Traffic Engineering System Based Onmulti-Topology Routing Techniques

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Abstract

Handling traffic dynamics in order to avoidnetwork congestion and subsequent service disruptions is one of the key tasks performed bycontemporary network management systems.Given the simple but rigid routing and forwardingfunctionalities in IP base environments, efficient resource management and control solutionsagainst dynamic traffic conditions is still yet tobe obtained. In this article, we introduce an efficient traffic engineering andmanagement system that performs adaptive traffic control by using multiple virtualized routingtopologies. The proposed system consists of twocomplementary components: offline link weightoptimization that takes as input the physical network topology and tries to produce maximumrouting path diversity across multiple virtualrouting topologies for long term operationthrough the optimized setting of link weights.Based on these diverse paths, adaptive trafficcontrol performs intelligent traffic splittingacross individual routing topologies in reactionto the monitored network dynamics at shorttimescale. According to our evaluation with realnetwork topologies and traffic traces, the proposed system is able to cope almost optimallywith unpredicted traffic dynamics and, as such, itconstitutes a new proposal for achieving betterquality of service and overall network performance in IP networks.

1. Introduction

Traffic Engineering (TE) is an essential aspect ofcontemporary network management. Offline TEapproaches aim to optimize network resources ina static manner, but require accurate estimationof traffic matrices in order to produce optimizednetwork configurations for long-term operation(a resource provisioning period each time, typically in the order of weeks or even longer). However, these approaches often exhibit operationalinefficiencies due to frequent and significant traffic dynamics in operational networks. Take thepublished traffic traces dataset in the GEANT network as an illustration. The actual maximum link utilization (MLU) dynamics is substantial on a daily basis, varying from less than 40 percent during off-peak time to more than 90 percent in busy hours! As such, using one single traffic matrix as input for offline computing a static TE configuration is not deemed as an efficient approach for resource optimization purposes in such dynamic environments.

Traffic engineering for plain IP-based net-works (we will be referring to these as IGP-based networks, as is common in the literature since they route traffic based on the Interior Gateway Protocol, OSPF or IS-IS) has received a lot of attention in the research community. Existing IGP-based TE mechanisms are only confined to offline operation and hence cannot cope efficiently with significant traffic dynamics. There are well known reasons for this limitation: IGP-based TE only allows for *static* traffic delivery through native IGP paths, without flexible traffic splitting for dynamic load balancing. In addition, changing IGP link weights in reaction to emerging network congestion may cause routing re-convergence problems those potentially disrupt ongoing traffic sessions. In effect, it has been recently argued that dynamic/online route re-computation is to be considered harmful even in the case of network failures [5], let alone for dealing with traffic dynamics.

In recent years, the concept of virtual net-works has received increasing attention from the research community, with the general spirit being to enable virtualized network resources on top of the same physical network infrastructure. Such resources not only include physical elements such as routers or links, but also soft resources such as logical network topologies through configurations that allow them to coexist gracefully. Our motivation differs from the existing proposals focusing on virtual network provisioning to support service differentiation, resource sharing or co-existing heterogeneous platforms [6]. Instead, we consider how multiple “equivalent” virtual net-work topologies, each having its own routing configuration (such as IGP link weight setting), can be used for multi-path enabled adaptive traffic engineering purposes in IP-based networks. Multi-topology aware Interior gateway routing protocols (MT-IGPs) [7] are used as the underlying platform for supporting the coexistence of multiple virtual IGP paths between source-destination (S-D) pairs on top of the physical network infrastructure.

In our proposal we introduce AMPLE (Adaptive MultitoPoLogy traffic Engineering), a holistic system based on virtualized IGP routing topologies for dynamic traffic engineering. The fundamental idea behind this scheme follows the strategy of *offline* provisioning of multiple diverse paths in the routing plane and online spreading of the traffic load for dynamic load balancing in the forwarding plane, as advocated in [5]. The approach can be briefly described as follows. MT-IGPs are used as the underlying routing protocol for providing traffic-agnostic intra-domain path diversity between all source-desti-nation pairs. With MT-IGP routing, customer traffic assigned to different virtual routing topologies (VRTs) follows distinct IGP paths according to the dedicated IGP link weight con-figurations within each VRT.

