King's Research Portal

DOI:
10.1109/TMC.2017.2741479

Document Version
Peer reviewed version

Link to publication record in King's Research Portal

Citation for published version (APA):
Farhoudi, M., Abrishamchi, B., Mihailovic, A., & Aghvami, A. H. (2018). Analysis of Practical Aspects of Multi-Plane Routing-based Load Balancing Approach for Future Link-State Convergent All-IP Access Networks. *IEEE Transactions on Mobile Computing*, *17*(4), 803-816. https://doi.org/10.1109/TMC.2017.2741479

Citing this paper
Please note that where the full-text provided on King's Research Portal is the Author Accepted Manuscript or Post-Print version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version for pagination, volume/issue, and date of publication details. And where the final published version is provided on the Research Portal, if citing you are again advised to check the publisher's website for any subsequent corrections.

General rights
Copyright and moral rights for the publications made accessible in the Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognize and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the Research Portal

Take down policy
If you believe that this document breaches copyright please contact librarypure@kcl.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 13. Jan. 2025

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMC.2017.2741479, IEEE Transactions on Mobile Computing

Analysis of Practical Aspects of Multi-Plane Routing-based Load Balancing Approach for Future Link-State Convergent All-IP Access Networks

Mohammad Farhoudi, *Member, IEEE,* Benyamin Abrishamchi, *Member, IEEE,* Andrej Mihailovic, *Member, IEEE,* and A.Hamid Aghvami, *Fellow, IEEE*

***Abstract*—With the expected surge in the global IP traffic, service providers would need to adapt accordingly to operate disruption and loss free networks supported with the developing IP infrastructure. With the disposal of the hierarchical network structure, radio access networks are moving towards a flat-IP architecture and novel topological set-ups in the backhaul. Hence, a routing paradigm that employs suitable Traffic Engineering (TE) techniques aligned with the developing nature of future access networks must be applied. It becomes imminent that the routing considerations for IP access networks converge with the ones found in conventional intra-domain routing. In this paper, Multi-Plane Routing (MPR) that consolidates various aspects in all-IP infrastructure is extensively studied in access network structures. We propose a MPR-based TE approach considering two different scenarios to reflect the evolution in the architectural design of access network structures under a realistic traffic scenario with a varying range of internal/external traffic. Moreover, a new optimization framework for the offline and online TE mechanisms of MPR have been formulated. Accordingly, a practical performance evaluation testing the validity of the aforementioned scenarios is presented. Our simulation results demonstrate extensive analysis in terms of several performance criteria in networks. It is convincingly shown that for ranges of topologies, MPR's utilization of whole topology in building path diversity in networks, allows for significant improvement of networks capacity, performance and support for meshing.**

***Index Terms*—Traffic engineering, link-state routing, intra-domain routing, multi-path routing, load balancing, IP access networks, backhaul networking.**

I. INTRODUCTION

THE rising number of exciting new devices associated with the growing context-aware and real-time applications over the Internet calls for a consistent transformation in the routing protocols supporting these applications. Correspondingly, it is becoming essential for cellular network operators and IP Network Providers (INPs) to adopt Traffic Engineering (TE) as an indispensable tool in managing networks' resources to meet this growing traffic demand on both inter- and intra-domain scales [1]. With the expected surge in the global IP traffic, there has been an adoption of open IP interfaces in the integrated backhaul network designs [2]. This is indicative of the cellular wired backhaul and Internet access based network designs converging on the IP-based infrastructure model. Henceforth, we refer to this design space as all-IP access networks. Since such networks are at the edges of the Internet routing fabric, we focus on intra-domain TE accordingly.

Intra-domain TE is categorized into the MPLS (Multiprotocol Label Switching)- and IP-based TE. Presently, MPLS is extensively deployed in access networks through which encapsulated IP packets are delivered over Labelled Switched Paths (LSPs). Explicit routing and arbitrary splitting of traffic are enabled through MPLS. However, scalability and robustness become an issue due to the complexity and overhead associated with building and maintaining LSPs to which flows are mapped and the extra information added to each packet [1]. IP-based TE is implemented through the manipulation of link weights in case of Interior Gateway Protocols (IGPs) such as Open Shortest Path First (OSPF) which is a commonly used intra-domain dynamic link-state IP IGP. As opposed to MPLS TE, IP TE does not facilitate explicit routing and arbitrary splitting of traffic intrinsically as it is based on the shortest-path routing principle with relatively slow recalculation of paths.

Equal-Cost Multi-Path (ECMP) is an add-on option of OSPF based on which traffic is split roughly equally between multiple paths of equivalent cost through hop-by-hop forwarding. ECMP can not be configured in complex large-scale topologies as the quality of OSPF TE can become arbitrarily poor compared to optimal TE due to the computational intractability to derive optimal link weights for large-scale networks [3]. There are notable studies on improving the optimality of IP-based intra-domain TE mechanisms based on ECMP. The studies consider the possibility of achieving some immediate load balancing using path diversity by capitalising on the flexible use of network topology.

The remainder of this paper is organized as follows: Section II presents an elaboration on background and novelty of the work. Section III sets out our system model and is comprised of the concept and the network model. The problem formulation and its associated notations are presented in section IV. Section V presents the experimental demonstrations. Finally, section VI concludes the paper.

II. BACKGROUND AND NOVELTY

A. Related Work

The legacy ECMP has been specifically adopted by authors in [4] for improved ECMP based load balancing purposes. This is achieved by having a sub-set of available next hops selected for each destination prefix rather than dispensing the traffic equally between all the possible available next hops. An optimal ECMP-based TE method was proposed in [5] where virtual links are installed alongside the existing physical ones with the aim of tackling the stringent equal traffic distribution solely between paths of equal least-cost. However, the aforementioned ECMP-based schemes are still dependent on the link weight setting, making them slow, subject to performance degradation and deviation from optimal TE. To address the latter issues, authors in [6] proposed an ECMP-based protocol that applies Network Entropy Maximization (NEM) based on which traffic is to be split among all the available paths enabling the arbitrary splitting of traffic. Recent work [7] reapplies NEM to provide load balancing in IP networks using uneven ECMP-facilitated traffic splitting by introducing an alternate set of links weights while preserving the shortest path conditions in networks. However, these protocols are dependent on occurrences of equal cost paths in segments of networks where routers are involved in the calculations of entire paths [6] and path reconfigurations are in the order of minutes [7].

Multi-Plane Routing (MPR) which was initially proposed in [8] aims to address the deficiencies associated with MPLS and OSPF/ECMP in increasingly relevant access networks' topologies. MPR is based on Multi-Topology OSPF (MT-OSPF) principle [9] that enables multiple instances of OSPF in an intra-domain network. MT-OSPF was primarily proposed for fast re-route in case of node/link failure but its principle was adapted for load balancing purposes in intra-domain networks [10]. MPR was built upon the use of MT-OSPF as applied in [10] for comprehensive network-wide load balancing by being specifically targeted for IP access network topologies. MPR is comprised of an offline TE method that serves to build logical Routing Planes (RPs) rendering a set of multiple shortest paths between all *Ingress - Egress* routers ahead of the traffic flow in the network that is then governed by an online TE approach. MPR's online TE approach was initially presented in [11] and [12] serving a practical purpose of an integrated solution of distributing IP sessions over RPs.

MPR's constructed logical RPs represent instances of OSPF such that path diversity is maximized. The RPs are built so that an optimum full utilization of links based on Full Path Diversity Index (FPDI) is achieved as outlined in [8]. Path diversity and its potential benefits in access networks was investigated in [13]. This study undermined the need for next-generation access networks' evolution to more meshing in topologies in order to exploit path diversity that can be achieved by multi-path routing. MPR achieves explicit routing and arbitrary splitting of traffic (as achieved under MPLS TE approach) by applying an IP-based TE approach. Therefore, the complexity and overhead associated with the MPLS TE approach can be avoided. Recent proposals [14] similarly classify and apply practicality in bridging the characteristics of explicit routing (e.g. MPLS) and destination-based routing (e.g. IP-based routing such as OSPF) toward the goals of path diversity offered by multi-path routing. Relevance of path diversity in access networks' evolution has inspired further studies on MPR in [15] and [16] that provide the foundations for this work. [15] contains a theoretical study of the offline's quality of RPs when extended with internal traffic routing paths subject to hop-constrained optimization. Early practical results with the added internal traffic distributions for one topology are presented in [16] with the readjusted online TE approach as compared with [11] and [12].

B. Discussion on the Investigated Practicality

The structure of IP access networks calls for new considerations in IP-routing mainly due to tree-like topologies. Access networks are generally comprised of a transit routing space that connects the access nodes to the core network through gateway. Traffic flows between gateway and access nodes in both directions, and between access nodes. Such access network structures are necessitated by the practical requirements of deployments. These requirements dictate network planning to conform with diverse topological layouts of heterogeneous access points and deployed infrastructures. In the recent evolution of networks [17], randomness of topological layouts imposes novel challenges for TE due to expected capacity constrains in backhaul links of interconnected femto, pico, micro and macro accesses. Furthermore, novel user mobility models have emerged for these network access structures aligned with the 5G development [18].

A reference scenario was studied for MPR in [11] and [12] where the RP structure's construct was such that only dedicated RPs (i.e. paths) for every *Gateway (GW)-Aggregation Router (AR)* pair were considered. Under this scenario, GW was considered to be the only possible anchoring point of traffic in the network, hence, bulk of traffic in the network would have been of downlink nature. Moreover, all the traffic was assumed to be external (i.e. have emanated externally) with the possible existence of internal traffic between the ARs being neglected. We extend and complete the analysis of MPR in access network structures by studying and comparing two cases considering the existence of both internal and external traffic (with both uplink and downlink nature) with the possibility of all the ARs and the GW being sources and destinations of traffic:

- Case I: The RP structure is comprised of multiple *GW-AR* pairs. This design concept is restricted to 3G environment's architectural functionality where the entire traffic destined for outside of the network towards the big Internet and the internal traffic between the ARs would pass through the GW. We are targeting to expand this model to converge the Internet routing and future cellular systems' requirements by modifying the RP structure, allowing for direct communication between the ARs as reflected in the design concept for case II.
- Case II: In this case, the RP structure is modified by including direct communication paths between ARs in addition to the duplex *GW-AR* pair, hence deploying the IGP's operation in full (i.e. OSPF). Our design concept is equally reflected in the trends towards a flat-IP structure in cellular networks where the increasing need for such structure has been emphasized [2] [19]. Accordingly, base stations are directly interconnected by IP and the forwarding domain barriers in these networks (i.e. radio access and core networks) are being abolished making

the new backhaul connection space open to diversification of paths via meshed hierarchical topological set-ups. In fact, with the expected increase in the backhaul traffic [20], wired backhaul links' overload could be alleviated by the diversity offered by MPR [17].

