Resource Efficiency and Latency in Dynamic IP-over-WSON Networks utilizing Flexrate Transponders

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Kurzfassung

Stetig zunehmende Verkehrsvolumina führen zu einem beträchtlichen Anstieg der Anforderungen an die in Kernnetzen verwendete Hardware. Ein dynamischer Netzbetrieb in Kombination mit dem Einsatz von Flexrate Transpondern verspricht ein beträchtliches Potential, die Effizienz im Kernnetzbetrieb zu steigern. Im Rahmen dieser Arbeit wurde der Zugewinn an topologischen Freiheitsgraden durch Flexrate Transponder anhand eines einfachen Modells untersucht. Dieses Modell wurde im Rahmen eines Verfahrens zur dynamischen Netzrekonfiguration eingesetzt, welches das Netz periodisch an die gegebenen Verkehrsanforderungen anpasst. Eine simulative Bewertung der Latenzen und der Ressourceneffizienz anhand der benötigten Line Cards zeigt, dass der Zugewinn an topologischer Flexibilität im vorgestellten Verfahren nahezu keine zusätzlichen Vorteile bietet, und, dass durch das Verfahren Übertragungsverzögerungen entstehen können, welche allerdings durch eine Erweiterung auf Kosten einer geringeren Effizienzsteigerung vermieden werden können.

Abstract

Continuously increasing traffic volumes raise hardware requirements of core networks considerably. Dynamic network operation combined with the use of flexrate transponders promises a viable potential for improved efficiency in core network operation. In this paper, we analyze the additional topological flexibility offered by flexrate transponders based on a simple model which is then used in a dynamic network reconfiguration approach adapting the network periodically according to the given traffic demands. We evaluate the resulting resource efficiency in terms of required line cards and latency by event-driven simulations. Results show that the gains in topological flexibility in the presented approach do not offer any additional advantage and that the approach can incur increased transmission latencies which can be avoided by an extension at a cost in terms of reduced efficiency gains.

1 Introduction

Traffic volumes in provider networks keep increasing at a rate of 22 % per year[1] [1] which forces operators to keep upgrading to more powerful network devices. This trend will most likely be accelerated by new access-technologies like FTTx and 5G [2] which promise end users significant boosts in data rates. Another important trend is the increase in the desire for flexible service provisioning which is an enabler for efficient cloud federation and various service chaining approaches [3, 4]. Finally, many emerging use cases, especially those based on network functions virtualization (NFV) and the Industrial Internet of Things (IIoT) require network connections of very low latency [4, 5].

Addressing all these factors comes at a cost to network operators. High-performance hardware is not just expensive to procure (capex), but also to maintain (opex). Spatial requirements and thermal management of devices and data center locations are becoming increasingly important and incur secondary costs. Although the devices themselves are becoming more efficient with every new generation, the overall power consumption is a growing cost driver. While the networks' access segments have so far required the largest share of the power consumption, the advent of FTTx, which is a highly energy-efficient technology compared to DSL, will likely prompt a shift towards the networks' cores [6].

Typically such transport networks are dimensioned amply in order to safely handle all expected traffic volumes and operated statically in order to ensure that service level agreements between operators and their customers are reliably met. Link utilization targets as low as 50 % have been reported by analysts [7]. This is further exacerbated by the fact that traffic fluctuates significantly with nightly low marks at 25 % of the peak traffic rate at day [8] with the latter being a typical reference point for network dimensioning.

While excessive dimensioning has solved the performance issues of the past, the present demand for increased flexibility provides an opportunity to switch to a more efficient mode of network operation. With the recent surge of interest into software-defined networking (SDN), operators are considering the advantages of reconfigurable network devices. This enables a dynamic mode of network oper-

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[1] Compound Annual Growth Rate 2015–2020

ation, where a central controller could activate, deactivate and reconfigure resources to match the present traffic demands more closely and therefore improve resource efficiency in the core network. This is especially interesting for so-called flexrate transponders since their adaptability creates additional degrees of freedom allowing more efficient network configurations.

