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A Practical Multi-Plane Routing-based Traffic Engineering Scheme in Evolutionary Convergent All-IP Access Networks

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***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. In this paper, Multi-Plane Routing (MPR) that consolidates various aspects in all-IP infrastructure is remodelled in consistent with this development. 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. Accordingly, a practical performance evaluation testing the validity of the aforementioned scenarios is presented. Our simulation results demonstrate a better achieved performance under the flat-IP structure in addition to MPR-based methods' superiority over legacy OSPF/Invcap. Performance degradation is observed with the rise in the internal traffic distribution for the different scenarios studied. Moreover, a new optimization framework for the offline and online TE mechanisms of MPR have been proposed.**

I. Introduction

THE growing number of exciting new devices associated with the rising context-aware and real-time applications over the Internet calls for a consistent transformation in the routing protocols supporting these applications. Correspondingly, IP Network Providers (INPs) need 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]. IP is now the dominant internetworking protocol and with the expected rise in the global IP traffic, there has been an adoption of open IP interfaces in the integrated backhaul network designs [2] which is indicative of the cellular wired backhaul and Internet access based network designs converging on the IP-based infrastructure model.

Intra-domain TE is categorized into the MPLS- 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 is enabled through MPLS where the scalability and robustness become an issue due to the complexity and overhead associated with building and maintaining LSPs to which flows are mapped. IP-based TE is implemented through the manipulation of link weights in case of Interior Gateway Protocols (IGPs) such as 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. 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].

A. Related Work and Background

Authors in [4] aim to ameliorate the legacy ECMP approach 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 subject to performance degradation and deviation from optimal TE. To address this issue, 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. However, this protocol requires the involvement of all the available paths for every *Ingress - Egress* pair making it inconsistent with the shortest-path nature of OSPF.

Multi-Plane Routing (MPR) which was proposed in [7] for access networks aims to address the deficiencies associated with MPLS and ECMP. MPR is based on Multi-Topology OSPF (MT-OSPF) principle that consolidates various aspects in the all-IP network infrastructure. MT-OSPF was primarily proposed for fast re-route in case of node/link failure whereas MPR employs MT-OSPF for comprehensive network-wide load balancing. MPR applies an offline TE method in order to build logical Routing Planes (RPs) that render a set of shortest paths ahead of the traffic flow in the network that is governed by an online TE approach. MPR applies a purely IP-based TE approach where multiple logical RPs that represent instances of OSPF are constructed such that path diversity is maximized.

The RPs are built such that an optimum full utilization of links based on Full Path Diversity Index (FPDI) is achieved as outlined in [7]. The path diversity potential benefits in access networks was investigated in [8]. This study undermined the need for next-generation access networks' evolution to more meshed 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 a purely IP-based TE approach. Therefore, the complexity and overhead associated with the MPLS TE approach can be avoided.

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 and the ingress/egress point to the core network through gateway. Traffic flows between gateway and access nodes in both directions, and between access nodes. A reference scenario was studied for MPR in [9] 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 source of traffic in the network hence the entire 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 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. In 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. In this case, the RP structure is modified by including direct communication paths between ARs in addition to the duplex *GW-AR* pair. 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], [10]. 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 [11], wired backhaul links' overload could be alleviated by the diversity offered by MPR.

B. Contributions

To summarize, the contributions of this paper are threefold. Firstly, we extended the analysis of MPR by considering a realistic traffic scenario with fluctuating internal/external traffic distribution of both uplink and downlink nature where all the ARs and the GW can be Ingress/Egress. This complements the study of MPR by providing a performance analysis in a realistic network scenario. To our knowledge, such a realistic simulated analysis that facilitates a comprehensive vision of the network's performance considering different possibilities, is absent in literature. Secondly, under such realistic traffic scenario, we remodelled MPR to resonate two cases that are reflective of the architectural evolution of cellular- and internet-based access networks and identified the case with superior performance. To our knowledge, despite research having looked into the underlying standards supporting flat-IP, the validity of such design concept has not been studied previously. Our proposed TE methodology under a variable traffic scenario provides a thorough analysis considering the versatile nature of traffic such that the possible growing extent of need for such IP-enabled direct communication is accommodated in our investigation. Thirdly, we proposed new optimization frameworks for both the offline and online TE mechanisms of MPR as there are no such existing frameworks to reflect MPR's routing functionality.