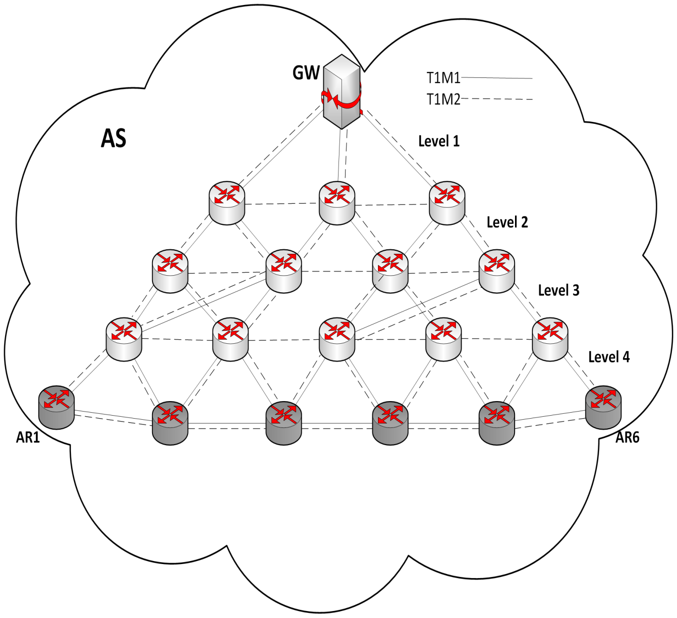


Fig. 1: Autonomous system comprised of 19 nodes and 32/41 links. Average node degree: 3.36/4.32. Total capacity (Gb): 11.94/15.34 (T_1 topologies are illustrated, TABLE I)

C. Contributions

This paper contains the following contributions:

- We revisit the multi-topology (i.e. RPs) construction problem in intra-domain networks. To this end, we prove MPR's offline RP construction problem as being the generalization of the minimum set cover problem which is NP and also NP-complete. Hence, the adoption of heuristics to solve such a problem is justified.
- We present optimization frameworks that formally describe the offline and online TE mechanisms of MPR. First, by leveraging the initial offline TE model for multi-topology construction [10] that was built upon in the initial MPR [8], we combine our approaches to the offline TE in [15] and [16] to enable hop-constrained path diversity across various topologies. Moreover, since we take into account an increased pairing of traffic sources and sinks, we design a corresponding new online TE model based on a multicommodity flow problem associated with different classes of flow demands.
- A thorough performance analysis of MPR is conducted investigating: i) diverse ranges of topologies and meshings; ii) realistic traffic scenarios with varying ratios of internal and external traffic; iii) traffic of both uplink and downlink nature where all the ARs and the GW can be *Ingress/Egress*. This extends the performance analysis of [16] where a single topology was examined, hence providing novel and more concrete conclusions compared to the first analysis of the early versions of MPR [12] (i.e. GW anchored traffic distribution scenario). To the best of our knowledge, such a thorough practical analysis that facilitates a comprehensive vision of the network's performance is absent in literature. We conclude by recommending our analytical strategy for the study of other load balancing approaches.
- To reinforce the practicality of our study, we conduct analyses of MPR in case I alongside case II. This looks forth to the architectural evolution of cellular and Internet-based access networks identifying the case with superior performance. To the best of our knowledge, despite research having looked into the underlying standards supporting flat-IP, the validity of such design concept has not been studied previously. To this end, the emerging utilisation of such IP-enabled direct communication is accommodated in our investigation.
- Finally, MPR's offline and online TE approaches are compared against that of MPLS which acts as it main rival in access network structures. In this context, the reliability of the aforementioned approaches is also evaluated.

III. SYSTEM MODEL

A. Concept

MPR divides the physical topology into multiple logical planes called RPs. Each RP is an instance of OSPF associated with a dedicated link weight configuration and it can overlap with another or share any subset of the underlying network [1]. MPR applies path diversity in building RPs using an offline algorithm that leads to the full utilization of resources (i.e. links) in the network. All the routers will have different Routing Information Bases (RIBs) (i.e. control plane) and Forwarding Information Bases (FIBs) (i.e. data plane) through which routes are defined in every RP. Each RIB/FIB represents one RP. MPR is originally envisioned to exploit the bits available in the Type of Service (ToS) field of IP packets, specifically, DiffServ integrated bits. DiffServ that was put forward by IETF in [21] is designed to facilitate multiple requisite QoS in the network and it supersedes the obsolete Type of Service (ToS) field whose bits are re-branded in DiffServ. Hence, in case DiffServ is used, there would be three unused bits (the fifth, sixth and seventh precedences) that can be used by MPR to mark each plane allowing up to 8 RPs to be supported. In case DiffServ is not used, MPR would have access to more bits, hence, more planes could be supported by ToS field (same or extended availability applies for IPv6 headers). Routers are configured to recognize the RPs through the unused bits. It was shown in [8] that up to 5 RPs are sufficient in case of MPR for similar network topologies as also substantiated in [22] for MT-OSPF. Consequently, MPR can exploit the structure in the IP header without imposing extra overhead onto each packet. This is opposed to MPLS where a 32-bit MPLS label stack is imposed on the IP packet

---

[1] We do not exclude the possibility of equal-cost multi-paths (ECMPs) occurring in the OSFP configuration of a RP. Regardless, each RP is used as one independent path diversity option from the *Ingress* to the *Egress*

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMC.2017.2741479, IEEE Transactions on Mobile Computing

TABLE I: Setup of the topologies

Topo	Nodes	ARs	Links	Avg. Node degree	Total capacity (Gb)	No. of RPs
T_1M_1	19	6	32	3.36	11.94	4
T_1M_2	19	6	41	4.32	15.34	5
T_2M_1	32	14	53	3.31	15.28	3
T_2M_2	32	14	67	4.19	18.40	5

by encapsulation causing overhead and router's configuration complexity.

MPR does not impede IP host mobility management solutions in IP access networks, neither end-to-end mobility (i.e. mobile IP) nor uses of mobility agents in access networks. MPR's routing solution runs separately from the mobility management functions such as tunnelling and IP address allocations. Since MPR also supports internal traffic as proposed in this paper, when mobility agents are used, traffic to and from them is subject to regular decisions of the MPR's online algorithm at the *Ingress* points. Hence, MPR supports any location of mobility agents in access networks. Traffic load balancing with MPR's online algorithm can coexist with load balancing solutions via mobility agents in similar access network topologies [23]. In case of the projected user mobility model for future 5G networks [18] that include coverage of heterogeneous cells, MPR would treat the occurrences of varying traffic from mobile users as a uniform scenario at the network layer. To this end, MPR's online TE model is expected to adapt accordingly as to cease up the routing resources/paths in the whole topology caused by the unbalanced traffic injection to and from the *Ingress* aggregation router(s) (i.e. serving cell(s)).

B. Investigated Network Model

The network in Fig. 1 represents an Autonomous System (AS) which constitutes a metropolitan or campus access network with a single gateway towards the big Internet. This reference fat-tree model is based on [24] where a meshed tree-based structure design has been suggested over other architectural designs as networks will have a significantly larger number of base stations and a much higher bandwidth demand at their edges (i.e. access points). TABLE I presents the specifications of the set of topologies of different meshings. Nodes are considered to be interconnected by wired Ethernet links. A $M/M/1$ queuing model is considered for every node. Topology 1 consists of 6 base stations acting as Aggregation Routers (ARs). Link capacities are randomly set up following a uniform distribution in [360, 400] for Level 1, [200, 240] for Level 2, [140, 180] for Level 3 and [60, 100] for Level 4 in the first topology studied (19 nodes). The second network studied (32 nodes) contains 14 ARs that are randomly distributed in the network as opposed to being strictly placed at the edge to provide more random configurations of networks. This topology is comprised of five levels where link capacities are generated in the following intervals: [360, 400] for Level 1, [160, 200] for Level 2, [110, 150] for Level 3 and 4, and finally [50, 90] for Level 5.

TABLE II: Main Parameter Descriptions

Notation	Description
$\mathcal{V}$	Set of nodes. $\mathcal{V}$=$\{v : v = 1, ..., V\}$
$\mathcal{E}$	Set of links. $\mathcal{E}$=$\{e : e = 1, ..., E\}$
$\mathcal{N}$	Set of Routing Planes (RPs). $\mathcal{N} : n = 1, ..., N$
$\mathcal{Z}$	Set of Label-Switched Paths (LSPs). $\mathcal{Z} : z = 1, ..., Z$
$\mathcal{D}$	Set of demands. $\mathcal{D}$=$\{d : d = 1, ..., D\}$
$\mathcal{H}_n^d$	Set of hops. $\mathcal{H}$=$\{h : h = 1, ..., H_n^d\}$
$\mathcal{B}$	Number of Users. $\mathcal{B} = \{b : b = 1, ..., B\}$
ϑ	Set of commodities. $\vartheta : \theta = 1, ..., \Theta$
$\rho_{\mathcal{N}}^{\mathcal{K}}$	Set of paths containing path (i.e. $P_{\mathcal{N}}^{\mathcal{D}}$) set
$\mathcal{Q}$	Set of sessions. $\mathcal{Q} = \{q : q = 1, ..., Q\}$
Γ	Set of weights for each constraint. $(\Gamma : \gamma = \gamma_0, \gamma_1 ..., \gamma_k)$
$\mathcal{T}$	Set of traffic types $\mathcal{T} = \{t : t = 1, ..., T\}$
$\Pi^{b,d}$	Traffic rate associated with user u and demand d
m_q	Additive QoS metrics associated with session q
c_q^t	QoS constraint of session q associated with traffic type t
$\varphi_\Gamma^t(p_n^d)$	Cost of a path associated with a RP for traffic type t
$C(b(p_n^d))$	Link capacity of the least available bandwidth on path p_n^d

IV. ANALYTICAL MODEL

A. Graph Theoretical Representation

TABLE II summarizes the important notations used in this paper. Let the topology of a given communication access network be represented by a connected directed graph $G = (\mathcal{V}, \mathcal{E})$, with a set $\mathcal{E}$=$\{e : e = 1, ..., E\}$ of edges with finite capacities C_e, and a set $\mathcal{V}$=$\{v : v = 1, ..., V\}$ of vertices. Let $\mathcal{K}$=$\{k : k = 1, ..., K\}$ symbolize the number of ARs in the network whereas the GW is symbolized as $K + 1$. Let the set of Routing Planes (RPs) be represented as $\mathcal{N}$=$\{n : n = 1, ..., N\}$. ϑ=$\{\theta : \theta = 1, ..., \Theta\}$ signifies the source and destination pairs of traffic in the network (i.e. *Ingress* and *Egress* points) also called commodities. Every $e \in \mathcal{E}$ is assigned with N distinct link weights denoted by $w(n, e); \forall n \in \mathcal{N}$. The network supports a set of overall traffic flows for every *Ingress* - *Egress* pair that we call demands and is denoted by $\mathcal{D}$=$\{d : d = 1, ..., D\}$. In addition to the GW as a possible source of traffic, let $AR_{\mathcal{A}}$ ($\subseteq AR_k$) be the source AR ($\mathcal{A}$=$\{a : a = 1, ..., A\}$). The *Egress* nodes are:

$$\textit{Egress} : \begin{cases} \{AR_k\}_{k=1}^{K}, \text{ when } \textit{GW} \text{ is } \textit{Ingress} \\ \{AR_k\}_{k=1, k\neq a}^{K} \cup \textit{GW}, \text{ when } AR_a \text{ is } \textit{Ingress} \end{cases} \tag{1}$$

