Survivable Green Optical Backbone Networks with Shared Path Protection

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Abstract: We propose a novel energy-efficient and survivable routing algorithm addressing the trade-off caused by conflicting objectives of energy saving and survivability, i.e. energy-efficient routing tends to pack while survivable strategies try to spread the traffic.
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1. Introduction
In order to reduce the power-consumption of optical WDM networks, energy-aware routing strategies has been developed and sleep mode of operation has been proposed to be used in network equipment [1]. Energy-efficient routing strategies tend to pack routes in order to put lightly loaded resources into sleep mode. However, in this way vulnerability to the failures is increasing. On the contrary, survivable routing strategies aim to spread the routes among different resources. For example, in shared path protection (SPP), primary paths need to be link-disjoint as much as possible in order to increase the shareability of the backup paths.

To overcome this trade-off energy-aware survivable routing strategies are needed, in particular in case of shared path protection to also address the efficient usage of backup resources. This problem has been studied in [2] where an ILP model for energy-efficient shared backup protection is proposed aiming at minimizing both capital and operational expenditures and enabling the sleep mode of operation for the fiber links associated only with the backup paths under the assumption that wake up times is sufficiently short in case of a failure. However, since the problem is NP-complete, ILP solutions are not scalable for larger problem sizes.

Therefore in this study, an efficient heuristic for energy-aware SPP (EASPP) is developed by using separate auxiliary graphs for primary and backup path routing to encourage both shareability and energy-efficiency. A tuning parameter $T$ helping to find a compromise between capacity and power consumption is applied. To evaluate the performance of EASPP, optimum solutions for two different objectives (minimizing (1) capacity or (2) energy) are used as benchmarks obtained by solving the ILP models proposed in [2]. It is observed that EASPP achieves a good compromise between capacity and power consumption. It improves the capacity consumption compared to the minimum-energy solution while achieving significant power savings over the minimum-capacity solution.

2. Energy-Aware Shared Path Protection (EASPP)
An energy-efficient algorithm for shared path protection (EASPP) is proposed in this section which minimizes both capacity and power consumption (see Algorithm 1). It tries to pack primary paths as much as possible. In order to minimize capacity consumption, shareability among backup paths is encouraged.

Given: The physical topology consisting of set of nodes and links with geographical distances as the link weights ($G(V,E)$), the set of lightpath requests $D[i]$, maximum number of wavelengths supported on each link ($W$) and power consumption values for amplifiers and optical switches described in Table 1 as in [2].

Find: A shared-path-protected primary, backup path pair for each request; total power consumption.

Objective: Minimize both capacity and power consumption to address survivability and energy-efficiency trade-off.

As it is shown in Algorithm 1, our approach has three stages. In the first stage lightpath requests in $D[i]$ are put into ascending order from shortest to the longest distance by calculating each route independently saved in Path[i] (candidate paths vector) (steps 1-2). Second and third stages are primary and backup paths routing (steps 3-7) with the link cost assignments as shown in Table 1. Step 3 updates link weights for primary path routing. In Step 4 and 5, $k$ paths with the least power consumption are found by running Yen’s algorithm [3] on $G_E$ (step 4) and in order to compensate capacity consumption, the one with the shortest distance is selected as the primary path (step 5). Finally backup path is routed in steps 6 and 7.

Primary path routing
Primary path routing uses the auxiliary graph $G_E(V,E)$ defined in Table 1 (a). Link weights are assigned to $G_E$ considering the additional power consumption in case the request chooses the candidate link. In Table 1 (a), case (I) corresponds to insufficient resources. Case (II) defines the links used by primary paths. Since optical switching power $E_s$ is a relatively small value this weight assignment encourages primary paths to pack. Therefore in order to tune this packing behavior we used a packing parameter $T$ for case (II). For the smaller values of $T$, more packing is encouraged, hence energy minimization. In case (III), links utilized by only backup paths are assigned a big cost ($M$)
representing the maximum power consumption of amplifiers when the longest path is turned into active mode from sleep in order to separate backup routes from primary. Case (IV) defines the additional power consumption when a link is turned on and used for the first time.

