesh network.

5.3 Wavelength Routing Schemes

NDF and SQP are shown to yield a better performance than other regenerator placement algorithms in Section 5.2. In this subsection, we compare different wavelength routing schemes (i.e., the combinations of regenerator allocation strategies and wavelength routing algorithms). We test the two wavelength routing heuristics, HD-SPF and HW-SPF, under the fragmentation and trace-back regenerator allocation strategies, based on the two regenerator placements produced by NDF and SQP, and select the better result between these two placements for each wavelength routing scheme under each level of traffic load. The results for two mesh networks are shown in Figs. 9 and 10.

The results show that the proposed HW-SPF wavelength routing algorithm significantly outperforms the HD-SPF algorithm. This is because HW-SPF takes into consideration the availability of both regenerators and wavelengths in the current network when the route of a lightpath is computed. It also provides some diversification mechanism to explore alternate routes with different regenerator distributions. In the medium-sized Pacific Bell network, the network performance under two regenerator allocation strategies is very close. In the large-sized USA network, the trace-back strategy outperforms the fragmentation strategy, which indicates that satisfying the constraint on BER should take priority over satisfying the constraint on wavelength continuity in large networks.

5.4 Number of Regeneration Capable Nodes (N) and Regenerators (X)

In this subsection, we measure the network performance under different numbers of regeneration

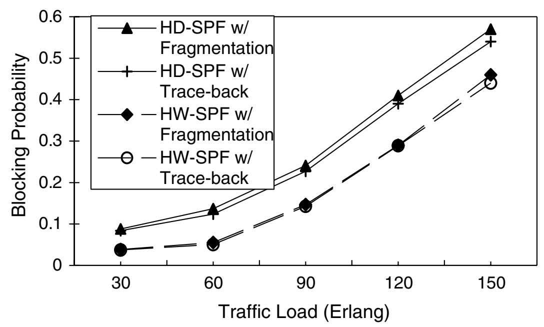

Fig. 9. Blocking probability vs. traffic load under different wavelength routing schemes in the 15-node/21-link Pacific Bell mesh network.

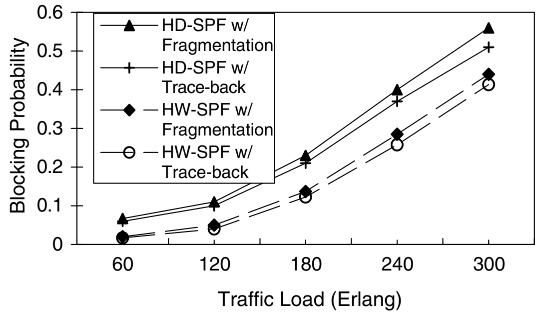

Fig. 10. Blocking probability vs. traffic load under different wavelength routing schemes in the 53-node/68-link USA mesh network.

capable nodes and regenerators. We employ the SQF regenerator placement algorithm and the HW-SPF-Trace-back wavelength routing scheme on the USA network, which was found to have similar results as on the 12-node ring network and the Pacific Bell network. We conduct the experiments under a light traffic load (90 Erlang) and a heavy traffic load, (270 Erlang) respectively.

Fig. 11 shows the blocking probability under different numbers of regeneration capable nodes and regenerators under a light traffic load. The line coincident with the axis $N = 0$ represents the blocking probability in a fully transparent network. The point at $N = 53$ and $X = *$ represents the blocking probability in a fully opaque network (see Section 5.1). We observe that either placing a large number of regenerators (e.g., $X = 16$) at a small number of regeneration capable nodes (e.g., $N = 11$) or placing a small number of regenerators (e.g., $X = 4$) at every regeneration capable node (i.e., $N = 53$) can produce significant performance improvement over a fully transparent network in terms of blocking probability. When the number of regeneration capable nodes or the number of regenerators at each node increases, the blocking probability continues to increase. When $N \geq 32$ and $X \geq 16$, the blocking probability is at most 3% higher than that of a fully opaque network (1%). Although this is three times higher, the absolute increase is still very small. Fig. 12 shows the results under a heavy traffic load. When $N \geq 32$ and $X \geq 8$, the translucent network can achieve a performance comparable to that of an opaque network (i.e., a blocking probability of 25% compared to 17%) under a heavy traffic load.

Figs. 13 and 14 show the tradeoff between the blocking probability and the total number of used regenerators under the light and heavy traffic loads, respectively. We normalize the total number of used regenerators in each experiment case to the number of regenerators in a fully opaque network (the fully opaque 53-node/68-link/16-wavelength USA network needs 2176 regenerators (see Section 5.1)). Fig. 13 shows that a drastic decrease in the

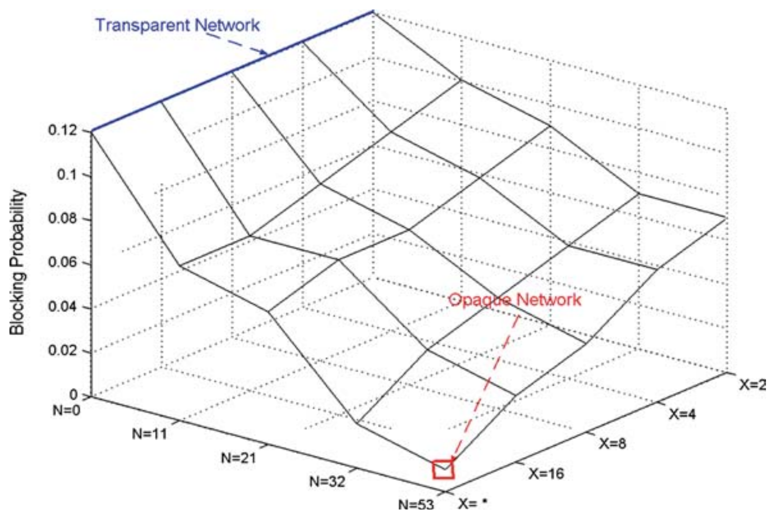

Fig. 11. Blocking probability vs. number of regeneration capable nodes (N) and number of regenerators at each node (X) in the USA network under a light traffic load (90 Erlang).

