Mobile routing in elastic optical networks

Ireneusz Szcześniak, Andrzej Jajszczyk, and Andrzej Pach
Department of Telecommunications
AGH University of Science and Technology
al. Mickiewicza 30
30-059 Kraków
Poland

***Abstract*—With the continuing growth of wireless high-bitrate services, the progressing integration of wireless and optical networks, and the eventual deployment of elastic optical networks, there is a need to support the mobile routing in the elastic optical networks. We propose a mobile routing algorithm which, in comparison with the two baseline routing algorithms, requires the lowest number of new links to configure when the connection is reconfigured, and achieves the highest probability of completing a connection. The performance evaluation was carried out with 1200 simulation runs.**

***Index Terms*—elastic optical networks, wireless access networks, mobile routing, flex-grid, spectrum fragmentation, mobile backhaul**

I. Introduction

The wireless access network traffic has increased manyfold in recent years and network operators are expecting its further dynamic increase which has to be serviced by the core optical network [1]. Currently, a user of the Long Term Evolution (LTE) network can download data at rates of tens of Mb/s, and the prototype LTE-Advanced networks have been demonstrated to achieve several Gb/s transmission, offering bitrates of hundreds of Mb/s for a single user.

The future optical networks are very likely to become elastic because they would utilize the limited erbium window more efficiently than the incumbent wavelength-division multiplexing (WDM) optical networks [2]. The flex-grid has now been standardized with 6.25 GHz channel spacing [3], but as the technology is deployed and further improved, we can expect smaller channel spacing in the future, supporting lower client bitrates.

Currently, the modern mobile backhaul is based on the passive optical networks (PONs) and it is unlikely to change in the near future because of the already-deployed optical distribution networks built in the tree topology specifically for PONs [4]. For the short term, a number of PON-based mobile backhaul architectures have been proposed, most notably Ethernet PON-Worldwide Interoperability for Microwave Access (EPON-WiMAX), 10 Gigabit Ethernet PON-LTE (10GEPON-LTE) or WDM-PON-LTE, but for the long term, the mobile backhaul requires a new and disruptive design in order to support the requirements of the advanced fourth generation (4G) and the fifth generation (5G) networks: high mobility, high bitrates, resiliency, and distributed control [5].

The highly-mobile high-bitrate wireless services are in the center of the research on the 5G networks. The 4G networks are reaching their bitrate limits, since elaborate modulation schemes result in modest bitrate increase. In order to offer very high bitrates, the 5G networks should have a large number of small cells (picocells or femtocells) and operate in high frequency bands, e.g. 60 GHz [6].

Mission-critical wireless services for business, the military, and the emergency services require the support for high mobility, high bitrate and minimal service disruptions. Furthermore, with demanding consumer applications, demanding consumer mobile users are likely to proliferate. The access user equipment (UE) installed in trains, trams and buses is currently proliferating. We argue that these mobile high-bitrate wireless services require the support of the elastic optical network (EON). Other services for regular users do not necessarily require this support.

Our contribution includes a novel mobile routing algorithm for elastic optical networks. We study its performance in comparison to other two mobile routing algorithms. A mobile client establishes a single bidirectional symmetric connection with a given number of subcarriers to a remote node and wants to stay connected as the client moves around. The remote node can be, for example, a gateway to a virtual private network through which the client gets secure access to various services.

We carry out the simulative performance evaluation of three routing algorithms with two policies of allocating spectrum. The metrics compared are the number of links to configure, the probability of establishing a connection, and the probability of completing a connection along with three metrics that augment the comparison. We obtained credible results by performing 1200 simulation runs.

The paper is organized as follows. In the following section we review key related works. In Section III we state the research problem, in Section IV we describe the considered solutions, and in Section VI we report the obtained performance evaluation results. Section VII concludes the article.