2 Dynamic Network Operation

A transport network is commonly modeled as a multi-layer network with at least a packet-oriented upper layer and a circuit-oriented lower layer. The upper, electrical layer typically makes use of IP/MPLS while the lower layer is based on a wavelength-switched optical technology such as DWDM. Sending data hop by hop in the electrical layer allows for a fine-granular routing and an efficient use of statistical multiplexing. The drawback is that routers need a sufficient number of such packet interfaces at every step of the way. These interfaces are rather expensive in terms of capex and also opex due to their high energy consumption. In contrast to a hop-by-hop routing, an optical circuit from source to destination, which bypasses these intermediate hops on the electrical layer, also eliminates the need for the packet interfaces at these hops and thereby reduces network cost. It does not require an intermediate termination and has constant power consumption regardless of its utilization, which is much lower than that of a packet interface according to our previous studies [9]. The potential drawback is the rather course granularity of optical circuits which means that operating a circuit at low utilization might be less efficient than sending this small amount of traffic hop by hop on an already established route.

A reconfigurable transport network is able to exploit this trade-off by dynamically adapting its resources and the routing according to the traffic load. This allows avoiding situations of low utilization thereby improving operational efficiency. Flexrate transponders offer a great potential since they can trade off transmission reach for data rate which significantly increases the number of possible circuit configurations. Reconfigurable transport networks utilizing flexible optical components are also known as elastic optical networks (EON). EONs have been shown to improve usage of optical spectrum, lower backup hardware stocks and reduce overall network cost among many other benefits [3, 10].

In this work we evaluate the resource requirements in terms of active router line cards since they are one of the most important cost factors among network hardware resources. We simulate the network hardware requirements based on a previously published hardware model [9] which allows for the simulation of all relevant components typically found in core networks. We will further extend this model by including flexrate transponders. They have the ability to adjust their transmission rate within certain boundaries which is beneficial since a reduced rate directly translates into a considerable gain in transmission reach. This can help eliminate intermediate hops on long distances exceeding the regular maximum transparent reach.

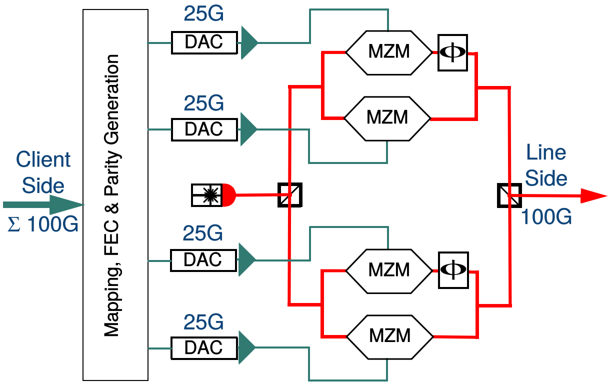

Figure 1 Principal components of the send-path of a simple flexrate transceiver

We use a simple model for flexible transceivers and transponders as part of a larger network reconfiguration approach in order to quantify possible resource efficiency improvements and effects on the average traffic latency. We will first outline the components and functionality of the flexrate transponder model, before giving a brief overview on our multi-layer network reconfiguration approach and details on the evaluation and results.

3 Flexible Optical Components

In order to provide a meaningful level of reconfigurability we assume the optical layer to use state-of-the-art colorless, directionless and contentionless ROADMs as well as full-band tunable transponders. We consider two types: A regular 100G PDM-QPSK transponder and a simple hypothetical flexrate transponder based on it. The latter can be switched to one of four data rates. Varying its modulation format between PDM-BPSK and PDM-QPSK allows data rates of 50 and 100 Gbit/s. By transmitting parity information on one lane data rates of 25 and 75 Gbit/s can be realized. The basic components are shown in Figure 1. The values for the transparent optical reach used in this work are illustrated in Table 1. While they are low compared to the latest available devices, they were chosen specifically in order to provide a meaningful relation to the lengths of fiber in our experiments. The value for 100 Gbit/s was fixed to cover the maximum single-hop distance in our experiments and the remaining values were scaled according to Equation (4) from [11]. Since all possible signals of both transponders, the 100G PDM-QPSK and this simple flexrate-design based on it, operate at identical symbol rates and do easily fit into the regular 50 GHz ITU-grid, we will not consider aspects of spectrum fragmentation in our experiments.

