Efficient multicasting technique for elastic optical network

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Abstract
The elastic optical network (EON) is the latest solution to increase the capacity of optical networks, as a response to the ever-increasing demand for traffic. To meet the EON mission, new algorithms and frameworks need to be designed. In this paper, a new algorithm based on EON is proposed that employs a subtree-based scheme to establish multicast transmissions. To solve the problems of routing, modulation level and spectrum allocation, the primary problem of EON with regard to resource allocation under wavelength continuity and wavelength contiguity constraints, as well as distance adaptive transmission, the proposed algorithm solves each subproblem by considering the existence of a solution for other subproblems. The authors take into account the effects of splitting the transient light at the intermediary nodes on the signal-to-noise ratio to enhance the accuracy of the resource allocation. The proposed scheme is extensively examined under different networks and compared with the existing multicasting benchmark. The simulation results show that the proposed scheme considerably increases the network capacity without placing any burden on the network.

1 | INTRODUCTION
The ever-increasing demand for data traffic along with users' demand for higher quality services, which are the needs of emerging applications such as the Internet of Things, social media application and video streaming, has led to new research to increase the capacity of the networks [1–5]. The elastic optical network (EON) is one of the major solutions to cope with this problem by embracing the new traffic characteristics [1]. Compared to its predecessor, wavelength division multiplexing (WDM), EON enjoys finer channel spacing. This feature enables the allocation of the spectrum to demands with variable spectrum needs without having to waste a portion of a large channel spectrum, as in the WDM standard [2]. Furthermore, unlike WDM, EONs allow flexible and dynamic selection of the modulation formats. This feature allows more efficient usage of the spectrum by allocation of more spectrally efficient modulation formats when the quality of signal does not undergo any serious physical impairment along its path. This feature, called distance adaptive transmission, is one of the key differences between EON and DWM [3,4]. At the same time, these flexibilities in EON add to the complexity of resource allocation: in order to fully define the resource allocation in EON, the links, spectrum range and modulation format of the signal at the transmitter, all need to be determined. This problem in EON is called routing, modulation level and spectrum allocation (RMSA). Solving this problem is subject to a few major constraints arising from the nature of the optical networks or flexibilities introduced by EON. First, the signal travelling from a source to a destination in EON will undergo optical/electrical conversion in no intermediary node (i.e. will remain in the optical domain along the path). As a result, the spectrum of the signal remains unchanged during this travel. This constraint is known as the wavelength continuity constraint. Another major constraint is called the wavelength contiguity: to send a signal that requires more than one frequency slice, EON basically distributes the bitrate over adjacent channels using the orthogonal frequency division multiplexing (OFDM) technique. This technique eliminates the need to allocate an extra guard band for each channel compared with the case where the required bandwidth between the source and destination is provided through a signal with separate bandwidths. Looking at this key feature of EON from the aspect of resource allocation, it means that to provide a signal that requires more than one slice, the slices must be guaranteed to be adjacent [6–8].
In many data transmission demands, it is required to create a connection between one node as the source and multiple nodes as destinations, known as multicast transmission [13–25].
There are many application cases in which multicasting is common or preferred over the point-to-point transmission, known as unicast transmission. The basic method for multicasting is to create separate light paths between the source and individual destinations. Although simple, it is not resource efficient because normally some destinations are close to each other and the signal can be split, somewhere close to the destination nodes, and sent to individual nodes instead of sending individual signals. This idea was the root of the well-known structure for multicasting known as the tree structure in which one tree-like structure is formed where the source is the root and the destinations are the leaves, and usually the allocated spectrum is contiguous in each link and uniform across the tree links [13]. Although more efficient than the previous method, this method has some serious drawbacks. Some of these drawbacks are inherent in the topology while others are particularly because of the characteristics of EON, which makes it essential to investigate for a more effective solution that removes or mitigates these drawbacks: for a demand in which the destinations are far from each other/the source, a typical case in multicasting, meeting wavelength continuity and contiguity is difficult because of the severe frequency defragmentation in EON networks. As a result, such demands are rejected, regardless of the resource efficiency of the tree structure. In other words, to solve RMSA, each framework should not only be resource saving, but should also consider the ease or the possibility of the resource allocation. The second inefficacy is that the signals that are sent to closer destinations have the same modulation format that is necessary for the other destinations. In EON, unlike other standards, closer destinations can take fewer spectrums per link to be served using DAT technique. Finally, the light travelling in optical networks remains in optical domain; therefore, the light power drops, when splitting the light in an intermediary node to send to different branches, and, hence, to provide signal with acceptable signal-to-noise ratio (SNR) at the destinations, only less spectrally efficient modulation formats can be employed.

