FSO-Based Reconfigurable Optical Networks: Source Routing for Decoupling Multilayer TE

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Abstract—**Reconfigurable layer 1 (L1) based on free-space optics (FSO) can unlock metropolitan multilayer networks for low-latency urban computing. We argue that traffic engineering (TE) at L1 can benefit from an L2 specialized connectivity tunneling system. In particular, we deploy polynomial Key-based Architecture (PolKA) for providing source-routing and tableless L2 forwarding for low-latency L3 connectivity. Considering FSO microclimate-induced lightpath optical signal-to-noise degradation, here we demonstrate the hitless properties provided by PolKA to L3 networks when performing quality of transmission (QoT) localized reconfigurations at L1.**

Index Terms—**FSO, Microclimate, QoT, OSNR, Optical Networks, Traffic Engineering.**

I. INTRODUCTION

Fiber-based communications are commonly used for high-speed transmission capacity, but in metropolitan areas when the cost of implementation is a barrier, a viable alternative is Free Space Optical Communications (FSO), which can offer point-to-point broadband wireless connectivity covering distances from hundreds of meters to tens of kilometers [1].

Optical networking enables routing lightpaths along FSO links, with higher layers benefiting from dense wavelength division multiplexing (DWDM). However, FSO faces technical challenges, particularly those linked to atmospheric issues [2].

Current networking technologies are not conceived to handle unstable links, like the ones provided by FSO. It is a well-known fact that frequent link state modifications may drive recalculations of end-to-end routing and also route flapping effects [3]. Nevertheless, FSO can conveniently replace fiber-based links in delivering the high capacity avoiding problems such as overcrowded ducts and the need of right of way permits. In addition, highly dynamic demands are posed to internet protocol (IP) in MANs, which need now to respond to urban computing services, where strict delay constraints are mandatory. Content processing and sharing in artificial intelligence (AI) between vehicles and distributed (edge) computing infrastructures have IPs (source and destination addresses) situated within MAN's reach [4]. Thus, low latency of optical networks L1 connectivity, and its reconfigurability capability, may be a key technology in such scenario. Unfortunately, there are intrinsically complex coupling effects to be managed when operating multilayer traffic engineering (TE) policies [5].

This paper exploits an alternative networking approach for decoupling multiyear issues from cost-effective IP-over-DWDM architectures for MANs with ZR+ and optical bypass (OBY) [6], but considering FSO providing the links interconnecting optical nodes. In such scenario, there will be frequent and localized lightpath TE-driven reconfigurations due to: i) Optical signal-to-noise ratio (OSNR) degradation under microclimate variations across MAN's geographic region; and ii) Optimal accommodation of dynamic demand matrix from urban computing applications and services on L1 for low latency. Such rearrangements at L1 will have an impact on upper layers. Coordinating control and management planes for L1 and L3 is a possibility, but L1 and L3 are in practice engineered independently, even with separate teams and using different platforms to maintain and operate [7].

For proper consolidation in FSO, however, we argue that decoupling multilayer issues is an important step for MANs when implementing efficient and agile TE strategies with strict delay constraints from urban computing. Our proposal uses polynomial key-based architecture (PolKA), which is a stateless source-routing L2 protocol that can be used for tunneling, and thus implementing TE-oriented resource allocation and traffic management strategies [8]. In this paper, we focus on harnessing PolKA's potential for decoupling optical packet layers for TE operations exploiting the fact that it is not a list-based source routing protocol. The subsequent sections of this paper are organized as follows: Section 2 brings the problem definition; Section 3 presents the experimental setup and presents the results; and, finally, Section 4 provides the concluding remarks.

II. PROBLEM DEFINITION AND PROPOSED SOLUTION

The performance of FSO links can be significantly affected by a range of environmental factors, such as fog, snow, rain, which can result in fading (i.e., time-dependent reduction of the received signal power) or in distortion of the wavefront [9]. Nevertheless, compared to conventional mmWave wireless, FSO has a different sensitivity to fog and rain, due to its much shorter wavelength, enabling it to compose hybrid solutions for high availability connectivity in the microclimate environment of MANs [1]. But tall buildings used to provide LOS for FSO may be the cause themselves of microclimate effects [10].

