RESEARCH ARTICLE

Employing FAMTAR and AHB to Achieve an Optical Resource-Efficient Multilayer IP-Over-EON SDN Network

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ABSTRACT With the global Internet traffic continuously growing, network operators face more and more challenges related to the management of their networks. Efficient utilization of the available network resources becomes crucial to maintain the desired Quality of Service level and control the upsurge in operational expenses. The combination of the Software-Defined Networking concept with the multi-layer network architecture can simplify the process of control and management of the network, its layers, and resources. In this paper, we propose a solution to enhance resource utilization in software-defined multi-layer optical networks. The proposed solution takes the advantages of the Software-Defined Networking, Flow-Aware Multi-Topology Adaptive Routing, and Automatic Hidden Bypasses mechanisms to ensure simultaneous, multi-path data transmissions in both IP and optical layers. The Software-Defined Networking controller manages both mentioned mechanisms, selects the best possible bypass, and allocates lightpaths to ensure that the optical spectral efficiency is optimal. The evaluation shows that the proposed solution for multi-layer software-defined network increases the overall network performance and resource utilization.

INDEX TERMS AHB, bypasses, EON, FAMTAR, flows, IP network, multi-layer network, optical network, routing, SDN.

I. INTRODUCTION

The total IP traffic continues a strong global increase. It is forecasted that there will be 1.4 billion Internet users more in 2023 than it was in 2018 and that there will be 29.3 billion networked devices in 2023, compared to 18.4 billion in 2018 [1]. Such a significant growth pressurizes network operators, who want to handle traffic with a guaranteed Quality of Service (QoS), to employ more efficient and effective utilization of network resources.

Software-Defined Networking (SDN) gained a lot of interest during recent years in the context of network management. SDN significantly simplifies the management of traffic in the network due to the fact that control and data planes are

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completely separated. The control plane – usually represented by the central controller – is responsible for decision-making, mainly about where packets should be sent in the data plane. Currently, the most common SDN use case is reactive control, where the SDN switches consult a decision for every IP flow with the controller. However, SDN may be also used in multi-layer networks, where the management of many layers is performed simultaneously in a single controller. Such an application brings a plenty of advantages to the management of the multi-layer networks. As a result of the global view of the network environment which SDN provides, the controller can control both layers according to the QoS requirements of the incoming traffic and optimize resources usage in a cross-layer manner. Simultaneous management of many layers in a single controller strongly simplifies network control and management of the network. However, expanding the

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controller's control range also raises concerns regarding the security or single point of failure aspects of the network's control plane.

In this paper, we propose a solution for multi-layer networks which aims to enhance the resource utilization of the network. Our solution takes an advantage of the SDN concept which is used to control the Flow-Aware Multi-Topology Adaptive Routing (FAMTAR) and the Automatic Hidden Bypasses (AHB) mechanisms selected to ensure simultaneous, multi-path data transmission in both IP and optical layers. Additionally, we propose an algorithm which goal is to find the best possible source-destination pair for the bypass and an intelligent, resource-oriented mechanism for both allocation and release of lightpaths in the optical layer based on current network demand distribution. The evaluation shows that the proposed solution can increase the overall network performance, reduce the losses over the network, and also possibly reduce energy demand due to the increased optical spectral efficiency.

Currently, many solutions that focus on resource utilization in multi-layer SDN exist, however, they mostly introduce a single layer optimization (like bypasses in the optical layer) and show how to perform the network control over multi-layer networks. This work shows how to implement a per-layer solution (FAMTAR for IP layer, and bypasses for optical layer) and how to handle them together in a centralized way.

The novelty of our article lies in simultaneous operation and management of IP and optical layers with FAMTAR and AHB mechanisms, which previously were used only in isolation in pure IP and optical networks, respectively. In order to use these mechanisms together, we propose a novel algorithm to find the best possible source-destination pair for bypass and intelligent allocation and release mechanisms for lightpaths in the optical layer.

The remainder of the paper is organized as follows. Section II presents the related work. Next, Section III presents the necessary background regarding multi-layer networks, FAMTAR, Elastic Optical Network (EON) and AHB. Section IV shows the overall system architecture and algorithms. In Section V, simulations performed in the heavily modified Mininet network emulator are discussed. The analysis is divided into two parts, which show the results of two examined scenarios under multiple configurations. Finally, Section VI concludes the paper.

II. RELATED WORK

To the best of our knowledge, no other paper presents FAMTAR, and AHB mechanisms used simultaneously in a multi-layer network. However, some works provide other mechanisms and solutions for multi-layer networks. We introduce the most prominent of them below.

The framework for IP over Optical Networks is presented in [2], where authors cover the requirements as well as mechanisms for establishing an IP-centric optical control plane together with architectural aspects of the IP transport over optical networks. Since that time, many researchers covered the topics of multi-layer network control with standard protocols [3], [4], [5], recently there is also some momentum in using artificial intelligence for that control [6], [7].

In [3] authors present cooperation between Segment Routing (SR), SDN and optical bypasses. Custom SDN solution is used to control edge node label stacking configuration and optical bypasses, which are used upon load variations. The routing policy for the optical bypass is based on the predefined threshold and does not require signaling protocols. Segment Routing is also explored in [4], where authors make use of it in two situations for a multi-layer network. Firstly combined with SDN and dynamic optical bypasses and secondly used to effectively load balance the traffic also among non-ECMP routes. Research in [5] also employs Segment Routing technology, however, in a 5G multi-layer, multi-domain network. The authors validate SDN-based network slicing for disaggregated 5G transport networks, with slices defined at multiple layers and provisioned over multiple domains.

