Upgrading Links with Ultra-Low Loss Fibers in a Survivable Elastic Optical Network

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ABSTRACT
The lifespan of a fiber cable is generally limited, typically 20 ~ 25 years. It is foreseen that there will be a large number of fiber cables expired and requiring to be upgraded in the near future since many fiber cables were deployed in the last century. Ultra-low loss (ULL) fibers promise enhanced transmission performance, which has been considered as an important candidate for replacing old standard single mode fibers (SSMFs). However, upgrading all the fibers in a network in one go will not only be prohibitively costly but will also be difficult to undertake because of the usually limited labor resources. Network operators are expected to upgrade only a partial set of network links at a time, in order to change over progressively to ULL fibers. Thus, how to upgrade network links with ULL fibers efficiently is important to investigate. In this paper, we address this problem for a survivable elastic optical network (EON). We consider three different fiber upgrading strategies – random, physical length based (PL), and least cost based (LC) strategies. We consider the routing, modulation format, and spectrum assignment (RMSA) problem for an EON with partially upgraded fiber links, aiming to minimize the number of frequency slots (FSs) used. The RMSA problem is formulated as a mixed integer linear programming (MILP) model. And also for handling large-size networks, a spectrum window plane (SWP) based heuristic algorithm is developed to incorporate the steps of ULL fiber upgradation and RMSA. Studies show that the number of FSs used decreases when the total link distance replaced increases, and a ULL fiber with a 0.168-dB/km attenuation coefficient is sufficient to achieve good performance and further reducing the coefficient would not bring much performance improvement.

Keywords: elastic optical network, ultra-low loss fiber, 1+1 path protection, RMSA.

1. INTRODUCTION
The lifespan of a fiber cable is generally limited, typically 20~25 years. Thus, it is foreseen that there will be a large number of fiber cables expired and requiring to be upgraded in the near future since many fiber cables were deployed in the last century. Ultra-low loss (ULL) fibers [1] promise enhanced transmission performance, which has been considered as an important candidate for replacing old standard single mode fibers (SSMFs). Today, ULL fibers such as SMF-28® ULL fiber from Corning [2] and FarbandTM® Ultra fiber from Changfei [3] have been commercially available. However, upgrading all the fibers in a network in one go will not only be prohibitively costly but will also be difficult to undertake because of the usually limited labor resources. Network operators are expected to upgrade only a partial set of network links at a time, in order to change over progressively to ULL fibers. Thus, how to upgrade network links with ULL fibers efficiently is important to investigate. Though there are many existing works on ULL fiber fabrication [6] and on the routing, modulation, and spectrum assignment (RMSA) problem in an EON, little effort (except [7]) has been made for the ULL fiber upgradation strategy in an EON. In this paper, we specifically consider ULL fiber upgradation in an EON with 1+1 path protection. We consider three fiber upgradation strategies, including the random, physical length (PL), and least cost (LC) strategies. We also develop a path-arc based mixed integer linear programming (MILP) model, aiming to minimize the maximum number of FSs used. For large-size networks, an SWP-based heuristic algorithm has also been proposed for faster computation. Simulation results show the efficiency of the proposed LC fiber upgradation strategy and the SWP-based heuristic algorithm.

2. RMSA AND ULL FIBER UPGRADATION
(1) Routing, Modulation Format, and Spectrum Assignment: RMSA is to find a route for lightpath establishment and to assign the modulation format and spectrum for the lightpath. We use the network example shown in Fig. 1 to illustrate this problem. Assume that there are four traffic demands in the network, including (A-B, 160 Gb/s), (A-C, 180 Gb/s), (B-C, 100 Gb/s), and (C-D, 170 Gb/s). The routes of the demands are A-B, A-C, B-C, and C-D, respectively. According to their individual OSNRs, we assign the most efficient modulation format or each of the channels based on the OSNR thresholds in Table 1. For example, the OSNR of lightpath A-B is 19 dB, which meets the OSNR threshold required by the modulation formats of QPSK and BPSK. For better spectrum efficiency, we assign QPSK to the channel, which requires 4 FSs to fully serve the
traffic demand. Similarly, for lightpaths A-C, B-C, and C-D, we should assign the modulation formats of QPSK and BPSK, respectively.