II. Related works

Our research results are well suited for radio-over-fiber (RoF) mobile backhaul which amalgamates the optical and wireless networks by transceiving subcarriers [7]. In [8] the authors propose a cost-effective RoF architecture which converts the 60 GHz radio subcarriers directly into the subcarriers of the optical erbium window, thus enabling the elastic optical networks to make inroads into mobile backhaul.

In [9] the authors propose the concept of the moving extended cell (MEC), which guarantees the high-bitrate connectivity for a highly mobile client by transceiving wireless signal for this client also in the picocells neighboring to the picocell in which the client currently resides. Our algorithm can be used to reconfigure quickly the high-bitrate connection when the client roams between picocells serviced by different hotels.

The research on mobile backhaul usually concentrates on PONs which integrate the wireless access network with the optical core network [4]. We concentrate on the mobile support of the EON required by the mobile backhaul, which will further gain in importance if the mobile backhaul becomes elastic.

In [10] the authors argue that the quality of service (QoS) of optical connections does not take into account the parameters of the connection setup, rerouting or tear down, such as the preemption probability, and therefore introduce the grade of service (GoS) for optical connections to address these parameters.

Our work contributes new results on the GoS of mobile routing in elastic optical networks. However, the performance of the rerouting algorithms discussed in [10] cannot be compared with the performance of the reconfiguration algorithms which we study, since in rerouting the source and destination nodes remain the same, while in reconfiguration the source node changes.

To the best of our knowledge, the mobile routing in elastic optical networks has not been studied before, and therefore we cannot compare the performance of our algorithm with some published results. For this reason in Section IV we describe two baseline algorithms used for comparison.

III. Problem statement

The elastic optical network is modeled by an undirected graph with the links having the attributes of the length and the available subcarriers. For each active client the network establishes a bidirectional unicast connection between two nodes by allocating subcarriers on undirected links. The network services a given number of clients which can be active and require connectivity or they can be idle. The details on client behavior are given in Section V.

As a client makes the transitions between network nodes, the optical network has to reconfigure the already established connection to maintain the client connectivity, because the connection has a new source node, while the remote node stays the same.

The problem is how to minimize the number of new links which require configuration in order to maintain connectivity when the client makes the transitions. We concentrate on the number of link configurations, since they require substantial time, and can cause service disruptions. In the next section we describe three algorithms for connection reconfiguration.

IV. Considered solutions

We study three algorithms for connection reconfiguration: complete, incremental, and curtailing. The complete and incremental are two baseline algorithms, and the curtailing algorithm is our novel contribution.

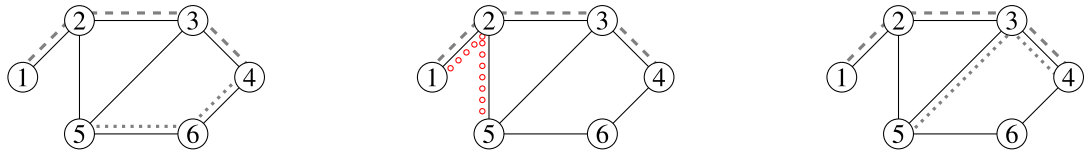
The complete reconfiguration is trivial: a new shortest-path connection is established between the new source node and the remote node. This reconfiguration requires end-to-end signaling to establish the connection anew. It is worth noting that this reconfiguration gives a chance to defragment the optical spectrum, as the connection is completely taken down and established anew with potentially different subcarriers. If the new connection uses different subcarriers than the previously established connection, all the links of the new path have to be configured. However, if the new connection uses the same subcarriers, then only the links not present in the already established connection have to be configured, thus reducing the number of the required link configurations.

The incremental reconfiguration algorithm searches for a shortest path between the new source node and the previous source node to *bridge* the already established connection with the new source node. This reconfiguration is attractive, because it reuses the already established connection, and because it does not require end-to-end signaling, but only the signaling between the new source node and the previous source node. However, this reconfiguration introduces the spectrum continuity constraint: the subcarriers of the new part of the connection have to be the same as the subcarriers of the already established connection. If no bridging path meeting the spectrum continuity constraint is found, the algorithm reverts to the complete reconfiguration.