Regarding artificial intelligence, authors in [6] present fully distributed multi-layer routing policies based on BIO-inspired ant colony optimization algorithm with online control for the optical and IP/MPLS layers. The algorithm presented by the authors assumes disjoint control planes for both optical and IP layers with the only local routing information in each network node, which represents a different approach than SDN, where network control is centralized. A reinforcement learning algorithm implementation is shown in [7]. The algorithm is used in SDN controller to provide a proper virtual multi-layer network resource allocation with fine service isolation. The introduced control loop, allows to improve resource utilization over the network nodes.

Some solutions [8], [9], [10] focus on network resilience problems rather than optimal resource allocation. Reference [8] addresses the problem of cross-layer orchestration to address IP router outages in IP-over-EON. The authors propose a set of multi-layer restoration algorithms which aim to minimize the operating expenses. Reference [9] addresses the problem of the survivability for IP over EON networks. The authors proposed a proactive restoration method for a joint multi-layer network, which was shown to achieve efficient resource usage and outperform the single-layer protection methods. Moreover, integer linear programming formulations were presented to provide survivability in the case of link or node failure in the network. Authors in [10] introduce a new SR scheme to recover traffic flows after a network failure event dynamically. They employ SDN controller to obtain a network topology but only when a failure occurs. The solution allows reducing the failure recovery time.

There is also a hardware-based approach for multi-layer network control. In [11] authors take advantage of the P4 switches rather than the SDN controller. Traffic is forwarded to the optical bypass once the predefined threshold is reached. Interestingly, the authors consider two cases for the bypass usage – reroute all packets or reroute just the portion which exceeded the threshold.

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Even though the number of solutions stated above exists, they mainly introduce one-layer optimization (like bypasses) and show how to perform the network control over multi-layer networks. This work shows how to implement a per-layer solution (FAMTAR for IP layer and bypasses for optical layer) and handle them together in a centralized way.

Some surveys cover many problems of multi-layer network management. Reference [12] is a broad survey that presents solutions that utilize SDN in multi-layer network architectures. Apart from delivering the solutions, their impact on the network stability and complexity is also analyzed. Another work for multi-layer networks is [13], where apart from the challenges, the authors focus also on network optimization.

III. BACKGROUND

This section provides the necessary background for the multi-layer network concept as well as mechanisms which were used, FAMTAR and AHB.

A. MULTI-LAYER NETWORKING

SDN-based multi-layer network refers to a multi-layer network with SDN applied for the network control. Multi-layer networking is an abstraction of network services being provided with multiple networking technologies (layers) and multiple routing/network domains. Two approaches can be considered in the context of multi-layer networking: vertical and horizontal [14].

In a vertical approach, multiple networking technologies connect to each other within a single domain. For instance, in the architecture proposed in this paper, the IP layer uses an underlying optical layer in order to provide services to higher layers. On the other hand, a horizontal approach may incorporate the same networking technologies in distinct domains in order to provide required services.

Figure 1 visualize both vertical and horizontal SDN based approaches with the layers corresponding to the ones considered in this article. Multiple controllers are often necessary in multi-layer networks due to the lack of common communication protocols between different vendor devices. In such a case, coordination of multiple controllers is assigned to the SDN orchestrator which main functions are end-to-end connectivity provisioning or translation of application level requirements into configuration requests for controllers.

Independent and isolated management of the layers has many drawbacks, especially in SDN. Such an approach brings more complexity to the control plane, which must be split and isolated for every layer in the network. Dynamic allocation of the layers' resources would be also more complex with each layer controlled independently. Finally, global knowledge about the network environment provided by the SDN would not be used to its full potential, because of the layers isolation.

Traffic engineering mechanisms aiming at congestion management or network optimization may strongly utilize the SDN multi-layer network. For instance, any congestion or anomaly in the network could be resolved by the

TABLE 1. Challenges in multi-layer SDN.

	Question
1	How to securely expose the data about the network to the SDN orchestrator?
2	How to securely request any configuration change from the SDN orchestrator to the infrastructure?
3	How to securely exchange data between multiple SDN controllers?
4	How to monitor the performance metrics, error alerts, or alarms coming from the network at the SDN orchestrator level?
5	In which simulator/emulator is it possible to test SDN multi-layer environment?
6	Finally, how to efficiently manage all controlled layers and their resources?

SDN controller at the proper layer, while keeping the resource usage as efficient as possible. With the global visibility of the network, SDN controller can perform simultaneous, integrated control of multiple layers in the network to fulfill the QoS requirements of the incoming traffic. Finally, SDN controller can dynamically decide which traffic demand is transmitted through which layer in order to increase the resources utilization even more.

The concept of multi-layer SDN raises new challenges which we define as a questions in Table 1.

B. FAMTAR

FAMTAR [15] is a multi-path adaptive routing mechanism based on the concept of flows. FAMTAR can work with every routing protocol being responsible for finding the best possible path between two endpoints, since it operates above the intra-domain routing protocol (IGP). In a scenario when there are no congestions in the network, all transmissions between those endpoints use the best path. However, when congestion occurs, flows which were already active remain on their primary path, while new flows are pushed to an alternative path. Therefore, the optimal paths change according to the congestion status of the links - FAMTAR uses the best path provided by the routing algorithm and in case of congestion automatically triggers finding new paths.