**Algorithm 1: EASPP (Energy-Aware Shared Path Protection)**

<table>
<thead>
<tr>
<th>Stage 1: Initial routing</th>
<th>Stages 2: Primary path routing</th>
<th>Stages 3: Backup path routing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. for each ( i \in D )</td>
<td>2. Sort ( D[i] ) according to increasing distance along ( path[i] )</td>
<td>6. Update link weights on ( G_D(V,E) ) according to (Table 1. (b))</td>
</tr>
<tr>
<td>Find ( Path[i] ): Dijkstra(i, ( G_D) )</td>
<td>for each ( i \in D )</td>
<td>7. ( B = \text{Dijkstra}(i, G_D) )</td>
</tr>
</tbody>
</table>

**Backup path routing**

Backup path routing uses the auxiliary graph \( G_D \) which is based on distances and encourages shareability as shown in Table 1 (b). Here case (I) corresponds to insufficient resources. (II) is the case when the link is used by a primary path and backup wavelengths on that link are not shareable. In this case a penalty is applied as we need to leave room for primary paths to be packed. In case (III), in order to encourage shareability, the smallest cost is assigned to the links accommodating backup paths with shareable wavelengths. Here, link vector technique [4] is used to track shareability information on links. In case (IV), in order to separate primary and backup paths as much as possible, second priority is given to the links used by only backup paths although the wavelengths are not shareable. Case (V) represents the unutilized links which is encouraged taking the third priority.

**Table 1: Cost assignments for (a) primary and (b) backup paths routing**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Cost Assignment</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) ( C_e ) for primary path routing for ( G_p(V,E) )</td>
<td>( \infty )</td>
<td>Weight of link ( e ), ( d_e ) : Distance of link ( e ), ( a_e ) : Power consumption of amplifiers on link ( e ), ( f_e ) : Number of free wavelengths on link ( e ), ( B_e ) : Number of wavelengths in the backup pool where shared wavelengths are reserved on link ( e ), ( v_e ) : Number of backup wavelengths reserved on link ( e ) to protect primary paths passing through link ( e' ), ( M ) : Amplifier power consumption of the longest path, ( E_s ) : Optical wavelength converters and 3D MEMS switching power consumption per wavelength, ( T ) : Packing parameter</td>
</tr>
<tr>
<td>(b) ( C_e ) for backup path routing for ( G_D(V,E) )</td>
<td>( \infty )</td>
<td>if ( e \in P ) or if ( (f_e = 0 \land \exists e' \in P : v_{e'} = B_{e'}) )</td>
</tr>
<tr>
<td>( T \times E_s )</td>
<td>if ( e \in P )</td>
<td>if ( e \in P \land \text{backup W not shareable} )</td>
</tr>
<tr>
<td>( M )</td>
<td>if ( e \in (B \setminus P) )</td>
<td>if ( e \in \text{backup W shareable} )</td>
</tr>
<tr>
<td>( E_s + a_e )</td>
<td>if ( e \notin (P \cap B) )</td>
<td>if ( e \in \text{backup W not shareable} )</td>
</tr>
<tr>
<td>( d_e )</td>
<td>if ( e \notin P )</td>
<td>if ( e \notin (P \cup B) )</td>
</tr>
<tr>
<td>( e \times d_e )</td>
<td>if ( e \in (B \setminus P) )</td>
<td>if ( e \in \text{backup W shareable} )</td>
</tr>
<tr>
<td>( e \times 5 d_e )</td>
<td>if ( e \in (B \setminus P) )</td>
<td>if ( e \in \text{backup W not shareable} )</td>
</tr>
<tr>
<td>( e \times 10 d_e )</td>
<td>if ( e \in (B \setminus P) )</td>
<td>if ( e \in \text{backup W shareable} )</td>
</tr>
</tbody>
</table>

3. **Illustrative Numerical Results**

For performance evaluation, EASPP is compared with conventional energy-unaware SPP (EUSPP) approach where capacity consumption is minimized. In order to evaluate the effect of sleep mode on SPP, power consumption in EUSPP is calculated for two cases: EUSPP-S where backup resources are in sleep mode and EUSPP-NS with backup resources being active. For a fair comparison, EUSPP follows two steps approach by routing primary paths on \( G \), the distance weighted graph and backup paths on a simplified version of \( G_D \). In Table 1 (b), instead of cases (II)-(IV) just shareable and non-shareable cases are taken into account with encouraging shareability by using the same cost function applied in case (III). Moreover, performance of EASPP is compared with optimum ILP solutions for 20 connection requests in Table 2.