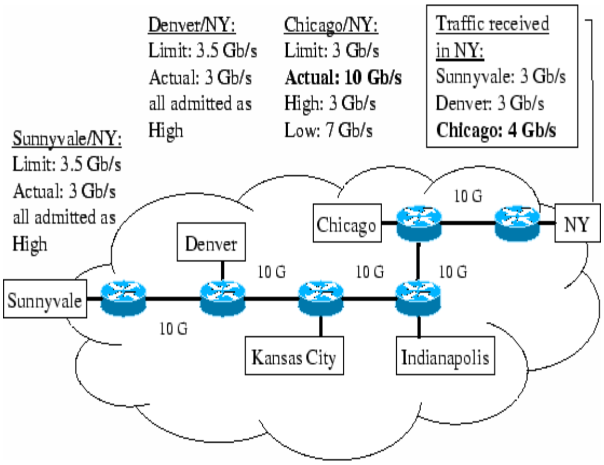

Figure 1.*Providing path diversity in the Abilene network topology.*

Figure 1 depicts an illustration of how path diversity can be achieved for S-D pairs in the Point-of-Presence (PoP) level Abilene network topology with three VRTs, by considering as an example from Sunny Vale to Washington. The *i*th number in the bracket associated with eachlink is the IGP weight assigned to it in the *i*th VRT. As illustrated in the figure, with each net-work link assigned distinct IGP link weights in the three VRTs, completely non-overlapping paths can be provisioned between the S-D pair. As such, the key task of the offline configuration is to compute MT-IGP link weights for providing maximum path diversity for every S-D pair. Once these link weights have been configured in the network, an adaptive algorithm in the for-warding plane performs traffic splitting ratio adjustment for load balancing across diverse IGP paths in short timescale (e.g. hourly or even more frequently) according to the monitored network and traffic conditions.

From a system point of view, AMPLE consists of two major components. The Offline Link Weight Optimization (OLWO) component focuses on the *static* dimensioning of the underlying network, with MT-IGP link weights computed for maximizing intra-domain path diversity across multiple VRTs. Once the optimized link weight configuration has been enforced onto the network, the Adaptive Traffic Control (ATC) component performs short timescale traffic splitting ratio adjustment for adaptive load balancing across diverse IGP paths in the engineered VRTs, according to the up-to-date monitored traffic conditions. Given the fact that traffic dynamics are both frequent and substantial in today's ISP net-works, our proposed TE system offers a promising solution to cope with this in an efficient manner.

Example for Providing Path Diversity in the Network

Path diversity generally describes that the source nodehave multiple routes to reach the destination.Number ofpaths for a packet to transit between two points

- ⇨ Inside an autonomous system network (ISP)
- ⇨ Fully link and PoP (Point of Presence) disjointpaths
- ⇨ Observed at IP level

2. SYSTEM OVERVIEW

Figure 2 presents an overall picture of the pro-posed AMPLE TE system, with Offline MT-IGP Link Weight Optimization (OLWO) and Adaptive Traffic Control (ATC) constituting the key components. As previously mentioned, the ultimate objective of OLWO is to provision offline maximum intra-domain path diversity in the routing plane, allowing the ATC component to adjust at short timescale the traffic assignment across individual VRTs in the forwarding plane. A salient novelty is that the optimization of the MT-IGP link weights does not rely on the avail-ability of the traffic matrix *a priori*, which plagues existing offline TE solutions due to the typical inaccuracy of traffic matrix estimations. Instead, our offline link weight optimization is only based on the characteristics of the network itself, i.e. the physical topology. The computed MT-IGP link weights are configured in individual routers, and the corresponding IGP paths within each VRT are populated in their local routing information bases (MT-RIBs). While OLWO focuses on static routing configuration in a long timescale (e.g. weekly or monthly), the ATC component provides complementary functionality to enable short timescale (e.g. hourly) control in response to the behavior of traffic that cannot be usually anticipated.

As shown in the figure, the input for ATC includes:

- The diverse MT-IGP paths according to the link weights computed by OLWO.
- Monitored network and traffic data such as incoming traffic volume and link utilizations.