AR_{fi} represents the first destination AR while AR_{la} represents the last destination AR in the network in one path set (ρ_n^k) pertaining to a particular source in the iteration. Subsequently, the source AR (AR_a) changes for the next iteration until all the ARs and the GW are covered (i.e. an instance of OSPF, one RP). The connections are duplex therefore, all the destinations can be sources as reflected in the overlapping RPs built for all the ARs and GW. Every RP is comprised of $\rho_n^{\mathcal{K}}$ = $\{\rho_n^k : k = 1, ..., K + 1\}$ set of shortest paths. $\rho_n^{\mathcal{K}}$ incorporates the demand-set $\mathcal{D}$ for $\{P_n^d\}_{d=1}^{D}$ in RP n for all the ARs and GW. Therefore, there are $\{P_n^d\}_{d=1}^{D} \subset \rho_n^{\mathcal{K}}$ acyclic shortest paths for RP n according to the link weight configuration W_n for that RP. The position of every link in path P_n^d is represented by a set of $\mathcal{H}_n^d = \{h : h = 1, ..., H_n^d\}$ hops from the *Ingress*. H_n indicates the maximum $\mathcal{H}_n^d$ in RP n. An $N \times E$ matrix R^d represents the link usage. $R_{eP_n^d}^d = 1$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMC.2017.2741479, IEEE Transactions on Mobile Computing

if path P_n of pair d uses link e and $R^d_{eP^d_n} = 0$ otherwise. Matrix R^d for demand d is:

$$R^d = \begin{bmatrix} R^d_{1P^d_1} & R^d_{2P^d_1} & \cdots & R^d_{EP^d_1} \\ R^d_{1P^d_2} & R^d_{2P^d_2} & \cdots & R^d_{EP^d_2} \\ \vdots & & & \\ R^d_{1P^d_N} & R^d_{2P^d_N} & \cdots & R^d_{EP^d_N} \end{bmatrix} \tag{2}$$

The set of paths $(\rho^1_n, \rho^2_n, ..., \rho^K_n, \rho^{K+1}_n)$ for all the ARs and GW amalgamate to represent one RP. Case I and case II were outlined in section II-B. In the first case where all the traffic travels through the core, path set ρ^k_n is represented as follows:

$$\rho^k_n = \left\{ \begin{array}{ll} AR_{\mathcal{S}} \Leftrightarrow GW & : P^{d=1}_n \\ AR_{\mathcal{S}} \Leftrightarrow GW \Leftrightarrow AR_{fi} \neq AR_{\mathcal{S}} & : P^{d=2}_n \\ \vdots & \\ AR_{\mathcal{S}} \Leftrightarrow GW \Leftrightarrow AR_{la} \neq AR_{\mathcal{S}} & : P^{d=K}_n \end{array} \right\} \tag{3}$$

In the second case, path-set ρ^k_n is:

$$\rho^k_n = \left\{ \begin{array}{ll} AR_{\mathcal{S}} \Leftrightarrow GW & : P^{d=1}_n \\ AR_{\mathcal{S}} \Leftrightarrow AR_{fi} \neq AR_{\mathcal{S}} & : P^{d=2}_n \\ \vdots & \\ AR_{\mathcal{S}} \Leftrightarrow AR_{la} \neq AR_{\mathcal{S}} & : P^{d=K}_n \end{array} \right\} \tag{4}$$

Where $\Leftrightarrow$ represents a duplex path through other nodes. The GW-AR pair is reserved in every RP for the case that the desired destination address is located outside of the network and vice versa. $d = 1$ represents the GW-AR pair in path-set ρ^1_n and the demand increments up to D that corresponds to the final *Ingress-Egress* pair in path-set ρ^{K+1}_n.

Every plane is a subset of the physical topology of the underlying network (i.e. uses all *Ingress*, *Egress* routers and a subset of the transit routers and links). A separate RIB/FIB is maintained for every subset/RP. For graph G, the sub-graph induced on a vertex subset/RP $\rho^{\mathcal{K}}_n \in G$ of V_G is denoted as $G(\rho^{\mathcal{K}}_n)$.

$$\begin{cases} V_{G(\rho^{\mathcal{K}}_n)} = \{u, v \in V_G | \exists e \in E_G\} \\ E_{G(\rho^{\mathcal{K}}_n)} = \{e \in E_G | e = \langle u, v \rangle \ \ u, v \in V_G\} \end{cases} \tag{5}$$

B. Offline TE Approach

A stated earlier, the offline TE approach yields RPs that will integrate into a finite RP set as a pre-runtime path diversity network planning step of MPR. In this section, we will first prove the NP-completeness of RP construction and selection that justifies MPR's application of heuristics to this end. Subsequently, we formulate MPR's RP construction problem (The pseudo-code is presented in **Algorithm 1**).

1) A Proof of NP-Completeness: As discussed earlier, MPR adapts the multi-topology OSPF approach in building multiple alternative paths between each source-destination pair through a network. MPR's offline algorithm is aimed at obtaining a set of RPs leading to the improvement of the projected link usage and path diversity in access networks. The prime objectives of the offline algorithm are as follows:

1) We aim to obtain a set $\mathcal{N}$ of $|\mathcal{N}| = N$ RPs.
2) Each RP $n \in \mathcal{N}$ contains a valid path for every source-destination pair in the underlying network.
3) Every link in the underlying network topology appears in at least one of the constructed RPs in the set. This also implies that the union of the planes renders the underlying topology.
4) Every link in the network is used at most $N - 1$ times.
5) The cost between every source-destination pair is minimum for each plane subject to the assigned link weights.

We demonstrate that the problem of interest, given the requirements stated above, is NP-complete. This is achieved herein by demonstrating that a well-known NP-complete problem is reducible, in polynomial time, to our problem. We commence this proof by summarizing the minimum set cover (MSC) and the minimum δ-set cover (δ-MSC) problems [25] below: [**Minimum Set Cover Problem**] Given a finite collection $\mathcal{S} = \{S_i\}^I_{i=1}$ of subsets of a universe U, a *set cover* $C \subseteq \mathcal{S}$ is a subcollection of the sets whose union is U (physical topology), i.e. $\bigcup_{S \in \mathcal{C}} = U$. Moreover, each $S \in \mathcal{C}$ has an associated non-negative cost c_S. The minimum set cover problem is to compute such a subcollection $\mathcal{N} \subseteq \mathcal{C}$ such that it is a set cover for U and its cost $\sum_{S \in \mathcal{S}} c_S$ is simultaneously minimized. It is notable that each S_i represents a candidate RP.

[**Minimum δ-Set Cover Problem**] Assuming that instances of the weighted set cover are such that each $S_i \in \mathcal{S}$ has at most δ elements then we have the δ-set cover problem. It is notable that the unweighted set cover is a special case of the weighted set cover problem. Likewise, the unweighted δ-set cover is a special case of the weighted δ-set cover problem. Furthermore, it is known that the MSC problem is NP-complete. To show that our problem is NP-complete it suffices to show that it is in NP and that the weighted MSC problem is reducible to our problem in polynomial time. Let the network topology being considered be defined by its connectivity graph $G = (\mathcal{V}, \mathcal{E})$ and its associated link weight function $w : \mathcal{E} \mapsto R_+$, that assigns a non-negative weight $w(e)$ to each edge $e \in \mathcal{E}$. It is understood that $\mathcal{V}$ and $\mathcal{E}$ are the set of all vertices/nodes and edges/links respectively of the underlying network. Define $\mathcal{S}$ to be a collection of distinct subsets of $\mathcal{E}$, that is to say: $\mathcal{S} = \{S_i\}^I_{i=1}$ where $S_i \subset \mathcal{E}$ for each $i = 1, 2, \ldots, I$ so that for any $i \neq j$, $S_i \neq S_j$. Such a collection of subsets can be obtained, for example by constructing all spanning trees of the underlying graph G [26]. Each tree S_i is simply a subset with at least $\delta + 1$ elements in addition to the transit routers (that are not sources or destinations) (edges 'e') chosen from $\mathcal{E}$; with an associated cost $c_{S_i} = \sum_{e \in S_i} w(e)$. It is easy to see that $\bigcup_{\forall i} S_i = \mathcal{E}$. Now given $\mathcal{S}$, each element S_i of it has a path between all possible source-destination pairs and so it is a valid RP. However our task here is to find the subcollection $\mathcal{N}$ of RPs of minimal cost that utilizes every link in the network. In other words, we desire an $\mathcal{N}$ such that $\bigcup_{S_i \in \mathcal{N}} = U$ and $\sum_{S_i \in \mathcal{N}} c_{S_i}$ is minimized. This is clearly the minimum set cover problem, by definition. It is now clear that our MPR problem is a generalization of this MSC problem, therefore it is in NP and also NP-complete.

2) Problem Formulation: We introduce a modified offline TE approach that incorporates hop-constraint optimization to build and select RPs while ensuring diversity ahead of traffic flow into the network. When applying the previously proposed offline algorithm [12] to build RPs connecting the *Ingress-Egress* pairs, it is not guaranteed that the shortest possible RP set in terms of hop-count would be selected. Therefore, the resultant paths would render long routes in terms of hop-count specially in case II where $AR - AR$ pairs are also connected directly. Under this case, some of these routes would pass through the gateway or through nodes located very high in the transit. This would not be desirable in our study to apply the MPR technique under the new scenario where access points communicate directly. We use hop-constraint to select an optimal set of RPs that meet our RP-construction objectives while avoiding redundant paths. We have adopted the hop-constraint optimization which was originally introduced in [27] for spanning tree constructions. Here, we have added more constraints and have reformulated certain representations in order to adjust the optimization problem to our work. Weight of link e between any two nodes (u, v) in plane n is denoted by $w(n, e)$ (i.e. $e = arc(u, v)$). Link Usage (LU) represents the number of RPs that include e in their shortest path across the given demands, which is defined as:

$$LU_e = \sum_{n\in\mathcal{N}}\sum_{d\in\mathcal{D}} R^d_{eP^d_n} \quad ,\forall e \in \mathcal{E} \;\; and \;\; \forall d \in \mathcal{D} \tag{6}$$

The maximum LU on every link is $LU_e = N - 1$ as initially proposed in [8] to ensure Full Path Diversity (FPD). The link weight computation between nodes (u, v) corresponding to an iterative process of penalising choices of links relative to previous RPs is given by:

$$\begin{aligned} w(n,e) = \frac{1}{C_e} + \frac{1}{n}\sum_{\rho=1}^{n-1} w(\rho, e) \\ + X \cdot \lambda_e(n) \end{aligned} \tag{7}$$

$\forall e \in \mathcal{E}$, $\forall \rho \in [1, n-1]$, where X is a multiplicative tuning parameter that is used for the granularity, whilst $\lambda_e(n)$ is chosen to be one of the following respective three equations that consecutively penalise links in the previous RP, amalgamation of links in all preceding RPs and the most used links across RPs:

$$\alpha_e(n) = \begin{cases} 1, \text{ if link } e \text{ is in a path in RP } n-1 \text{ ;} \\ 0\text{,otherwise} \end{cases} \tag{8}$$

$$\beta_e(n) = \sum_{n=1}^{N-1} \alpha_e(n) \tag{9}$$

$$\gamma_e(n) = \max_{d\in\mathcal{D}} \left(\sum_{n=1}^{N-1} \alpha^d_e(n) \right) \tag{10}$$

The link weight assignment calculates N set of positive link weights $W_n = \{w(n, e) : 1 \leq w(n, e) \leq Z, \forall n \in \mathcal{N}, \forall e \in \mathcal{E}\}$, and $Z(= 2^{16} - 1)$ as the highest value that OSPF can handle. More RPs will be tested with a higher value of X that ranges from 1 to X_{max} incremented by 1 with $X_{max} = \{2; 4; 8; 16; 32; 64\}$. $w(n, e)$ considers the involvement of a link in RP $N-1$. The RP construction algorithm is iterative by nature. The Pearson product−moment correlation coefficient is applied in step 7 of **Algorithm 1**, as initially adopted in MPR [12] to maximize diversity.

