wavelength interleaving technique in [5] would also suffer from the lasing path between two adjacent modules. However, when the proposed BADA modules were used, there exists no lasing path because of their asymmetric configuration.

Conclusion: We have proposed and demonstrated a novel BADA module, in which multiple reflection paths and lasing paths are structurally removed. The proposed module was configured with asymmetric fold-back optical paths. Since the proposed BADA module does not use OBPFs for the suppression of reflection and lasing paths, the periodic property of the AWG can be fully utilised. We believe that the proposed BADA module is more cost-effective than the previously proposed structures.

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Restoration with wavelength conversion in WDM networks

Y. Luo and N. Ansari

The integer linear programming formulas are derived and the relaxed heuristic algorithm is proposed to restore paths in WDM networks with wavelength converters. Compared with the disjoint path protection and the shared path protection methods, the proposed heuristic algorithm has much better performance in terms of recovery cost, additive latency, and restoration coverage.

Introduction: Substantial research [1–4] has focused on the survivability of WDM networks without wavelength conversion. With the development of wavelength converters [5], wavelength conversion (WC) is being conceived as a necessary function for WDM networks, and it relaxes the wavelength management requirements throughout the network [6]. By allowing wavelengths to be assigned on a link-to-link basis, a connection can be set up as long as any wavelength is free on intermediate links.

To handle the on-line restoration issue with WC, we formulate the restoration problem for a single link fault by integer linear programming (ILP). The heuristic algorithm is proposed as a sub-optimum solution for fast on-line restoration. It allows sharing spare capacity among several single link faults, improving the network flexibility and resource efficiency. The analysis on recovery cost, additive latency, and coverage verifies that our heuristic algorithm performs much better than traditional disjoint path projection (DPP) and shared path projection (SPP) methods.

Problem description: Consider a directed graph $G(V,E)$, where V is the node set and E is the link set, E_{ij} represents the link from node i to node j; W is the maximum number of wavelengths on all links; H_{P_l}, Q_{P_l} and C_{P_l} are the transmission cost, wavelength conversion cost and total cost of path P_l, respectively.

Given m working paths $\{P_1, P_2, \ldots, P_m\}$ before link T fails, in which the first x paths, $\{P_1, P_2, \ldots, P_x\}$ go through link T, the traffic in the working path P_k is denoted as $|P_k|$, C_i^{st} is the wavelength conversion cost from wavelength s to t in node i, and $C^{E_{ij}}$ is the transmission cost using link E_{ij}. We introduce three indicators:

$$E_{ij}^{sP_k} = \begin{cases} 1, & \text{link } E_{ij} \text{ uses wavelength } s \text{ for working path } P_k \\ 0, & \text{otherwise} \end{cases}$$

$$\bar{E}_{ij}^{sP_l} = \begin{cases} 1, & \text{link } E_{ij} \text{ uses wavelength } s \text{ for working path } P_l \\ 0, & \text{otherwise} \end{cases} \quad \text{and}$$

$$I_{vP_l}^{st} = \begin{cases} 1, & \text{restoration path } P_l \text{ coverts wavelength } s \text{ to } t \text{ at node } v \\ 0, & \text{otherwise} \end{cases}$$

Assume $\{\bar{P}_1, \bar{P}_2, \ldots, \bar{P}_y\}$ are the restoration paths for link T fault. Using ILP, the restoration problem can be formulated as:

$$\text{minimising the restoration cost: } \min \sum_{P_l=\bar{P}_1}^{\bar{P}_y} C_{P_l} \tag{1}$$

subject to the following constraints:

$$\text{path restoration cost constraint: } C_{P_l} = H_{P_l} + Q_{P_l}, \; P_l \in \{\bar{P}_1, \bar{P}_2, \ldots, \bar{P}_y\} \tag{2}$$

$$\text{wavelength conversion cost: } Q_{P_l} = \sum_{t=1}^{W} \sum_{s=1}^{W} \sum_{v=1}^{n} C_v^{st} I_{vP_l}^{st}, \quad P_l \in \{\bar{P}_1, \bar{P}_2, \ldots, \bar{P}_y\} \tag{3}$$