To accomplish that, a FAMTAR router stores Flow Forwarding Table (FFT) together with a classic routing table. In FFT each flow has a corresponding entry which represents the interface to which packets of this flow are forwarded. This information is taken from the current routing table when the flow is added to the FFT, i.e., when its first packet appears. For flows that are present in the FFT the routing table is not consulted, therefore FFT is used to execute the majority of the packet routing tasks. Entries in the FFT are static and do not reflect routing table changes.

Once a state close to congestion is noticed on one of the links, the adjacent router updates the cost of this link with a predefined high value. This link is then perceived as congested. Updated link cost appears as a standard change in the routing protocol, which spreads this information as a standard topology change message. When routers receive this information, they compute new paths which are likely to avoid congested links. Routing tables are updated with the newly computed paths. However, this update affects only new flows. The flows which were active before that event are
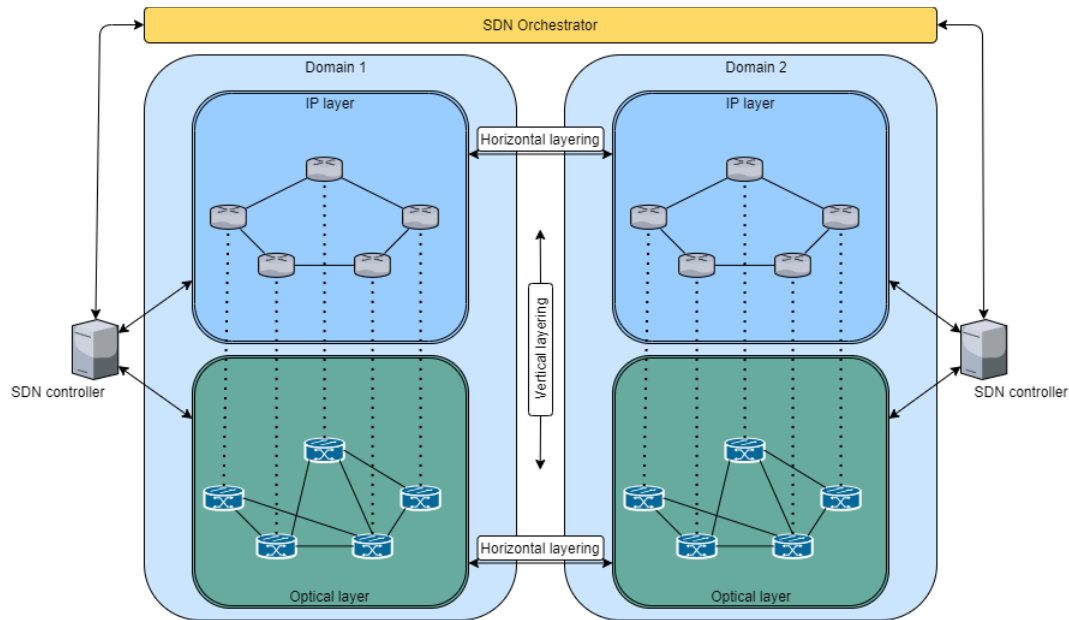
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FIGURE 1. SDN multi-layer network.

still routed on their existing paths, stored in the FFT. Even though congested links still forward flows which were active before the congestion was noticed, no new transmissions start on that links. The original cost of the link is recovered after some time, once the congestion on the link is over. Note that FAMTAR requires a router to detect congestion on one of its links. The method to determine the congestion is not specified, although any congestion indicator can be used (e.g., link load, queue occupancy, packet queuing delay, and so on).

C. AHB
Many solutions linked with optical bypassing have been proposed in the recent literature. The Automatic Hidden Bypasses (AHB) mechanism was firstly presented in [16] and it extends a hidden bypass functionality described in [17] by adding bypass creation automatization under SDN environment. The optical network efficiency is increased by congestions minimization occurring in the IP layer. When the utilization of any link exceeds a certain threshold, new lightpaths can be created. The mechanism assumes using as many optical resources as necessary in each situation. The authors present a solution to dynamically set a bypass with a given path that offloads traffic from regularly used links based on incoming demands. Others have proposed several ways to realize optical bypasses. Such mechanisms do not require routing table updates propagation over all network devices. Only an ingress node of the bypass is aware of the routing table change and that it has to forward the traffic into the bypass rather than to the interface indicated by the routing table.

This means that bypasses are created and removed down based on existing demands. The network decides when and how to create a new bypass, as well as which transmissions

should use it. The analysis presented in this paper shows that AHB can provide lower delays and higher throughput. The mechanism yields excellent results in both low and high-loaded networks. Bypasses can be created manually by network operators or automatically in centralized or distributed systems.

The mechanism was also introduced into IP-over-EON architecture in [18]. In EON, the optical spectrum used for the transmission is divided into narrow frequency slices (slots). The slots are reserved by setting an end-to-end path between the optical network devices. The frequency of the slots used over the path has to be static over all-optical hops. The bandwidth of the created path is defined by the number of selected slots and a modulation format.