Table 1. FS capacities and OSNR thresholds of four modulation formats [7].

<table>
<thead>
<tr>
<th>Modulation Format</th>
<th>FS Capacity (Gb/s)</th>
<th>OSNR Threshold (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>25</td>
<td>14.03</td>
</tr>
<tr>
<td>QPSK</td>
<td>50</td>
<td>17.01</td>
</tr>
<tr>
<td>8-QAM</td>
<td>75</td>
<td>20.37</td>
</tr>
<tr>
<td>16-QAM</td>
<td>100</td>
<td>22.4</td>
</tr>
</tbody>
</table>

Figure 1. Example of routing, modulation format, and spectrum assignment.

(2) ULL Fiber Upgradation in EONs: For a larger-size network, it is not realistic to upgrade all the network links with ULL fibers. Thus, efficient strategies are needed to guide the ULL fiber upgradation (UFU). Based on the RSMA in Fig. 1, Fig. 2 shows an example on how different ULL fiber upgradations can affect the spectrum utilization of a network. We consider the case \{X, Y\} where two fiber links X and Y are to be upgraded. Figure 2 compares the two upgradation scenarios, i.e., \{A-B, A-C\} and \{B-C, B-D\}.

Figure 2(a) shows the scenario of upgrading links A-B and A-C. After the upgradation, optical channels (A-B) and (A-C) can use more efficient modulation formats, i.e., 8-QAM and 16-QAM, which corresponds to smaller number of FSs required on links A-B and A-C. However, for the entire network, the maximum number of FSs used is still 11 because there is no reduction of FS usage on link B-C. In contrast, if links B-D and B-C are upgraded [as shown in Fig. 2(b)], the number of FSs used can be reduced to 6, which corresponds to more than 45% spectrum resource reduction. This example illustrates the importance of an efficient ULL fiber upgradation strategy for improving spectrum resource utilization when such upgradations are planned.

3. ULL FIBER UPGRADATION FOR SURVIVABLE ELASTIC OPTICAL NETWORKS

(1) Problem Statement: We aim to find optimal ULL fiber upgradation for an EON considering 1+1 path protection. This optimization problem is defined as follows. Consider a network topology denoted as \( G_p = (N, L) \), where \( N \) is the set of network nodes and \( L \) is the set of network links. A static traffic demand matrix denoted as \( [\lambda_{sd}] \) is also given where each element is the traffic demand in units of Gb/s between node pair \((s, d)\). The set of candidate routes for lightpath establishment between the node pair is assumed to be pre-calculated by the link-disjoint k-shortest path (KSP) algorithm. The shortest one is used for establishing a working lightpath, and the others are used for establishing its corresponding protection lightpath. OSNR is calculated for each path with the assumption of EDFA placement as in [8]. The constraints for the optimization problem are: (1) All of the traffic demands between the node pairs must be served. (2) The spectrum assignment is subject to the constraints of spectrum contiguity and spectrum continuity and, moreover, all the lightpaths that share a common link should not use the same FSs. (3) To assign a modulation format to a lightpath, its OSNR must meet the OSNR threshold required by the modulation format. (4) For network protection, the protection lightpath requires dedicated spare capacity. (5) The total distance of upgraded fiber links is limited. The problem aims to minimize the maximum number FSs used when a certain percentage of links (measured in distance) is upgraded with ULL fibers.