$$\text{transmission cost: } H_{P_l} = \sum_{s=1}^{W} \sum_{j=1}^{n} \sum_{i=1}^{n} C^{E_{ij}} \bar{E}_{ij}^{sP_l}, \; P_l \in \{\bar{P}_1, \bar{P}_2, \ldots, \bar{P}_y\} \tag{4}$$

wavelength conversion constraint in a node:

$$\sum_{s=1}^{W} \sum_{t=1}^{W} I_{vP_l}^{st} = \sum_{s=1}^{W} \sum_{j=1}^{n} \bar{E}_{vj}^{sP_l}, \; P_l \in \{\bar{P}_1, \bar{P}_2, \ldots, \bar{P}_y\}, \; v \in \{1, 2, \ldots, n\}, \tag{5}$$

$$\sum_{s=1}^{W} I_{vP_l}^{st} \leq 1, \; P_l \in \{\bar{P}_1, \bar{P}_2, \ldots, \bar{P}_y\}, \; v \in \{1, 2, \ldots, n\}, \tag{6}$$

$$\sum_{t=1}^{W} I_{vP_l}^{st} \leq 1, \; P_l \in \{\bar{P}_1, \bar{P}_2, \ldots, \bar{P}_y\}, \; v \in \{1, 2, \ldots, n\}, \tag{7}$$

wavelength constraint in a link:

$$\sum_{P_l=\bar{P}_1}^{\bar{P}_y} \sum_{P_k=P_1}^{P_x} \sum_{s=1}^{W} (E_{ij}^{sP_k} + \bar{E}_{ij}^{sP_l}) \leq W, \; v \text{ and } j \in \{1, 2, \ldots, n\} \tag{8}$$

$$\text{traffic restoration constraint: } \sum_{P_k=P_1}^{P_x} |P_k| = \sum_{P_l=\bar{P}_1}^{\bar{P}_y} |P_l| \tag{9}$$

Minimising the total restoration cost for the fault of link T is the goal of ILP (1). The cost has two factors: the wavelength conversion cost Q_{P_l} for a path is the sum of the conversion cost in each node of this path (3); the transmission cost H_{P_l} for a path equals the sum of the transmission cost in each link of this path (4). Several constraints are applied: first, the wavelength conversion constraint in a node (5); second, in a node, a specific wavelength only appears at most once in the incoming links (6), and only appears at most once in the outgoing links (7); third, the wavelengths in a link are no more than the maximum number of wavelengths W in the whole WDM network (8). If the restoration scheme meets (9), it is a complete restoration, i.e. all traffics in the fault link are recovered; otherwise, it is a maximum restoration, restoring as many traffics as possible.

Heuristic algorithm: The above problem is a routing and wavelength assignment (RWA) issue. It is NP-complete with $O(nW^2 + n^2W)$ variables and $O(nW^2y + n^2Wy)$ constraints, where n is the number of nodes, W is the maximum number of wavelengths, and y is the number of traffics when link T fails. To support the real-time on-line restoration, we propose the heuristic restoration algorithm (HRA): in the off-line processing, alternate paths for a node pair are listed into *PathSet* in the ascending order in cost. Assume alternate path $\bar{P}_y$ goes through node n with incoming wavelength λ_1^{in}; if the same wavelength λ_1^{out} is available in the outgoing port, assign λ_1^{out} to λ_1^{in}, and no wavelength conversion cost in node n is incurred for this path; if λ_1^{out} is unavailable in the outgoing port, wavelength conversion is made, and the corresponding wavelength conversion cost is added into this path. In the on-line processing, split the traffics in link T into several subtraffics based on their source–destination node pairs; then release the network resource along the subtraffic paths; from *PathSet*, select the first fault-link-disjoint path as the restoration path.