A third solution, for example, [21], attempts to remove the above-mentioned scalability and efficiency problems. In this technique, usually different subsets of destinations are served separately through smaller independent trees which may use different links, spectrum, or both from each other. To illustrate its advantages, consider Figure 1. Assume that a demand to send a data from a source to several destinations is supposed to be provisioned through the links as shown in the Figure 1a, and Figure 1b shows the availability of the spectrum over the links in blanks white. Let’s also assume that five slices per link are required to serve these destinations. Then, the total spectrum usage of the tree would be 30. The resources for such a tree cannot be allocated because there are no five continuous frequency slices on the links. Thus, the demand is rejected. Now, consider a second solution: assume that one subtree is used to serve the destinations d1 and another subtree is used to serve the destinations d2 and d3 as in Figure 1c. In the blue subtree, there is one less light splitting compared to Figure 1a, and for the green subtree, there is no light splitting and the destination is very close to the source, hence, for which an efficient modulation format can be used. Let’s assume that, as a result, the number of required slices per link, now, is 4 and 2 for the blue and the green subtree, respectively. The subtrees can now be established through different spectrum ranges as in Figure 1d. Also, their spectrum usage is 20 for the blue subtree and 8 for the green subtree, totalling 24 for this demand.

**FIGURE 1** Light-tree multicasting and its alternative
Therefore, compared to the tree structure, this structure allows the allocation of the resources and provides resource savings.

In the context of EONs, few works have studied subtree-based RMSA multicasting, with different assumptions of the network data traffic or system models. In this paper, a new subtree-based model is proposed to optimise the network capacity. As stated above, to provide a certain efficiency of networks, the authors take into account power-loss effects resulting from splitting of the light at the nodes required for multicasting.

The solutions of the RMSA problem are usually either based on integer linear programming (ILP) or algorithms. ILPs provide the optimal solution using the network and model assumptions. However, because of the high complexity of the RMSA problem, they are slow and more useful for use in network planning. For dynamic scenarios where an immediate response (i.e., immediate resource allocation) is desired on the arrival of the demands, a quick solution is needed. In this paper, an algorithm is provided for the dynamic scenario. The ILP-based solution is not studied here.

The rest of this paper is organised as follows. Section 2 reviews the related research work. Section 3 presents the proposed algorithm. In Section 4, the provided algorithm is tested and the results are examined. Finally, Section 5 concludes the paper.

2 RELATED WORK

Several works have been recently proposed in the EON context using different network models or objectives than that considered here. For example, in [9], an efficient genetic algorithm (GA) based in conjunction with an ILP-based optimization is proposed for EON. However, they address unicast communication, as opposed to multicast transmission, studied in this paper. In another work, [10], the authors present a genetic-based algorithm to solve RMSA under hybrid communications. Another research in the context of multicasting in EON proposes a flow aggregation model to delete invalid links and hence alleviates spectrum redundancy [11].

Many works have been done on multicast provisioning that are based on DWM networks, for example, [13–15]. However, for EON networks, they may be neither applicable nor efficient, because of the different characteristics of the EONs. The authors in [13] provided two light-tree schemes and compared them with the light-path technique for multicast IP traffic in WDM networks and concluded that the tree schemes had less call-blocking probability. A research group in [14] provides a dynamic grooming algorithm for multicast networking that supports multi-hop traffic grooming. They developed this algorithm to address multicast traffic grooming in WDM networks. They showed that their technique has better performance than light-path multicasting. The authors in [15] addressed the problem of multicast provisioning in mixed-line-rate WDM optical networks to satisfy the quality of transmission. They demonstrated that their proposed methods provide efficient multicasting for small- and medium-sized networks.