The network topology used in this study is the Cost 239 European Network [5] with 11 nodes and 26 bidirectional links with link distances from 180 to 1000km. Each link supports \( W=16 \) wavelengths. Connection requests are generated according to uniform distribution among source and destination nodes. Each request requires the bandwidth of a full wavelength channel operating at rate 10Gbps. Power consumption parameters are set according to [6] as follows: Optical wavelength converters and 3D MEMS switching per wavelength consumes a total \( E_s = 1.757W \) of power. Power consumed by in-line amplifiers is calculated by the formula \( a_e = E_a A_e \) where \( E_a = 9W \) (power consumption of an in-line amplifier) and \( A_e = \frac{d_e}{80km} \times 2 \) (number of in-line amplifiers on link \( e \)).

Total power \( = E_s p + \sum_{e \in P} a_e l_e \) where \( p \) denotes W links used by primary paths and \( l_e \) equals to one if link \( e \) is used by primary paths. In EASPP \( T=20 \) and \( M=306 \). The results in Fig.1-3 are obtained with \( T=20 \) which gives the best capacity and power consumption among the tested values. In order to show the impact of tuning parameter, we demonstrated the results for both \( T=1 \) and \( T=20 \) in Table 2.

Table 2 compares EASPP with the upper and lower bounds, i.e. the two ILPs where (1) capacity consumption is minimized and (2) power consumption is minimized. EASPP overcomes the capacity consumption drawback of the optimum energy case, and at the same time still has significant savings in power consumption. EASPP \( T=20 \) saves up to 53% of wavelength-links used by primary paths compared to minimum-energy ILP and up to 30% reduction of
power consumption compared to minimum-capacity ILP. When the packing parameter $T$ is tuned to 1, the energy saving increases to 46% while the capacity consumption gain decreases to 33%.

As the future work the performance will be analyzed by showing that in survivable optical networks, Intel Corporation running time is in sleep mode and therefore less number of links used by both primary and backup paths.

It can be switched into sleep mode option cannot be enabled and there will be no gain in terms of power consumption. By taking into consideration energy-efficiency in the routing phase, EASPP performs much better than energy unaware approaches even at the moderate traffic load, and saves up to 30% and 52% power compared to EUSPP-S and EUSPP-NS respectively.

Fig. 2 shows the wavelength-link usage by primary and backup paths as a function of number of connection requests in energy-aware and unaware approaches. In order to gain in power consumption, we need to trade capacity consumption. EASPP packs primary paths as much as possible which can lead to taking longer paths. In order to gain in energy, EASPP trades up to 20% and 24% of primary and backup wavelength usage over EUSPP. Number of links utilized by only primary paths (P), both primary and backup paths (P∩B) and only backup paths (B) is shown in Fig. 3 for EASPP and in Fig. 4 for EUSPP, respectively. Note that only and only links ∈BP can be switched into the sleep mode. Therefore, in EASPP packing primary paths results in having more links in sleep mode and therefore less number of links used by both primary and backup paths. It is worth noting that EASPP running time is 1 seconds under a personal computer running Windows 7 OS with 2 GB of installed memory and Intel Core 2 Duo CPU clocked at 1.80 GHz for 200 connection requests while ILP model is not scalable for the same amount of demands.

**4. Conclusion**

In this study the trade-off between capacity and power consumption in survivable optical networks is addressed and an efficient algorithm is developed for SPP to minimize both power and capacity consumption, introducing a tuning parameter $T$ to find a compromise. The results of energy-aware approach are compared with the optimum solutions of ILPs for minimum-energy and minimum-capacity cases as benchmarking and with a conventional EUSPP. It is shown that EASPP achieves up to 52% power saving over EUSPP-NS with a small trade in capacity consumption. As the future work the performance will be analyzed by using different network topologies.

**References**