Table 1 Transparent Optical Reach

25 Gbit/s	50 Gbit/s	75 Gbit/s	100 Gbit/s
3510 km	2850 km	2470 km	2200 km

4 Multi-Layer Network Reconfiguration Problem

Our optimization problem is derived from VTCR [12] through the addition of constraints regarding the circuit realization using flexrate transponders. In short, the goal is repeatedly finding a network configuration for subsequent intervals in time such that a given objective function judging the network state is minimized under a number of conditions. The network consists of nodes connected by optical fibers which represent the links of the physical topology. Any two nodes can be connected by a circuit spanning a series of these links as long as the total length of this circuit does not exceed the maximum transparent reach as shown in Table 1. This offers a distinct advantage for flexrate transponders since their adaptability allows more freedom in establishing circuits.

We assume full wavelength conversion capability at any node the circuit traverses. The set of active circuits defines the virtual topology which is the network topology as seen from the perspective of the routers. Routing weights are set inversely proportional to the lengths of the virtual links. We assume the traffic demands, i. e. the maximum data rate between any two nodes, to be known for the next interval. These traffic demands are then routed in the virtual topology. Establishing new circuits requires unused ports on the source and destination nodes and sufficient available capacity on all necessary fiber links in order to allow for a hitless reconfiguration.

The input parameters are therefore the physical topology, the installed resources, the set of demands and the previous configuration of the network. The objective is to determine a configuration of minimal objective value including minimal blocking for a time interval. A configuration consists of a virtual topology, the hardware resources occupied and an assignment of demands to circuits. For the presented evaluation two distinct objective functions have been used.

$$\left(\sum_{e \in C_a} f_\alpha(e)\right) + \beta \cdot t_T + \mu \cdot n_B + \nu \cdot t_B \qquad (1)$$

The resource objective function Equation (1) is largely identical to Equation (1) in [12] with C_a being the set of active circuits and f_α representing a function which determines the line card activity corresponding to circuit e. This accounts for the fact that since line cards have several ports, activation or deactivation of a circuit might not immediately affect the number of active line cards. The electrically processed data volume t_T, referred to as transit traffic, is added in the objective to dissuade intermediate circuit termination. Finally, there are terms adding cost for blocked circuits ($\mu \cdot n_B$) and blocked traffic ($\nu \cdot t_B$).

$$\frac{\left(\sum_{d \in D} \frac{n_r}{c} \cdot f_\lambda(d)\right)}{|D|} + \mu \cdot n_B + \nu \cdot t_B \qquad (2)$$

The latency objective function Equation (2) retains the terms for blocked traffic and blocked circuits, but instead of the number of active line cards it minimizes the average latency of the set of routed demands D. It uses f_λ to find the length of fiber traversed by a traffic demand d according to its routing and multiplies it by the quotient of the refractive index of the fiber n_r, which we consider to be identical for all fibers in the network, and the speed of light c.

5 Solution Method

The approach used to solve the reconfiguration problem outlined in the previous section combines Simulated Annealing (SA) with a number of deterministic algorithms, specifically for the setup of circuits.

SA is a meta-heuristic algorithm which starts from a randomly generated solution which it iteratively improves upon by perturbation, i. e. the random introduction and evaluation of small changes, and selection of the most promising among these to be the candidate solution for the next iteration. This selection process will also accept a less optimal candidate solution with a certain probability which exponentially decreases during the algorithm's runtime. This allows for a wide coverage of the solution space during the initial iterations and will lead to a refinement of the best candidate solution found in later iterations. The algorithm terminates when the differences between all candidate solutions found within an iteration falls below a certain threshold.

The SA algorithm is used to determine the optimal virtual topology. The perturbation is realized by either adding or removing a single directed virtual link. After a topology has been found, we set the routing weights for the traffic demands as explained in section 4 and use a shortest-paths algorithm to determine the routes.

To establish the virtual links in the optical layer a set of circuits of sufficient spare capacity has to be found or set up. We consider every virtual link separately starting from the shortest. First we use the existing circuits of the previous configuration. If less capacity is needed than in the last iteration then circuits are deactivated. If more capacity is needed unused resources are determined and assigned to set up a new circuit. When looking for new line cards to be used, the method will prefer the line card which already has the largest number of active circuits in order to minimize the number of active line cards required. If no line card with spare capacity can be found then the traffic demand will be marked as blocked.