We formulate MPR's offline approach as a constrained shortest path routing problem. This approach aims to minimize the chance that for a given demand all RPs share a single link and to maximize the possibility of any link being used in at least one RP ensuring a set of shortest possible paths concatenating to represent one RP, while also aiming to equivalently minimize $\sum_{e\in P^d_n} w(n, e)$ for every P^d_n. The decision variables are defined as followed: $R^d_{(uv)P^d_n}$ is defined as the binary directed variable which indicates whether $arc(u, v)$ is in the minimal tree and $Z^d_{(uv)P^d_n}$ is the directed binary flow variable that indicates whether $arc(u, v)$ is included in the only path from the *Ingress* t to the *Egress* node $s \in$ *Egress* at position h in RP n.

$$Z^d_{(uv)P^d_n} = \begin{cases} 1, \text{ if arc}(u,v) \text{ is in the path from root node t} \\ \quad \text{to node } s, s \neq u \\ 0, otherwise \end{cases} \tag{11}$$

$$\begin{aligned}
\text{min} \quad & \sum_{n\in\mathcal{N}}\sum_{d\in\mathcal{D}}\sum_{(u,v)\epsilon V} R^d_{(uv)P^d_n}.w(n,e) \\
\text{s.t.} \quad & \sum_{v:(u,v)\in\mathcal{E}} R^d_{(uv)P^d_n} - \sum_{v:(v,u)\in\mathcal{E}} R^d_{(vu)P^d_n} = \\
& \begin{cases} 1, \text{ for } u = s \\ 0, \text{ for } u \in V \setminus \{s,t\}, \\ -1, \text{ for } u = t \end{cases} && (a) \\
& 1 \leq LU_e \leq N-1 && (b) \\
& \sum_{(u)\epsilon V} Z^d_{(uv)P^d_n} - \sum_{(u)\epsilon V \neq t} Z^d_{(uv)P^d_n} = 0 \\
& \forall s, v\epsilon V \neq AR_{\mathcal{S}}/GW, v \neq s && (c) \\
& \sum_{(u)\epsilon V} Z^d_{(uv)P^d_n} = 1, \qquad \forall v\epsilon V \neq AR_{\mathcal{S}}/GW && (d) \\
& \sum_{n\in\mathcal{N}}\sum_{d\in\mathcal{D}}\sum_{(u,v)\epsilon\mathcal{E}} Z^d_{(uv)P^d_n} \leq H.D.N && (e) \\
& Z^d_{(uv)P^d_n} \leq R^d_{(uv)P^d_n}, \forall(u,v)\epsilon E, s\epsilon V \neq AR_{\mathcal{S}}/GW && (f) \\
& R^d_{(uv)P^d_n} = \{0,1\}, \forall(uv) \in \mathcal{E}, \forall d \in \mathcal{D}, \forall n \in \mathcal{N}
\end{aligned} \tag{12}$$

Where $H = \max\limits_{d,n}\{H^d_n\}$ and demand d is such that it includes t as the *Ingress* node and s as the *Egress* node. This optimization problem ensures that there exist a set of independent loop-free least-cost path sets of the least possible number of hops with every link being used at least once and at most $N - 1$ times (ensuring diversity). Our suggested modified approach defines a termination point in the iterative

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMC.2017.2741479, IEEE Transactions on Mobile Computing

RP construction algorithm subject to the above optimization framework constraints as opposed to the previously proposed offline TE where no such constrained framework was set out. As a result of this optimization, every plane-set would become constrained by a hop number denoted by H (i.e. $\max\limits_{d,n}\{H_d^n\}$) while ensuring diversity. As stated earlier in section III-A and shown in [8] and [22], 3-5 planes would be sufficient in achieving near-optimal performance subject to the considered topologies and meshings. Therefore, we control the hop-constrained iterative RP construction algorithm to allow for the construction of planes up to 6 depending on the topology and level of meshing. Constraint (a) ensures that every node in the path is in the solution and has only one arc entering it. Constraint (b) stipulates that every link will end up being used at-least once and at-most $N-1$ times ensuring diversity. Constraint (c) states that only one arc enters a node in position h in any path and there is only one arc leaving that node in position $h+1$. Constraints (d) and (e) ensure that only one arc in position h enters the destination node for every demand in every path-set ρ_n^k. These two constraints guarantee the feasibility of the solution. Constraint (f) states that if $arc(u,v)$ is included in the solution, it exists in the path between the source and its corresponding destination node. In our study, $X=64$ in the weight function, results in the best set of RPs obtained under the tested topologies.

Algorithm 1 Offline Algorithm for Building RPs

```
1: procedure RPs-CONSTRUCTION
2:    Build the first InvCap link weights-based RP
3:    if prime objectives (1-5) are met: jump to step 9
else: go to step 4
end if
4:    for $X = 1 : X_{max}$
Derive sets of weights for candidate RPs using the methods in equations (9), (10) & (11) respectively
end for
5:    Run Dijkstra to create candidate RPs based on the sets
6:    for $n = 1 : X_{max}$
if the candidate RP $n$ meets objectives 2, 4 & 5:
Record the candidate RP and its hop-length value $H_n$
end if
end for
7:    Find the best RP $n$ originating from step 6 (three methods) through correlation with the lowest possible hop-length while ensuring constraints' criteria are met (i.e. equation(12))
8:    Go back to step 3 (i.e. the verification process)
9:    RPs are obtained consisting of AR-AR and AR-GW pairs corresponding to case I or case II
10: end procedure
```

C. Online TE Approach

Routing in a network can be represented as a multi-commodity flow problem with multiple flow demands associated with different *Ingress* and *Egress* nodes for each plane. A flow demand corresponds to IP sessions, and once a plane is chosen it remains unchanged for duration of the session.

$$\sum_{v:(u,v)\in\mathcal{E}} f^{\delta}_{(uv)P_n^d} - \sum_{v:(v,u)\in\mathcal{E}} f^{\delta}_{(vu)P_n^d} = \begin{cases} d_u^{\delta}, \text{ for } u=s \\ 0, \text{ for } u\in V-\{s,t\}, \\ -d_u^{\delta}, \text{ for } u=t \end{cases} \tag{13}$$

$$f_{uv} = \sum_{\delta\in\vartheta} f_{uv}^{\delta} \le c_{uv} \qquad \forall(u,v)\in\mathcal{E} \tag{14}$$

$$f_{uv}^{\delta} \ge 0 \qquad \forall\delta\in\vartheta, \forall(u,v)\in\mathcal{E} \tag{15}$$

where d_u^{δ} represents the amount of traffic contributed to the network by node u for commodity δ. (13) signifies the flow conversation constraints and (14) represents the capacity constraints. We keep the objective of achieving a practical maximum use of diverse network topological configurations/RPs facilitated by the offline algorithm. The options of paths subject to every RP layout are cumulatively considered through online decisions made at *Ingress/source*. To this end, we consider the application of heuristics namely MPR and its extension QoS-aware MPR (QMPR) in a multi-commodity flow scenario. MPR's online TE approach was initially introduced in [11]. As opposed to the previously considered singular source case, we have adopted a realistic online traffic scenario where both the GW and the ARs can be sources and destinations of traffic simultaneously giving rise to the breakdown of traffic to internal and external nature. Additionally, we put forward a more complete formulation of MPR's online routing complemented with an optimization framework.

In the network; a set of users is defined as $\mathcal{B}=\{b : b=1,...,B\}$. $\mathcal{T}=\{t : t=1,...,T\}$ indicates the set of traffic types. $\mathcal{Q}=\{q : q=1,...,Q\}$ represents the set of sessions whereas m_q signifies the additive QoS metrics associated with every session q. c_q^t is defined as the QoS constraint of session q associated with traffic type t. $\Pi^{b,d}$ indicates the traffic rate associated with user b and demand d. $||\Pi^{b,d}||_0$ signifies the non-zero non-negative entries of $||\Pi^{b,d}||$. MPR applies a plane selection policy for each session to ensure a regulated traffic flow in the network. This policy is enforced by the sources (i.e. GW and ARs). In case of MPR, the cost of RPs are solely determined based on the available bandwidth and if there is more than one RP available, one RP is selected randomly. In case of QMPR, when a packet arrives at a source, the qualified RPs in terms of bandwidth are first picked out, subsequently the packet's classification gets verified and hence its associated Service Level Requirement (SLR) (i.e. jitter, latency, packet loss) is obtained based on which the plane selection policy is applied. Consequently, RPs that do not meet the required criteria for the concerning traffic class are pruned and the most suitable RP with the lowest cost is selected. At this stage, in case of the existence of more than one RP that meets the QoS criteria, the RP with the highest available bottleneck bandwidth is selected. In case of both MPR and QMPR, once the qualified RP is selected, the packet is forwarded on the chosen RP followed by the rest of the packets of the session (Online pseudo-code is presented in **Algorithm 2**).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMC.2017.2741479, IEEE Transactions on Mobile Computing

The cost function for any path p_n^d is represented as follows as a summation of real time costs of each link in the path:

$$\varphi_\Gamma^t(p_n^d) = \Psi . \sum_{uv \in P_n^d} \sum_{q \in \mathcal{Q}} R_{uvP_n^d}^d \left(\frac{m_q(uv)}{c_q^t} \right) . \gamma_q + Y . \left(\frac{b(p_n^d) - ||\Pi^{b,d}||_0}{C(b(p_n^d))} \right)^{-1} \tag{16}$$

Where $\gamma_q \in [0,1]$ is the binary factor used to associate session q with its QoS requirements. $b(p_n^d)$ represents the available bandwidth on path p_n^d. The available bandwidth is calculated by taking into consideration the bottleneck on every path at various instances:

$$\begin{aligned} b(p_n^d) = & \min_{(e_{uv,n}) \in p_n^d} \quad b(e_{uv,n}) \\ & \text{Where:} \quad \{e_{uv} | (u,v) \in \mathcal{V}^2, \forall u \neq v, \forall n \in \mathcal{N}\} \\ & \qquad b(p_n^d) = \{b(e_{uv,n}) | (e_{uv,n}) \in p_n^d, \forall n \in \mathcal{N}\} \end{aligned} \tag{17}$$

Ψ is the binary factor which is 1 when any path p_n^d meets the minimum bottleneck requirement as outlined above. Y symbolises the binary variable which is equal to 1 in case of both the QoS and bottleneck requirements are met for more than one candidate RP hence the one with the highest bottleneck bandwidth is selected. We formulate our optimization problem based on the general OSPF TE optimization framework proposed in [28]. MPR's online TE aims to maximize throughput while routing the traffic through the optimum path taking into account the associated cost which is sought to be minimised along with the traffic rate on every path on the RP set available. Our MPR-based formulation takes into account the existence of different types of traffic in the network whereas access to multiple paths is facilitated through the offline RP construction TE approach.

$$\begin{aligned} \max \quad & \sum_{q \in \mathcal{Q}} \alpha_q \Phi_q - \sum_{q \in \mathcal{Q}} \sum_{p_n^d \epsilon \rho_\mathcal{N}} \varphi_\Gamma^t(p_n^d) ||\Pi^{b,d}||_0 \\ \text{s.t.} \quad & ||\Pi^{b,d}||_0 \ \leq \ b(p_n^d) \\ & m_q(p_n^d) \equiv \sum_{e_{u,v},n \in p_n^d} m_q(e_{u,v},n) \leq c_q^t \\ & \forall d \in \mathcal{D}, \forall b \in \mathcal{B}, \forall n \in \mathcal{N}, \forall t \in \tau, \gamma_k \in [0,1] \end{aligned} \tag{18}$$

Where throughput of session q associated with any user and demand on path p_n^d is: $\Phi_q = \sum_{p_n^d \epsilon \rho_\mathcal{N}} ||\Pi^{b,d}||_0$. α_q represents the optimum path for every session considering its associated cost. The constraints ensure the validity of the path in terms of meeting the minimum bottleneck requirement in addition to the QoS requirements associated with the corresponding session.

