Provisioning and Recovery in Flexible Optical Networks using Ant Colony Optimization

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***Abstract*—Artificial intelligence techniques may play a significant role in the control of elastic optical networks by offering improved performance over traditional dynamic provisioning and recovery methods. In this work, we propose a fully distributed routing algorithm based on the Ant Colony Optimization (ACO) meta-heuristics associated with crankback re-routing extensions. Simulations have demonstrated that the proposed ACO-based algorithm outperforms the fixed-alternate approach. They also demonstrate that the proposed approach achieves similar levels of bandwidth blocking probability and restorability compared to an adaptive routing algorithm that relies on the OSPF-TE routing protocol, with much lower levels of control overhead, comparable levels of setup time, and without a significant increase in the restoration time. We also evaluate the trade-offs in using a trunk reservation policy for the proposed approach.**

***Index Terms*—Ant Colony Optimization; Routing and Spectrum Assignment problem; Restoration; GMPLS control plane.**

I. INTRODUCTION

ARTIFICIAL intelligence (AI) techniques are promising candidates for the management of optical networks [1]. Indeed, carefully designed AI methods may offer improved performance over traditional dynamic provisioning techniques. Elastic Optical Networks (EONs) [2], which provides enhanced flexibility and efficiency compared to wavelength-routed optical networks, have been specially benefited from those improvements [1].

The goal of this paper is to present a fully distributed, adaptive routing algorithm for EONs based on the Ant Colony Optimization (ACO) meta-heuristics [3]. In fact, the distributed, self-organizing nature of ACO algorithms make them viable solutions for the automated resource discovery and maintenance at the control plane of optical networks [4].

Indeed, most adaptive routing algorithms [5] assume an accurate global knowledge of the network state. However, as the data traffic is becoming more dynamic, a control plane that relies on the link-state update mechanism may not have accurate information on available optical network resources without placing an enormous processing load on the network elements or without utilizing significant capacity of the control channels of the network [6].

On the contrary, in fully distributed managed networks, the route calculation and the allocation of network resources are performed in a hop-by-hop fashion [7], where each network node examines a setup request based on its local state knowledge. If the node has enough resources to meet the request, it determines the next hop on the request path. Otherwise, backtracking is used to find a new candidate path.

The motivation for the use of the ACO framework is that crankback re-routing extensions [4], [8], [9] can be incorporated into the route calculation to achieve improved backtracking, which may tackle the issues commonly attributed to fully distributed routing algorithms [7]: (i) global optimization of the network cannot be attained as routing decisions are made in isolation; and (ii) highly variable, unpredictable setup times.

In this context, the contribution of this work is the proposal of a Routing and Spectrum Assignment (RSA) algorithm based on ACO with a crankback mechanism that is suitable for both the establishment of lightpaths during the normal operation of the network and the recovering of lightpaths affected by single-link or single-node failures. Note that prior works in ACO-based RSA algorithms [10], [11] take into consideration neither the use of crankback re-routing nor the recovery of lightpaths affected by a failure.

The remainder of the paper is organized as follows. We propose the ACO-based RSA algorithm and describe the RSA algorithms used for comparison in Section II, detailing the simulations carried out for assessing them in Section III. The results obtained through simulations are shown and discussed in Section IV. Finally, in Section V, conclusions are drawn.

II. ROUTING AND SPECTRUM ASSIGNMENT (RSA) ALGORITHMS

The dynamic RSA problem can be stated as follows [1]: for each connection request that arrives in the network, a suitable route and a set of frequency slots of available spectrum in the flexible grid has to be provisioned for a lightpath between a pair of source and destination nodes. The RSA problem has two important constraints [2]. The first, which is called the continuity constraint, determines that the same set of frequency slots has to be allocated in all links traversed by the lightpath. The other one, which is called the contiguity constraint, states that the frequency slots must be contiguous

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to each other. The aim of the RSA algorithms of this work is to minimize the bandwidth blocking probability of the network.

The dynamic RSA algorithms can be off-line or adaptive. For the off-line category, the routes are calculated off-line and the network state is not used for the route or spectrum assignment algorithms. The fixed-alternate routing (FAR) [5] algorithm considers a set of fixed, previously calculated k-shortest paths and it is an example of an off-line algorithm.