The curtailing reconfiguration is similar to the incremental reconfiguration in that it attempts to reuse the already established connection by bridging. However, in contrast to the incremental reconfiguration, the curtailing reconfiguration does not fail at the first unsuccessful bridging attempt to the previous source node, but instead the attempts are made for all the nodes of the already established connection, including the destination node. The bridging path has to meet the spectrum continuity constraint unless the bridging is attempted to the destination node. The algorithm chooses the bridging path with the lowest number of links, curtails the established connection at the respective node, and makes the bridging. If no bridging path meeting the spectrum continuity constraint is found, the algorithm reverts to the complete reconfiguration.

Fig. 1 illustrates the main differences between the reconfiguration types. As an example we use a graph with links representing fibers of the same cost, but its exact value is irrelevant. Each of the subfigures illustrates the reconfiguration of the same connection with node 1 as the source node and node 4 as the destination node. The connection is reconfigured for the new source node 5. The connection is shown with dashed lines before the reconfiguration and with dotted lines after the reconfiguration.

As shown in Fig. 1a, the complete reconfiguration can reconfigure a connection so that no link is reused. As shown in Fig. 1b, the incremental reconfiguration fails at the bridging attempt, because the bridging path, shown with red circles, would have to use the subcarriers along the link from node 1 to node 2 already taken by the connection. Finally, as shown in Fig. 1c, the curtailing reconfiguration examines all bridging



(a) complete (b) incremental (c) curtailing

Fig. 1: Examples of reconfigurations.

paths and as a result the reconfigured connection is shorter, and yet the link between node 3 and node 4 is reused, unlike for the complete reconfiguration.

V. Simulation Setting

We generated graphs by selecting two different random end nodes for each link, so that the graph was random, loopless, and connected.

Given a node pair and a number of requested subcarriers, we search for a shortest path provided that the subcarriers are contiguous (the contiguity constraint) and that they are the same along the whole path (the continuity constraint), which in the literature is called the routing and spectrum assignment (RSA) problem. We use a constrained Dijkstra algorithm to find not only a shortest path, but also a set of all available spectrum fragments along the path. We define a spectrum fragment as a set of contiguous subcarriers. From the set of fragments found, we choose exactly the number of requested contiguous subcarriers according to one of two policies: the *first available* or the *fittest available*. In the first available policy, the subcarriers with the lowest number are chosen. In the fittest available policy, the subcarriers from the fragment with the lowest number of subcarriers are chosen which still can handle the demand.

A client can be either idle or active. The client stays idle for the number of hours that follows the exponential distribution with the mean of μ_{idle} hours. After the idle period, the client becomes active at a randomly chosen source node, and attempts to establish a shortest-path connection to a randomly chosen remote node. If the attempt fails, the client goes idle again, otherwise the client is active for the time which follows the exponential distribution with the mean of μ_{stay} hours. After this time the client makes a transition to a new source node which requires the reconfiguration of the connection. The new source node is chosen from one of the neighbors of the previous source node of the connection. If the attempt fails, the client goes idle, otherwise the client stays active for another μ_{stay} hours on average. The number of transitions the client attempts follows the Poisson distribution with the mean of λ_t, after which the client goes idle. Therefore, the client is active for the mean time of $\mu_{active} = (\lambda_t + 1)\mu_{stay}$, provided the connection is completed, i.e., all the reconfiguration requests are successful.

Furthermore, the number of subcarriers a client requests is constant throughout the duration of the connection and follows the distribution of $(Poisson(\lambda_{sc-1})+1)$ with the mean of λ_{sc}, i.e., the Poisson distribution with one added in order to avoid getting zero.

