Impairment-aware traffic grooming in WDM optical networks

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A novel heuristic algorithm that considers transmission impairment (especially amplified spontaneous emission (ASE) noise) is developed for traffic grooming in wavelength division multiplexing (WDM) optical networks. Span constraints, which are determined by the impairment, are added to constrain the maximal transparent reach limit of a lightpath. Under span constraints, a series of short lightpaths will be built up explicitly to relay traffic when a single lightpath cannot meet the requirement of transmission quality. Both problem formulations and heuristic algorithms are given for impairment-aware traffic grooming. Numerical results show that the successful routing of each low-speed traffic stream is guaranteed and the efficiency of wavelength channels and lightpath usage are both improved by considering transmission impairment.

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In wavelength division multiplexing (WDM) optical networks, the bandwidth of a traffic stream can be much lower than that of a lightpath. To efficiently utilize the bandwidth of a lightpath and reduce the number of transceivers, low-speed traffic streams should be groomed into high-speed lightpaths[1−3]. When establishing a lightpath, various physical impairments will limit the maximal transparent reach of a lightpath, including attenuation, chromatic dispersion, amplified spontaneous emission (ASE) noise, etc.[4,5] As a low-speed traffic stream is carried on one or more lightpaths, its transmission quality is determined by the longest lightpath. So it is significant to study the impact of impairment-aware algorithms on traffic grooming in WDM optical networks.

The effects of most physical impairments can be reduced in optical domain. For example, attenuation and chromatic dispersion can be compensated by insertion of optical amplifiers or dispersion-compensating fibers in a link. However, accumulation of ASE noise cannot be eliminated in optical domain, and thus becomes a dominant physical layer impairment that limits the maximal transparent reach of a lightpath. To maintain an acceptable signal-to-noise ratio (SNR) level at the receiver side, the number of optical amplifiers (OAs), which are ASE noise source, along a lightpath should not exceed a maximum value (M)[5,6]. If a lightpath traverses more than M OAs (M spans, a fiber span refers to a segment between two OAs), the signal quality will degrade below the requirement, and the traffic travelling across the lightpath may not be received correctly.

In Ref. [7], ASE noise is taken into consideration and an optimization algorithm is presented to divide a large WDM network into a few optical transparent islands. But its demand unit is an end-to-end lightpath, not a low-speed traffic stream that is considered in this letter. In Refs. [8–10] that consider other transmission impairment, the traffic unit is also a lightpath. In addition, when routing a connection request, a single lightpath is used. If no single lightpath meets the requirement of transmission quality, the connection request will be blocked. However, there may be no direct lightpath that meets the transmission requirement between some node pairs, so the connection request is destined to be blocked. In this letter, we present an impairment-aware heuristic algorithm, which finds out the node pairs with no direct lightpaths meeting the transmission requirement and selects a series of short lightpaths to relay traffic between them. It guarantees each low-speed traffic stream to be successfully routed, and improves the efficiency of wavelength channel and lightpath usage.

As ASE noise of OAs exists, the maximum number of OAs or spans of a lightpath going through is limited. Several factors affect the maximum span M, including bit rate B_0 of a lightpath, gain G and the excess noise factor n_{sp} of OA, optical power P_L launched at the transmitter, and transmitter-receiver technology (e.g., forward error correction (FEC)). Assuming all OAs deployed in a physical link have the same parameters, an upper bound on M can be derived as[5]

$$M \leq \left\lfloor \frac{P_{\mathrm{L}}}{2\mathrm{SNR}_{\min} n_{\mathrm{sp}} hv(G-1)B_0} \right\rfloor, \qquad (1)$$

where h=6.63×10^{-34} J/Hz is the Planck's constant, v is the carrier frequency, $\mathrm{SNR}_{\min}$ is the acceptable optical SNR level at a receiver, and $\lfloor x \rfloor$ is the maximum integer that is less than or equal to x.