V. PERFORMANCE EVALUATION

In this section, the performance of the routing schemes are presented and evaluated. Section V-A sets out the experiment settings. Performance under a simulation scenario with practical evaluation criteria is presented in section V-B. Section V-C encompasses comparisons against MPLS.

Algorithm 2 Online Plane Selection Algorithm

```
procedure POLICY-PS
    Packet arrives at Ingress $AR_a/GW$ destined for Egress
    If $\left\|\Pi^{b,d}\right\|_0 \leq b(p_n^d)$, for at least $n \in \mathcal{N}$ then
        Admit the session
        Conduct lookup for the associated traffic class $t \in \tau$
    Ascertain QoS requirements $c_q^t$ for traffic class $t$
    Remove all RPs in $\mathcal{N}$ that do not satisfy SLRs for each $q \in \mathcal{Q}$ and retrieve set $\mathcal{CP}$
    Calculate cost for each RP
$\varphi_\Gamma^t(p_{cp_i}^d) = \Psi . \sum_{uv \in P_n^d} \sum_{q \in \mathcal{Q}} R_{uvP_n^d}^d \left( \frac{m_q(uv)}{c_q^t} \right) . \gamma_q + Y . \left( \frac{b(p_n^d) - ||\Pi^{b,d}||_0}{C(b(p_n^d))} \right)^{-1}$
Select RP $cp_1$ with the lowest cost $\varphi_\Gamma^t$ for the incoming session given: $\varphi_\Gamma^t(cp_1) \leq \varphi_\Gamma^t(cp_2) \leq ... \leq \varphi_\Gamma^t(N - \bar{\mathcal{CP}})$
else Reject session
end if
end procedure
```

A. Experiment settings

We evaluate our MPR-based framework using extensive packet level NS2-based simulations interfaced with Matlab. Sets of topologies with different meshings (as presented in TABLE I) are used for our study. Initially, the performance of different methodologies for varying internal/external traffic distributions under different scenarios (i.e. case I & case II as outlined in section II-B) are presented and evaluated. Subsequently, the performance of MPR and QMPR under different meshing scenarios is compared with MPLS. For both of the studies, legacy OSPF and OSPF InvCap approaches are used as the baseline methods for comparisons. It is important to mention that the legacy OSPF method and OSPF InvCap method are differentiated based on link weights set to 1 (hop-count based) and inverse capacity-based weight setting, respectively. It is also notable that no significant differences were observed between the legacy OSPF and OSPF InvCap approaches as a result of the experiments conducted. With regards to the number of RPs needed, it was concluded in earlier studies for MT-OSPF [22] that overall near-optimal network performance in terms of cost and link utilization can be achieved with up to 3-5 RPs as also substantiated in [8] for MPR. Incoming sessions of different traffic classes (as represented in TABLE III) are randomly generated. Sources and destinations of traffic and the duration of the corresponding flows are also randomly selected throughout the simulation time. As the simulation runs, traffic is generated with a decreasing session arrival time so as to load the network until congestion level. With a new session request at the source of traffic (i.e. an AR or the gateway), the latter checks for bandwidth availability on the set of potential path(s) to reach the destination, regardless of the method used (OSPF, InvCap, MPR, MPLS or QMPR). Given the link-state nature of the aforementioned TE strategies, ARs and the GW are aware of the traffic dynamics and the links' status in the network at different time frames. Traffic rate is increased by reducing inter-arrival times of sessions at *Ingress*es over a simulated real time of 12 seconds. In case of the T_1 topology, the overall traffic volume in the network increases up to approximately 330 Mb/s, whereas in case of the T_2 topology, the traffic volume goes up to 480 Mb/s. Beyond these points, mainly between 11 and 12 seconds, the network becomes significantly congested and packet rate drops as a consequence. Same conditions are applied to case I and case II simulations.

TABLE III: Traffic types[1] and associated QoS requirements.

Traffic Class	Data Rate	Mean Duration	QoS requirements		
			Latency	Jitter	Packet loss
Class 1	Low (≈ 150 Kbps)	180 sec	40-65 ms	0.5-2 ms	0.1-0.5 %
Class 2	Medium (≈ 250 Kbps)	300 sec	4-5 s	*none*	5 %
Class 3	Low (≈ 128 Kbps)	200 sec	300-600 ms	2 ms	5 %
Class 4	High (≈ 500 Kbps)	360 sec	300 ms	30 ms	1 %
Class 5	Low (≈ 100 Kbps)	90 sec	*no specific requirement*		

[1] Applications examples; Class 1 : VoIP, Class 2 : streaming video, Class 3 : streaming audio, Class 4 : interactive video, Class 5 : best effort data.

B. Performance under practically-oriented NS2-based simulations

In this subsection, the performance of different methodologies under fluctuating internal/external traffic distribution for different scenarios (i.e. case I & case II as outlined in section II-B) are presented and analysed in terms of various metrics. This study corresponds to an analysis under a realistic traffic scenario with two cases that are reflective of the architectural evolution of access networks as discussed in section II. MPR's offline TE is implemented through Matlab simulations to build RPs ahead of the traffic flow. NS2 simulations are then applied for the online TE mechanism for MPR and QMPR as described in subsection IV-C along with OSPF/InvCap. Different metrics are analysed by being averaged over snapshots throughout the simulation time for different traffic percentage distributions.

1) Blocking Rate (%): Blocking rate represents the number of sessions that have not been transmitted into the network in relation to the ones having been successfully delivered throughout the simulation time. Blocking occurs as the network becomes gradually congested leading to the obstruction of new sessions at *Ingress/source*. The rendered mean session blocking rate, as observed in Fig. 2, is lower in case II than case I as the bottleneck of the entire traffic traversing the GW has been alleviated. The blocking rate for the MPR-based methods is lower due to higher path diversity as compared to the OSPF/InvCap methods where a much fewer number of paths are available. As compared with MPR, the blocking rate for QMPR is slightly higher in both case I and II. This indicates that the enforced QoS requirements have rendered greater blocked traffic. Moreover, the mean blocking rate has consistently increased for all the methodologies across the topologies in line with the intensification of the internal traffic distribution. It can be also observed that blocking is generally higher in case of the second topology-set (i.e. T_2M_1, T_2M_2) as the traffic flow distribution is different. This is due to the comparatively higher traffic load on the network incurred by more traffic sources in spite of the larger network size. The blocking has declined across both of the topology-sets in line with the increase in meshing as a higher number of links and RPs become available in consequence, to route the traffic [2].

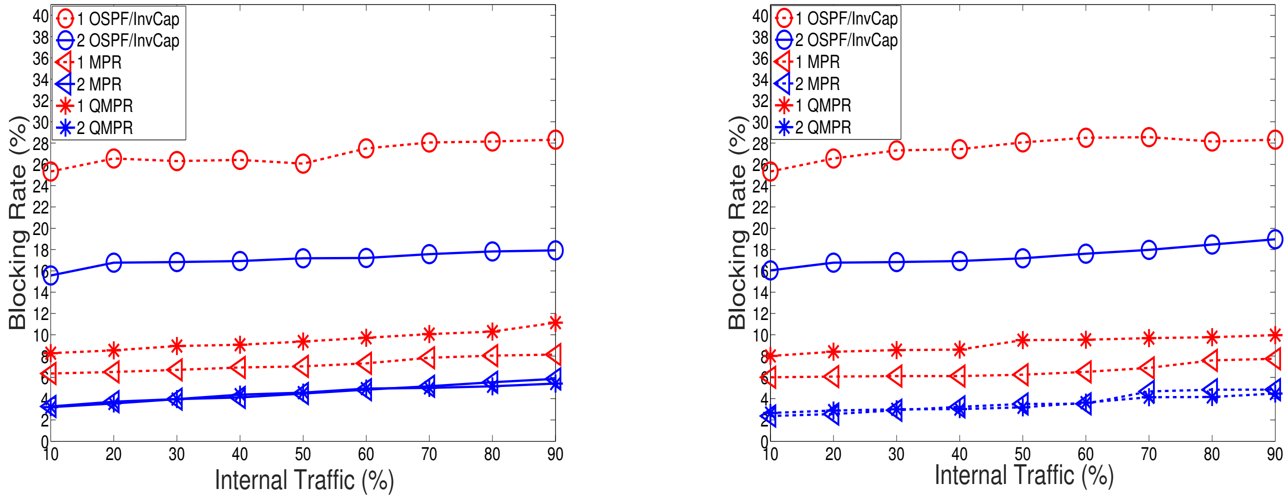
2) Packet Loss Rate (%): Packet loss rate represents the number of packets having been dropped in relation to the ones having been successfully delivered throughout the simulation time. Packet loss occurs due to insufficient queue capacities caused by the increasing congestion in the network. As observed in Fig. 3, the rendered average packet loss rate is lower in case II than case I. This is due to higher congestion and blocking triggered by less path diversity for traffic sources in case I (where the entire traffic passes through the GW), having led to the loss of more packets. The loss rate in case of the MPR-based methods is lower due to the higher path diversity for the incoming sessions as compared with OSPF/InvCap. QMPR outperforms MPR in terms of loss rate as the packet distribution into the network is regulated based on the QoS requirements, hence resulting in a lower loss of sent packets. With the intensification of the internal traffic distribution, loss rate has increased correspondingly across all the topologies. This is due to the higher congestion caused by the lack of residual capacity relative to the surging internal traffic demand throughout the network. It can be also observed that the packet loss rate declines as the meshing increases across both of the topology-sets since more links and RPs become available with the rise in meshing. Moreover, a generally higher loss rate has occurred in case of the second topology in which the traffic flow distribution model is different due to the comparatively higher traffic load on the network incurred by more traffic sources.

