

Augmented In-Band Telemetry to the User Equipment for Beyond 5G Converged Packet-Optical Networks

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Abstract Traffic monitoring through in-band telemetry is extended up to the User Equipment (UE), providing accurate e2e latency measurement. The UE becomes aware of its experienced service performance, enabling autonomous operations for faster automatic source-based Edge-Cloud steering.

Introduction

In the 5G architecture, latency critical applications are supported through a converged packet optical infrastructure that ranges from the cloud to the edge computing resources. In this context, P4-based In-band Network Telemetry (INT) has emerged as a candidate technology enabling the monitoring of the actual edge-cloud experienced latency^[1-3]. In case of critical service conditions, the SDN Controller (/Orchestrator) is typically involved to recover adequate service conditions.

Beyond 5G (B5G) is now calling for a fully end-to-end (e2e) architecture, where the infrastructure is extended up to the B5G user equipment (UE) ^[4]. In addition, B5G aims at providing self-management of (pre-planned) services, thus avoiding the SDN controller intervention during critical events while minimizing control overhead.

In this work we propose to extend P4 INT up to the 5G user equipment and perform INT-triggered source-based steering to the most suitable cloud-edge node satisfying the required service latency. The solution resorts to extended P4-based INT programmability and is implemented and evaluated in a hybrid multi-segment testbed including a real wireless domain, a packet-switched backhaul and an SDN disaggregated metro-core optical domain running optical telemetry against soft failure events.

INT in 5G converged packet-optical network

Fig. 1 shows the network scenario motivating the proposed augmented INT system. A 5G network is connected to a cloud data center by means of a backhaul and metro-core optical network with P4 programmable bare metal switches (i.e., N1-N6 in Fig. 1) running in-band telemetry (INT). Services offered to 5G users are deployed on cloud resources and closer edge node resources E1 and E2, depending on service requirements in terms of bounded latency.

Typically, INT is programmed at each switch to

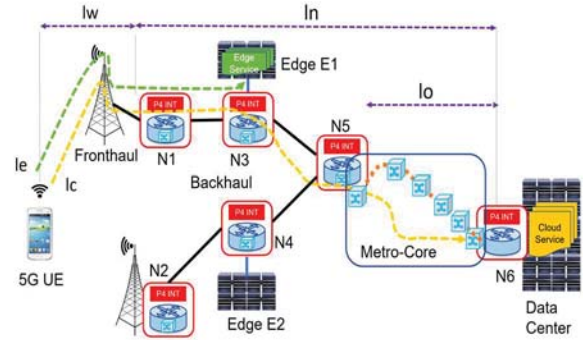


Fig. 1: 5G Edge Cloud traffic in INT-enabled SDN wired network: monitored and unmonitored latencies.

push custom headers to selected traffic flows, for example conveying information on the actual latency spent by packets within each node (i.e., hop latency). Thus, INT is capable of monitoring intra-switch latencies. Instead, link latencies may not be retrieved since they would require synchronization among all nodes, typically not available in an e2e scenario with multiple domains. In a fully packet-switched wired network such approach is appropriate to detect latency variations, typically occurring inside the switch due to congestion, queueing and buffering. However, in a wired-wireless e2e path including multi-layer optical networks, significant link latency variations may occur, not monitored by INT. First, in a multi-layer network, a working lightpath in the optical layer may be re-routed along a longer distance path (e.g., upon recovery or optimization), thus increasing link latency without affecting the IP layer end points. For example, soft failures detected by optical telemetry may trigger the optical SDN controller to exclude a compromised optical link and reconfigure the lightpath to a longer backup path ^[5]. Second, the Radio Access Network (RAN) system (i.e., wireless links and different functional split among Distributed -DU and Centralized Unit -CU), is subject to latency variations due to mobility, users subscription, queueing delay, frame alignment and transmission processing ^[6]. This means that, in the case of wired-wireless

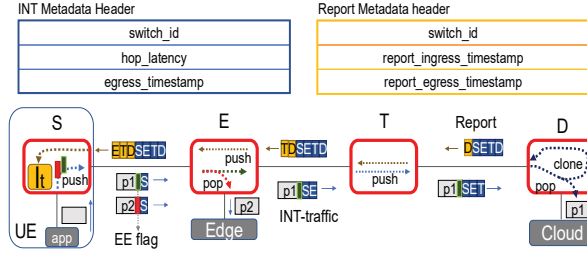


Fig. 2: INT/Report Headers pushed at each node, Augmented INT and source-based cloud-edge steering.

connectivity including optical domains, standard INT is unaware of the e2e latency and is not able to guarantee latency-bounded service monitoring.