If resources could be found then the optical circuit is routed along the shortest path between these line cards. If the optical spectrum is depleted on any link in-between, the link will be excluded and a new shortest path will be determined. If either there are no more links left or the maximum transparent reach is exceeded, the traffic demand will be marked as blocked. Following a successful assignment of a path, the assignment of the operation mode for flexrate transponders is determined by setting the maximum data rate admissible for the length of the requested circuit. Since the spectral occupation is assumed to be invariant and all penalties in OSNR are already approximated by using Equation (4) from [11] the only remaining parameter is the impact on opex. Since we evaluate the net-

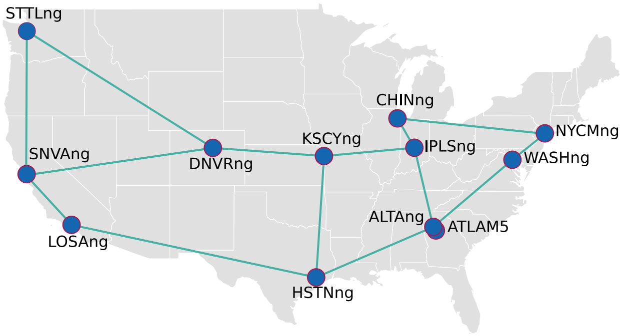

Figure 2 Topology of the Abilene network

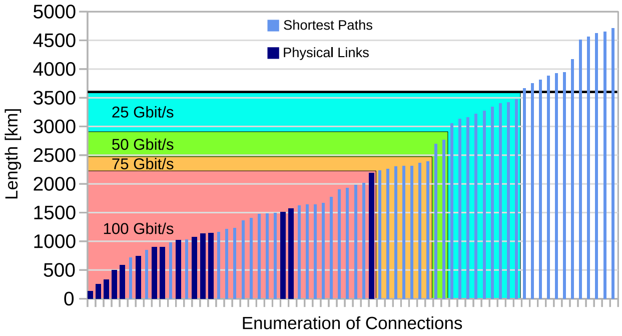

Figure 3 Link and shortest path lengths of the Abilene network sorted by length

work regarding the number of line cards needed, the exact amount of reduction in the energy consumption at modes of lower data rates does not have any impact and is therefore not considered in these simulations. The values on route lengths, line cards used and blocked traffic and links are then used in the objective functions Equation (1) and Equation (2) to determine the state of the network configuration.

6 Evaluation

As previously outlined, we evaluate two metrics. In order to determine resource efficiency we focus on the number of active router line cards needed to fulfill the traffic demands since their number scales quickly with increasing traffic loads. Furthermore, we evaluate the average latency through propagation delay in fiber experienced by the traffic demands. We assume that every fiber can accommodate 80 wavelengths and that every line card has 4 ports of which each can deliver 100 Gbit/s.

A topology covering a large geographic area was chosen from SNDLib [13]. The Abilene reference network depicted in Figure 2 consists of 12 nodes and 15 links with link lengths ranging from 132 to 2200 km. As outlined in section 3, a 100G-circuit can cover any physical link. Figure 3 shows the lengths of all shortest path connections for all combinations of any two nodes as source and destination. The darker bars indicate when a shortest path is identical to a physical link between the respective nodes. The colored background areas show which of these paths can be covered by which mode of the transponder modes. About 54.5 % of all shortest paths can be covered by the regular 100G-circuits. The flexrate transponder can increase the topological flexibility in terms of shortest paths by 50 % covering 54 of the 66 or about 82 % of possible paths. It should be noted that, unsurprisingly, the 25G-mode alone is responsible for more than half of this increase, while the 50G-mode adds only 2 additional connections.

Along with the network topology the SNDLib [13] also hosts traffic traces which had been recorded in the actual networks the topologies belong to. We took 48 hours of these traffic traces and applied a scaling factor to the demand matrices to create different load situations similar to [12]. The initial dimensioning of resources is determined by using our approach for twice the average of the expected maximum load over these 48 hours which is in line with typical dimensioning approaches of core network operators in order to account for uncertainties. We evaluate our approach regarding port and line card activity, as well as latency using intervals of 15 minutes in an event-driven simulation based on the IKR SimLib [14].