An example of bypass creation is shown in Figure 2. In Figure 2 a simple multi-layer network architecture is considered. The network comprises two layers: IP, where IP routers reside, and the optical (EON) layer where optical (fiber) links physically connect optical nodes (cross-connects). Additionally, we assume that each IP router is bound with an optical cross-connect - this is typical for existing carrier networks. Thanks to the bypass mechanism only the selected optical resources (slots) are revealed to the IP layer. The remaining spectrum is denoted as hidden resources and can be used when congestions occur. Therefore, a new lightpath is established without creating a virtual link when a request cannot be served in the IP layer due to the lack of resources. This lightpath is then used to offload new traffic. Once the transmission on the bypass ends, the lightpath is removed and optical resources are released.

One of the key challenges facing EON is the Routing and Spectrum Allocation (RSA) problem, which focuses on
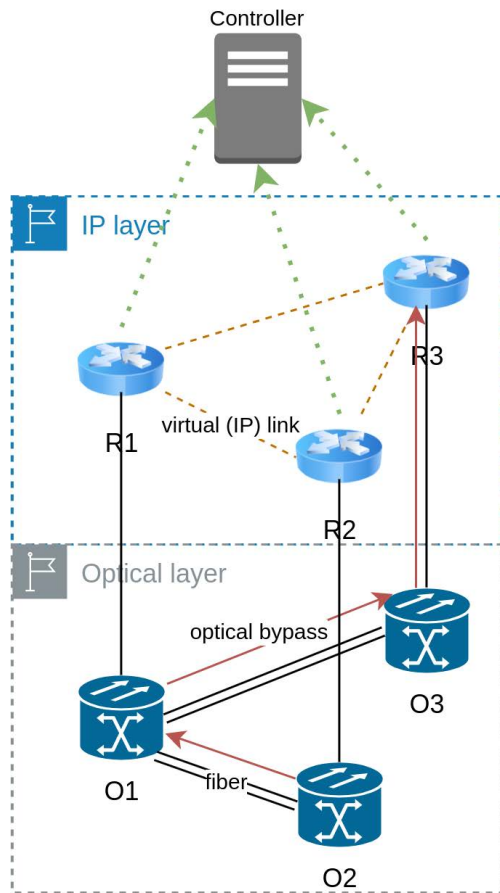
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FIGURE 2. Example of a bypass creation.

finding the assignment method of an appropriate number of slots to handle an individual connection. Usually, bypasses consume slots reserved for their implementation and not used during the standard network operation (without bypasses). Sometimes the setup of bypasses is broadcasted at the IP layer, and sometimes bypasses are hidden.

IV. SYSTEM ARCHITECTURE

This section presents the proposed solution, including the overall system architecture and details of algorithms.

At first, we have divided physical resources (optical slots) and assigned them to both IP and optical layers. Optical slots assigned to the IP layer are used to create IP layer links between adjacent routers. On the other hand, slots reserved for the optical layer are used to dynamically create bypasses when congestions occur in the network. Such an approach assures that both layers are separated and allows more efficient resource management.

Management and operation of the FAMTAR and AHB mechanisms in the SDN controller are shown on the block diagram in Figure 3. As it can be seen, the SDN controller manages both IP and optical layers simultaneously. The main control loop ① is called at regular time intervals and iterates over all links in the network.

IP layer processing starts with a crucial question of whether the examined link is in the optical or IP layer (link is a bypass or not). If a link is not a bypass ②, then the FAMTAR mechanism is employed. If the examined link's load is greater than the FAMTAR's activation threshold and the link's cost wasn't already increased, then the cost of that link is set to a predefined high value ③. This message is then spread across the topology as explained in III-B. Otherwise, when the examined link's load is not greater than the FAMTAR's activation threshold, the controller performs a check if the cost of that link was already increased and if a load of that link is lower than the FAMTAR's deactivation threshold. If that condition is true ④, then the controller sets the cost of the link to its original value.

The optical layer control mechanism starts with a question of whether the examined link's load is greater than the Bypass Creation Threshold (BCT). If the answer to that question is true, then the controller requests the FFT statistics from the network node ⑤. The algorithm for bypass calculation presented in the Algorithm 1 is executed right after the FFT statistics are successfully gathered. The algorithm aims to find the best source-destination bypass to deal with the over-loaded link. Based on the flow entries gathered from the FFT of the overloaded link, the algorithm returns the best possible source-destination pair based on our custom metric computed for all of the source-destination pairs. This custom metric is expressed as a float value which is a result of the multiplication of the values of the following parameters:

$$metric = hops \cdot rate \cdot nodes\_usage \cdot modulation$$

As it is known, multiplication will only work if there is an agreement that low or high values of all parameters are better. In this scenario, the metric is better if all parameters have high values - it is more likely that the pair for this metric will be treated as the best option for bypass. For a more in-depth explanation, we define those parameters as:

- *hops* – the number of hops between source-destination pair, we prefer that the bypass omits as many nodes in the IP layer as possible,
- *rate* – current flow rate, value in Mbps, we would like to feed the bypass with more significant flows, rather than many little ones,
- *nodes_usage* – custom metric described by Equation 1 which is a sum of square roots of the utilization of all nodes in the flow path divided by the path length, represents the forwarding plane utilization for the nodes on the current path for the flow. The higher the value, the more saturated nodes are on the flow path. Therefore we prefer to withdraw flows from the IP layer of heavily utilized nodes,

$$nodes\_usage = \sum_{n=1}^{L-1} \frac{\sqrt{\dfrac{current\_node\_throughput}{maximum\_node\_throughput}}}{L-2}$$

$$(1)$$

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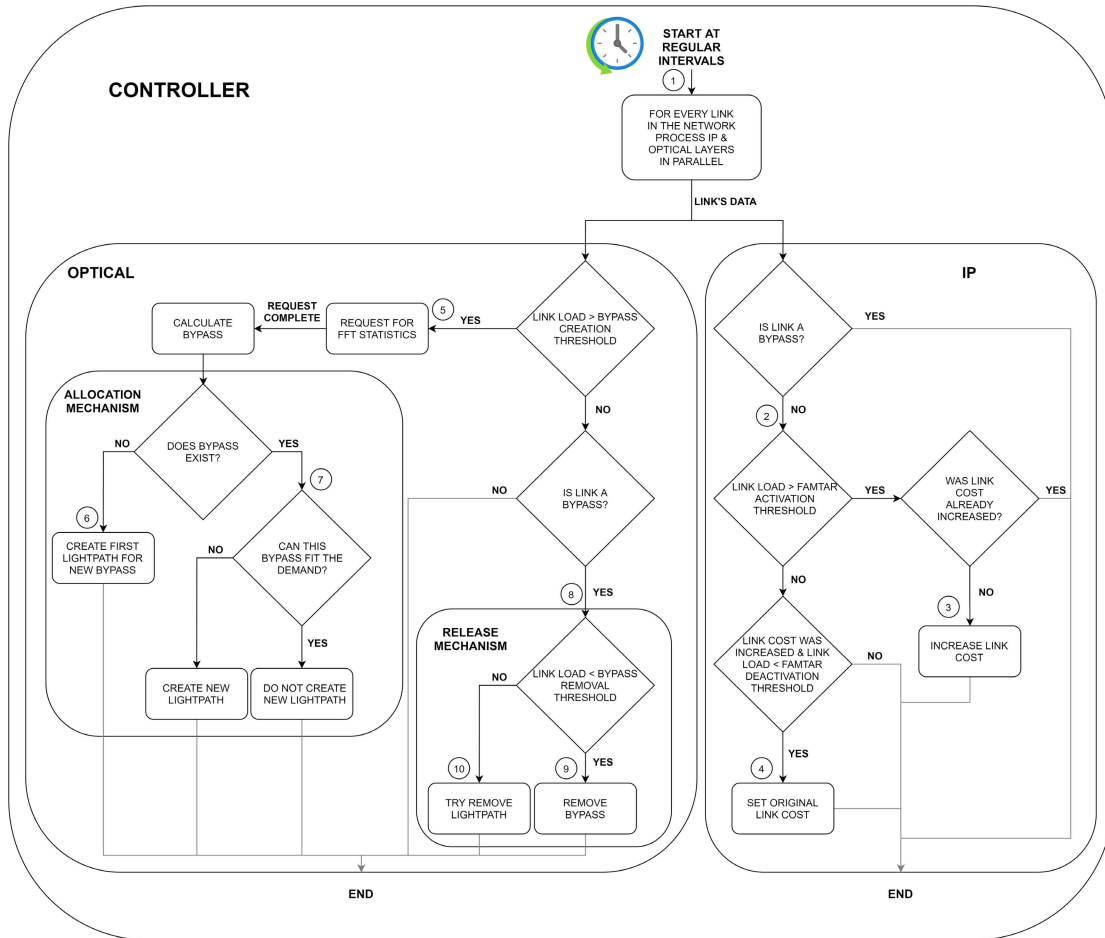

FIGURE 3. Algorithm processing all links in the network.

• *modulation* – the maximum modulation order value that is possible to reach between source-destination nodes. It is important as the proposed system doesn't use optical regenerators.

Once the *metric_by_pair* container is filled with the metric values, the best source-destination pair with the biggest average value of the metrics is then selected as a source and destination for the bypass.

After the algorithm for bypass calculation is executed, a lightpath for that bypass can be allocated. In order to further maximize resource utilization, we propose an intelligent lightpath allocation mechanism.

The allocation mechanism can be divided into two cases. In the first case, when a bypass for a given source-destination pair does not exist ⑥, it is created together with the first lightpath for that pair. Allocating a new lightpath in the optical layer requires solving the routing, modulation, and spectrum assignment (RMSA) problem. For this purpose, we use the Generic Dijkstra algorithm [19], which finds optimal solutions to dynamic RMSA problem, at the same time being considerably faster than other algorithms [20]. By optimal solution we mean the shortest possible path taking

into account spectrum continuity and continuity constraints enabling supporting a given request. We use the open-source Python implementation of the algorithm provided in [20].

In the second case, when a bypass for a given source-destination pair already exists ⑦, an additional lightpath for that bypass will be created if the demand will not fit in that bypass's remaining bandwidth. In this way, we make sure that bypass is used to its full potential and that slots in the optical layer are not over-allocated. After allocation, we reroute flows from the overloaded link that passes by bypass edges.