On the contrary, for the adaptive category, the network state is taken into consideration by the RSA algorithm.

To obtain the network state of the optical network, one typical way is to use the link-state update mechanism of the OSPF-TE routing protocol [12]. OSPF-TE maintains at each node an identical database containing the network state information, which is called the Link State Database (LSDB).

At periodic intervals Δ, adjacent network nodes flood the network with messages containing information about their link state. These messages are called "Link State Advertisement" (LSA) and carried by OSPF-TE type "Link State Update" (LSU) packets. After all participating nodes receive the LSU packets, the LSDB is updated and routes can be calculated accordingly to the new state of the network by the RSA algorithm. For EONs, which use the notion of Frequency Slot Unit (FSU) to describe the flexible optical grid resources, LSA messages are described in [13].

An example of an adaptive algorithm for the RSA problem is Least Loaded RSA (LLRSA) [14], which has as its characteristic to perform spectrum allocation homogeneously along with the different links of the network.

In LLRSA, for each connection request, a list of the k-shortest paths between the source and destination nodes [15] are taken into account and the least-loaded route between them is the one chosen to try to fulfill this request. To determine the least-loaded route, the algorithm queries the node's LSDB for the state of all links that belong to the path of each route and calculates the number of available continuous slots throughout it, selecting the one with the largest value. Therefore, inaccuracy between the current state of the network and the state of LSDB may decrease the efficiency of the routing algorithm [16]. Once the route is determined, it is up to the RSVP-TE protocol [17] to establish the lightpath.

A. Proposed ACO-based RSA algorithm

Ant Colony Optimization is a class of AI algorithms that is inspired by the foraging behavior of natural ants [3]. AntNet [18] is an algorithm based on ACO metaheuristics whose main application is routing in telecommunication networks. Indeed, it has proved to be an effective approach for routing packets in packet-switching networks [18], being competitive with other state-of-the-art algorithms.

The original AntNet algorithm was later adapted to be used in optical networks, such as those based on wavelength routing [4] and Optical Packet Switching (OPS) technology [19], and IP-over-Optical networks [20], [21].

For elastic optical networks, we propose the use of a similar heuristic function as proposed in wavelength-routed networks [4], [21], which accounts for the instantaneous availability of frequency slot units on the link connecting to the next hop:

$$h_n = \left(\frac{s_n^a}{S}\right)^f \tag{1}$$

where s_n^a is the number of available FSUs on neighbor n, S is the total number of FSUs deployed on the link and f is a power factor for enhancing the difference in the wavelength availability among neighbor nodes.

It is worth mentioning that the process of finding good routes for the lightpaths in the network is fully distributed. Current pheromone values are used to guide the establishment of a Label-Switched Path (LSP) by the RSVP-TE signaling protocol. By using segment-based crankback re-routing extensions [4], [8], [9], a node can reissue an LSP setup to circumvent blocked resources until an alternate, feasible route is found. The number of re-routing attempts is limited at each node to mitigate the increase in setup latency and to prevent excessive network usage at the control plane.

Note that the heuristic function proposed in the equation 1 cannot capture spectrum fragmentation due to the contiguity constraint of the RSA problem. One possible solution to support the coexistence of multi-bandwidth services without incurring contiguity fragmentation is by using a Trunk Reservation (TR) policy [22] for each service type with different bandwidth demands.

B. Restoration

An important feature of the network is its survivability, which refers to the ability of the network to keep connections in operation after failures. To ensure survivability, there are two recovery methods [23], [24]: protection and restoration.

In this work, we employ restoration as the recovery mechanism. Restoration is the process of recovering connections or routes affected by a failure using the available spare capacity of the network after the occurrence of the failure.

We consider end-to-end restoration without route pre-computation [4], [23], [24]. Due to its ease of implementation, a "break-before-make" [23] scheme is used.

For the FAR algorithm, we assume that the ingress node of the failed LSP has full knowledge of the new topology after failure, whereas the LLRSA algorithm can learn the new topology state from the OSPF-TE link-state update mechanism. Note that, for ACO-based routing, after the failure notification, local crankback information is used to recover from network failure [4], which helps to mitigate the effect of obsolete paths [9].