In addition, it has been found that the maximum achievable path length is much affected by microclimate, in particular, under foggy conditions for links deployed in urban areas [1]. Thus, TE in L1 must dynamically manage transparency

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level of optical paths in the FSO in reconfigurable optical networks, which can overcome physical layer problems caused by adverse whether conditions by packet level router-assisted signal regeneration. A simple scenario that illustrates a linear segment from a mesh multilayer MAN is presented Fig. 1, assuming that the routing and wavelength assignment (RWA) within L1's TE designated the "blue" lambda, which in reality would be an infrared (IR) wavelength from the DWDM spectrum, to serve a traffic demand between Building 1 and 5. Due "heavy rain" close to Building 1, increased signal attenuation to reach Building 2 will be detected by the OSNR monitoring system. The same happens at Building 5. Classically, the optical network management cares for quality of transmission (QoT) by monitoring OSNR of lightpaths. More recently, however, IP-over-DWDM can even provide such L1 visibility to L3 elements [7]. Thus, TE policy at L1 determines that the "blue" lambda must go through re-amplification, reshaping, and re-timing (3R) at Building 2; and then again at Building 4. A cost-effective approach for 3R is simply to *drop* this "blue" lambda at those buildings to the packet level; forward it to the port leading to *add* input of ROADM as shown in Fig. 1. Note that "blue" lambda is in cut-through at Building 3 meaning that no electronic processing is involved at that hop. Fully optical re-amplification may be used at ROADM in Building 3 to compensate for free-space propagation losses, but optical amplification always degrades OSNR due to amplified spontaneous emission (ASE) addition. As a result, OSNR is the metric to be used for triggering TE L1 rearrangements.

Note that the TE algorithms above L1 are, for instance, concerned with load balancing and they can be severely affected by lightpath rearrangement. L3 reacheability is usually given by routing protocols and they can be compromised when physical connectivity is modified. Creating a L2 for extra flexibility is an option to be tested. In contrast with protocols like segment routing (SR), PolKA is not based on a list-based approach for providing source routing. In PolKA, the entire path for packets to follow is encoded at the source using a (global) *routeID*, which is then independently, and not sequentially, decoded at each hop. L3 reachability would be then provided by L2 tunnels that would be potentially insensitive to microclimate-driven lightpath local reconfigurations.

A brief description of how PolKA tunneling works in favor of our goal is as follows, further details on its architecture can be found in [8]. By using node's (local) *nodeID*, the forwarding port to be used at that hop (*portID*) is promptly decoded from *routeID* using a simple MOD (i.e., the remainder of division) operation locally [8]. As a result, the forwarding port can be decoded from *routeID* regardless of the actual sequence of past (or future) hops taken by a packet. For illustrative purposes, in Fig.1, suppose a packet is labeled at source with *routeID* = 25 and ingresses at Building 1. When it reaches *nodeID* = 7, the packet is lead to *portID* 4 since $25\ MOD(7) = 4$. By the same principle, at *nodeID* = 5 in Building 2, it shall follow to *portID* 0. Note that the ROADM that connects *nodeID* = 4 in Building 3 is in a OBY state, whereas the other optical nodes are in add & drop for "blue" lambda is concerned. The packet goes to Building 3, but skips *nodeID* = 4 and directly access Building 4 optically. Once there, it reaches *nodeID* = 9 and then follows to *portID* 1 going to Building 5. As this is the endpoint of this particular lightpath, the packet egresses the lightpath via *portID* = 3 because $25\ MOD(11) = 3$.

The core concept here is the fact that a source-routed path for this L2 tunnel calculated involving all electronic hops along the path, as *routeID* = 25 in Fig.1, enables TE at L1 to independently decide to go toward transparency and back, without the need of: i) Updating *routeID*; or ii) Coordinating it with L3 elements. In the example above, ROADMs can be operated to include *nodeID* = 4 by dropping "blue" lambda at Building 3 (in case, for instance, the "heavy rain" replaces "light fog" around that building); or it could even skip both *nodeID* = 5 and *nodeID* = 9, evolving toward a transparent lightpath from Building 1 to 5, in case weather conditions evolve to clear skies.

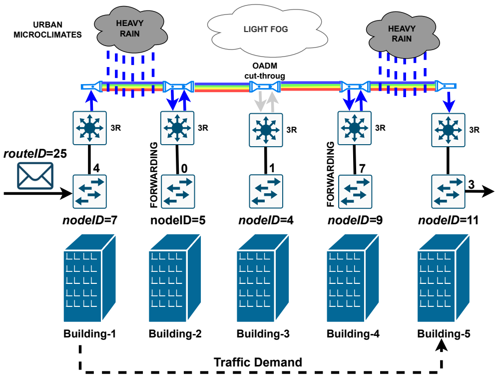

Figure 1: Illustration for a linear segment of an FSO-based multilayer (mesh) network in metropolitan areas [9] under microclimate variations [10] affecting lightpath's reach [1].

III. EXPERIMENTAL SETUP AND RESULTS

Our methodology is based on network emulations for realistic prototyping. The prototype goes under functionality tests, using ICMP-based tests (ping) for L3 connectivity evaluation; and also under performance tests quantified in terms of (iperf) throughput experiments. In order to provide a benchmark for L3 connectivity, a scenario considering standard OSPF-enabled devices with kernel-based Quagga [11] in also presented. In this case, regular Ethernet L2 is used to connect transceivers from FSO-based reconfigurable optical networks.