In the context of EON, the authors of [16–19, 27, 28] have addressed the RMSA solution for multicast routing in EON, which is primarily based on tree structure formation topologies. In [16], the authors provide an ILP-based solution and an algorithm solution for static and dynamic scenarios and show that their method is efficient; they also take into account the limitation considered for splitting degree on the nodes. In [17], a research group studied different topologies for multicasting in EONs using ILP and algorithms. They showed that their tree-based algorithm is more efficient than individually serving the destinations. The research group in [18] designed a GA for all optical multicasting, and by comparison, they showed that it outperforms conventional solutions in which the shortest path tree is utilised. Walkowiak et al. [19] introduced new tree-based models by ILP formulation and algorithms and demonstrated their efficiencies by comparison with other works.

Some recent research works have studied multicasting using subtree-based topologies [20–23]. In [20], the authors provide an ILP-based multicasting as well as an algorithm. They show that the formed subtree models are more efficient than tree-based models. The problem considered in their work, however, was routing and spectrum allocation. In other words, they did not take into account modulation-level selection, which is one of the key features of EONs. In [21], the authors developed subtree-based multicasting, based on the assumption that the data source in each demand is more than one node and each subtree formed by their models covers a subset of destination roots in a different source node. They provide ILP models as well as an algorithm for their work. Another research in [22] employs light forests based on rate-less network coding. Their proposed technique attempts to decrease defragmentation that is inherent in optical networks, especially by allowing the spectrum discontinuity for different subtrees. Another research group addresses subtree-based multicasting in [23]. They provide different solutions and they show that the provided solutions are streamlined. However, in their models, the effect of splitting light on the SNR of the signal has not been taken into account. The authors in [24] present a multicasting model to enhance efficiency by providing the flexibility to separate public services from private/secure services. The same group in [25] proposes a multicast flow aggregation scheme which is based on non-equal granularity light tree with the objective of reducing the spectrum efficiency for a variety of applications.

3 PROPOSED SCHEME

3.1 Network model

In this paper, a network is considered where bidirectional fibre links have been used to connect different nodes. Uniform channel spacing has been used with the central wavelength spacing of 12.5 GHz. The total frequency channels are 40 per link, each of which is referred to as a frequency slice or slice. At the node level, optical bypass is assumed for any data that is either
not rooted or not destined at the node. In other words, it is assumed that the light remains in the optical domain from the source to the destinations. Demands can arrive at the network at any time. There is no prior-to-arrival information about the demands. Upon arrival, a demand is represented as \(r(\text{src}, D, b)\), in which \(\text{src}\) is the source node, \(D\) is the set of the destination nodes, and \(b\) is the required bitrate. For each demand, the requested data rate varies from 1 to 50 Gb/s. There is no information about the duration of the demand. It is assumed that resource allocation is required immediately upon receiving the demand (i.e. it cannot be postponed) and no interruption or pause is acceptable during the data transmission. The category of demands that is usually intended to transfer bulk data, and in which delay and pause are acceptable as long as the total data is transferred before a preset time, is not considered here. It is assumed that there is a choice to dynamically select a modulation format for each signal. The modulation formats \(m\) used here are \(m = 0, 1, 2, 3\) to signify binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 8-quadrature amplitude modulation (8-QAM), and 16-QAM. It is assumed that they can support the data rate of 12.5, 25, 37.5, and 50 Gb/s per frequency slice. It is also assumed that for bitrates that require more than one slice, the allocated slices are adjacent using orthogonal frequency modulation. In either case, for each signal, one extra slice is reserved as the guard band of the signal. The distance that the signal can travel without serious physical impairment has an inverse relationship with the spectrum efficiency of the modulation format. Therefore, the proposed algorithm attempts to use a more spectrally efficient modulation format if the distance between the source and the destination allows it. For these modulation formats, the reach values in [26] are used, which were obtained by means of experiments: 5000, 2500, 1250, and 625 km for BPSK, QPSK, 8-QAM, and 16-QAM, respectively. As mentioned earlier, splitting of the light which is implemented using passive elements poses additional impairment on the signal quality. To consider this effect, a few models have been proposed in the literature. Without losing generality, the authors used the model as follows [27, 28]:

\[
\text{Reach}(n) = \frac{\text{reach}}{\log(n) + 1}
\]

where \(\text{reach}\) is the reach of a modulation format and \(\text{Reach}(n)\) is the reach of the same modulation format if it is used in a tree/subtree with \(n\) destinations. Therefore, this model further limits the reach of the modulation formats if the signal split as in multicasting and the \(\text{Reach}\) is the maximum distance that the source can have from any of the \(n\) destinations in the tree/subtree. Table 1 summarises the values for different subtree sizes. In sum, as an example for calculating the required slices for each demand, let us assume that for a subtree with three destinations and a bitrate request of 44 Gb/s, the algorithm finds that, based on the number of destinations and their distances to the source, the modulation format QPSK is the most efficient format that can be used. Then, the number of required frequency slices is 3, \([44/25]+1\), in which one slice has been added as the guard band. Also, it is assumed that a total of eight transceivers are needed to accomplish this connection. (Two transceivers at the source and two transceivers at each destination.)

### Table 1: Reach of different modulation formats

|        | \(n = 1\) | \(n = 2\) | \(n = 3\) | \(n = 4\) |
|--------|-----------|-----------|-----------|-----------|
| BPSK   | 5000      | 3842      | 3385      | 3120      |
| QPSK   | 2500      | 1920      | 1692      | 1560      |
| 8-QAM  | 1250      | 960       | 846       | 775       |
| 16-QAM | 625       | 480       | 432       | 387       |

| Abbreviations: 8-QAM, 8-quadrature amplitude modulation; 16-QAM, 16-quadrature amplitude modulation; BPSK, binary phase shift keying; QPSK, quadrature phase shift keying. |

### 3.2 Proposed multicasting algorithm

All decisions and the calculation of the paths are managed after the demand is received. The ultimate goal is that the destinations be divided between different subsets and each subset be served through one independent subtree. No frequency slice in a link can be used by more than one subtree. However, the goal is implemented through the consecutive process of the destinations.

In the proposed algorithm, several tasks are managed. To find a path between a source and one destination, the shortest path algorithm (SPA) is the primary algorithm. In the proposed algorithm, \(SPA(\text{src}, d)\) stands for the execution of SPA between a node as the source, \(\text{src}\), and another node as the destination, \(d\). The goal of SPA is to find a path that has the least total weights of the links compared with other paths. The authors take advantage of this algorithm to choose the paths that require the least resources to be allocated, including the links and frequency slices. Different metrics will be used as the weights of the links in this algorithm. The physical length of a link is referred to as \(cst1\) and \(cst2\), which is defined similar to [16], based on the link physical length and the spectrum usage of the link as follows:

\[
cst2 = \frac{\text{length}}{\max(\text{length})} + \beta \sum_{k} \frac{k}{|S|}
\]