At each short-time interval, ATC computes a new traffic splitting ratio across individual VRTs for re-assigning traffic in an optimal way to the diverse IGP paths between each S-D pair. This functionality is handled by a centralized TE manager who has complete knowledge of the network topology and periodically gathers the up-

to-date monitored traffic conditions of the operating network. These new splitting ratios are then configured by the TE manager to individual source PoP nodes, who use this configuration for remarking the multi-topology identifiers (MT-IDs) of their locally originated traffic according-ly. The TE manager function can be realized as a dedicated server, but for robustness and resilience it can be implemented in a distributed replicated manner for avoiding the existence of a single point of failure. In the next section we present the detailed design of individual components in the AMPLE system.
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3. COMPONENT SPECIFICATION

3.1 OFFLINE LINK WEIGHT OPTIMIZATION

First of all, a fundamental issue in OLWO is how to determine the definition of "path diversity" between PoPs for traffic engineering. Let's consider the following two scenarios of MT-IGP link weight configuration. In the first case, highly diverse paths (e.g. end-to-end disjoint ones) are available for some PoP-level S-D pairs, while for some other pairs individual paths are completely overlapping with each other across all VRTs. In the second case, none of the S-D pairs have dis-joint paths, but none of them are completely overlapping either. Obviously, in the first case if any "critical" link that is shared by all paths becomes congested, its load cannot be alleviated through adjusting traffic splitting ratios at the associated sources, as their traffic will inevitably travel through this link no matter which VRT is used. Hence, our strategy targets the second scenario by achieving "balanced" path diversity across all S-D pairs.

Toward this end, we define the binary metric of Full Degree of Involvement (FDoI) to evaluate the overall path diversity for a given MT-IGP link weight configuration. More specifically, the FDoI value for a link with respect to an S-D pair is set to 1 if this link is shared by the shortest IGP paths across all VRTs for that S-D pair; otherwise it is set to 0. Let's take Fig. 1 as an example again. The FDoI value for the link from Sunny Vale to LA with regard to the S-D pair (Seattle, LA) is 1, as this link is part of all the shortest IGP paths between Seattle and LA across the three VRTs. In comparison, the FDoI value for the same link with regard to the S-D pair (Sunny Vale, Washington) is 0, as alternate routes are available via Denver in other VRTs. The optimization objective of OLWO is to minimize the sum of FDoI values across all network links with regard to all S-D pairs. If this sum is equal to 0, then no critical link is formed given the underlying MT-IGP link weights, which means that at least one source in the network will always be able to find alternative path(s) to bypass the over-loaded link given any single link congestion scenario.

Our solution is based on an offline optimization algorithm for maximizing path diversityacross multiple VRTs (see [1] for details), and our evaluation based on two operational net-works shows good path diversity performance: only three VRTs are sufficient to avoid any critical link for the GEANT network topology, while the Abilene topology needs four VRTs to achieve the same goal. As we will show later, even without necessarily creating high path diversity for every S-D pair, there is a high chance of achieving near-optimal TE performance based on the MT-IGP link weight setting in OLWO.

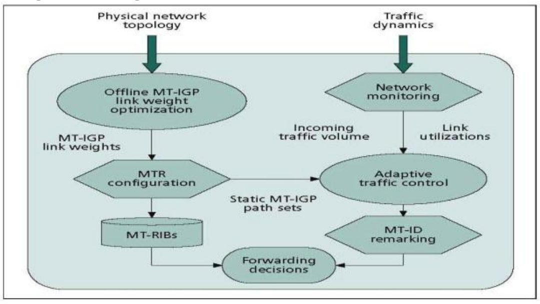

Figure 2: AMPLE system overview.

3.2 NETWORK MONITORING

Network monitoring is responsible for collecting up-to-date traffic conditions in real-time and plays an important role for supporting the ATC operations. AMPLE adopts a hop-by-hop based monitoring mechanism that is similar to the proposal of [8]. The basic idea is that a dedicated monitoring agent deployed at every PoP node is responsible for monitoring:

- The volume of the traffic originated by the local customers toward other PoPs (intra-PoP traffic is ignored).
- The utilization of the directly attachedinter-PoP links.

As shown in Fig. 3, this monitoring agent gathers data on the locally originated traffic volume from all the access routers (ARs) attached to customers at the PoP. Meanwhile the agent also collects the utilization of the directly attached inter-PoP links from individual backbone routers (BRs).

These statistics are then used by the central TE manager for updating its maintained traffic engineeringinformation base (TIB, to be introduced in the next section) and computing traffic splitting ratios for the next interval. Such a hop-by-hop based paradigm works efficiently in a TE system with a central manager. The main reason is that new traffic splitting ratios are computed by the TE manager who is able to have the global view of the network, enabling it to achieve a global optimum in traffic control.