A network state of traffic grooming can be represented as a 4-tuple (PT (physical topology), VT (virtual topology), T (traffic matrix), WT (network resources such as wavelength and transceivers)). Define a physical topology PT=$\{V_{\mathrm{p}}, E_{\mathrm{p}}, D_{\mathrm{p}}\}$, in which V_{p} is a set of physical nodes, E_{p} is a set of undirected edges, and D_{p} is a set of edge weights. A node in V_{p} is supposed to be an integrated unit of an optical node and an access node (e.g., a label switch router (LSR)). An edge in E_{p} is a pair of fibers in both directions. A weight $\mathrm{d}_{m,n}$ in D_{p} is the number of OAS placed between nodes m and n. VT is defined as a directed graph VT=$\{V_{\mathrm{L}}, E_{\mathrm{L}}\}$, in which E_{L} is the lightpath set, V_{L} is the set of nodes connected by lightpaths in E_{L}. Variable $l_{m,n}^{i,j}$ is equal to 1 if a lightpath from nodes i to j goes through the physical link between nodes m and n, otherwise 0. So there is

$$\sum_{m,n} d_{m,n} \times l_{m,n}^{i,j} \leq M, \quad \forall i, j, \tag{2}$$

which shows the span constraints determined by ASE noise. It means a lightpath traverses at the most M spans. The span constraints could be translated into hop constraints when each physical link has the same length (the same number of OAs placed in each physical link).

The traffic demand T is defined as a set of one or more low-speed traffic matrices, denoted as T=$\{T_k\}$. Each k corresponds to one traffic matrix and T_k=$\{T_{k,s,d}\}$. For example, assuming the capacity C of a lightpath is optical carrier (OC)-48, there may be one low-speed traffic matrix for OC-1, OC-3c, OC-12c, and OC-48c, respectively. The bandwidth between each node pair of T_k is multiples of OC-k. Each traffic $T_{k,s,d}$ is originated from an access node and terminated in another access node.

Given PT and T, finding out VT to minimize WT under constraints in expression (2) is the aim of this letter. The following performance parameters will be investigated.

1) Successful routing rate:

$R_{\mathrm{suc}} = \sum\limits_{k,s,d} t_{k,s,d} \Big/ \sum\limits_{k,s,d} T_{k,s,d}$, where $t_{k,s,d}$ is the number of kth-type traffic successfully routed, and $T_{k,s,d}$ is all of kth-type traffic to be routed from nodes s to d. (A traffic is successfully routed if it can be received correctly. So no lightpath with more spans than M is traversed by it.)

2) Average traffic hop distance (ATHD):

ATHD=$\sum\limits_{k,s,d} (t_{k,s,d} \times h_{k,s,d}) \Big/ \sum\limits_{k,s,d} t_{k,s,d}$, where $h_{k,s,d}$ is the number of lightpaths that traffic $t_{k,s,d}$ goes through.

3) Average lightpath hop distance (ALHD):

ALHD=$\sum\limits_{i,j} (o_{i,j} \times l_{i,j}) \Big/ \sum\limits_{i,j} l_{i,j}$, where $o_{i,j}$ is the number of optical hops a lightpath traverses, $l_{i,j}$ is the number of lightpaths established between nodes i and j.

4) Wavelength channel efficiency:

$W_{\mathrm{eff}} = \sum\limits_{k,s,d} t_{k,s,d} \Big/ (n_{\mathrm{w}} \times C)$, where n_{w} is the total number of wavelength channels used, C is the wavelength channel capacity.

5) Lightpath efficiency:

$L_{\mathrm{eff}} = \sum\limits_{k,s,d} t_{k,s,d} \Big/ (n_{\mathrm{L}} \times C)$, where n_{L} is the total number of lightpaths established.

The basic idea behind our heuristic is: when routing a low speed traffic stream, try to route it first in current VT; when it cannot be routed in current VT, new lightpaths will be established to accommodate it. If the number of spans traversed by a direct lightpath between the traffic's source and destination nodes is smaller than M, a single lightpath is established; otherwise, two or more short lightpaths will be built up to relay the traffic. Each of them must have a span number no greater than M.

To get lightpaths that do not violate span constraints, Floyd algorithm is used on PT to calculate the shortest paths between each node pair. Based on the calculated result, a new graph G is derived. An edge with weight 1 will be added into G if the shortest distance between its endpoints is not greater than M. An extended Floyd algorithm is used on this new graph G to get K-shortest routes between each node pair. An edge of the new graph corresponds to a lightpath, and each of the K-shortest routes includes a series of lightpaths. When a direct lightpath cannot be set up, the shortest route is chosen to minimize the total number of transceivers, and the lightpaths corresponding to the edges of the route will be built up. If several routes have the same distance, one that makes transceivers uniformly distributed is selected.