III. SIMULATION

In order to evaluate the RSA algorithms, we use the CORONET Continental United States (CONUS) topology [6], [25]. It is a hypothetical fiber-optic backbone network developed for use in researching large-scale networks. It is composed of 75 nodes and 99 bi-directional links. The length of each link is calculated as the aerial distance between the end nodes of the link, inflated by 20% to represent terrestrial routing.

We consider a Poisson traffic with 4 service types with different bandwidth demands, where the probability of arrival for a service type is inversely proportional to the number of FSUs requested, as depicted in Table I.

TABLE I
SERVICE TYPES AND THEIR PROBABILITY OF ARRIVAL.

Number of FSUs	**Bandwidth (GHz)**	**Probability of arrival**
1	12.5	8/15
2	25	4/15
4	50	2/15
8	100	1/15

Lightpath requests are uniformly distributed between source and destination pairs. The duration of each lightpath follows an exponential distribution with a mean value of 100 s. The simulations are carried out with 320 FSUs of 12.5 GHz per link, and a First-fit approach is used for the spectrum assignment sub-problem.

We assume that the FAR and LLRSA algorithms try up to two alternate paths (2^{nd} and 3^{rd}-shortest-paths as explained in Section II). The ant approach allows for up to 2 re-routing attempts at each node when a feasible route cannot be found [4], [9]. For the TR simulations, each service type has 80 FSUs, which is proportional to the bandwidth demand.

We consider that the maximum number of hops allowed for ant or RSVP-TE messages is equal to the number of nodes of the network topology. We also consider $f = 5$. The remaining simulation parameters can be found in [4].

A. *Metrics*

The bandwidth blocking probability considers the ratio between the blocked bandwidth to the total requested bandwidth.

The communication overhead accounts for the aggregated bandwidth used by the control messages, i.e., ants and OSPF-TE messages. We assume that the ants are implemented as raw IPv4 datagrams, which are composed of a 40-byte header plus a 4-byte identifier for each node it traverses.

The OSPF-TE type LSU packet has a fixed size according to the number of neighbors of each node. Given the 320 frequency slots used in this work, each neighbor contributes a 56-byte LSA payload [13]. Thus, considering LSA, OSPF-TE, and IPv4 headers, nodes with only two neighbors generate 176 bytes, with 3 neighbors 232 bytes, and with 4 neighbors 288 bytes for each LSU packet.

The time spent in successfully establishing/restoring a lightpath is also an important metric [26]. Hence, the setup/restoration time measures the transmission time at each traversed link along with the processing time at each traversed node needed for the *Path*, *Resv*, and eventual *PathErr* messages to set up/recover a connection as described in [4], [9]. For this work, we assume that the processing time at each node can be neglected.

IV. NUMERICAL RESULTS

In the following graphs, each plotted point is the average of 10 different runs, where each run executed 10^5 requests, and the error bar indicates the 95% confidence interval.

Figure 1a shows that the bandwidth blocking probability of the adaptive algorithms, i.e., ACO and LLRSA, are much lower compared to the fixed-alternate algorithm.

For the LLRSA, the Δ interval for updating the LSDB is a very important parameter. For a value of $\Delta = 100$ s, the LSDB information may become outdated, impairing the routing performance. This indicates that Δ should be much smaller than the average duration of the lightpaths. On the contrary, the ACO-based routing seems to be less impacted by the global ant launching rate R_{ants} parameter. As a result, the LLRSA with $\Delta = 10$ s and the ACO algorithm with $R_{ants} = 1$ or 10 ant/s have very similar results.

The TR policy does not perform well until the load of 650 erlangs. For loads ≥ 650 erlangs, the TR policy outperforms the remaining algorithms. A possible explanation is that the reduction effect in trunking efficiency [27] dominates the lighter loads, whereas the elimination effect of the fragmentation due to the contiguity constraint dominates the higher loads.