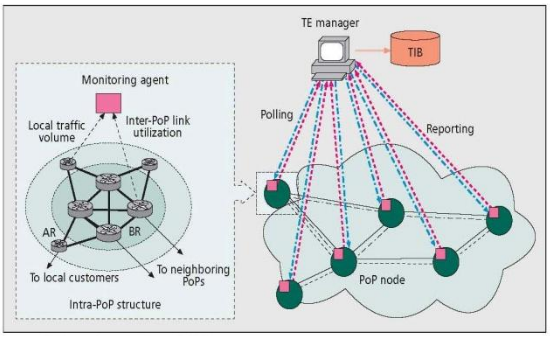

Figure 3.Network monitoring and ATC.

3.3 ADAPTIVE TRAFFIC CONTROL

Given the optimized MT-IGP link weights produced by OLWO, adaptive traffic control (ATC) can be invoked at short-time intervals during operation in order to re-optimize the utilization of network resources in reaction to traffic dynamics. The optimization objective of ATC is to minimize the maximum link utilization (MLU), which is defined as the highest utilization among all the links in the network. The rationale behind ATC is to perform periodic and incremental traffic splitting ratio re-adjustments across VRTs based on traffic pattern "continuity" at short a timescale, but without necessarily performing a global routing re-optimization process from scratch every time. In this section, we present a lightweight but efficient algorithm that can be applied for adaptive adjustment of the traffic splitting ratio at individual PoP source nodes to achieve this goal. In a periodic fashion, the following two operations are performed:

- Measure the incoming traffic volume and the network load for the current interval as described in the previous section.
- Compute new traffic splitting ratios at individual PoPsource nodes based on the splitting ratio configuration in the previous interval, according to the newly measuredtraffic demand and the network load for dynamic load balancing.

Figure 4 presents the structure of our proposedTIB, which consists of two inter-related repositories, namely the Link List (LL) and the S-D Pair List (SDPL). The LL maintains a list of entries for individual network links. Each LL entry records the latest monitored utilization of a link and the involvement of this link in the IGP paths between associated S-D pairs in individual VRTs. More specifically, for each VRT, if the IGP path between an S-D pair includes this link, then the ID of this S-D pair is recorded in the LL entry. It is worth mentioning that this involvement information remains static after the MT-IGP link weights have been configured (static information is presented in black in Fig. 4, while dynamic information that needs to be updated periodically at short timescale is shown in red). On the other hand, the SDPL consists of a list of entries, each for a specific S-D pair with the most recently measured traffic volume from S to D. Each SDPL entry also maintains a list of subentries for different VRTs, with each recording the splitting ratio of the traffic from S to D, as well as the ID of the bottleneck link along the IGP path for that S-D pair in the corresponding topology.

ATC is performed based on the up-to-date data maintained in the TIB. We start the ATC algorithm description by defining the following parameters:

- $t(u,v)$ — traffic from the source PoP node u to the destination PoP node v.
- $\phi_{u,v}(r)$ — traffic splitting ratio of $t(u,v)$ at u on routing topology r, $0.0 \le \phi_{u,v}(r) \le 1.0$.

The algorithm consists of the following threesteps. We define an iteration counter y which isset initially to zero.

Step 1: Identify the most utilized link $l$max inthe network, which can be simply achieved byvisiting the updated LL in the TIB.

Step 2: For the set of S-D pairs whose trafficflows are routed through $l$max in *at least one butnot all* the routing topologies (i.e. *FDoI*= 0),consider each one at a time and compute its newtraffic splitting ratio among the VRTs until thefirst feasible one is identified (see details in thefollow-up description). A feasible traffic flowmeans that, with the new splitting ratios, the utilizationof $l$max can be reduced without introducingnew hot spots with utilization higher than theoriginal value. To support this operation, all feasibleS-D pairs that meet the above requirementare identified from the entry of $l$max in the LL.

Step 3: If such a feasible traffic flow is found,accept the corresponding new splitting ratioadjustment. Increment the counter y by one andgo to Step 1 if the maximum K iterations havenot been reached (i.e. $y \le K$). If no feasible trafficflow exists or $y = K$, the algorithm stops andthe latest resulting values for the traffic splittingratio are configured in the corresponding entryin the SPDL in order to be executed by individualsource PoP nodes.