(2) MILP Model: We develop a path-arc based MILP model to formulate the above problem, in which the UFU and RMSA problems are jointly solved. The sets, parameters, and variables of the model are as follows. \( L \) is the set of network links, \( R \) is the set of node pairs. \( B_r \) is the set of backup path between node pair \( r, r \in R \). \( M \) is the set of modulation formats, including BPSK, QPSK, 8-QAM, and 16-QAM. \( \epsilon_{r} \) = 1 when the working lightpaths between node pair \( r \) and node pair \( t \) share a common link; 0, otherwise. \( f_{d} \) is the number of FSs required for
establishing lightpaths between node pair \( r \) when modulation format \( m \) is used. This is calculated as the traffic demand between the node pair divided by the spectral efficiency of the modulation format. \( OSNR_{rec}^{m} \) is the reciprocal of the OSNR threshold required for establishing an optical channel with modulation format \( m \). \( \gamma_{1}^{r} = 1 \) when the working lightpath between node pair \( r \) traverses link \( l \), 0, otherwise. \( \delta_{b,a}^{r} = 1 \) when the backup path \( b \) of node pair \( r \) traverses link \( l \), 0, otherwise. \( \theta_{b,a}^{r} = 1 \) when working route of node pair \( r \) and backup path \( a \) of node pair \( r \) share a common link; 0, otherwise. \( \sigma_{b,r}^{a} = 1 \) when backup path \( a \) of node pair \( r \) and backup path \( b \) of node pair \( r \) share a common link; 0, otherwise. \( OSNR_{rec}^{b,a} \) is the reciprocal of the ONSR value contributed by link \( l \) if it is an SSMF. Note that this OSNR is a linear value. \( OSNR_{rec}^{b} \) is the reciprocal of the ONSR value contributed by link \( l \) if it is a ULL fiber. \( \eta \) is the distance of link \( l \) (in km). \( Q \) is the percentage of upgraded ULL fiber distance in the entire network, which is defined as the ratio of the total distance of the links upgraded with ULL fibers to that of all the links in the network. \( \mathcal{V} \) is a large value.

The variables are defined as follows. \( S_{t}^{r} \) is an integer variable denoting the starting index of FSs assigned to the working lightpath between node pair \( r \). \( e_{l}^{r} \) is an integer variable denoting the starting index of FSs assigned to the backup path \( b \) of node pair \( r \). \( \rho_{b}^{r} \) is a binary variable that equals 1 if backup path \( b \) of node pair \( r \) is chosen for establishing a protection lightpath; 0, otherwise. \( \chi_{l}^{r} \) is a binary variable that equals 1 when the starting index of FSs assigned to the working lightpath between node pair \( r \) is larger than that of node pair \( t \), i.e., \( S_{t}^{r} > S_{t}^{a} \). \( y_{r,a}^{l} \) is a binary variable that equals 1 when the starting index of FSs assigned to the working lightpath between node pair \( r \) is larger than the protection lightpath \( a \) of node pair \( t \), i.e., \( S_{t}^{r} > e_{l}^{r} \). \( \phi_{b,r}^{a} \) is a binary variable that equals 1 when the starting FS index of protection lightpath \( b \) between node pair \( r \) is larger than that of protection lightpath \( a \) between node pair \( t \), i.e., \( e_{l}^{b} > e_{l}^{a} \). \( \lambda_{l}^{m} \) denotes the reciprocal of the OSNR value of the working lightpath between node pair \( r \). \( OSNR_{rec}^{b,a} \) denotes the reciprocal of the OSNR value of the protection lightpath between node pair \( r \) if it is established on backup path \( b \). \( \delta_{l}^{m} \) is a binary variable that equals 1 when modulation format \( m \) is used for the working lightpath between node pair \( r \); 0, otherwise. \( \zeta_{l}^{m} \) is a binary variable that equals 1 when modulation format \( m \) is used for the protection lightpath between node pair \( r \); 0, otherwise. \( \tau_{l} \) is a binary parameter that equals 1 if the network link \( l \) is upgraded with a ULL fiber; 0, otherwise. \( F_{r}^{p} \) is the number of FSs required for the working lightpath between node pair \( r \). \( P_{r}^{f} \) is the number of FSs required for the protection lightpath between node pair \( r \). \( C \) is the maximum index of FSs used in the network.