VI. Simulation Results

We carried out simulations to compare the performance of the three routing algorithms and the two spectrum allocation policies for different network loads.

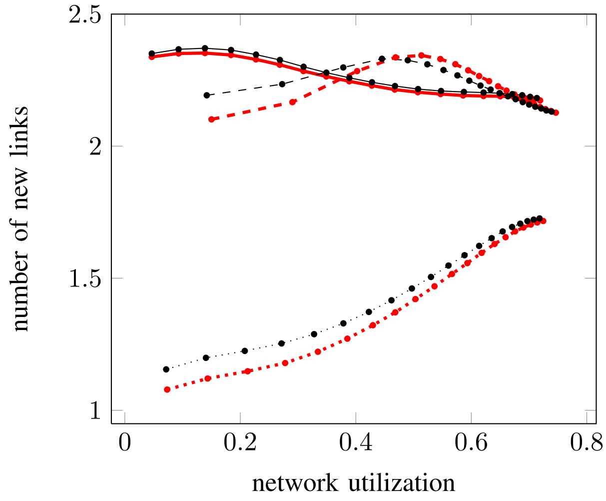
We simulated random networks with 50 nodes and 200 links, each link having 400 subcarriers dedicated to servicing mobile traffic, while the regular, background traffic could take the remaining subcarriers. The length of links was uniformly randomly distributed between 5 and 30 km to model a network of a large city, which is a plausible assumption about a future, high-capacity EON supporting a large number of high-bitrate clients over a relatively small area. In the search for shortest paths, we did not consider paths longer than 100 km. To model a client behavior in business hours, we assumed $\mu_{idle} = 16$ h, $\mu_{stay} = 1$ h, $\lambda_t = 7$, and $\lambda_{sc} = 2$.

The network load was varied by varying the number of clients from 500 to 10000 with a step of 500. We also varied the routing algorithm and the spectrum allocation policy. Therefore, there were twenty network loads, three routing algorithms, and two spectrum allocation policies varied, totaling 120 simulation configurations.

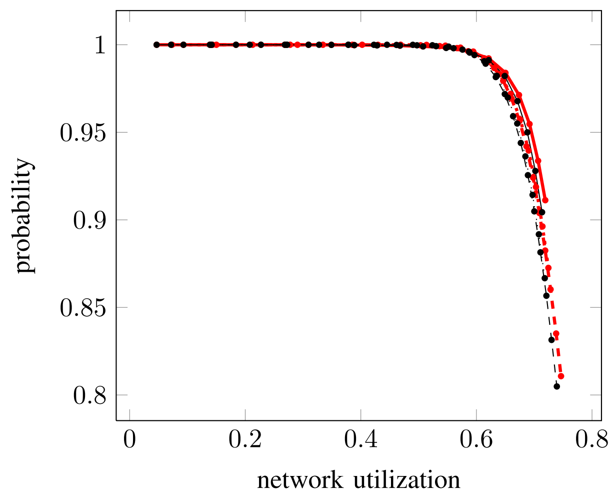
The results for the statistical population of the simulation runs with the given configuration were estimated using the results for a statistical sample of ten simulation runs with the same configuration. We carried out 1200 simulation runs, since there were 120 samples, and each sample had ten runs. While the runs in a sample have the same configuration (i.e., the same number of clients, etc.), they have different randomly-generated networks and network loads by seeding the random number generator with different values.

To calculate statistics for a sample, a number of measured values, e.g. the number of new links to configure, were gathered during a simulation run. For a simulation run, an average of a measured value was produced based on the results reported for every simulation hour. Every simulation run simulated one hundred hours of the system. We calculated the sample mean of the measured value using the averages obtained for the simulation runs in a sample. Then we calculated the relative standard error of the sample mean of the measured value. We deem the derived sample means estimate credibly the population means since the relative standard errors of the sample means were below 1%.