The parameter K controls the algorithm torepeat at most K iterations in order to avoidlong running time. The value of K can be carefullydetermined by taking into account thetrade-off between the TE performance and systemcomplexity. In Step 2, the task is to examinethe feasibility of reducing the load of themost utilized link by decreasing the splittingratios of a traffic flow assigned to the routingtopologies that use this link, and shift a proportionof the relevant traffic to alternative pathswith lower utilization in other topologies. Morespecifically, the adjustment works as follows.First, a deviation of the traffic splitting ratio,denoted by δ where $0.0 < \delta \leq 1.0$, is taken outfor trial. For the traffic flow $t(u,v)$ under consideration,
let$R+$ be the set of routing topologiesin which the IGP paths from u to v traverse $l$max.The main idea is to decrease the sum of trafficsplitting ratios on all the routing topologies in$R+$ by δ and at the same time to increase thesum of the ratios on other topologies that donot use $l$max by δ. (We denote this set of topologiesby $R–$ where $R– = R \backslash R+$.) Specifically, forall the topologies in $R+$, which share a commonlink with the same (maximum) utilization, theirtraffic splitting ratios are evenly decreased.Hence, the new traffic splitting ratio for eachrouting topology in $R+$ becomes:

$$\varphi u,v(r)' = \varphi u,v(r) - \delta/R+ \;\forall r \in R+$$

On the other hand, let μrbe the bottlenecklink utilization of the IGP path in routing topology$r \in R–$. To obtain μr, the TE manager shouldfirst identify the ID of the bottleneck link alongthe IGP path between the associated S-D pairfrom the SDPL, and then refer to the LL toobtain its utilization. The traffic splitting ratio ofeach routing topology in $R–$ increases in aninverse proportion to its current bottleneck linkutilization, i.e.

$$\phi_{u,v}(r)' = \phi_{u,v}(r) + \left(\frac{1-\mu_r}{\sum\limits_{r \in R^-} 1-\mu_r} \times \delta \right) \quad \forall r \in R^-$$

The lower (higher) the bottleneck link utilization,the higher (lower) the traffic splitting ratiowill be increased.An important issue to be considered is thevalue setting for δ. If not appropriately set, itmay either lead to slow convergence or overshootthe traffic splitting ratio, both of which areundesirable. On one hand, too large value of δmay miss the chance to obtain desirable splittingratios due to the large gap between each trial.On the other hand, too small (i.e. too conservative)value of δ may cause the algorithm to performmany iterations before the mostappropriate value of δ is found, thus causingslow convergence to the equilibrium. Taking thisconsideration into account, we apply an algorithmto perform an exponential increment of δstarting from a sufficiently small value. If thisadjustment is able to continuously reduce theutilization of $l$max without introducing negativenew splitting ratios on $R+$, the value of δ will beincreased exponentially for the next trial until nofurther improvement on the utilization can bemade or the value of δ reaches 1.0 (i.e. the maximumtraffic splitting ratio that can be applied).

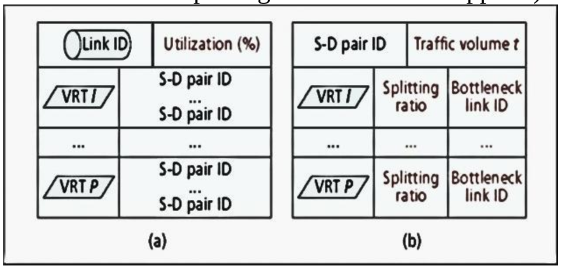

Figure 4. Traffic engineering information base structure: a) entry structure of LL; and b) entry structure of SDPL.

4. WORKING AS A WHOLE SYSTEM

After presenting the detailed information onindividual components, we now briefly describehow they work in unison as a whole TE system.First, optimized MT-IGP link weights are configuredon top of the underlying MT-IGP platformand remain static until the next offline OWLOcycle. During this period, ATC plays the majorrole for adaptively re-balancing the load accordingto the traffic dynamics in short-time intervals.As a bootstrap procedure, the initial traffic splittingis evenly distributed across VRTs, but thiswill be recomputed based on follow-up trafficmonitoring results. The TE manageraccordingly updates the traffic volume betweeneach S-D pair in the SDPL and link utilizationinformation stored in the LL of the TIB. Accordingto the obtained link utilization information**,**the bottleneck link IDalong the IGP pathsbetween individual S-D pairs in each VRT is also updated in the SDPL. Based on the updatedinformation, the TE manager computes the newtraffic splitting ratio for each S-D pair acrossindividual routing topologies. These new splittingratios are configured in the SDPL and the TEmanager then instructs all the source PoP nodeswithin the network to use these new values fortraffic splitting during the next interval. In addition,these values in the SDPL will also be usedas the starting point for the future computationof the splitting ratios in the next interval. Onceeach source PoP node has received the new valuesfor traffic splitting from the central TE manager,it enforces them by remarking the MT-IDvalues carried by the locally originated trafficpackets in the new proportions across individualrouting topologies.