**Objective**: Minimize \( C \), aiming to minimize the maximum number of FSs used in the entire network when a certain percentage of fiber links (in distance) are upgraded with ULL fibers. This is subject to the following constraints. (1) ensures that the maximum index of FSs used in the whole network is greater than the ending FS index of the working lightpath between any node pair. (2) ensures that sufficient FSs are assigned to a working lightpath so as to accommodate all the traffic demand between the node pair. (3) and (4) ensure that the allocated spectra for the working lightpaths between different node pairs do not overlap on any of their common links (if there are any). (5) calculates the OSNR value for the working lightpath between each node pair after the upgradation of ULL fibers. (6) ensures that each established working lightpath meets the OSNR threshold required by the selected modulation format. (7) ensures that there is only one modulation format selected for the working lightpath between each node pair. (8) ensures that the percentage of upgraded ULL fibers in the network is no greater than the percentage \( Q \).

For establishing working lightpaths, we have the following constraints. (9) ensures that the maximum index of FSs used in the whole network is greater than the ending FS index of the protection lightpath between any node pair. (10) ensures that there is only one protection path selected for establishing the protection lightpath.
between any node pair. (11) means that a backup path between any node pair can be assigned with a starting FS index only if it is selected for establishing a protection lightpath. (12) corresponds to (2) for the protection lightpath, which ensures that sufficient FSs are assigned to accommodate all the traffic demand between the node pair. (13)-(15) ensure that the working and protection lightpaths between any node pairs do not overlap on any of their common links (if there are any). (16) and (17) ensure that the allocated spectra for protection lightpaths between different node pairs do not overlap on any of their common links. (18) calculates the OSNR value for the protection lightpath between each node pair after the ULL fiber upgradation. (19) ensures that the established protection lightpath meets the OSNR threshold required by the selected modulation format. (20) guarantees that there is only one modulation format selected for establishing the protection lightpath between each node pair.

4. HEURISTIC ALGORITHMS

The MILP model can optimally solve the UFU-RMSA problem for a small network. However, its computational complexity would be high when used to solve the problem for a large network. Therefore, we also develop an efficient heuristic algorithm to solve this problem, which would be useful in large networks. Specifically, we decompose the UFU-RMSA problem into two sub-problems, i.e., the UFU and RMSA problems. For the RMSA problem, we extend the SWP-based algorithm of [9] to establish working and protection lightpaths. Due to the page limit, we do not provide the detail of this algorithm. For the UFU problem, we consider three strategies to find the set of network links to be upgraded. The first one selects the links randomly, called the random strategy. The second one selects the links based on their physical distances from the longest to the shortest, called the physical length (PL) based strategy. The third one selects the links based on a cost (defined later), called the least cost (LC) based strategy. This strategy upgrades network links with ULL fibers based on a criterion called the maximum number of FSs used in the entire network. To find the best link for the upgradation, we keep on trying to upgrade a network link, and then employing the SWP-based algorithm to find the maximum number of FSs used in the entire network. After trying all the candidate links, we choose the one with the smallest number of FSs used and upgrade it with a ULL fiber. We repeat the same process until a sufficient percentage of network links (in total distance) is upgraded.