The average number of hops followed by *Path* and eventual *PathErr* messages of successfully established lightpaths is shown in Figure 1b. Due to the segment re-routing of the crankback mechanism, the ACO algorithm exhibits longer paths for the route signaling compared to the FAR and LLRSA algorithms. The elimination of the fragmentation due to the contiguity constraint allows for more alternate feasible paths in the topology for the TR policy, which leads to longer paths.

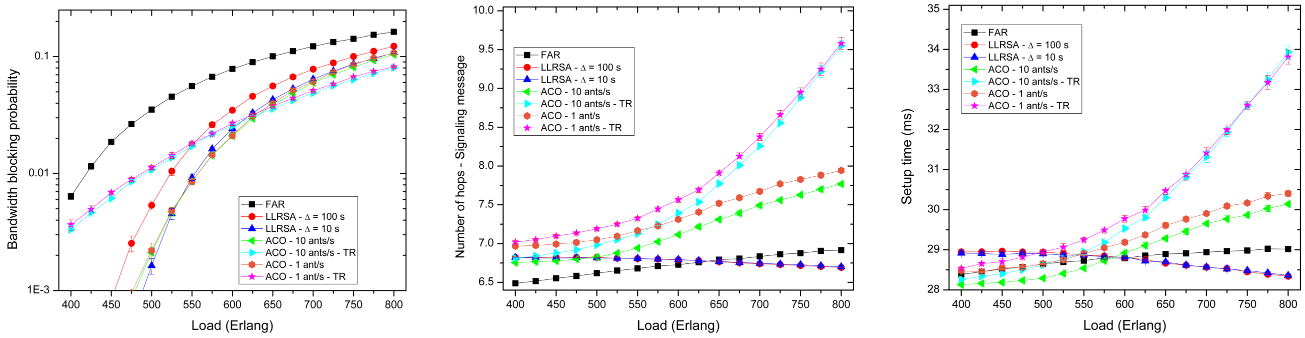
The setup time for establishing a lightpath is depicted in Figure 1c. Longer signaling paths, as observed in Figure 1b, result in longer setup times. Except for the higher loads in the TR policy, all algorithms exhibit quite similar setup times.

The communication overhead generated by the control messages at the control plane is shown in Figure 1d. Forward and backward ants are considered for the ACO algorithm, while only the LSU packet overhead without any acknowledgment packet is taken into consideration as described in Subsection III-A. The LLRSA algorithm generates much more communication overhead on the control channels than the ACO algorithm. For a similar level of overhead, the ACO algorithm with $R_{ants} = 10$ ants/s offers much better performance, in terms of bandwidth blocking probability, than the LLRSA algorithm with $\Delta = 100$ s. Note that as the FAR algorithm only use off-line information, there is no control overhead.

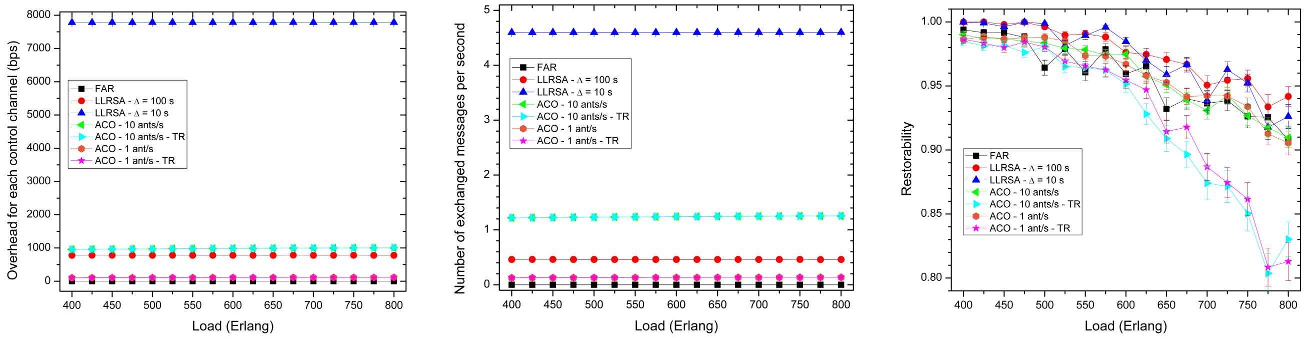
The average number of individual control messages per second exchanged between network nodes is shown in Figure 1e. The number of LSU packets exchanged by the OSPF-TE protocol is much larger than the number of ants exchanged by the ACO algorithm. Moreover, the distribution of the ants wandering in the network is very smooth, whereas the flooding mechanism of the OSPF-TE protocol works in periodic bursts of LSU packets.