The rest of this paper is organized as follows: Section II sets out our system model. The problem formulation and its associated notations are presented in section III. Section IV presents the experimental demonstrations. Finally, section V concludes the paper.

II. System Model

A. Concept

MPR partitions the network into several logical planes enabling the routers in a OSPF zone to maintain several independent logical RPs. Each RP represents an instance of OSPF associated with a dedicated link weight setting and it can overlap with another or share any subset of the underlying network. In our study, each router will have different Routing Information Bases (RIBs) and Forwarding Information Bases (FIBs) through which routes to other ARs and gateway are defined in every RP. Each RIB/FIB represents one RP. MPR is envisioned to be configured using the IP-header integrated Type of Service (ToS)/Differentiated Service (DiffServ) unused bits (i.e. 3 precedences) (as put forward by IETF in [12]) supporting up to 8 RPs. In earlier studies for MT-OSPF [13], it was concluded 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 for MPR in [7].

B. Experimental Setup

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 [14]. The network is comprised of 14 base stations acting as Aggregation Routers. Nodes are considered to be interconnected by wired Ethernet links. A $M/M/1$ queuing model is considered for every node. Link capacities are set depending on the level they belong to in our reference network. They 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.

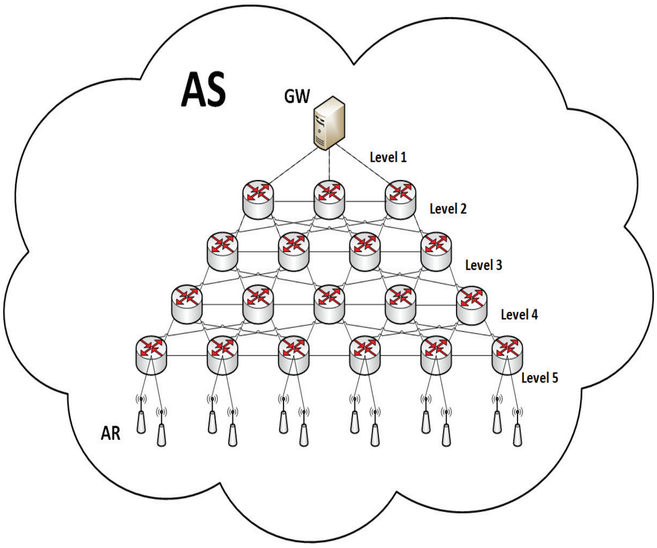

Fig. 1: Autonomous system comprised of 32 nodes and 67 links. Average node degree: 4.19. Total capacity (Gb): 18.40

III. MPR's TE Mechanism

A. Graph Theoretical Representation

Topology of a given communication access network is represented by a connected directed graph $G = (\mathcal{V}, \mathcal{E})$. The network is comprised of a set of $\mathcal{E}$=$\{e : e = 1, ..., E\}$ edges with finite capacities C_e, and a set of $\mathcal{V}$=$\{v : v = 1, ..., V\}$ vertices. Let $\mathcal{K} : k = 1, ..., K$ symbolize the number of ARs in the network, and let the set of Routing Planes (RPs) be represented as $\mathcal{N} : n = 1, ..., N$. 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 demands for every *Ingress - Egress* pair denoted by $\mathcal{D}$=$\{d : d = 1, ..., D\}$. The egress nodes are $Egress : \{GW and\ \{AR_k\}_{k=1}^{k} \setminus \{AR_s\}_{s=1}^{S}\}$. Let f symbolize the number of destination nodes. Let $AR_{\mathcal{S}}$ ($\subseteq AR_k$) be the source AR ($\mathcal{S}$=$\{s : s = 1, ..., S\}$). AR_{fi} ($\in AR_k$) represents the first destination AR while AR_{la} ($\in AR_k$) represents the last destination AR on the network in one iteration before the source AR ($AR_{\mathcal{S}}$) changes for the next iteration until all the ARs are covered. 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 routing plane 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 demand d and 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 $\mathcal{H} = \{h : h = 1, ..., H\}$ hops. An $N \times E$ matrix R^d represents the link usage. $R_{eP_n^d}^d = 1$ if path P_n of pair d uses link e and $R_{eP_n^d}^d = 0$ otherwise. Matrix R^d for demand d is:

$$R^d = \begin{bmatrix} R_{1P_1^d}^d & R_{2P_1^d}^d & \cdots & R_{EP_1^d}^d \\ R_{1P_2^d}^d & R_{2P_2^d}^d & \cdots & R_{EP_2^d}^d \\ \vdots & & & \\ R_{1P_N^d}^d & R_{2P_N^d}^d & \cdots & R_{EP_N^d}^d \end{bmatrix} \tag{1}$$