Following Fig. 1, UE service towards the cloud experiences excessive latency l_c , however the INT system is able to monitor only the intra-switch latencies of the N1-N6 segment, without detecting any significant issue. However, l_o latency in the metro-core network may change due, e.g., to an optical lightpath recovery in the N5-N6 link, increasing the overall wired network segment latency l_n . In addition, the RAN wireless and fronthaul link is introducing additional unmonitored l_w latency. The service might be steered to path N2-N6, thus requiring handover, however l_n would remain high. Alternatively, the same traffic might be consumed by the local Edge node E1, experiencing a reduced and allowed latency $l_e < l_c$. Unfortunately, the INT domain is unaware of both l_o and l_w thus leaving the UE with an e2e unmonitored service delay.

Proposed augmented INT and source-based cloud-edge steering

To enable B5G e2e monitoring and dynamic cloud-edge steering without involving the controller, we propose to augment the P4-based INT system including the mobile user equipment (UE) in the INT domain. The solution includes three main novelties: a) UE inclusion in the INT domain, b) extended handling of the INT Report packet to compute link latencies and c) automatic source-based Edge-Cloud steering.

First, a programmable switch is implemented into the UE as a service app (e.g., under the form of a lightweight virtual container) and programmed by the Orchestrator to act as INT source node. Referring to upload service traffic, as shown in Fig. 2, INT is programmed between source (S), transit (T) (including the Edge switch E) and destination (D) nodes. Node S is co-located with the UE, adding its own INT headers. Node D is co-located with the data center and removes all INT headers providing traffic transparently to the server. Similarly, E nodes are programmed to pop INT headers only to traffic steered towards the Edge.

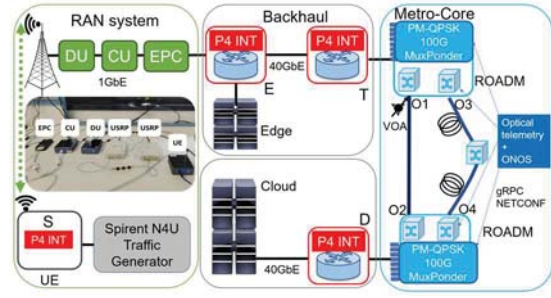


Fig. 3: Experimental network testbed.

Second, differently with respect to standard INT, node D is programmed to recirculate a *Report* traffic packet in the backward direction up to S. The Report packet, traditionally destined to the SDN controller via a control plane port, besides

INT information collected in the forward direction (e.g., hop latencies), is extended to be pushed with the ingress and egress timestamps measured at each node in the backward direction resorting to extended INT P4 code. This allows to compute link latencies. Since P4 switches timestamps are referred to the local P4 switch bootstrap time, latencies need to be computed referring to differential times related to the same switch. When the Report reaches S, the switch is able to compute also the wireless link latency and stores the total e2e latency l_t in a P4 register.

Third, service traffic generated by the UE is INT-tagged by S with a novel INT shim header flag called EnableEdge (EE). The flag indicates whether l_t stored in S exceeds a pre-determined bound latency threshold (Th) imposed by the service. The flag is inspected only by E node. In the case the flag is active, E automatically pops INT headers and steers traffic to the edge. This way, the UE performs source-based steering imposing traffic to reach the closer edge when $l_t > Th$, without involving controllers. To avoid instabilities, EE is activated when a pre-determined number of packets experience $l_t > Th$, utilizing a further occurrence P4 counter.

Experimental Demonstration

The proposed augmented P4 INT has been implemented and evaluated in a hybrid wired-wireless network testbed, shown in Fig. 3. The wired backhaul network segment is composed by 40 Gigabit Ethernet interfaces and a stack of Linux box P4 switches running Behavioral Mode version 2 (BMv2) and implementing augmented INT P4 code over INT code version 2.1^[7]. The metro-core segment includes a pair of disaggregated ROADMs equipped with Ericsson PM-QPSK 100G muxponders and two Finisar WSS each, acting as configurable degrees. Two bidirectional optical paths O1-O2 and O3-O4 may

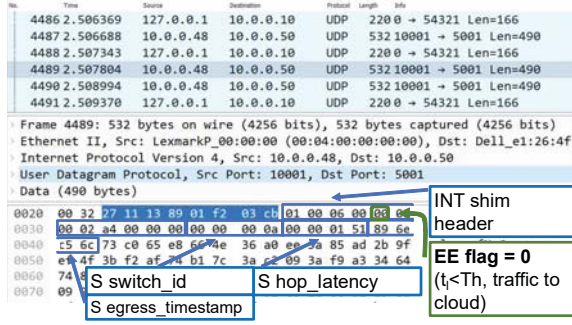


Fig. 3: Wireshark capture at the UE (switch S): INT headers

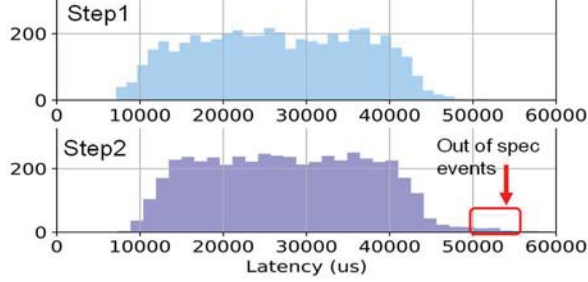


Fig. 5: RAN latency distribution (link S-E)