3) Delay (ms): As observable in TABLE IV and TABLE V, a higher mean delay is incurred with case I as longer routes are traversed as compared to case II. Furthermore, a lower queuing delay occurs in case II due to the higher path diversity available for sources of traffic as opposed to case I where the entire traffic passes through the GW. This leads to the accelerated queue processing in case II. A higher delay is incurred in the MPR-based methods as shortest-hop routes are not always used and more traffic is delivered. It was shown in [28] that for OSPF TE, the price for a higher throughput facilitated by multiple available paths is the heightened average delay caused by growth in the average path length. It was also shown in [29] that as demand surpasses a certain amount, delay would be correspondingly higher as more traffic is delivered in case of multi-path routing. Moreover, in both cases, delay has increased with the rise in the internal traffic distribution. This is the consequence of the higher traffic density having led to longer queue processing times, and a higher overall number of hops having been traversed. It can be also observed that the delay in case of the second set of topologies is higher, as the network is larger in terms of nodes and links, with

---

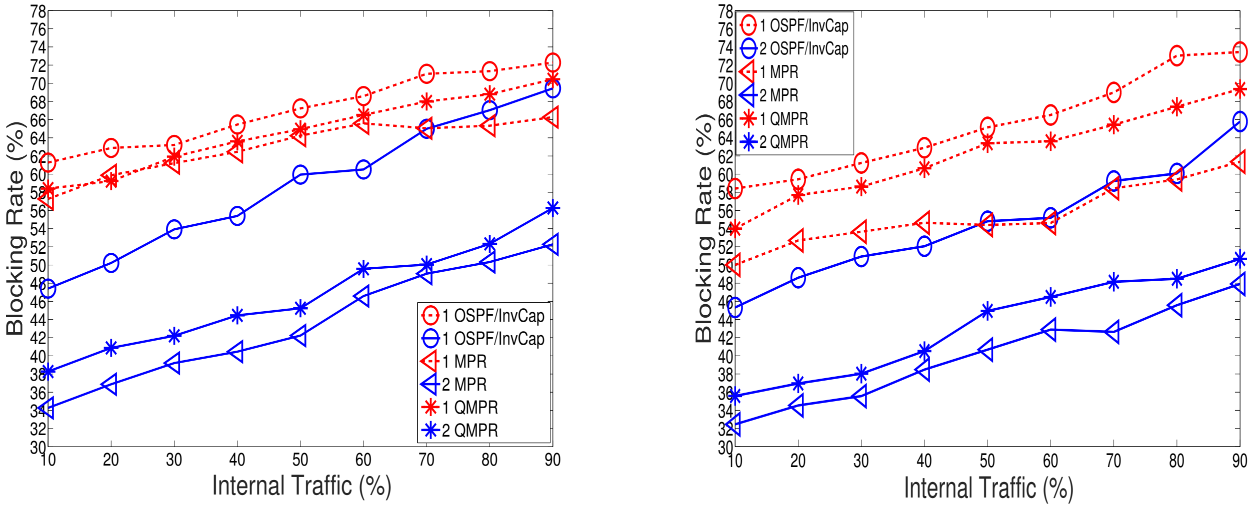
[2] This behavior intuitively suggests that as networks become randomly larger in size and include more traffic sources, the transient space should increase (routers and meshing) accordingly to accommodate for demands

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMC.2017.2741479, IEEE Transactions on Mobile Computing



(a) T_1M_1 Topology

(b) T_1M_2 Topology



(c) T_2M_1 Topology

(d) T_2M_2 Topology

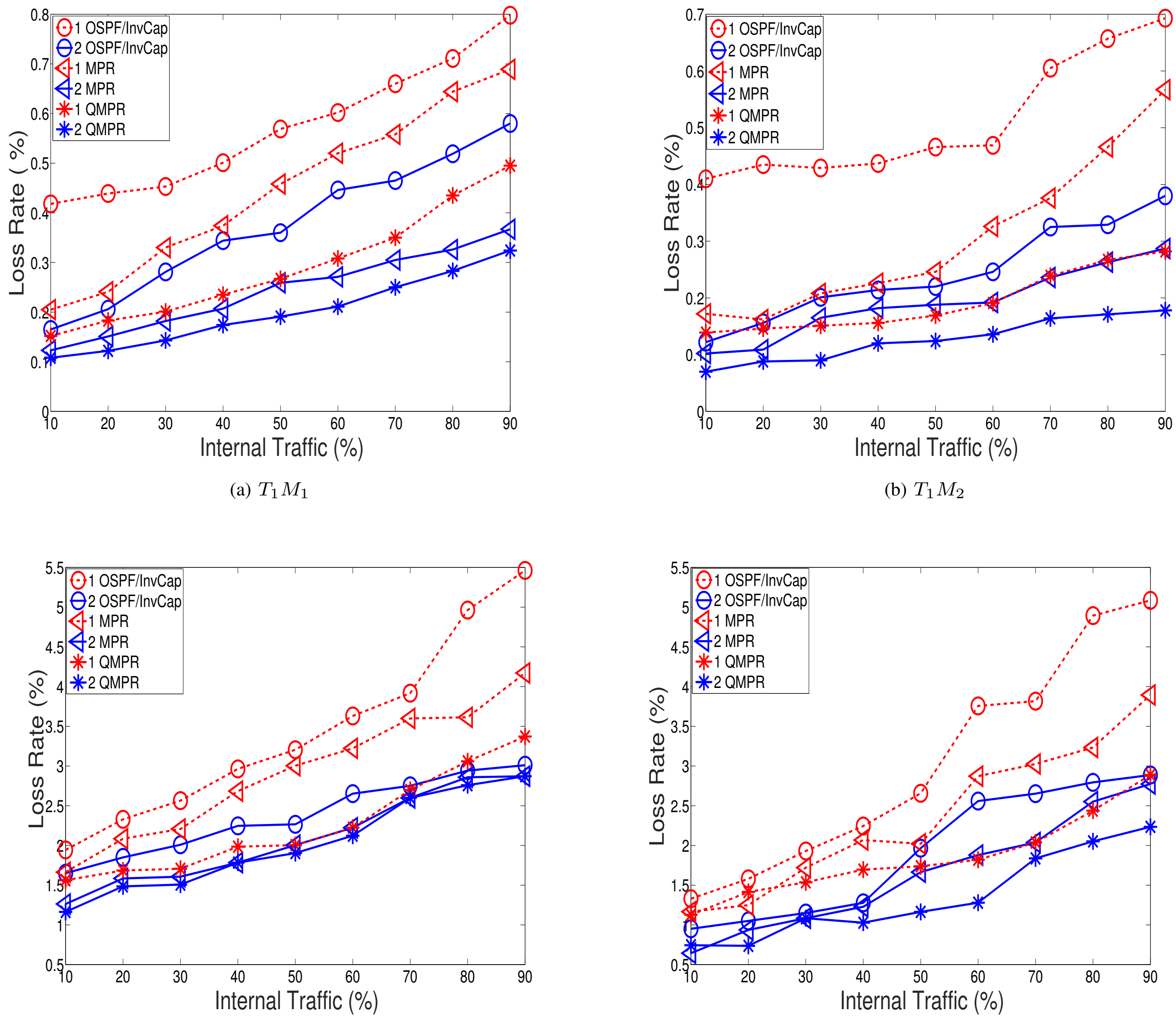
Fig. 2: Blocking Rate (%)

a higher traffic density. The results demonstrate a general decline in delay in line with the rise in meshing across both of the topology-sets. This is thanks to the availability of more links and RPs helping lift the congestion in the network, in consideration of the average delay on every link being largely dependent on its residual capacity based on the well-known Kleinrock independence approximation [30]. Therefore, it can be concluded that the increase in meshing facilitates a better distribution of traffic and the consequent reduction of queuing times that results in a lower overall delay.

4) Throughput (Mb/s): TABLE VI and TABLE VII represent the mean throughput achieved across the topologies under varying traffic percentages. The achieved mean throughput is generally higher in case II for different routing strategies as compared with case I. This can be justified by the higher path diversity available in case II resulting in larger amount of data being delivered. The MPR-based methods outperform OSPF/InvCap as traffic can be split over several paths in case of MPR, leading to improved load balancing in the network and increased packet delivery correspondingly. The average of the overall achieved throughput for both cases has declined with the rise in the internal traffic distribution aligned with the surge in blocking. Additionally, it can be observed that throughput has risen in line with the increase in meshing as the session blocking rate has declined correspondingly for both topology-sets. It can be also observed that a generally higher throughput has been achieved in case of the second topology-set where more traffic gets injected into the network.

We have also conducted a performance analysis of *Maximum Link Utilization (MLU)*, the results of which are presented and discussed in more detail in APPENDIX A. In general, MLU is lower in case II as compared with case I due to the better distribution of traffic. Similarly, MLU decreases with more meshing in the network.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMC.2017.2741479, IEEE Transactions on Mobile Computing



(a) T_1M_1 (b) T_1M_2

(c) T_2M_1 (d) T_2M_2

Fig. 3: Packet Loss Rate

C. MPR vs. MPLS

MPR's advantages over MPLS were discussed in section I. Additionally, it is important to note that as opposed to MPLS where only end-to-end pairs connected through LSPs (i.e. tunnels) are considered in the TE strategy, MPR's approach is holistic given its link-state nature and offline TE approach (as it takes into account the entire network's topology i.e. resources). Here, we compare the two methodologies in terms of both online and offline TE mechanisms. Due to the complexity and overhead associated with MPLS implementation (see section I and [1]), we consider the simulation scenario described in [12] (previously referred to as GW anchored scenario). In this scenario, the number of *Ingress-Egress* pairs is smaller than that of section V-B thus reducing the effects of the scalability and overhead issues affiliated with MPLS.

1) Reliability: MPR's offline TE approach as oulined in [8] was applied to build RPs for different meshings (TABLE I) ahead of the traffic flow in the network. In case of MPLS, Dijkstra-based K-path routing was applied to build the same number of paths as in the MPR case to allow for the creation of Z multiple paths for every *Ingress -Egress* pair. Meanwhile, it is ensured that there would exist one edge-disjoint path (or atleast a maximum number of edges being disjoint if not all) with a hop-count threshold [1]. In MPLS offline TE (network planning phase), LSPs are obtained based on a set of given metrics as detailed in [1] (namely hop-threshold and an edge-disjoint path) hence reducing the number of LSPs to as many as desired by the network planner. This approach aims to alleviate the scalability issues in LSP construction. Accordingly, we set the criteria such that the number of LSPs is the same as the number of RPs in the MPR case (i.e. equivalent to our configuration) $(Z \equiv N)$.