The set of path $(\rho_n^1, \rho_n^2, ..., \rho_n^K, \rho_n^{K+1})$ for all the ARs and GW represent one RP. Case I and case II were outlined in subsection I-A. In the first case where all the traffic travels through the core, path set ρ_n^k is represented as follows:

$$\rho_n^k = \begin{Bmatrix} AR_{\mathcal{S}} \to GW & : P_n^{d_k=1} \\ AR_{\mathcal{S}} \to GW \to AR_{fi} \neq AR_{\mathcal{S}} & : P_n^{d_k=2} \\ \vdots & \\ AR_{\mathcal{S}} \to GW \to AR_{la} \neq AR_{\mathcal{S}} & : P_n^{d_k=f} \end{Bmatrix} \tag{2}$$

In the second case, path-set ρ_n^k is:

$$\rho_n^k = \begin{Bmatrix} AR_{\mathcal{S}} \to GW & : P_n^{d_k=1} \\ AR_{\mathcal{S}} \to AR_{fi} \neq AR_{\mathcal{S}} & : P_n^{d_k=2} \\ \vdots & \\ AR_{\mathcal{S}} \to AR_{la} \neq AR_{\mathcal{S}} & : P_n^{d_k=f} \end{Bmatrix} \tag{3}$$

Where $\to$ represents a 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_n^1 and the demand increments up to D that corresponds to the final *Ingress-Egress* pair in path-set ρ_n^{K+1}. Let $\bar{\varphi}_s$ represent the average length of the shortest path in terms of hop-count from any source u to all the destinations v across the available planes under a given topology. $\varphi_n^k(u, v)$ is the length of the shortest path between nodes $u \in Ingress$ and $v \in Egress$ in every path-set ρ_n^k.

$$\bar{\varphi}_s = \frac{1}{N}\left(\sum_{n=1}^{N}\sum_{k=1}^{K+1}\left(\frac{1}{V-1}\sum_{(u,v)\epsilon V, v\neq u}\varphi_n^k(u,v)\right)\right) \tag{4}$$

Every plane is a subset of the physical topology of the underlying network. A separate RIB/FIB is maintained for every subset. For graph G, the sub-graph induced on a vertex subset $\rho_n^{\mathcal{K}} \in G$ of V_G is denoted as $G(\rho_n^{\mathcal{K}})$.

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

B. MPR Offline RP Construction

We introduce a modified offline TE approach to build RPs ahead of traffic flow into the network. Link usage represents the number of RPs that include e in their shortest path across the given demands, which is defined as:

$$LU_e = \sum_{n\in\mathcal{N}}\sum_{d\in\mathcal{D}} R_{eP_n^d}^d \quad , \forall e \in \mathcal{E} \ \ and \ \ \forall d \in \mathcal{D} \tag{6}$$

The maximum LU on every link is $LU_e = N - 1$ as initially proposed in [7] to ensure Full Path Diversity (FPD). The weight for demand d between nodes (u, v) is given by:

$$w_{uv}^d(n, e) = \frac{1}{C_e} + \frac{1}{N}\sum_{n=1}^{N-1} w(n, e) \quad + \alpha_e(n) \cdot X \tag{7}$$

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

X is a multiplicative parameter that is used for the granularity. The link weight assignment calculates N set of positive link weights $W_n = \{w(n,e) : 1 \le w(n,e) \le Z, \forall n \in \mathcal{N}, \forall e \in \mathcal{E}\}$, 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 $X_{max} = \{2; 4; 8; 16; 32; 64\}$. $w^d_{uv}(n,e)$ considers the involvement of a link in RP $N-1$. We formulate MPR's offline approach as a constrained shortest path routing problem that 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, while also aiming to equivalently minimize $\sum_{(e_{uv,n})\in P^d_n} w^d_{uv}(n,e)$ for every P^d_n.