7 Simulation Results

Simulations in the Abilene network using only 100G-devices and using only flexrate-devices have been conducted for various volumes of traffic and with both functions, the resource objective Equation (1) and the latency objective Equation (2). Additionally a number of simulations using purely static configurations and a simple rerouting combined with sleep modes have been included for reference purposes.

7.1 Dynamic Port Activity

Figure 4 shows the number of active ports for both device types for an average peak traffic demand of 300 Gbit/s. It can be seen that in the case of flexrate the network requires on average a mere 2.34 % fewer active ports to handle the traffic. As expected from the analysis in section 6 there is hardly any activity of ports in the 50G-mode. Despite the significant increase in topological freedom offered, only few ports operate in 25G-mode. Increased efficiency of

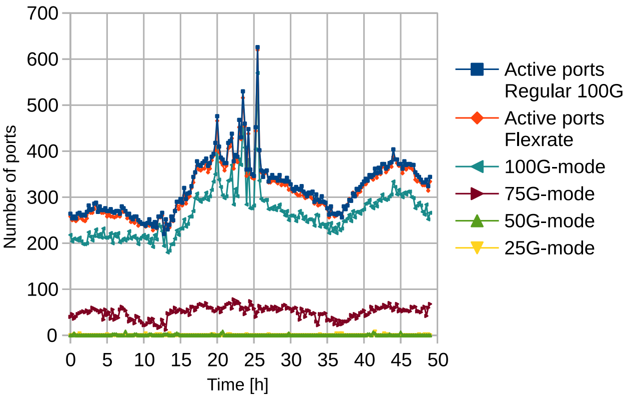

Figure 4 Port activity comparison for 300 Gbit/s average peak demand

statistical multiplexing at larger data rates leads to a traffic grooming so efficient, that it can hardly be counteracted by more direct links. This effect can also be observed at the large peaks between hours 20 and 26 when spikes in the traffic demands lead to a sharp increase in 100G-mode circuits while the 75G-mode circuits get deactivated, because their traffic can more efficiently be groomed into the spare capacity of the newly setup 100G-mode circuits.

7.2 Latency

Figure 5 Latency for 300 Gbit/s average peak demand

While we have shown that the developed methods provide resource-efficient network configurations [9], we also need to consider the impact on other performance metrics. Previous work has shown how network-wide stability can be retained in the face of rapid reconfigurations [12], but the effects on quality of service parameters need also be considered. Among the most relevant metrics are latency and jitter due to their importance for video streaming and voice telephony services which require sufficiently low bounds. Figure 5 shows the average and maximum latency values for both, regular and flexrate devices during the 48 hours of simulated network operation. Simulations using Equation (1) are designated "Res. obj.", while "Lat. obj." indicates the usage of Equation (2).

The average latency typically does not exceed 15 ms which is well below typical non-critical SLAs offered for the USA. The mean value of the average latency for each simulation interval is at 12.6 ms for 100G. For flexrate, the value is slightly higher at 13.3 ms. The variance of the average latency is 0.293 ms for 100G and at 0.369 ms for the flexrate case which is tolerable for best effort traffic, but is already on the verge of violating more demanding private customer SLAs. These values turn problematic however, when viewing the maximum variance encountered. The latency variance increases to a critical 10.9 ms for 100G and 10.2 ms for flexrate. The flexrate case has a slight advantage here since it is able to balance capacities a bit more smoothly on the longest of paths, where small excursions in routing otherwise accumulate jitter.

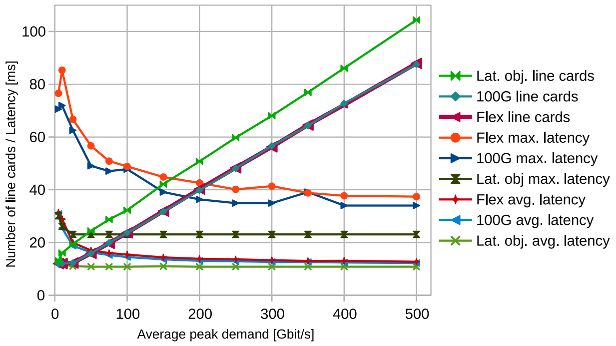

Figure 6 Resource usage and latency for increasing average peak demand

This situation is much improved for the latency objective case. These simulations have been conducted with 100G-devices since flexrate cannot offer any advantage when only considering propagation delay-based latency. The results show that the scheme works effectively towards minimizing latency and its variance. Slight dips in the average latency are caused by a temporary reduction in the number of traffic demands for one specific network node which seems to be subject to a migration process to different hardware.