Reliability is defined as the probability of the session for every *Ingress-Egress* pair (i.e. commodity) not being interrupted

TABLE IV: Delay (ms) for the first topology

Traffic	**OSPF/InvCap**				**MPR**				**QMPR**			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2
10	4.82	4.82	3.94	3.94	12.01	10.03	10.00	9.65	11.26	9.96	10.06	7.06
20	5.03	5.03	4.03	4.03	12.22	10.27	10.46	9.74	11.70	10.20	10.38	7.37
30	5.23	5.23	4.11	4.11	12.63	10.54	11.01	10.04	11.84	10.22	10.49	7.49
40	5.43	5.43	4.32	4.32	12.81	10.76	11.22	10.26	12.01	10.27	10.65	7.65
50	5.46	5.46	4.56	4.56	13.39	11.47	11.56	10.47	12.21	10.30	10.89	7.89
60	5.92	5.92	4.78	4.78	13.56	11.62	11.84	10.95	12.55	10.35	10.10	8.10
70	6.01	6.01	4.80	4.80	13.75	11.85	12.41	11.01	12.86	10.52	10.35	8.35
80	6.54	6.54	4.85	4.85	13.96	11.95	12.21	11.20	12.94	10.88	10.54	8.54
90	6.84	6.84	4.87	4.87	15.02	12.02	12.56	11.37	13.59	11.03	10.83	8.83

TABLE V: Delay (ms) for the second topology

Traffic	**OSPF/InvCap**				**MPR**				**QMPR**			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2
10	81	81	48	48	159.8	152.1	109.4	100.5	138.5	129.5	92.5	80.1
20	81.4	81.4	48.3	48.3	160.4	152.8	109.6	100.5	139.8	129.8	92.8	80.8
30	81.8	81.8	48.8	48.8	161.3	153.1	110	100.6	140	130	93	81
40	82.3	82.3	49	49	162	153.8	110.3	100.6	140.5	130.6	93.1	81.2
50	82.7	82.7	49.3	49.3	162.7	154.2	110.8	101.1	140.8	131	93.4	81.6
60	83	83	49.7	49.7	163.6	154.8	111	101.3	141.3	131.2	93.8	81.7
70	83.5	83.5	50	50	164.7	155	111.3	101.7	141.7	131.9	94.1	82
80	83.8	83.8	50.2	50.2	165.3	155.7	111.8	102	142.3	132.2	94.5	82.7
90	84.2	84.2	50.4	50.4	165.9	156.3	112	102.1	142.8	132.8	95.3	82.9

TABLE VI: Throughput (Mb/s) for the first topology

Traffic	**OSPF/InvCap**				**MPR**				**QMPR**			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2
10	30.01	30.01	26.86	26.74	40.37	50.28	51.82	58.14	40.25	48.30	48.78	55.84
20	29.92	29.92	26.52	26.45	40.35	50.21	51.25	57.62	40.2	48.16	48.21	55.82
30	29.92	29.92	26.49	26.39	40.48	50.50	50.87	57.60	40.29	48.1	47.92	55.74
40	29.88	29.88	26.44	26.37	40.26	49.91	50.39	57.40	40.17	47.93	47.54	55.61
50	29.82	29.82	26.4	26.3	40.18	49.81	50.12	57.03	40.16	47.39	47.11	54.81
60	29.77	29.77	26.35	26.28	40.12	49.49	49.15	56.43	40.07	46.9	48.49	54.62
70	29.61	29.61	26.32	26.22	40.9	49.38	49.06	56.53	40.03	46.92	46.82	54.47
80	29.59	29.59	26.29	26.18	40.42	49.26	48.73	56.11	40	46.51	46.68	54.22
90	29.47	29.47	26.18	26.12	40.29	48.8	48.65	56.04	39.95	46.19	46.57	54.03

by any factors such as link failure [31]. Lower reliability can have a negative impact on service delivery and QoS performance [32]. If failure is associated with some probability p, with the assumption that failures are independent and equal for all the links, the probability of a path with h arcs being operational is given by $(1-p)^h$ [33]. The links would also get penalized if included in more than one plane or overlap with other LSP paths. Consequently, the overall reliability per demand across a set of available independent planes can be derived as follows:

$$Reliability \propto \sum_{d=1}^{D} \frac{1}{N} \left(\sum_{n=1}^{N} \prod_{h=1}^{H_n^d} (1-p)^{\sum_{n=1}^{N} R^d_{eP^d_n}} \right) \tag{19}$$

It is easy to conclude that every individual path in one plane with a lower hop-count would have a higher reliability. It is also notable that with more diversity and fewer paths overlapping, reliability would increase. TABLE VIII illustrates the reliability indicator for all the demands across the total number of available RPs/LSPs. The reliability in case of the MPLS method is consistently lower as compared to MPR (considering the number of constructed LSPs and RPs are equivalent). This is mainly due to more links having been overused and hence further penalized throughout the constructed LSP paths in comparison with MPR (where the offline algorithm considers the whole topology and uses all the links). Consequently, it can be stated that more meshing is possible in

TABLE VII: Throughput (Mb/s) for the second topology

Traffic	**OSPF/InvCap**				**MPR**				**QMPR**			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2
10	31.29	31.29	47.44	47.44	47.44	52.52	102.2	120	42.84	48.52	97.39	115
20	31.26	31.26	47.15	47.15	47.15	52.53	102.1	120.3	42.45	48.53	96.34	115
30	31.15	31.15	47.02	47.02	46.18	52.43	101.1	120.8	42.18	48.43	97.84	115.7
40	30.30	30.30	46.51	46.51	46.63	51.61	100.5	120.1	42.51	47.61	96.35	114
50	30.08	30.08	46.24	46.24	45.24	51.46	100.5	119.5	42.14	46.63	97.36	114.4
60	30.18	30.18	46.44	46.44	45.39	50.54	100.4	118.7	41.44	46.54	96.19	113.3
70	30.19	30.19	46.14	46.14	45.24	50.70	100.2	116.2	41.44	46.21	96.65	113.1
80	30.07	30.07	45.21	45.21	45.21	50.34	99.83	114.9	41.21	44.54	96.14	112.6
90	30.04	30.04	44.08	44.08	45.08	50.15	99.45	113.2	41.08	42.15	96.61	112.3

networks that favor MPR with minimal construction overhead of planes. The results obtained in TABLE VIII are based on a set of distinct probabilities of failure having been randomly distributed among the links.

TABLE VIII: Reliability

TE Method	T_1M_1	T_1M_2	T_2M_1	T_2M_2
MPR	0.73	0.53	0.62	0.49
MPLS	0.51	0.47	0.41	0.45

2) Online Performance Comparison: In case of the MPLS-based TE where pre-constructed static LSPs are used, traffic and resource optimization are achieved through online forwarding adaptation [1]. In case of MPR and QMPR, the plane selection policy as described in subsection IV-C, is applied to route traffic among the available RPs. Different metrics are analysed by being averaged over snapshots throughout the simulation time.

TABLE IX (a) illustrates the throughput for various strategies. With MPR, the availability of a diverse set of routes across the demand set facilitates the splitting of traffic over several diverse paths, leading to improved load balancing within the network. In MPLS, the smaller throughput as compared to MPR is a result of a lower diversity that causes a higher blocking of traffic. The higher blocking rate in case of QMPR which is due to the exertion of QoS criteria, leads to its slightly worse performance compared with MPR and MPLS in certain topologies. The existence of only one route for every demand in case of the OSPF/InvCap method results in higher blocking and lower throughput. It can be also observed that throughput is generally higher in case of different routing methods for the second set of topologies as compared with the first set which is smaller in terms of links and nodes. This is due to relatively larger traffic volume in the second topology thanks to more traffic sources as explained earlier in section V-A.

As observed in TABLE IX (b), the blocking rate is lower in case of MPR as compared with MPLS. This is because of a higher number of available paths with the required bandwidth thanks to the higher diversity. The blocking rate in case of OSPF is the highest as there exist a much fewer number of available paths. In QMPR, the best RP (i.e. the best path) is selected for routing every incoming session towards its destination based on the QoS requirements and the state of the RP. This results in more sessions being blocked due to the lack of available qualified paths. Moreover, a higher blocking rate has occurred in case of the second set of topologies ($T2My$) as compared to the first set ($T1My$) which is due to the different traffic distribution model as explained previously (i.e. section V-A).

As observed in TABLE IX (c), the Maximum Link Utilization (MLU) is lower in case of MPR as compared to MPLS and OSPF. This is due to the availability of multiple diverse paths and the full utilization of resources (i.e links) in the network in case of MPR. QMPR's application leads to generally lower MLU as traffic is engineered based on QoS requirements. This corresponds to less traffic flowing in the network due to the enforced QoS criteria causing deferrals. It can be also concluded that the network gets congested faster in case of MPLS and OSPF as compared with the MPR methods. With the increase in meshing across the topologies, the general trend points to the reduction in MLU as a result of a higher number of available links in the network.

In case of MPR and QMPR, as shortest-hop routes are not always used, higher delays are experienced by the sessions forwarded onto the RPs. TABLE IX (d) demonstrates the higher delay in case of MPR and QMPR. The lower delay in case of MPLS is due to shorter routes in terms of hops having been traversed. However, with the increase in the network meshing and number of nodes, it can be observed that the MPLS performance worsens. OSPF uses a single shortest route for every demand resulting in the lowest delay in comparison. It is important to note that more packets are delivered in case of MPR and QMPR (where the entire network's routing resources are utilised) leading to a higher overall delay at the cost of a higher throughput and a smaller blocking rate. As mentioned in section V-B-3, there is a trade-off between delivering more traffic with multi-path routing over longer paths, and increased average delay [28], [29]. Therefore, it can be concluded that multi-path routing would lead to seemingly higher delays as there is less session blocking. In other words, the delay minimization objective in multi-path routing surpasses that of static shortest path routing with less path

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMC.2017.2741479, IEEE Transactions on Mobile Computing

TABLE IX: MPR vs. MPLS

TE Method	T_1M_1	T_1M_2	T_2M_1	T_2M_2
OSPF	34	34	47.5	47.5
MPR	50.6	51.2	77	77.7
QMPR	49.5	49.7	70.8	71.1
MPLS	46.8	50	72.2	74.4

(a) Throughput (Mb/s)

TE Method	T_1M_1	T_1M_2	T_2M_1	T_2M_2
OSPF	17.8	17.9	61.1	61.1
MPR	6.3	6.1	52.2	50.1
QMPR	9.4	8.3	54.1	53.9
MPLS	9.2	8.4	56.1	52.4

(b) Blocking Rate(%)

TE Method	T_1M_1	T_1M_2	T_2M_1	T_2M_2
OSPF	0.816	0.816	0.932	0.932
MPR	0.79	0.78	0.92	0.911
QMPR	0.71	0.69	0.914	0.907
MPLS	0.808	0.806	0.924	0.921

(c) Maximum Link Utilization (MLU)

TE Method	T_1M_1	T_1M_2	T_2M_1	T_2M_2
OSPF	6	6	100	100
MPR	16.6	35.1	110.1	119.2
QMPR	14.7	16.6	109.8	118.9
MPLS	11.2	13.3	109.9	118.92

(d) Delay (ms)

diversity. This is because of more traffic being admitted with the gradual overflowing of network comparatively in case of multi-path routing. Additionally, a generally higher delay is incurred in the second set of topologies as compared to the first set, which is due to the larger size of the network. It is important to note that the delay in access networks might be negligible as compared with the delay to and from the Internet. Moreover, as planes do not change for sessions once the first packet is admitted, there are no variations in packet delays in normal load situations and transport layers would not be disrupted.