be activated. Primary path O1-O2 is 1km long, backup path O3-O4 is a geographical multi-span link. The ROADMs are handled by a ONOS-based SDN controller running NETCONF/YANG API and gRPC optical telemetry services monitoring the BER and the OSNR at the muxponder cards^[8]. The RAN components - UE, DU, CU are deployed in NUC mini-PC and the Evolved Packet Core (EPC) is deployed in UP-Board mini-PC (see Fig. 3). The OpenAirInterface (OAI)^[9] open-source software is considered for the RAN deployment, and the radio hardware units are prototyped using Ettus B210. The Option 2 functional split with 25 resource blocks and single-input-single-output is considered for the DU-CU interface. The UE runs BMv2 as a container to act as source INT node S. Upload service traffic, provided by the Spirent N4U traffic generator co-located at the UE, is a constant bit rate UDP flow towards the cloud server. INT is initially activated between S and D through the S-E-T-D path to steer traffic to the cloud server. E2e service latency threshold T_h is set to 50ms^[10]. The evaluation considers three link latency variation steps. In step 1 the service is connected to the cloud using O1-O2 optical path (telemetry-monitored BER 1.9×10^{-8} , OSNR 38.5 dB) and the RAN is considered without secondary services. In step 2, fronthaul traffic coexistence with additional secondary services^[11] is considered, which further introduces an additional latency in the e2e link. Secondary services are emulated by introducing iperf traffic (i.e., 600 Mb/s) in the DU-CU interface. In step 3, including the RAN latency of step 2, a variation of the VOA at O1 induces a soft failure in O1-O2 causing a degraded 10^{-2}

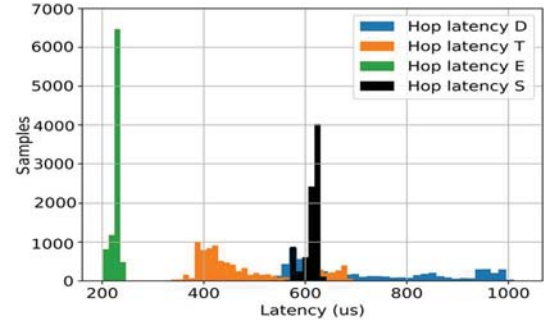


Fig. 4: BMv2 hop latencies distribution

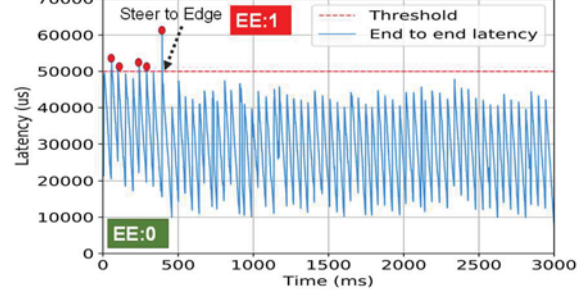


Fig. 6: E2E latency in step 3: cloud-edge steering event.

BER. The optical telemetry notifies ONOS triggering make-before-break restoration to O3-O4 avoiding hard failures, however originating a further latency increase in the optical domain. Fig. 3 shows a Wireshark capture of INT-tagged traffic packets at the UE (source IP 10.0.0.48), showing the shim header with the novel EE flag and the metadata header pushed by S. Report packet are also received by S (frames recirculated by D, source IP 127.0.0.1). Fig. 4 reports the monitored BMv2 hop latencies, all within 1ms, where S and D experience improved INT processing. Fig. 5 shows the RAN latency distribution in step 1 (always below 50ms) and step 2 (sporadic out-of-spec events exceeding 50ms). Such critical latencies are monitored directly by the UE traffic itself. Fig.6 depicts the monitored e2e latency for a flow sequence (1 packet/ms) in step 3, after optical restoration. The figure shows a high number of above Threshold events that trigger, at around time $t=500$ ms, the EE flag activation at S. Then, traffic is steered to the edge experiencing a reduction of the average latency of around 6ms, due to the exclusion of the edge-cloud segments, successfully guaranteeing in-spec e2e latency for all the flow packets.

Conclusions

A novel P4 augmented INT solution providing detailed e2e latency to the UE is proposed and evaluated in a converged packet-optical network including RAN. Results showed the effectiveness of the system to steer cloud traffic to the edge upon out-of-spec e2e latency without any controller intervention. Results also highlight the novel key feature of monitoring RAN latencies up to the UE for future B5G deployments.

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