where the first term is the normalised length of the link, \(\beta\) is a tuning coefficient and the summation calculates the fraction of the frequency slices in the link that are in use. In the summation, the binary variable \(k\) is 1, if the frequency slice \(s\) is in use and \(|S|\) is the set of all frequency slices within the link. The goal of the first term is to find shorter routes and, hence, be able to use more efficient modulation formats. The second term tries to avoid the selection of the links that are already heavily in use. Therefore, this cost definition aims at efficient resource usage and at the same time avoids bottleneck as well as uniform distribution of the resource allocation.
Figure 2 shows the proposed algorithm. First, in lines 1–7, destinations are sorted based on their distances to the source. For this, $SPA(src, d)$ is executed, in line 3, for which the weight of each link is $cst1$. In line 7, all destinations are sorted: the farthest destination is named $d_1$, the closest $d_N$. The number of destinations; and the remaining are indexed accordingly. In line 8, the weights of the links are changed to $cst2$. Then, in lines 10–35, the routing, modulation level, and spectrum allocation are consecutively performed for individual destinations: in line 11, $SPA(src, d)$ is executed to find the path between the source and the destination. In line 12, the most spectrally efficient modulation format is determined based on the calculated path. In line 13, based on the maximum supported bitrate of the modulation format and the requested bitrate of the demand, the minimum required number of the frequency slices per link is calculated. In line 14, the algorithm checks whether there are available spectrum slices over the calculated path. If there is enough free spectrum, it calculates the cost of using this path, which is defined as the total number of frequency slices in each link, $f$, multiplied by the number of links of the path, $|pth|$. If there is no free spectrum, it sets the cost of the path to infinity to guarantee that this path will not be selected in the next steps. For this destination, in lines 20–22, other routes that connect the source to the destination, by joining other subtrees that have been formed prior to this destination in the demand, are found. In this step, the total cost of the joining is also calculated (the joining algorithm and the calculation of the cost shown in Figure 3 are described later). Then, in line 23, the path that requires the least resources is chosen as the final route for the destination. In lines 24–26, if there is no path with a finite cost, then any selected path will have the cost of infinity and the demand is rejected. In the case of finite cost, if the selected path is one of those created by joining a subtree, in lines 20–22, then it means that just an already existing subtree has been expanded to accommodate this path, hence the
corresponding subtree is updated in lines 31 and 32. On the contrary, if the selected path is one that was created as a separate path, in lines 12–19, then this path will be a new subtree which can be expanded while finding the best path for the succeeding destinations. The algorithm that calculates the path by joining a subtree is shown in Figure 3. In this function, first, the spectrum usage of the original subtree is calculated in line 2. Then the weights of those links of the network that are shared with the subtree are set to zero. The rest have the weights $cst2$. Then, $SPA(src, d)$ is executed in line 4 and parts of the resulting path not existing in the subtree are added to it as the new links of the subtree. For this new expanded subtree, based on its longest branch and the number of destinations, in line 6, a new modulation format is determined in line 7. Then, the spectrum usage of the new subtree is calculated, in line 8, and by subtracting it from the cost calculated, in line 2, the total cost of adding this destination is calculated, in line 10. Therefore, this cost not only includes the resources on the added links but also includes the extra spectrum usage on the original subtree links which may be required as the possible change in modulation format. The algorithm checks whether there will be enough spectrum to accommodate the new expanded tree in case it is chosen to provision destination $d$. If the free spectrum does not exist, the cost of using this tree will be set to infinity, in line 13.

In sum, this algorithm tries to find the route, by looking at the required modulation formats and the availability of the spectrum, as well as the efficiency of the paths; by selecting the paths that best serve these factors, the subtrees are formed.

The worst-case time complexity of the algorithm is $O(N^2 \times |D|^2 \times |S|)$, where $|D|$ is the number of the

![Figure 4](image1.png)

**Figure 4** (a) NSFNet and (b) US Backbone network topologies

![Figure 5](image2.png)

**Figure 5** Blocking probability and (b) transceiver usage under US backbone network with five destinations per demand
destinations per demand, \( N \) is the number of the nodes in the network, and \( |S| \) is the number of frequency slices in each link.

### 4 | NUMERICAL RESULTS

In this section, several experiments are conducted to evaluate the proposed algorithm. Specifically, the capacity of the network to serve the demands and the total transceivers that are used for each served demand are measured. In terms of practicability, the execution times of the algorithms are evaluated.