Figure 6 shows the behavior regarding latency and resource usage for different traffic scenarios varying the average peak demand. For scenarios with very low traffic demands the topology converges to a minimal spanning tree since this is the most resource efficient configuration. However, the impact on latency is significant since routing on a tree of minimal connectivity results in many excessively long routes. Once the average peak demand is close to or below the circuit capacity of 100 Gbit/s the latency rises significantly since the sum of all the traffic at a node can now be handled by a single interface. For values below 30 Gbit/s even the latency objective function cannot maintain its performance due to a lack of available interfaces: In such extreme cases the dimensioning using twice the hardware normally required will yield only 2 interfaces which cannot guarantee shortest paths at sites of a nodal degree greater than 2.

7.3 Resource Efficiency

As most of the increase in resource efficiency stems from the combination of traffic grooming and an accordingly optimized topology, minimizing delays will incur an increased demand for resources. This effect is clearly visible in Figure 7 where we compare the required number of line cards for all three cases. On average the simulation using flexrate devices reduces the number of active line cards by just 1 % compared to the regular 100G devices, which matches the results from Figure 4. Using the latency objective requires a 20.8 % increase in active line cards which is significant, but still much more efficient than the reference cases included in this graph. The line designated "Sleep-mode" represents a simulation where no reconfiguration of the topology is used. In this approach line cards are deactivated for intervals during which they are not needed due to reduced traffic volumes and subsequently the traffic routing is adjusted accordingly. This approach requires on average 60.3 % more line cards than the fully dynamic operation. Finally, a traditional configuration with static topology and static traffic routing is included featuring 192 line cards throughout the network.

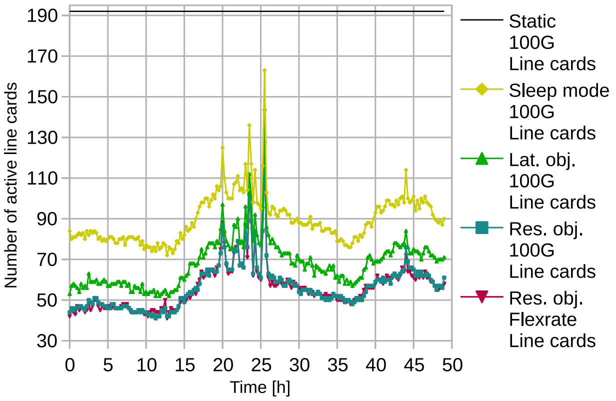

Figure 7 Line card activity for 300 Gbit/s average peak demand

Considering Figure 6 both, 100G and flexrate cases, perform similarly well regardless of the amount of traffic. The latency objective is also maintaining its efficiency with an almost constant offset to the former cases. This offset can be explained by the need to provide shortest paths, no matter how much traffic needs to be routed.

8 Conclusion

In this paper we have presented a Simulated Annealing-based method to determine optimal configurations for multi-layer core networks utilizing flexrate transponders allowing for dynamic network operation in order to improve efficiency and latency. We have evaluated the performance of our approach through simulation. While our simple flexrate model showed little potential for additional gains in efficiency, further research will have to determine if a more fine-granular configurability is better suited to this task. Furthermore, the simulations have shown that a dynamic reconfiguration can have significant impact on latency prompting the development of a latency-optimized version of our mechanism which results in optimal latency figures at a 20.8 % increase in resource cost. Future work will establish whether different transponder models or scenarios can offer more significant savings and will extend the mechanism to consider individual demand latency requirements.

9 Acknowledgements

This work has been performed in the framework of the CELTIC EUREKA project SENDATE-TANDEM (Project ID C2015/3-2), and it is partly funded by the German BMBF (Project ID 16KIS0458). The authors alone are responsible for the content of the paper.

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