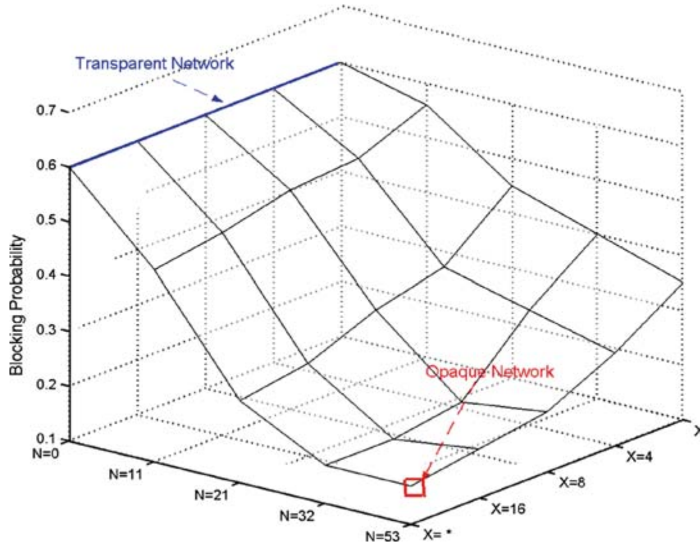

Fig. 12. Blocking probability vs. number of regeneration capable nodes (N) and number of regenerators at each node (X) in the USA network under a heavy traffic load (270 Erlang).

number of used regenerators only results in a slight increase in blocking probability under a light traffic load. If we consider a blocking probability of 4% acceptable, the network only needs 24% regenerators compared to the fully opaque network. In other words, we can save up to 76% network cost for regenerators. Fig. 14 shows the similar trend. If we consider a blocking probability of 25% is acceptable under a heavy traffic load, we can save up to 88% network cost for regenerators. Comparing Fig. 14 to Fig. 13, we can observe that the benefit of sparse regeneration in a heavily loaded translucent network is more significant than in a lightly loaded translucent network.

6 Conclusion and Future Work

In this paper, we studied a translucent wavelength-routed optical network architecture that effectively overcomes the signal quality degradation and wavelength contention in a fully transparent network while using much less wavelength-convertible 3R O/E/O regenerators than a fully opaque network. We used the sparse regeneration technique to realize such a translucent network, which can significantly reduce network blocking probability. We addressed both the regenerator placement and wavelength routing problems under sparse regeneration in translucent networks. We proposed and tested the performance

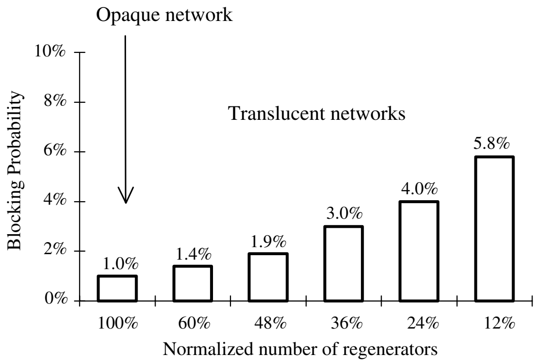

Fig. 13. Blocking probability vs. total number of used regenerators (normalized to the number of regenerators in an opaque network) under a light traffic load (90 Erlang).

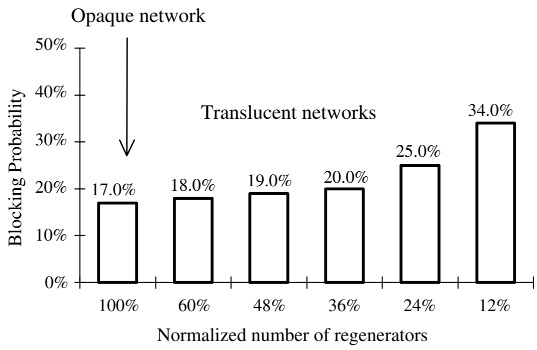

Fig. 14. Blocking probability vs. total number of used regenerators (normalized to the number of regenerators in an opaque network) under a heavy traffic load (270 Erlang).

of several regenerator placement algorithms and wavelength routing schemes. We recommend that the SQP regenerator placement algorithm and the HW-SPF-Trace-back wavelength routing scheme be used in all kinds of network topologies. In irregular mesh topologies, the NDF regenerator placement algorithm may also yield a good performance. Our experimental results further showed that increasing the number of regeneration capable nodes and/or the number of regenerators at each node can improve network performance significantly. Compared to their opaque counterparts, the translucent networks (e.g., the 53-node/68-link USA mesh network) with a slightly compromised performance in terms of blocking probability allow us to save up to 76% and 88% network cost for regenerators under light and heavy traffic loads, respectively.

We plan to investigate regenerator placement and wavelength routing under some non-uniform traffic distributions in our future work. We also plan to incorporate protection requirements into our network design and wavelength routing problems under sparse regeneration.

Note

1. A fully opaque network needs one regenerator for each wavelength on each incoming fiber link at each node. The total number of regenerators in a fully opaque network can be calculated as $2 \times |E| \times W$, where $|E|$ is the number of bi-directional links. A fully opaque USA network needs $2 \times 68 \times 16 = 2176$ regenerators.

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