In this context, we can argue that the ACO algorithm is more scalable than adaptive algorithms that rely upon a global accurate view of the network state as provided by a link-state update mechanism, such as the LLRSA algorithm.

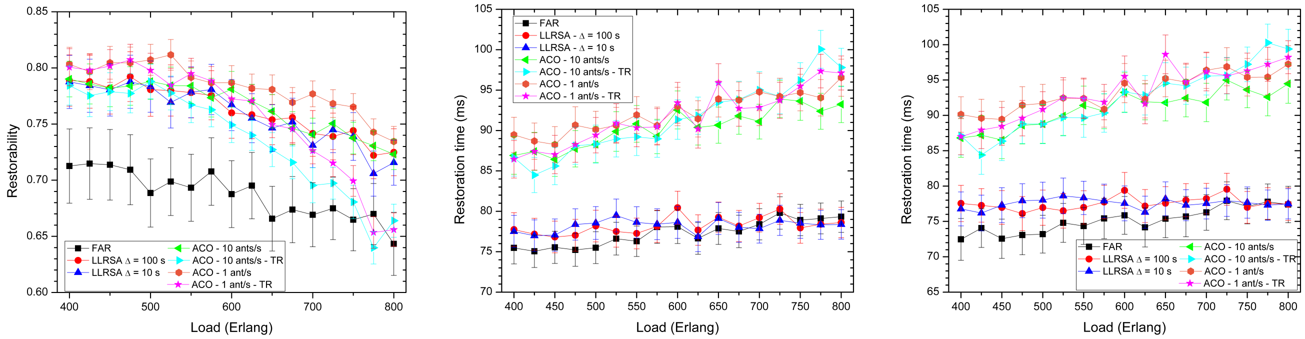
For evaluating the restorability [4] under single network failure scenarios, we consider all possible single failures in



(a) Bandwidth blocking probability. (b) Number of hops for signaling messages in the forward direction. (c) Setup time for established lightpaths.



(d) Communication overhead. (e) Number of control messages. (f) Link failure - restorability.



(g) Node failure - restorability. (h) Link failure - restoration time. (i) Node failure - restoration time.

Fig. 1. Evaluation of the RSA algorithms for the CORONET CONUS network.

four different times of the simulation to get a smaller margin of error. Each plotted point in the following graphs depicts the obtained average value and the error bar indicates the 95% confidence interval.

In Figure 1f, we can observe that all algorithms offer a similar restorability in case of single-link failures, except for the TR policy in the higher loads. For the single-node failure scenario, as shown in Figure 1g, the FAR algorithm cannot recover as many lightpaths as the adaptive algorithms. The LLRSA and the ACO algorithms have a similar restorability, except for the TR policy in higher loads.

In Figures 1h and 1i, it is shown that the ACO algorithms have restoration times that are typically from 20 to 25% higher than the FAR and LLRSA algorithms.

V. CONCLUSIONS

In this work, we propose a fully distributed, adaptive routing algorithm for the provisioning and recovery of lightpaths in EON, which is based on the ACO metaheuristics. The proposed algorithm outperforms, in terms of bandwidth blocking probability, the fixed-alternate approach. Moreover, the adaptive RSA algorithm that relies on full topology knowledge may exhibit low performance, in the case where the global network state in the database is not up-to-date, or raise scalability concerns due to the much higher quantity of routing information needed to be exchanged across the network nodes to achieve a performance equivalent to the proposed approach.

Moreover, the proposed algorithm obtains similar setup times compared to the traditional RSA algorithms, except for the higher loads when the TR policy is considered.

For the failure scenarios, the proposed ant algorithm has a similar restorability performance compared to the adaptive algorithm, except for the higher loads of the single-node failure case when the TR policy is considered. However, the proposed algorithm incurs in restoration times around 25% higher than traditional RSA algorithms.

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