To get K-shortest routes of G, a preprocessing needs to be executed before grooming. The pseudocode for the heuristic is as follows.

Input: PT, T.

Output: VT, WT.

Preprocessing:

Step 1: Floyd algorithm is used on PT to calculate the shortest path between each node pair.

Step 2: A new graph G is derived, in which an edge with weight 1 is added if the distance of its shortest path is not greater than M.

Step 3: Extended Floyd algorithm is used on G to find out K-shortest paths $P = \{p_{sd,k}\}$.

Grooming:

Step 1: For both nodes s and d, if T_{sd}, the sum of traffic between s and d, is greater than or equal to C, $\lfloor T_{sd}/C \rfloor$ new lightpaths need to be established.

Step 1.1: If there is an edge between s and d in G, add $\lfloor T_{sd}/C \rfloor$ direct lightpaths into VT. Otherwise, add $\lfloor T_{sd}/C \rfloor$ series of lightpaths into VT according to P.

Step 1.2: Route $\lfloor T_{sd}/C \rfloor \times C$ traffic in added lightpaths, and delete them from T. As the granularity of a low-speed traffic stream in this letter is assumed to be just like synchronous optical network (SONET), all SONET-granularity traffic with capacity $n \times C$ can be exactly routed in n lightpaths with no bifurcation and no capacity spared. Because of space consideration, we do not prove it here.

Step 2: Groom the left traffic $\{t_{sd} = T_{sd} - \lfloor T_{sd}/C \rfloor \times C\}$.

Step 2.1: Sorting t_{sd} in a descending order and place it in a list L.

Step 2.2: Route each traffic t in L. For each granularity OC-k that is less than or equal to t, (a) generate a weighted graph G_{w}. An edge with the weight $1/r$ will be added into G_{w} if the residual capacity r of a lightpath in VT is larger than or equal to OC-k. (b) Dijkstra's algorithm is used on G_{w} to find a route between source and destination node of t. (c) If a route is found, groom all OC-k traffic of t into the lightpaths on the route, delete them from t, go back to (a) for next granularity OC-$(k-1)$; otherwise, add one or one series of lightpath (like Step 1.1) into VT to accommodate all the left traffic and delete t from L, then go back to Step 2.2 for next t.

Step 3: Route VT on PT with the shortest path, and do the wavelength assignment with first-fit approach.

In the phase of preprocessing, the complexity of Floyd algorithm (Step 1) is $o(|V|^3)$, and the calculation of K-shortest paths (Step 2) is $o(|V|^3 \times K^2)$. In the phase of grooming, the complexity of each step is as follows: traffic sorting (Step 2.1) is $o(|V|^2 \times \log |V|^2)$; traffic routing in VT (Step 2.2) can be formulated as $o(|T| \times |V| \log |V| \times K)$; routing VT on PT (Step 3) is $o(|V|^2 \times W)$. Consequently, the total complexity of impairment-aware traffic grooming algorithm is $o(|V|^3 + |V|^3 \times K^2 + |V|^2 \times \log |V|^2 + |T| \times |V| \log |V| \times K + |V|^2 \times W)$. As the value of K is often chosen to be 2 or 3 (no greater than 5), the complexity can be rewritten as $o(|V|^3 + |V|^2 \times \log |V| + |T| \times |V| \log |V| + |V|^2 \times W)$. So, the heuristic algorithm can be used for medium and large-scale networks.

Assuming $P_L=-2$ dBm, $n_{sp}=2.5$, $SNR_{min}=16$ dB (without FEC), $G=26$ dB, $B_0=2.5$ Gbps, and $v=193.1$ THz ($\lambda = 1552.52$ nm), then M is 25 according to Eq. (1).

Firstly a six-node seven-link network (Fig. 1(a)) is used as an example to demonstrate the performance of our algorithm. Its edge is weighted by the length of each physical link. If an OA is inserted every 80 km, Fig. 1(b) is derived. With span constraints of $M=25$ on Fig. 1(b), only the lightpath represented by an edge in Fig. 1(c) can be established. With no edge in Fig. 1(c), a series of edges must be concatenated to go from its source to destination. For example, when a new lightpath from nodes 1 to 4 needs to be set up, as a direct lightpath does not exist in Fig. 1(c), one of two shortest routes (1→3→4 and 1→6→4) may be chosen to relay traffic. That is, two lightpaths will be established instead of one direct lightpath.