A PolKA source-routing prototype is implemented at (user-level) software switch *bmv2 simple_switch* with the v1model architecture as the target devide. Although this user-level PolKA may eventually underperform against kernel-based table OSPF, all the necessary functionalities demanded by PolKA, including the configuration of *CRC* polynomials for setting *NodeID* and *RouteID* calculations are present [8]. Mininet-Optical is used for realistic reconfigurable optical network layer [12] with FSO-based links respecting geographical aspects of MANs described in the literature, e.g., [1], [9]. A large set of physical layer issues can be tested alongside

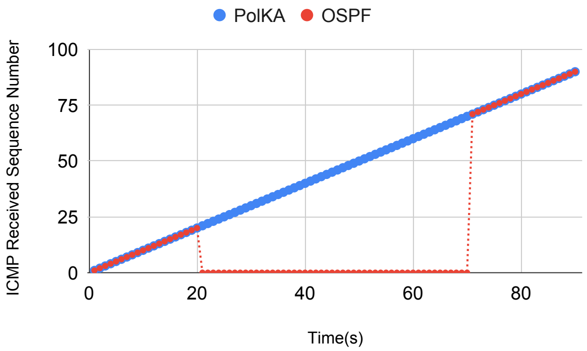

Figure 2: ICMP sequence number for received packets for Polka and OSPF with L1 reconfiguration done at 20s

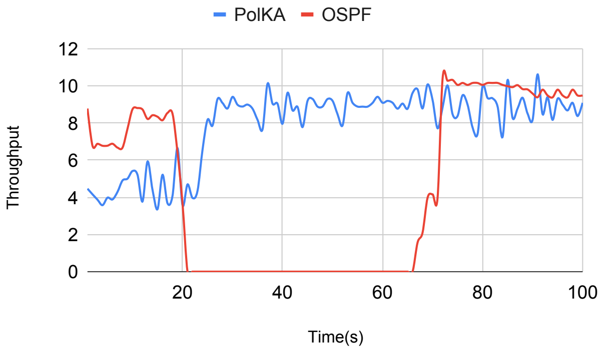

Figure 3: TCP throughput reaction to L1 reconfiguration at 20s done to bypass contending flow.

regular network protocols using our multilayer emulation framework. Nevertheless, for the purpose of this paper, a simple L1 event over a linear segment is studied: opaque to translucent reconfiguration, the latter depicted in Fig. 1.

The first functional test is to monitor ICMP echo-request (ping) for L3 connectivity test during the TE reconfiguration to cut-through at the corresponding ROADM in Building 3. Fig. 2 brings the sequence numbers for both OSPF and PolKA during that event. The gap in OSPF's curve is due to time taken for it to re-adapt to the new physical topology seen from L3's perspective, whereas PolKA provides uninterrupted L3 connectivity. As expected, the PolKA tunnel is not impacted by that sort of L1 rearrangement. Note that reconvergence takes around 50s to happen in OSPF. The second test focuses on the performance of TCP flows and implements background traffic that competes for link resources with our flow of interest (from Building 1 and heads to Building 5). As the weather conditions improve, TE at higher layer has another motivation, which is to improve the performance of the flow of interest by skipping electronic processing at Building 3. In this emulated scenario, link capacity is set at 10 Mbps for FSO links. The flow competing with our flow of interest is groomed on the originally opaque lightpath at Building 2 and leaves at Building 3. Fig.3 presents iperf-measured throughput outcomes for both OSPF-based and PolKA L3 connectivity from the flow of interest only. Note that before the 20s, both PolKA and OSPF oscillate around half of link capacity. As soon as the L1 reconfiguration is performed at ROADM in Building 3 at 20s, TCP immediately ramps up to its congestion window of our flow of interest grabbing the whole link capacity when PolKA is used. However, TCP working over an OSPF-based network has to deal with successive packet losses during the reconvergence of its routing tables, as already seen in Fig. 2. The gap in fig.3 for OSPF will reduce the average throughput achieved by our flow of interest.

IV. Conclusion and Future Works

PolKA's L2 tunneling for provisioning low-latency L3 connectivity built over microclimate-impacted FSO links was demonstrated. TE can handle separately FSO's physical layer issues avoiding reachability problems caused by the convergence interval of OSPF-based routing protocols when adapting L1 for dynamics of microclimate variations. Future works will address larger network instances, FSO propagation models, and AI mechanisms over OSNR monitoring for automation of TE policies. In addition, key-based source routing in PolKA has traffic steering properties and this, like in [13] service function chaining, may be used for consolidating the implementation of multilayer TE solutions.

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