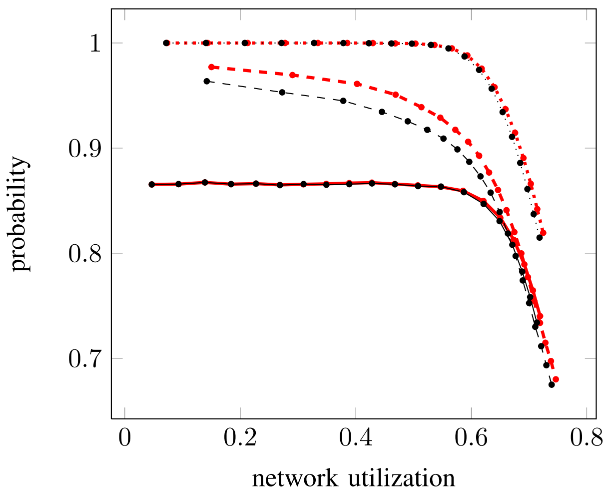
Figures 2a-2f show the sample means of the measured values as dots connected by lines. The sample means are reported as the function of network utilization, i.e., the ratio of the number of all used subcarriers to the number of subcarriers on all links. The figures do not report the standard errors as error bars, because they were too small to be drawn as the



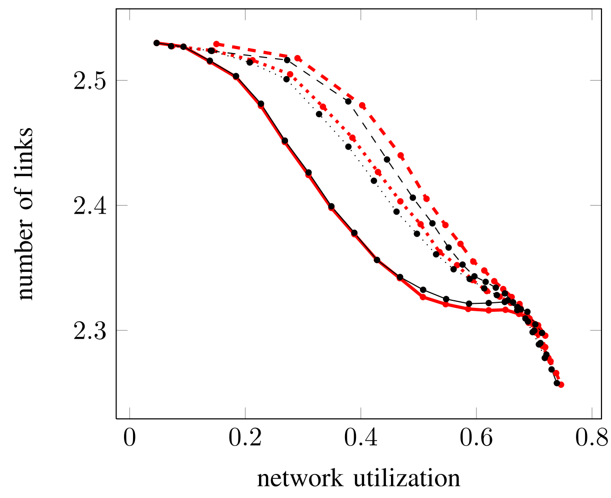
(a) The number of new links to configure.



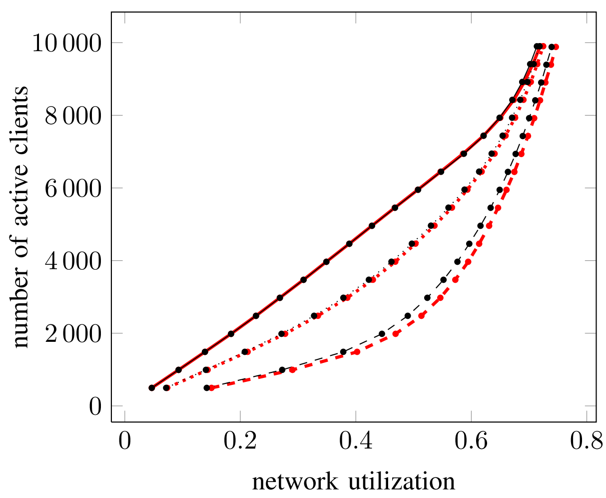
(b) The probability of establishing a connection.



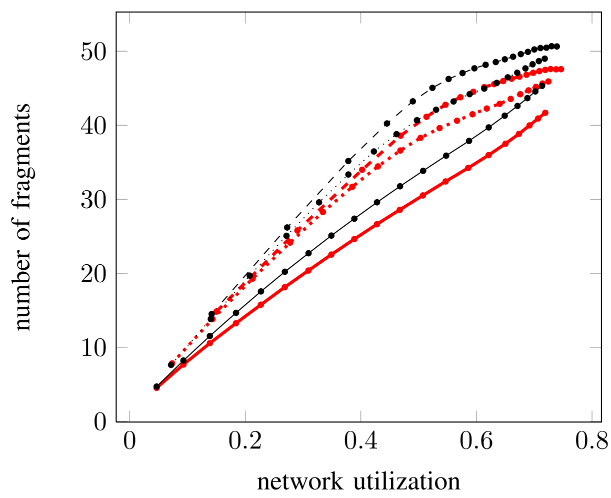
(c) The probability of completing a connection.