On the other hand, if the answer to the first question whether the examined link's load is greater than the BCT is false, and the currently processed link is a bypass, then the proposed release mechanism is executed ⑧. Because of its design, bypass loses rather than gains traffic. Therefore, it only takes a portion of the traffic that existed at the exact moment of its creation, and new flows are not forwarded through it. A bypass should be removed and therefore release resources once the transmission on it ends. However, in order to boost the efficiency, it is more than reasonable to unset the bypass earlier, i.e., when the utilization of its resources

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Algorithm 1 Bypass Calculation

Input: F - list of flows on overloaded link, N - node
Output: Metrics for all possible (src,dst) pairs
foreach *flow* $f \in F$ **do**
    $rate \leftarrow f.rate$
    $p \leftarrow f.path$
    $l \leftarrow length(p)$
    if $p \neq \emptyset$ **and** $l > 2$ **then**
        for $s \leftarrow 0$ **to** $l - 1$ **do**
            $src \leftarrow p[s]$
            for $d \leftarrow l - 2$ **to** l **do**
                $dst \leftarrow p[d]$
                $hops \leftarrow l - 2$
                if $d - s < 1$ **or** $dst = N$ **then**
                    break
                end
                $metric =$
                $hops * rate * nodes\_usage * modulation$
                $metric\_by\_pair[src, dst].append(metric)$
            end
        end
    end
end
$best\_src\_dst\_pair = max(avg(metric\_by\_pair))$
return $best\_src\_dst\_pair$

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falls below a certain threshold, referred to as Bypass Removal Threshold (BRT).

Release mechanism, similarly to allocation mechanism, aims to maximize resource utilization, and it can also be divided into two scenarios. As mentioned earlier, the bitrate on every link (including bypass links) in the network is measured at regular intervals. In the first scenario, when a bitrate on a bypass falls below the BRT, the whole bypass is removed (all lightpaths from that bypass are removed) ⑨. On the other hand, when the load is greater than BRT, we check how much bandwidth of the bypass is unused. Lightpath with the bandwidth which is the closest to this value and lower than it at the same time is then removed ⑩. In this way, slots are released and may be used by the next lightpath, which may potentially handle forthcoming burst traffic.

V. EVALUATION

The simulations were performed in the heavily modified Mininet network emulator. In control plane, we used custom-build Python-based multi-layer SDN controller, supporting only necessary operations. The controller was responsible both for managing emulated optical layer resources and routing and traffic engineering in the network. In data plane, we extended the Click-based FAMTAR router implementation provided in [21] with the elements necessary to communicate with the controller and operate in multi-layer architecture. At the beginning of each simulation, two classes of *veth* Linux tunnels were created between the nodes: direct

IP layer interfaces between nodes directly connected in the emulated topology and bypass interfaces between all pairs of nodes in the network. Direct interfaces were used in the calculation of IP layer routing table and for FAMTAR operation. Bypass interfaces were not visible for IP layer routing purposes and initially had their bandwidth set to 0. When a new lightpath was created by the controller on a particular source-destination pair, bandwidth of a corresponding bypass interface was being increased accordingly. After allocating a new lightpath, the most significant flows on that relation were individually redirected to the bypass from direct IP links by changing their outgoing interface entries in FFT. Similarly, when a lightpath was removed by the controller, bandwidth of a corresponding bypass interface was decreased and flows leftover on that interface were redirected back to direct IP interfaces.

We evaluated the performance of the proposed solution under various scenarios. We show that the presented bypass algorithm implementation is able to outperform standard FAMTAR implementation in given cases, as well as, save network resources.

A. SETUP

FIGURE 4. Polish network topology.

Figure 4 presents the network topology used in our experiments. Simulation parameters are summarized in Table 2. UDP and HTTP traffic generators were placed in each of the 12 nodes. Network traffic was generated according to the realistic flow distribution mixtures, provided in [22]. The models were derived from a 30-day long NetFlow trace recorded at the edge of a campus network, consisting of 4 billion flows. UDP traffic was generated using the flow length model described by equations in Appendix A.3.1 in [22]. In the case of HTTP generators, request size was modeled by flow size equations which are provided in Appendix A.2.4 in [22]. Every link was divided into 100 independent EON slots in

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TABLE 2. Simulation parameters.

Parameter	Value
Bypass creation threshold (BCT)	0.9
Bypass removal threshold (BRT)	0.2
FAMTAR activation threshold	0.7
FAMTAR deactivation threshold	0.4
Simulation length [hours]	4
Number of nodes	12
Number of links	18 (bidirectional)
Link lengths	79 - 355 km
Optical link capacity [slots]	100
Direct slots assignment [slots]	25, 50, 85, 90, 95, 100
UDP generators rates [Mbps]	45, 60, 75, 90
HTTP generators rates [Mbps]	45, 60, 75, 90

each direction, that represent frequency slices described in Section III. Depending on the input parameter, a given number of optical slots were used to create a direct link in the IP layer (direct slots assignment), and the rest of the slots were reserved for future AHB scheduling. Each simulation lasted for 4 hours wall time, where one hour represented a daily traffic envelope cycle. The traffic generators rate was the second input parameter. We conducted simulations with four generator rates that represented different levels of network saturation. Flows of UDP and HTTP traffic were created independently, with equal access to the medium. The offered traffic rates of generators were set equally for UDP and HTTP, however, the offered traffic of HTTP generators does not include the traffic needed for retransmission, and thus, this traffic can be higher depending on the TCP losses in the network. We defined the network saturation levels based on the UDP and HTTP generators rates as below:

- Non-saturated network: 45+45 Mbps (90 Mbps in total)
- Saturated network: 60+60 Mbps (120 Mbps)
- Heavily saturated network: 75+75 Mbps (150 Mbps)
- Over-saturated network: 90+90 Mbps (180 Mbps)

For every input parameter pair (number of pre-assigned slots, generator rates), simulation was repeated 5-10 times to achieve the relative error lower than 1% for the network traffic parameters based on Student's t-distribution with the significance level α equal to 0.05. These relative errors are visualized in every figure as error bars. We focused on the comparison of the following parameters:

- Average flow rate
- UDP traffic loss
- HTTP traffic rate degradation
- Size of the Flow Forwarding Tables (FFTs)
- Optical layer usage (EON slots)

Additionally, we had to make the following limitations to perform emulations successfully, especially for the optical layer. The first one assumed that the emulation environment did not contain amplifiers and regenerators. Secondly, because of the hardware limitations, traffic generators were limited to generating traffic in Mbps order of magnitude. Since the EON slot can carry traffic with higher transmission

rate, the obtained results should be rescaled considering nonlinear behaviors.