C is assumed to be OC-48c. Traffic is generated following the distribution OC-1:OC-3:OC-12:OC-48 = 16:8:2:1. Traffic is also uniformly distributed between each pair of nodes. In Table 1, 1792 OC-1 traffic is randomly generated in total.

From Table 1, the conclusions can be drawn:

1) All traffic can be successfully routed under span constraints. If no span constraints are imposed, only 70.4% traffic is successfully routed. That is, there is 29.6% traffic going through at least a lightpath whose span length is greater than M.

2) Compared with no span constraints, more transceivers (T_{rs}) are used (55 instead of 48), but less wavelength channels (W_c) (78 against 85) with span constraints. So with consideration of traffic's successful routing, lightpath efficiency is worse, but wavelength channel efficiency is better under span constraints. This is because more short lightpaths are established with span constraints imposed. Short lightpaths provide more opportunity for a wavelength channel to be multiplexed by low speed traffic streams.

3) If calculating L_{eff} and W_{eff} with successfully routed traffic, L_{eff} will be 54.8% and W_{eff} 30.9% (value in the parentheses in Table 1) under no span constraints, while L_{eff} and W_{eff} remain unchanged under span constraints. So the latter has the better performance for both L_{eff} and W_{eff}.

4) With span constraints, ATHD is bigger, and ALHD is smaller. That means, in average, more traffic hops traversed by a traffic, but less optical hops (or wavelength channels) passed by a lightpath.

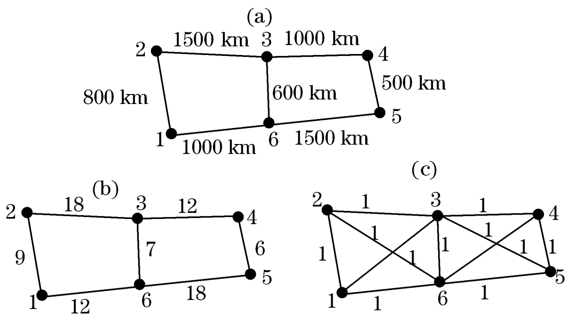

Fig. 1. Sample of six-node seven-link wide-area network. (a) Weighted by length[1], (b) weighted by number of OAs, (c) new graph derived with span constraints of $M=25$.

Table 1. Numerical Results Under Span and No-Span Constraints

Constraints	R_{suc}	T_{rs}	W_c	L_{eff} (No Failed)	W_{eff} (No Failed)	ATHD	ALHD
Span	100	55	78	67.9	47.9	1.37	1.42
No Span	70.4	48	85	77.8(54.8)	43.9(30.9)	1.13	1.77

In Fig. 2, traffic relayed in each node is analyzed. As can be seen in Fig. 2(a), with span constraints, more traffic (209 and 283 OC-1, respectively) is relayed in nodes 3 and 6. It makes more transmitters and receivers (at least 11) configured in nodes 3 and 6. So both nodes 3 and 6 are traffic switch centers. It is because comparing with other nodes, both nodes 3 and 6 have a bigger node degree of 5, as shown in Fig. 1(c). So there is more chance for nodes 3 and 6 to relay traffic.

When no span constraints are imposed, less traffic is relayed in the network, 238 against 659 OC-1 of span constraints. It is because more traffic is transferred in a direct lightpath with worse signal quality.

With span constraints, traffic switch centers can be found out from the graph derived by the Floyd algorithm. More transceivers should be deployed in the switch centers. It is meaningful for transceiver configuration when building a network.

In Fig. 3, network performance versus traffic load is given. Traffic load is measured by γ (X axis), in which the total traffic generated will be $n(n-1)\gamma$. It can be found that: 1) with span constraints, all traffic is successfully routed, while only 40%−80% traffic successfully routed under no span constraints; 2) L_{eff} and W_{eff} increase when γ increases; 3) under span constraints, W_{eff} performance is better than that of no span constraints, even if failed traffic is not excluded under no span

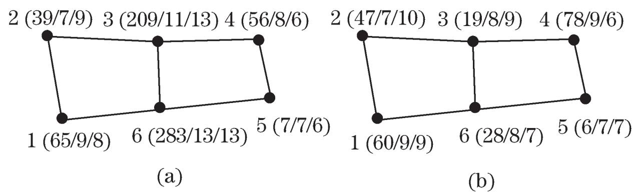

Fig. 2. Relayed traffic and transceiver distributions. The node is labeled as node (relayed traffic/transmitters/receivers). Traffic is measured in unit of OC-1. (a) Span constraints of $M=25$ (659 relayed traffic), (b) no span constraints (238 relayed traffic).