The provided results are based on numerical simulation. The MATLAB platform is used for this purpose. The machine used was a laptop with three cores, 2.4 GHz speed, and 6 GB memory. The conducted examinations are under the networks in Figure 4 known as the NSFNet and US backbone topologies. The load applied to the networks was defined as the average number of demands per time unit multiplied by the average duration of each demand. For each load, 10,000 demands are applied to the network. The distribution of the demands follows a Poisson distribution function with \( \lambda = 10 \) and the duration of the demands follows an exponential distribution function with variable \( \mu \) to set the different loads. The number of destinations in each experiment is either two or five to evaluate the behaviour of the algorithms, when the number of destinations is small and big, respectively.

| TABLE 2 | Execution time (s) |
|---------|------------------|
|          | Mean    | Var.           |
| Two destinations |
| US backbone Proposed | 0.0204  | 0.0000109     |
| C/DMRSA       | 0.0171  | 0.00000649    |
| NSFNet Proposed | 0.0196  | 0.0000067     |
| C/DMRSA       | 0.0167  | 0.0000067     |
| Five destinations |
| US Backbone Proposed | 0.04138 | 0.000041      |
| C/DMRSA       | 0.0285  | 0.0000251     |
| NSFNet Proposed | 0.05    | 0.0003839     |
| C/DMRSA       | 0.0283  | 0.0000075     |
Figure 5 shows the blocking probability and the transceiver use for the US backbone network with five destinations. As can be seen, the proposed protocol rejects less number of the demands compared with C/DMRSA. The network capacity increase of an algorithm compared with another algorithm is defined as the ratio of the loads under which both algorithms provide the same blocking probability. By this definition, as can be seen, the proposed algorithm can successfully increase the capacity from 20% to 50% at different loads compared with C/DMRSA. The transceiver usage in both algorithms generally have a declining slope because in higher loads, the demands that require a higher spectrum, because of long distances between the source and destinations or higher requested bitrate, are rejected and these will be normally the demands, too, that on average need more transceivers. This effect is more obvious for C/DMRSA because the blocking probability is higher. That justifies why the average transceivers in CDMRSA are lower when the load is higher. Figure 6 shows similar results for the case of the NSFNet network experiment.

In another experiment, the network is loaded with demands in which two destinations were considered per demand. Figure 7 shows the results of this experiment. As can be seen, the proposed algorithm shows a less blocking probability. In this test, however, the improvements are not as high as in the previous tests. In fact, one of the main disadvantages of the tree-based scheme was related to the fact that meeting wavelength continuity and contiguity in a big tree structure is difficult. Therefore, when the number of destinations is low, as in the case in this experiment, the resulted tree is also small and, hence, the above-mentioned disadvantages of the tree-based scheme are less effective.

Finally, Table 2 summarises the execution times of the proposed algorithm and C/DMRSA in different scenarios. As expected, the execution time for demands with a larger number of destinations is bigger. Both the algorithms are fast. However, the tree algorithm has a shorter execution time. It should be noted that the actual (in a real network with many powerful computers) execution time will be less considering the resource limitation had when conducting these experiments. Last but not least, these algorithms can be parallelised to further reduce the execution time.

Here, the behaviour of the algorithms is compared under two additional scenarios. First, when there is one destination per demand and the other when the number of destinations is very high. In the first case, both the proposed algorithm and the multicast model execute a single SPA algorithm using their corresponding cost functions, which means these two multicasting techniques behave identically as expected. Figure 8 shows the results of simulations for the second scenario when the number of destinations is 20 under US backbone network. As can be observed, even under very light loads, the C/DMRSA multicast protocol blocks almost all of the demands. This happens because with such a high number of destinations, (1) suggests that even by using BPSK (which has the longest reach modulation in our modulation technique pools), the distance between the source and each of the destinations must not exceed a small value (2100 km). Then, for each demand, at least one destination is further than this from the source, so the demand is simply blocked. Therefore, the difference between the blocking probabilities in this figure does not translate into the resource efficiency/inefficiency of the algorithms.

5 | CONCLUSION

A new multicasting technique is proposed to increase the resource efficiency of the multicasting as well as mitigating the spectrum defragmentation that exists in EONs. The examination of the proposed technique under real-size networks showed that it increases the capacity of the networks by 20%–35% by keeping the usage of transceivers at the same level.

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