HRA is a relaxed linear programming: it reduces the size of *PathSet* by limiting the hop count in the alternate paths, relaxes the wavelength consistency by allowing wavelength conversion in nodes, and relaxes the traffic constraint (9) by using maximum restoration. The pseudocode is listed here:

```
Input: network topology $G(V,E)$, working path $P = \{P_1, P_2, \ldots, P_x\}$,
       conversion cost $C_i^{st}$, transmission cost $C^{E_{ij}}$,
       alternate paths set PathSet for all node pairs $(i,j)$,
       alternate path hop limit $h$,
       alternate path number limit $k$, link fault $T$
Output: restoration path $\bar{P} = \{\bar{P}_1, \bar{P}_2, \ldots, \bar{P}_y\}$
Begin
  PathSet = limit_path_hop(PathSet,h,k);
  PathSet = wavelength_assign(PathSet, V,E);
  CostList = get_cost(PathSet);
  PathSet = list_pathset(PathSet, V,CostList); //off-line processing
  TrafficList = split_traffic(T,P);
  For all traffics in link T{
    Path = get_alternate_path(PathSet, TrafficList, T);
    if Path is not empty
    {$\bar{P}$ = add_path(Path);}}        //on-line processing
End
```

Performance analysis: Simulations on the NSFNET topology with 14 nodes and 21 links are conducted. Each link is a fibre in the WDM network. There are eight wavelengths in a fibre and all nodes are configured with all-optical wavelength converters. Initially, 25 working paths are set up, and the traffic in each working path is one wavelength bandwidth. The average hop count is 2.3, and we limit the hops of the recovery paths to five. The transmission cost for each link and the conversion cost in each node are both 1 unit.

Table 1: Recovery cost (units)

Link fault	DPP	SPP	HRA
Link 6	37	34	32
Link 7	26	24	24
Link 9	-	33	31
Link 10	-	17	17
Link 12	26	24	23
Link 18	19	17	15
Average	27	24.83	23.67

Table 2: Additive latency: each entry i/j refers to i additional hops and j additional conversions

Link fault	DPP	SPP	HRA
Link 6	6/9	6/6	5/5
Link 7	6/5	5/4	5/4
Link 9	-/-	5/10	4/9
Link 10	-/-	2/7	2/7
Link 12	8/6	7/5	6/5
Link 18	3/7	3/5	2/4
Average	5.75/6.75	4.67/6.17	4/5.67

Table 1 shows that HRA incurs less recovery cost than SPP because HRA selects the failed-link-disjoint restoration paths, while SPP selects the all-link-disjoint paths. The DPP scheme cannot find all recovery paths within the limited hop count, and the recovery cost is infinite in the scenarios of link 9 and link 10 faults. Additional hops and additional wavelength conversions in the recovery paths lead to additive latency. HRA requires the least number of hop count and conversions to restore paths while DPP requires the most (Table 2). Due to the limit of hop count and low network degree, there may not exist recovery paths for each link fault. Simulations show that HRA and SPP achieve 100% coverage, completely recovering the traffics disconnected by a link fault, while DPP only recovers 67% of the link faults.

Conclusions: To capitalise on the wavelength conversion capability of WDM networks, new ILP formulas for restoration have been introduced, and the heuristic algorithm, HRA, has been proposed. By properly relaxing the ILP constraints, HRA can greatly improve the recovery cost, additive latency and provide complete single link faults restoration coverage for WDM networks.

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Singlemode fibre transmission using 1.2 μm band GaInAs/GaAs surface emitting laser

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Singlemode fibre (SMF) transmission using a 1.2 μm band GaInAs/GaAs vertical cavity surface emitting laser (VCSEL) is demonstrated. It was observed that the short optical pulse with a pulse width of 60 ps was compressed to 50 ps after transmitting in a 10 km-long SMF due to the frequency chirp of a VCSEL and the negative fibre dispersion at 1.2 μm. This result indicates that this new wavelength window would enable high bit rate data transmission beyond 10 Gbit/s without chirp penalties.

Introduction: A long-wavelength vertical cavity surface emitting laser (VCSEL) is very promising for use in high-speed metro-area networks owing to its potentially low-cost production, low power consumption and two-dimensional array configuration. A highly strained GaInAs/GaAs quantum well (QW) VCSEL is one of the candidates for this purpose. This material is advantageous owing to its high material quality and excellent temperature characteristics [1]. 1.2 μm VCSELs have a potentiality of data transmission beyond 10 Gbit/s over 10 km [2]. A new wavelength window of 1.1 to 1.2 μm has a negative dispersion in conventional singlemode fibres (SMFs), resulting in optical pulse compression with the help of frequency chirp. It is important to examine the linewidth enhancement factor α of highly strained GaInAs/GaAs VCSELs for discussing the ultimate transmission bandwidth at this new wavelength window.