5. EXPERIMENTAL RESULTS

In order to evaluate the performance ofAMPLE, we use the real topologies and traffictraces from the GEANT and Abilene networksthat are provided by the TOTEM Project [10].We present results based on a seven-day longtraffic traces dataset. Although the dataset in[10] provides traffic traces measured every fiveminutes, for consistency with the GEANT scenario,we also use seven-day long traffic matricesat the interval of every 15 minutes. In this articlewe compare the following optimization methods:

Actual: The actual static link weight setting inthe current operational networks. MT-IGP routingis not used.

Multi-TM: We use the TOTEM toolbox tocompute a set of static link weights for multipletraffic matrices. The objective is to make theIGP TE robust to traffic demand uncertainty [3].Specifically, the link weights are computed at thebeginning of each day based on the sampledtraffic matrices (one per hour) on the same dayof the previous week. MT-IGP routing is notused.

AMPLE-n: Our proposed adaptive TE algorithmthat runs based on *n* MT-IGP routingtopologies with their link weights computed bythe OLWO. The ATC operations are performedat 15 minute intervals according to the latestmeasured traffic conditions.

Optimal: As the baseline for our comparisons,we use the GNU Linear Programming Kit(GLPK) function in the TOTEM toolbox tocompute the optimal MLU for each distinct trafficmatrix associated with the given topologies.Figure 5 plots the MLU versus the time intervalsof traffic traces for the GEANT and Abilenenetworks. From the figure we can have anoverall glance of the traffic dynamics pattern inboth networks during the sampling period. In afurther evaluation, Table 1 shows results of thefollowing additional statistics that are derivedfrom Fig. 5:

• **Average maximum link utilization (AMU):** The average value of the MLU across all thetraffic traces during the seven-day period.

• **Highest maximum link utilization (HMU):** The highest value of the MLU across allthe traffic traces during the period.

• **Proportion to near-optimal performance (PNO):** The percentage over all the traffictraces in which AMPLE can achieve nearoptimalperformance. We define here themeaning of near-optimality to be the MLUthat is within 3 percent of the gap fromOptimal.

An overall observation is that *AMPLE cansubstantially reduce the MLU for most of the traffic traces*. For example, in the GEANT network,the *Actual* link weight approach produces AMUthat is 86 percent higher than that of the optimalvalue, whereas with AMPLE the value variesbetween 0.1 percent and 43 percent, dependingon the number of routing topologies that areused. In general, the larger the number of routingtopologies used, the closer to the optimalperformance can be achieved. Similar results arealso observed for the HMU performance.For the PNO metric in Table 1, if AMPLE isbased on two routing topologies, the value is only13.1 percent but it still performs significantly betterthan all the other approaches. We can nowstart to see the practical usefulness of ourapproach for improving network utilization:When the number of routing topologies increasesto three, the PNO boosts up to 78.3 percent.With 99.6 percent of all the traffic traces,

6. SUMMARY

In this article we have introduced AMPLE, anovel TE system based on virtualized IGP routing that enables short timescale traffic control against unexpected traffic dynamics using multitopology IGP-based networks. The framework encompasses two major components, namely, Offline Link Weight Optimization (OLWO) and Adaptive Traffic Control (ATC). The OLWO component takes the physical network topology as the input and aims to produce maximum IGP path diversity across multiple routing topologies through the optimized setting of MT-IGP link weights. Based on these diverse paths, the ATC component performs intelligent traffic splitting adjustments across individual routing topologies in reaction to the monitored network dynamics at short timescale. Our experiments based on the GEANT and Abilene networks and their real traffic traces have shown that AMPLE has a high chance of achieving near-optimal network performance with only a small number of routing topologies, although this is yet to be further verified with traffic traces data from other operational networks when available. A potential direction in our future work is to consider a holistic TE paradigm based on AMPLE, which is able to simultaneously tackle both traffic and network dynamics, for instance network failures.

Table 1: MLU performance statistics.

Optimization Method	GEANT (%)			Abilene (%)		
	AMU	HMU	PNO	AMU	HMU	PNO
Optimal	30.05	52.82	—	12.2	33.42	—
Actual	55.74	96.91	0	19.59	63.24	1.19
Multi-TM	48.56	104.15	0.44	53.2	230	0.15
AMPLE-2	42.9	94.61	13.08	18.61	60.96	64.14
AMPLE-3	31.95	60.36	78.34	12.36	33.44	88.69
AMPLE-4	30.08	52.88	99.56	12.4	49.6	97.77

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