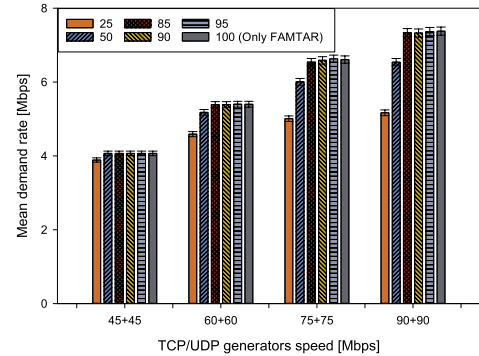### B. RESULTS
1) FLOW RATE

FIGURE 5. TCP and UDP mean demand rate.

The results in Figure 5 depict that increasing the number of direct slots between nodes in the network leads to increased traffic carrying capacity of the entire system. However, we can make two further observations. First, when 85 and more slots are allocated for direct IP layer connection, the traffic rate shows no or little change for the non-saturated network scenario. Second, the allocation of 5 slots for future bypass (95 for direct slots), introduces no additional loss even for over-saturated network case.

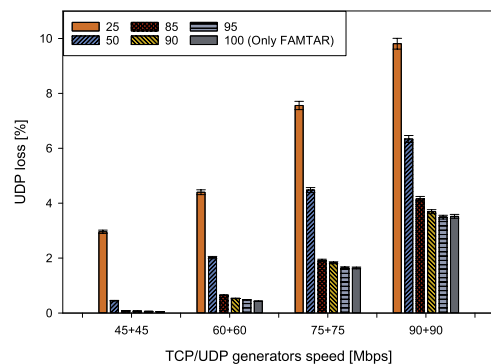#### 2) TRAFFIC LOSS/DEGRADATION

FIGURE 6. UDP loss.

Figures 6 and 7 show average UDP loss and average HTTP degradation parameter, respectively. The UDP loss is the percent of sent traffic that could not be carried by the network and did not reach the destination. In the case of HTTP traffic, which is a TCP-based protocol, traffic loss would not be an appropriate measure, as TCP limits its rate in order to maintain a constant loss. Instead, we define a HTTP badness parameter, which is a value that presents the level of degradation of the HTTP connection. The HTTP badness is calculated as a deviation of observed flow rate from its nominal rate,
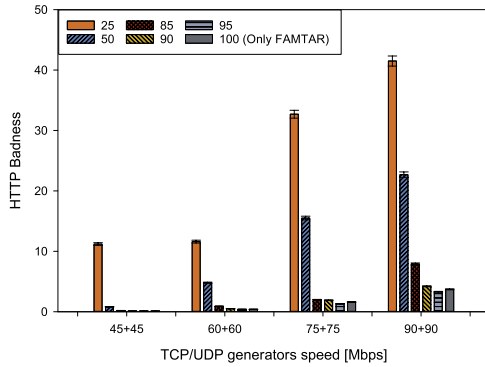
FIGURE 7. HTTP badness.

with the equation: $\frac{flow\_rate}{flow\_rate\_limit} - 1$. This means that a badness of a non-degraded flow, which transmits at its nominal rate, is equal to 0, whereas a rate lower than the nominal (higher flow completion time) would result in a higher badness. Such an approach makes HTTP badness metric similar to UDP traffic loss.

We can observe that the allocation of 90 and more slots for the direct IP layer does not change the level of both UDP loss and HTTP badness for every tested network throughput.
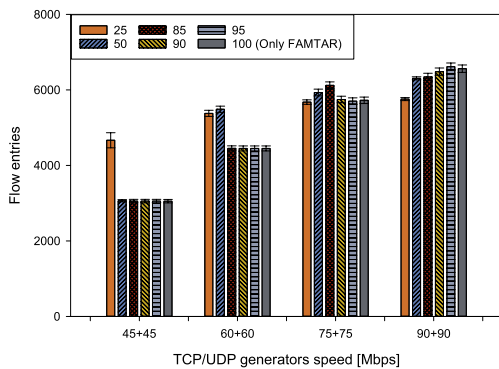
3) SIZE OF THE FFTs

FIGURE 8. Mean flow forwarding table size during simulation.