5. TEST CONDITIONS AND PERFORMANCE ANALYSES

To evaluate the performance of the proposed heuristic algorithm, we considered two test networks: a six-node, nine-link (n6s9) network and the 24-node, 43-link USNET network. We assume that there are a maximum of 320 FSs in each fiber link and each FS has a 12.5-GHz bandwidth. The optical amplifiers on each fiber link are SMF-28® whose attenuation coefficient is 0.168 dB/km. The OSNR calculation for each lightpath has deployed at equal distances with an amplification span no greater than 80 km. The type of ULL fiber is Corning nine-link (n6s9) network and the 24-node, 43-link USNET network. We assume that there are a maximum of 320 FSs in each fiber link and each FS has a 12.5-GHz bandwidth. The optical amplifiers on each fiber link are SMF-28® whose attenuation coefficient is 0.168 dB/km. The OSNR calculation for each lightpath has deployed at equal distances with an amplification span no greater than 80 km. The type of ULL fiber is Corning nine-link (n6s9) network and the 24-node, 43-link USNET network. We assume that there are a maximum of 320 FSs in each fiber link and each FS has a 12.5-GHz bandwidth. The optical amplifiers on each fiber link are SMF-28® whose attenuation coefficient is 0.168 dB/km. The OSNR calculation for each lightpath has deployed at equal distances with an amplification span no greater than 80 km.

We can see that the maximum number of FSs used decreases with an increasing percentage of ULL upgradation. This is because the upgradation of ULL fibers can improve the OSNRs of lightpaths, which allows more efficient modulation formats to be used and therefore requires fewer FSs for each lightpath. Comparing the three fiber upgradation strategies, we see that the LC strategy requires a smaller number of FSs than the other two strategies. This is attributed to the fact the LC strategy always upgrades the links first whose upgradation will lead to the greatest decrease in FS usage in the entire network. Therefore, this will help to improve the spectrum utilization. In contrast, the random strategy chooses the links to be upgraded randomly while the PL strategy simply selects the longest links first for upgradation. Therefore, these approaches cannot ensure a global spectrum utilization improvement from the perspective of the overall network.
We also find that the heuristic algorithm using the LC strategy performs very close to the MILP model, which verifies the efficiency of the proposed algorithm. Specifically, when all the links are upgraded with ULL fibers, we see that the cases of LC_SWP, Random_SWP, and PL_SWP all perform close to the MILP model, which verifies the efficiency of the SWP-based algorithm since all the upgradation strategies have the same set of ULL fiber links. Note that in Fig. 3(a), the MILP model cannot find an optimal solution for the n6s9 network with 20% ULL fiber upgradation when $X = 1000$ Gb/s.

| Table 2. Number of links upgraded with the different approaches. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | MILP_n6s9 | Random_n6s9 | PL_n6s9 | LC_n6s9 | MILP_USNET | Random_USNET | PL_USNET | LC_USNET |
| 20%             | 2         | 2            | 10       | 1       | 2          | 8            |
| 40%             | 3         | 4            | 20       | 3       | 12         | 15           |
| 60%             | 5         | 5            | 27       | 4       | 21         | 22           |
| 80%             | 7         | 7            | 36       | 6       | 30         | 33           |
| 100%            | 9         | 9            | 43       | 9       | 43         | 43           |

![Figure 3. Performance comparison of different approaches.](image)

![Figure 4. Impact of attenuation coefficients.](image)

Under the assumption that all the fibers are upgraded, Fig. 4 shows how the attenuation coefficients impact the maximum number of FSs used in the n6s9 and USNET networks. We find that the maximum number of FSs used increases with an increasing attenuation coefficient in both of the networks. It is interesting to see a saturation phenomenon, i.e., when the attenuation coefficient is lower than 0.168 dB/km, decreasing it further does not lead to a significant reduction of the maximum number of FSs used. This observation implies that, the ULL fiber with 0.168 dB/km would be efficient enough to achieve a good spectrum utilization.

6. CONCLUSIONS

We studied the ULL fiber upgradation problem for an EON with 1+1 path protection. We considered the random, PL, and LC fiber upgradation strategies and evaluated their efficiency by solving the RMSA problem with upgraded fiber links. An MILP model and an SWP-based heuristic algorithm were also developed for the above problem. Simulation results showed that the LC strategy performs better than the PL and random strategies and is almost as efficient as the MILP model from the perspectives of number of links upgraded and the maximum number of FSs used in the entire network. Results also show that an attenuation coefficient of 0.168 dB/km is sufficient to achieve an efficient spectrum utilization for an EON.

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