$$
\begin{aligned}
\min \quad & \sum_{n\in\mathcal{N}} \sum_{d\in\mathcal{D}} \sum_{(u,v)\epsilon V} R^d_{(uv)P^d_n} . w^d_{uv}(n,e) \\
\text{s.t.} \quad & \sum_{v:(u,v)\in\mathcal{E}} R^d_{(uv)P^d_n} - \sum_{v:(v,u)\in\mathcal{E}} R^d_{(vu)P^d_n} = \\
& \begin{cases} 1, \text{ for } u = s \\ 0, \text{ for } u \in V - \{s,v\}, \\ -1, \text{ for } u = t \end{cases} \\
& 1 \le (LU_e =) \sum_{n\in\mathcal{N}} \sum_{d\in\mathcal{D}} R^d_{(uv)P^d_n} \le N - 1 \\
& R^d_{(uv)P^d_n} = [0,1], \forall (uv) \in E, \forall d \in \mathcal{D}, \forall n \in \mathcal{N}
\end{aligned} \tag{9}
$$

This optimization problem ensures that there exist a set of independent loop-free least-cost path sets with every link being used at least once and at most $N-1$ times. Our suggested modified approach defines a termination point in the 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.

C. MPR Online TE Mechanism

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^t_q 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. We formulate MPR's online TE optimization based on [15] where only a special case for delay-sensitive traffic was considered and it was assumed that there exists access to shortest paths with flexible splitting of traffic over those paths with no specific supporting protocol. 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. MPR's online TE optimization objective is to minimize the associated cost depending on the path residual capacity and traffic type's associated QoS requirements for every session while also aiming to minimize the total traffic rate on every available path facilitated by the distribution of traffic among multiple paths (RPs). It is also ensured that the capacity constraint of every link is met. MPR's online TE optimization (i.e. RP selection policy) is presented below:

$$
\begin{aligned}
\min \quad & \sum_{d\in\mathcal{D}} \sum_{n\in\mathcal{N}} Y^d_{P^d_n} \sum_{uv\in P^d_n} R^d_{uvP^d_n} \Big((\frac{m_q(uv)}{c^t_q})^{\gamma_q} + (\frac{C_{uv}}{\widetilde{C}_{uv} - ||\Pi^{b,d}_{uv,n}||_0}) \Big) \\
\text{s.t.} \quad & L_{uv} \le C_{uv}, \big(L_{uv} = \sum_{d\in\mathcal{D}} \sum_{n\in\mathcal{N}} \sum_{b\in\mathcal{B}} ||\Pi^{b,d}_{uv,n}||_0 \big) \\
& \sum_{n\in\mathcal{N}} Y^d_{P^d_n} = X^d \\
& Y^d_{P^d_n} \ge 0 \\
& m_q(P^d_n) \equiv \sum_{uv\in P^d_n} R^d_{uvP^d_n} . m_q(uv) \le c^t_q \\
& \forall d \in \mathcal{D}, \forall b \in \mathcal{B}, \forall n \in \mathcal{N}, \forall q \in \mathcal{Q}, \forall (uv) \in E, \gamma_q \in [0,1]
\end{aligned} \tag{10}
$$

$Y^d_{p^d_n}$ represents the traffic rate on path P^d_n associated with demand d and RP n. X^d is indicative of the total traffic rate for demand d. $R^d_{uvP^d_n}$ is the routing matrix associated with link uv on path P^d_n (equation 1). $\widetilde{C}_{uv}$ signifies the residual capacity on link uv with link capacity C_{uv}. $||\Pi^{b,d}_{uv,n}||_0$ is indicative of the non-zero non-negative entries of $\Pi^{b,d}$ associated with plane n and link uv. The load on link uv is signified by L_{uv}. γ_q variables allow to give more priority to the concerning QoS parameters. RP selection policy is applied by MPR which is implemented through the sources (i.e. GW and ARs). In case of MPR, the available bandwidth on the RPs is initially determined and in case of the availability of more than one RP in terms of bandwidth requirements, the one with the highest bandwidth is selected. In case of QoS-MPR (QMPR), the qualified RPs in terms of bandwidth are selected taking into consideration packet's classification as determined based on its associated Service Level Requirement (SLR). Consequently, RPs that do not meet the requisite benchmarks associated with the concerning traffic class are eliminated with the most suitable RP in terms of our objective function being picked.