Figure 8 shows the change of Flow Forwarding Table (FFT) size. From this data, we can see two things. Firstly, as the number of direct slots remains small (25, 50) and the network is not fully saturated, the average FFT size is higher for these parameters than for the higher number of direct slots. We can explain that by the cooperation schema between FAMTAR and bypasses. FAMTAR starts to create additional routing paths as the electric layer starts to saturate earlier. This leads to an increased number of flow rules on the network devices. Secondly, as we saturate the whole network (increase the generator speeds), we can observe that there exists a limit to how FAMTAR can evolve. The FFT size between heavily saturated and over-saturated network increased only by 7% for 25 direct slots case, whereas for the

95 and 100 (only FAMTAR) direct slots cases and the same saturation levels, we observed an almost 50% increase.
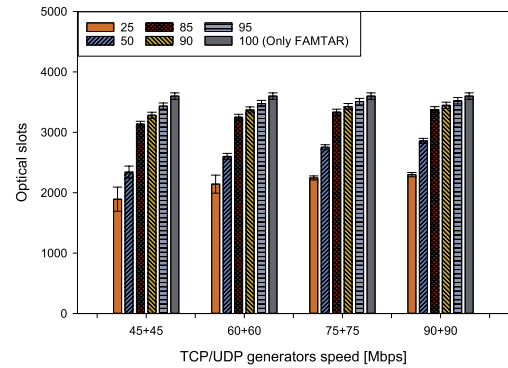
4) OPTICAL LAYER USAGE

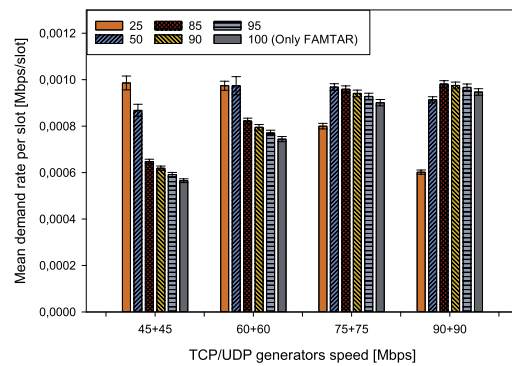**FIGURE 9. Used optical slots.**

FIGURE 10. TCP and UDP rate per slot.

One of the key advantages of the hidden bypasses solution is that it allows keeping optical resources unallocated until the heavy load occurs. Figure 9 presents average numbers of slots usage. We can observe that the slots usage depends more on the initial slots allocation, rather than the network usage. As by our EON bypass creation algorithm definition, the bypass requires at least two direct links and uses the same slot (λ) over all segments. That creates gaps over the segments spectrum that cannot be allocated for future demands. Because of that the number of slots that can be allocated decreases together with the initial slots allocation parameter and reduce possible network throughput for these parameters. That behavior does not impact results with 85 and more slots, as the number of possible bypasses is lower. The spectral efficiency for bypasses is presented in figure 10. We can observe that in every bypass configuration, we exchange more data per slot than in a non-bypass environment. However, even though, the maximum value is for 25 and 50 initial slots, we have to reject that network configuration because of huge network losses for these input parameters.

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5) ENERGY SAVINGS ESTIMATES

The proposed solution impacts both on energy used by optical transponders and IP routers port, as the not allocated sub-transponders can be switched off, and requirements for IP routing are decreased by bypassing an electric layer. Based on Energy Consumption Models presented in [23], [24] and [25], there are the most important factors in terms of network's energy efficiency. The energy model was not implemented for this research. Thus, we try to estimate the energy savings. As described in [24], for large traffic volumes, we can drop the constant parameters used in the power usage models and follow the estimates per traffic sent (W/bps). Our network does not contain amplifiers or regenerators thus we estimate the energy savings considering only IP routers and optical transponders. The description of the energy savings for the Heavily Saturated Network (150 Mbps) with 85 initial direct slots allocated is as follows.

- Optical layer - Our network model assumes the usage of fully sliceable transponders with 100 sub-transponders. During the simulation, on average 92% of sub-transponders are enabled. In the basic scenario, all sub-transponders are allocated. Thus, we get 8% gain in the optical layer energy usage as we omit other optical network elements. However, it is important to mention that the energy consumed by Optical cross-connects (OXCs) does not change between mentioned scenarios, and thus the energy gain will be a bit smaller.

- Electrical layer - During the simulation, the electrical layer served 5% less traffic compared to the basic scenario. The average bypass created during simulation has a length of 4 (2 intermediate nodes), and these intermediate nodes do not carry the bypassed traffic. As we also skip the constant part of the electrical layer, we can estimate the energy gain to be about 5%.

We estimate that depending on the initial optical allocation (lower than 85%), the power consumption can be limited up to 10% without significant losses in the traffic.

VI. CONCLUSION

This paper presents a novel cooperation technique between FAMTAR and AHB mechanisms and an algorithm which aims to minimize IP layer usage and thus minimize the power consumed by electric layer. The objectives of the proposed system were reached and the conducted simulations have proved the efficiency of the presented cooperation model and the algorithm. We notice that reservation of some initial resources for AHB can reduce losses over the network and possibly, reduce energy demand due to increased optical spectral efficiency. As per conducted experiments, we clearly see that usage of 90 direct slots allows to serve the traffic comparable to only FAMTAR allocation for every network saturation case and saves 4 to 9 percent of the optical network resources in the same time. Our evaluation shows that cooperation between FAMTAR and AHB using the introduced algorithm can increase the overall network performance observed by FAMTAR itself.

In the future, we plan to determine more dependencies between the mechanisms, as well as, examine precisely the possible energy efficiency level.

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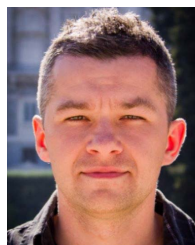
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