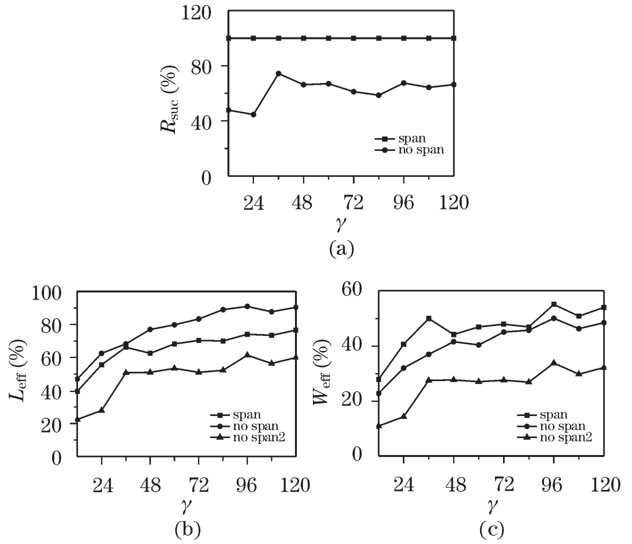

Fig. 3. Network performance versus traffic load. "Span" means network performance is derived under span constraints; "no span" for no span constraints with failed traffic not excluded; "no span2" excludes failed traffic.

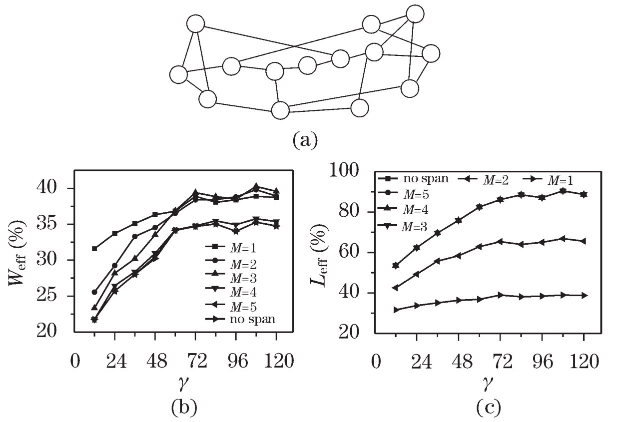

Fig. 4. (a) Physical topology of NSFNET network, (b) W_{eff}, and (c) L_{eff} with different M in NSFNET network.

constraints; 4) under span constraints, L_{eff} is poorer than that of no span constraints when failed traffic is not excluded, but better when failed traffic is excluded. The latter L_{eff} is a more suitable one to reflect the performance of no span constraints.

In Fig. 4, a larger network NSFNET is used to demonstrate the performance of different M. As the placement of optical amplifiers in each physical link of NSFNET is unknown, the number of physical links traversed by a lightpath is used as its span length. Traffic is similarly generated as six-node seven-link network. The following results can be derived from Fig. 4.

1) W_{eff} increases when γ increases, as shown in Fig. 4(b). More traffic improves wavelength channel efficiency because there are more chances for a wavelength channel to be multiplexed by a low-speed traffic stream; W_{eff} increases when M decreases at most instances. Smaller M refers to short lightpaths. So short lightpath establishment not only achieves good signal quality at its receiver side, but also improves the wavelength channel efficiency of a network.

2) L_{eff} increases when γ or M increases, as shown in Fig. 4(c). More traffic improves lightpath efficiency because there are more chances for a lightpath to be multiplexed by a low-speed traffic stream. When M increases, long lightpaths are allowed to be established between mass traffic node pairs. In addition, traffic in long lightpaths is assumed to be successfully routed. So less lightpaths need to be set up in virtual topology and the lightpath efficiency is improved. But when M increases, the signal quality of a lightpath may be worse in the receiver side.

In conclusion, we formulate an impairment-aware traffic grooming problem and present a novel heuristic algorithm for it. With impairment considered, span constraints are added, which make short lightpaths established. The algorithm guarantees each low-speed traffic stream to be successfully routed with good signal quality. It also achieves good performance of wavelength channel and lightpath efficiency.

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