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

Traffic Class	Data Rate	Mean Duration	QoS requirements		
			Latency	Jitter	Packet loss
Class 1	Low ($\approx$ 150 Kbps)	180 s	40-65 ms	0.5-2 ms	0.1-0.5 %
Class 2	Medium ($\approx$ 250 Kbps)	300 s	4-5 s	*none*	5 %
Class 3	Low ($\approx$ 128 Kbps)	200 s	300-600 ms	2 ms	5 %
Class 4	High ($\approx$ 500 Kbps)	360 s	300 ms	30 ms	1 %
Class 5	Low ($\approx$ 100 Kbps)	90 s	*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.

IV. Performance Evaluation

In this section, the performance of different methodologies for varying internal/external traffic distribution under different scenarios (i.e. case I & case II as outlined in subsection I-A) in terms of various metrics are presented and analysed based on the results obtained using packet-level NS2 simulations interfaced with Matlab. Initially, MPR's offline TE is applied using Matlab simulations to build RPs ahead of the traffic introduction into the network that is implemented using NS2.

Traffic	OSPF/Invcap		MPR		QMPR	
(%)	Case I	Case II	Case I	Case II	Case I	Case II
10	81	48.06	152.12	100.52	129.53	80.16
20	81.43	48.32	152.85	100.58	129.84	80.84
30	81.86	48.86	153.16	100.63	130.03	81
40	82.36	49.04	153.87	100.69	130.65	81.26
50	82.76	49.32	154.21	101.12	131.03	81.61
60	83.01	49.74	154.84	101.35	131.26	81.73
70	83.53	50.01	155.05	101.74	131.92	82.01
80	83.81	50.21	155.74	102.03	132.21	82.74
90	84.22	50.46	156.35	102.12	132.85	82.94

TABLE II: Delay (ms)

Subsequently, incoming sessions of different traffic classes (as represented in TABLE I) are generated with complete random nature. 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 an aggregation router or the gateway (i.e. source), the latter checks for bandwidth availability on the set of path(s) to reach the destination, regardless of the method used (OSPF, InvCap, MPR, or QMPR). In case of MPR and QMPR, the online TE mechanism as described in subsection III-C, is applied to route traffic among the RPs. Different metrics are analysed by being averaged over snapshots throughout the simulation time for different traffic percentage distributions. It is important to note that the OSPF method and the Invcap method are differentiated based on link weights set to 1 (hop-count based) and inverse capacity-based weight setting, consecutively. Due to the proximity of results under these two methodologies, we present their associated results as one.

1) Delay (ms)

As it can be observed from TABLE II, a higher mean delay is resulted with case I as longer routes are traversed compared to case II where also a lower queuing delay is resulted due to the higher available path diversity for sources of traffic as opposed to case I where the entire traffic passes through the GW. This leads to the speeding up of the queue processing in case II as compared to case I. A higher delay is resulted in case of the MPR-based methods as shortest-hop routes are not always used and more traffic is delivered. It was shown in [16] that for OSPF TE, the price for a higher throughput facilitated by multiple available paths is the increased average delay caused by growth in the average path length. It was also shown in [15] 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's distribution which is due to the higher traffic density causing larger queue processing times and a higher overall number of hops having been traversed.

2) Maximum Link Utilization (MLU)

As observed in Fig. 2, the MLU is lower in case II as compared to case I, which is due to better traffic distribution as opposed to case I where all the traffic traverses the GW. The resulted MLU does not exhibit much variation for different traffic distributions since the total average MLU for the entire network is expected to be almost consistent, without much variation, for the entire traffic under different routing strategies. MLU is lower for the MPR-based methods as expected, due to the availability of multiple paths as compared to legacy OSPF/Invcap. Compared with MPR, QMPR has achieved a lower MLU as traffic is engineered based on QoS requirements resulting in less traffic flowing in the network.