(d) The number of links of an established connection.



(e) The number of active clients.



(f) The number of available spectrum fragments.

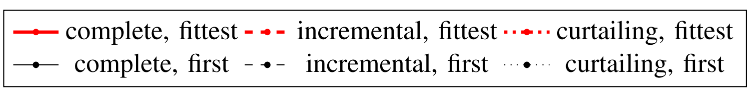


Fig. 2: Simulation results.

aforementioned relative standard errors were below 1%.

Figures 2a, 2b, and 2c report the three measured values of main interest: the number of new links for connection reconfiguration, the probability of establishing a new connection, and the probability of completing a connection, respectively. Figures 2d, 2e, and 2f report another three measured values which augment the performance evaluation: the number of links of a connection at the time it is established, the number of active clients, and the number of spectrum fragments, respectively.

In each figure there are six data sets plotted for three routing algorithms and two spectrum allocation policies. The results for the complete reconfiguration are reported with the solid curves, for the incremental reconfiguration with the dashed curves, and for the curtailing reconfiguration with the dotted curves. The thickness of the curves reports the spectrum allocation policy used: the thin curves are for the first available policy, and the thick red curves for the fittest available policy.

Fig. 2a shows the number of new links to configure in order to reconfigure a connection, provided the reconfiguration succeeds. The curtailing algorithm achieves the lowest number of links to configure for all loads in comparison with the other algorithms.

Fig. 2b shows that the probability of establishing a connection is comparable for all routing algorithms and spectrum allocation policies. Around the utilization of 0.6, the network is unable to fulfill all connection requests, and so the probability starts to decrease, and reaches the minimum around the utilization of 0.8. Even though the clients are increasingly likely to have their connection requests rejected, the number of active clients (i.e., clients with established connections) keeps increasing as seen in Fig. 2e, which may seem contradictory. Indeed, there are more connections being established, but the connections with the fewer number of links and the fewer number of subcarriers are more likely established, as suggested by Fig. 2d.

Fig. 2c shows the probability of completing a connection, i.e., the probability that the connection was successfully reconfigured the requested number of times until the client went idle. Connections are the most likely to complete with the curtailing reconfiguration. As expected, the probability decreases as the utilization increases, starting at the utilization of 0.6.

There is little difference caused by the spectrum allocation policy used, as the thin curves (for the first available policy) and the thick red curves (for the fittest available policy) match closely in the figures. This is rather surprising for the complete reconfiguration which can reconfigure a connection with different subcarriers, while for the other algorithms a small difference is expected, since they operate under the spectrum continuity constraint.

The utilization of the network falls short of the maximum, reaching at most 0.8, which is caused by the fragmented spectrum. Fig. 2f shows the number of available spectrum fragments. For the utilization of 0.8, there are on average 80 subcarriers left on a link, and since there are about 40 fragments available, then the fragments have on average a singe subcarrier. The spectrum continuity constraint makes the single subcarriers increasingly hard to use as the utilization increases, and finally makes it impossible for the utilization of about 0.8.

VII. Conclusion

In the proposed mobile routing algorithm, we achieved the key objective of lowering the number of new links to configure at the time connection needs reconfiguration. Furthermore, the algorithm achieves high probabilities of establishing and completing connections. For these reasons we believe the algorithm can be useful for routing highly-mobile high-bitrate services.

The proposed reconfiguration algorithm could also be used in link restoration of connections in elastic optical networks, where a connection rerouting is localized to the end nodes of the failed optical link.

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