VI. CONCLUSION

In this paper, IP TE-based MPR has been remodelled to suit the future all-IP access network structures by utilising the entire network's routing resources. The evolution of network architecture designs as reflected in the trend towards a flat-IP structure, along with the rise of IP-based real-time applications call for a consistent routing paradigm. MPR augments the constrained shortest-path routing paradigm allowing the network to deploy path diversity by concurrently maintaining several independent logical topologies. The resultant diversity allows for network wide load balancing and is suited to various topological configurations. Being facilitated by multiple OSPF topology instances in networks that are controlled by offline and online algorithms, MPR achieves path diversity with minimal extra protocol overhead. We have applied heuristics for both offline and online TE solutions respectively, due to the NP-complete nature of finding suitable RPs in diverse practical topologies, and use of multiple QoS metrics for realistic traffic types to be supported by network's routing. Two cases that are reflective of the evolution in the network architecture design have been investigated in terms of various metrics under fluctuating internal/external traffic distributions to emulate a comprehensive realistic traffic scenario that facilitates a thorough performance evaluation. In addition to the demonstration of MPR-based methods' superiority over legacy OSPF/InvCap methods, it has been shown that the flat-IP based design concept (case II) outperforms the hierarchical-based concept (case I). Moreover, the surge in the internal traffic ratio has resulted in performance degradation under both network architecture design concepts but has generally improved with more meshing in the networks. It has been also shown that MPR outperforms MPLS in terms of reliability and online TE mechanism besides the MPR's ease of protocol deployment. For future work, MPR will be investigated under a heterogeneous environment in alignment with the developing 5G concepts and extended to accommodate for the revolutionary Tactile Internet. Moreover, MPR's application in networks of random nature (random graphs) will be thoroughly studied.

REFERENCES

[1] N. Wang, K. Ho, G. Pavlou, and M. Howarth, "An overview of routing optimization for internet traffic engineering," *IEEE Communications Surveys Tutorials*, vol. 10, no. 1, pp. 36–56, Jan. 2008.

[2] H. Raza, "A brief survey of radio access network backhaul evolution: part ii," *IEEE Communications Magazine*, vol. 51, no. 5, pp. 170–177, May 2013.

[3] B. Fortz and M. Thorup, "Increasing internet capacity using local search," *Computational Optimization and Applications*, vol. 29, no. 1, pp. 13–48, 2004.

[4] A. Sridharan, R. Guerin, and C. Diot, "Achieving near-optimal traffic engineering solutions for current OSPF/IS-IS networks," *IEEE/ACM Transactions on Networking*, vol. 13, no. 2, pp. 234–247, April 2005.

[5] K. Nemeth, A. Korosi, and G. Retvari, "Optimal OSPF traffic engineering using legacy Equal Cost Multipath load balancing," in *IFIP Networking Conference*, May 2013, pp. 1–9.

[6] D. Xu, M. Chiang, and J. Rexford, "Link-state routing with hop-by-hop forwarding can achieve optimal traffic engineering," in *IEEE 27th Conference on Computer Communications*, Apr 2008.

[7] K. Xu, M. Shen, H. Liu, J. Liu, F. Li, and T. Li, "Achieving optimal traffic engineering using a generalized routing framework," *IEEE Transactions on Parallel and Distributed Systems*, vol. 27, no. 1, pp. 51–65, Jan 2016.

[8] A. Jaron, A. Mihailovic, and A. Aghvami, "Introducing multi-plane routing for next-generation all-IP wireless access networks," in *IEEE International Conference on Communications*, Jun 2012, pp. 2856–2860.

[9] P. Psenak, S. M. L. Nguyen, P. Pillay-Esnault, and A. Roya, "Multi-topology routing in OSPF," *IETF*, p. RFC 4915 (2007).

[10] N. Wang, K.-H. Ho, and G. Pavlou, "Adaptive multi-topology IGP based traffic engineering with near-optimal network performance," in *Proceedings of the 7th International IFIP-TC6 Networking Conference on AdHoc and Sensor Networks*. Springer-Verlag, 2008, pp. 654–666.

[11] A. Jaron, M. Danel, P. Faucheux, A. Mihailovic, and A. Aghvami, "Qos-aware multi-plane routing for future IP-based access networks," in *IEEE Global Communications Conference*, Dec 2012, pp. 2803–2808.

[12] A. Jaron, A. Mihailovic, and A. Aghvami, "Qos-aware multi-plane routing method for OSPF-based IP access networks," *Computer Networks*, vol. 99, pp. 1 – 14, 2016.

[13] L. Muscariello, D. Perino, and D. Rossi, "Do next generation networks need path diversity?" in *IEEE International Conference on Communications*, Jun 2009, pp. 1–6.

[14] J. Zhang, K. Xi, and H. Chao, "Load balancing in IP Networks using generalized destination-based multipath routing," *IEEE/ACM Transactions on Networking*, vol. 23, no. 6, pp. 1959–1969, Dec 2015.

[15] M. Farhoudi, A. Jaron, A. Mihailovic, and H. Aghvami, "A new approach for routing plane construction in future multi-plane routing based wireless IP access networks," in *IEEE Wireless and Networking Conference*, Apr 2016.

[16] M. Farhoudi, B. Abrishamchi, A. Mihailovic, and H. Aghvami, "A practical multi-plane routing-based traffic engineering scheme in evolutionary convergent all-IP access networks," in *23rd International Conference on Telecommunications*, May 2016.

[17] M. Mirahsan, R. Schoenen, H. Yanikomeroglu, G. Senarath, and N. Dung-Dao, "User-in-the-loop for hethetnets with backhaul capacity constraints," *IEEE Wireless Communications*, vol. 22, no. 5, pp. 50–57, Oct 2015.

[18] X. Ge, J. Ye, Y. Yang, and Q. Li, "User mobility evaluation for 5G small cell networks based on individual mobility model," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 528–541, March 2016.

[19] M. Frickea, A. Heckwolfa, R. Herberb, R. Nitschc, S. Schwarzed, S. Vod, and S. Weveringe, "Requirements of 4G-Based mobile broadband on future transport networks,," *Journal of Telecommunications and Information Technology*, 2012.

[20] X. Ge, H. Cheng, M. Guizani, and T. Han, "5G wireless backhaul networks: challenges and research advances," *IEEE Network*, vol. 28, no. 6, pp. 6–11, Nov 2014.

[21] F. B. K. Nichols, S. Blake and D. Black, "Definition of the Differentiated Services Field (DS Field) in the IPv4 and IPv6 headers," *RFC 2474*.

[22] J. Wang, Y. Yang, L. Xiao, and K. Nahrstedt, "Edge-based traffic engineering for OSPF networks," *Computer Networks*, vol. 48, no. 4, pp. 605 – 625, 2005.

[23] A. Jaron, P. Pangalos, A. Mihailovic, and A.-H. Aghvami, "Proactive autonomic load uniformisation with mobility management for wireless internet protocol IP access networks," *IET Networks*, vol. 1, no. 4, pp. 229–238, Dec. 2012.

[24] D. Amzallag, J. Naor, and D. Raz, "Algorithmic aspects of access networks design in B3G/4G cellular networks," in *IEEE 26th International Conference on Computer Communications*, May 2007, pp. 991–999.

[25] R. Hassin and A. Levin, "A better-than-greedy approximation algorithm for the minimum set cover problem," *SIAM J. Comput.*, vol. 35, no. 1, pp. 189–200, Jul. 2005.

[26] H. N. Gabow and E. W. Myers, "Finding all spanning trees of directed and undirected graphs," *SIAM Journal on Computing*, vol. 7, no. 3, pp. 280–287, 1978.

[27] L. Gouveia and C. Requejo, "A new lagrangian relaxation approach for the hop-constrained minimum spanning tree problem," *European Journal of Operational Research*, vol. 132, no. 3, pp. 539–552, 2001.

[28] G. Retvari and T. Cinkler, "Practical OSPF traffic engineering," *IEEE Communications Letters*, vol. 8, no. 11, pp. 689–691, Nov 2004.

[29] U. Javed, M. Suchara, J. He, and J. Rexford, "Multipath protocol for delay-sensitive traffic," in *Communication Systems and Networks and Workshops. (COMSNETS)*, Jan 2009, pp. 1–8.

[30] D. Bertsekas, R. Gallager, and P. Humblet, *Data networks*. Prentice-Hall International New Jersey, 1992, vol. 2.

[31] M. Monteiro, D. Fontes, and F. Fontes, *Examining Robustness and Vulnerability of Networked Systems*. IOS, 2014.

[32] M. Rebaiaia and D. Kadi, *Network Reliability Evaluation and Optimization: Methods, Algorithms and Software Tools*, ser. CIRRELT (Collection), 2013.

[33] M. Monteiro, D. Fontes, and F. Fontes, "Hop-constrained tree shaped networks," *Foundation for Science and Technology*, 2012.

Mohammad Farhoudi received both his B.Eng. degree (First Class Honours) in electronic engineering and his MSc. degree in mobile and personal communications from King's College London, in 2010 and 2011 respectively. He is currently working towards his PhD. degree at the Centre for Telecommunications Research, King's College London. His research interests include Future Internet, IP routing/mobility, Haptics communications, IoT and machine-to-machine communications.

Benyamin Abrishamchi received his B.Eng. degree in electronic engineering and his MSc. degree (Distinction) in mobile and personal communications from King's College London, in 2011 and 2012 respectively. He also holds a MSc. degree in risk management and financial engineering from Imperial College London. He is currently working towards his PhD. degree at the Centre for Telecommunications Research, King's College London. His research interests include Future Internet, IP routing/mobility, Haptics communications, and IoT.

Andrej Mihailovic received his B.Eng., MSc. and PhD. degrees all from King's College London, in 96, 97 and 2004 respectively. His main experience in King's in collaborative and individual projects: BRITISH TELECOM project on IP mobility (1998-2000), FP5 EU projects: BRAIN (2000-2001) and MIND (2001-2002) on IP access networks, individual project with SIEMENS, Germany (2002-2004) on IP moving networks, FP6 EU projects: E2R I (2004-2006) as the leader of sWP1.2 Architecture Models and Reconfigurability Management, and then in E2R II (2006-2008) as the main liaison in the WWI Cross Issues on System Interfaces/Architecture between the leading EU Integrated Projects, then, EU FP7 project Self-NET (2008-2011) as the leader of WP1: System Architecture for Cognitive Network Management. He has also participated in standardizations Groups: IEEE P1900.4 on Reconfiguration of multi-radio systems (in 2007) and ESTIs Autonomic network engineering for the self-managing future internet AFI (2011-2013). Andrej also worked as an expert for University of Montenegro under EU REGPOT Project Fore-MONT (2013-2016) on IoT solutions. He is also an EU Expert/Project Evaluator. Research areas include: Future Internet, IP routing/mobility, IoT and self-managed and cognitive systems.

Abdol-Hamid Aghvami is a Professor of telecommunications engineering with King's College London, London, U.K. He was a Visiting Professor with NTT Radio Communication Systems Laboratories, Japan, in 1990, Senior Research Fellow with BT Laboratories from 1998 to 1999, and an Executive Advisor with Wireless Facilities Inc., San Diego, CA, USA, from 1996 to 2002. He has authored over 600 technical papers and given invited talks and courses world wide on various aspects of personal and mobile radio communications. Prof. Aghvami was a member of the Board of Governors of the IEEE Communications Society from 2001 to 2003, was a Distinguished Lecturer of the IEEE Communications Society from 2004 to 2007, and has been a Member, Chairman, and Vice-Chairman of the Technical Program and Organizing Committees of a large number of international conferences. He is also the founder of the International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), a major yearly conference attracting nearly 1000 attendees. He was the recipient of the IEEE Technical Committee on Personal Communications (TCPC) Recognition Award in 2005 for his outstanding technical contributions to the communications field and for his service to the scientific and engineering communities. He is a Fellow of the Royal Academy of Engineering and IET. He was the recipient of a 2009 Fellowship of the Wireless World Research Forum in recognition of his personal contributions to the wireless world.