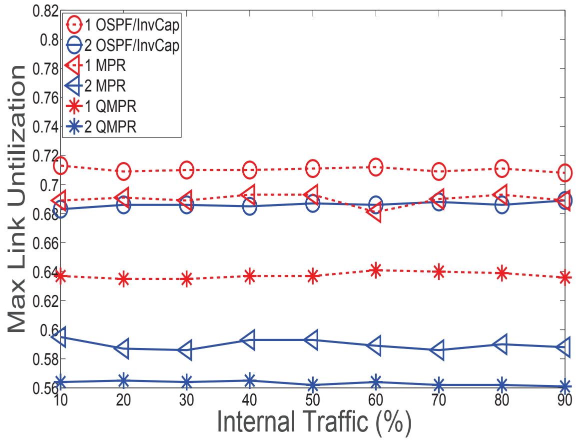

Fig. 2: Maximum Link Utilization

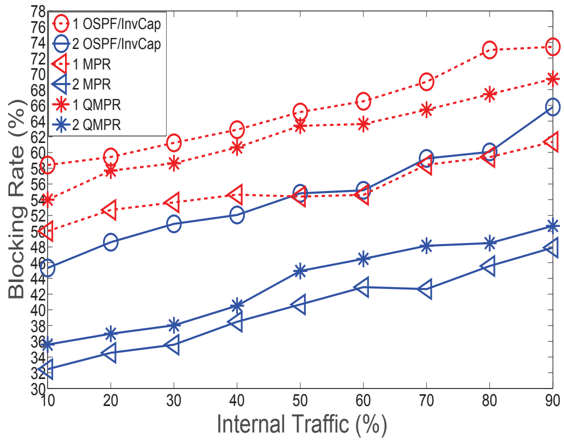

Fig. 3: Blocking Rate (%)

3) Blocking Rate (%)

The resulted mean blocking rate, as observed in Fig. 3, is lower in case II as the bottleneckness of the entire traffic traversing the GW has been avoided. 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 case I and II. This is indicative of the additional imposed QoS requirements having resulted in higher blocked traffic. Moreover, the mean blocking rate has increased in case of all the methodologies with the intensification of the internal traffic distribution.

4) Packet Loss Rate (%)

As observed in Fig. 4, the resulted average packet loss rate is lower in case II as compared to case I which is due

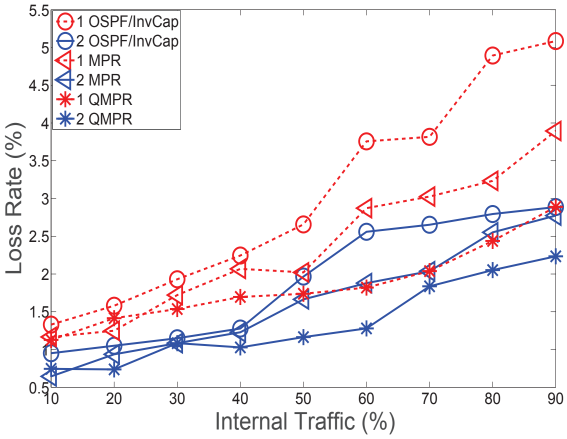

Fig. 4: Packet Loss Rate (%)

Traffic	OSPF/Invcap		MPR		QMPR	
(%)	Case I	Case II	Case I	Case II	Case I	Case II
10	31.29	47.44	52.52	120.05	48.52	115.06
20	31.26	47.15	52.53	120.37	48.53	115.08
30	31.15	47.02	52.43	120.82	48.43	115.70
40	30.30	46.51	51.61	120.15	47.61	114.01
50	30.08	46.24	51.46	119.57	46.63	114.43
60	30.18	46.44	50.54	118.76	46.54	113.39
70	30.19	46.14	50.70	116.25	46.21	113.15
80	30.07	45.21	50.34	114.96	44.54	112.66
90	30.04	44.08	50.15	113.28	42.15	112.37

TABLE III: Throughput (Mb/s)

to higher congestion and blocking triggered by less diversity for traffic sources in case I (where the entire traffic passes through the GW), causing 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 resulting in a lower loss of sent packets. With the intensification of the internal traffic distribution, loss rate has increased correspondingly, which is due to the higher congestion throughout the network.

5) Throughput (Mb/s)

TABLE III represents the achieved network's average throughput under varying traffic percentages. As observed, the achieved throughput is generally higher in case II for different routing strategies as compared with case I. This can be justified by the higher 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 balancing of the load in the network and higher packet delivery. The average overall achieved throughput has declined with the rise in the internal traffic distribution aligned with the surge in blocking for both cases.

V. Conclusion

In this paper, IP TE-based MPR has been remodelled to suit the future all-IP access network structures. 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 demand a new consistent routing paradigm. This paradigm allows the network to maintain several independent logical topologies which can be used to balance the traffic load in the network. 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 outperforms the hierarchical-based concept. Moreover, the surge in the internal traffic ratio has resulted in performance degradation under both network architecture design concepts. For future work, MPR will be investigated under a heterogeneous environment in alignment with the developing 5G concepts.

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