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5G-XHaul: A novel wireless-optical SDN transport network to support joint 5G backhaul and fronthaul services

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***Abstract*—The increased carrier bandwidth and the number of antenna elements expected in 5G networks require a redesign of the traditional IP-based backhaul and CPRI-based fronthaul interfaces used in 4G networks. We envision future mobile networks to encompass these legacy interfaces together with novel 5G RAN functional splits. In this scenario, a consistent transport network architecture able to jointly support backhaul and 4G/5G fronthaul interfaces is of paramount importance. In this paper we present 5G-XHaul, a novel transport network architecture featuring wireless and optical technologies and a multi-technology software defined control plane, which is able to jointly support backhaul and fronthaul services. We have deployed and validated the 5G-XHaul architecture in a city-wide testbed in Bristol.**

***Index Terms*—Radio Access Networks, 5G, fronthaul, backhaul, optical networks, SDN**

I. INTRODUCTION

To date, 4G networks have been deployed using two main types of architectures: Distributed Radio Access Networks (D-RANs), where a full base station stack is included in each cell site; and Centralized RANs (C-RANs), where the cell site only features the Remote Radio Heads (RRHs) and the radiating elements, and the Baseband Units (BBUs) are centralized in a remote location. The C-RAN architecture is more energy efficient and augments network capacity through inter-cell coordination, but imposes very strict requirements on the transport network connecting the RRHs and the BBUs, known as fronthaul. Instead, D-RAN only requires the transport of IP packets between the cell site and the core network through a transport network, commonly known as backhaul. In current deployments, fronthaul and backhaul are implemented as entirely separate networks based on different technologies.

The C-RAN architecture is, in its current form, based on digitized radio samples, e.g. Common Public Radio Interface (CPRI), which does not scale to 5G RANs. Hence, alternative RAN functional splits between the cell site and a centralized location have been proposed that trade-off centralization gains with reduced requirements to the transport network [1]. This work has led to the eCPRI standard [2], supporting a variety of functional splits. 3GPP has also embraced a 5G RAN architecture able to support multiple functional splits, where a base station is split into a Centralized Unit (CU), a Distributed Unit (DU), and a Remote Unit (RU) [3].

We argue that several RAN functional splits will coexist in the upcoming 4G/5G landscape, featuring D-RAN in situations where backhaul is limited (e.g. Small Cells), traditional CPRI-based fronthaul for 4G networks, and novel eCPRI-based fronthaul for future 5G RANs. A unified transport network architecture is needed to serve all these interfaces while supporting multi-tenancy, through a cohesive set of data-plane technologies and a common control and management plane that minimizes operational costs.

This paper describes and evaluates a novel transport architecture referred to as 5G-XHaul. It features wireless and optical technologies and a control plane based on Software Defined Networking (SDN) that is able to jointly transport fronthaul and backhaul services. Our contribution is complementary to Ericsson's Transport Intelligent Function (TIFs) described in [4], whereby the 5G-XHaul network could be considered an SDN enabled underlay interacting with Ericsson's TIF. In addition, unlike China Mobile's Slice Packet Network (SPN) [5], which uses an Ethernet-based transport, 5G-XHaul advocates for a solution that provides flexible allocations for a transport slice directly within the optical domain. To the best of our knowledge, this is the first work where a joint backhaul/fronthaul transport network is experimentally demonstrated in a realistic city-wide testbed.

II. THE 5G-XHAUL ARCHITECTURE

A. 5G-XHaul Data Plane architecture

We envision 5G RANs consisting of two different layers. A first layer of macro-cells collocated with the already deployed 4G grid. 5G macro-cells are expected to operate with an exemplary carrier bandwidth of 100 MHz in the 3.5 GHz band. This layer will be complemented with a dense layer of Small Cells deployed on lamp posts or street furniture, which may operate at millimeter wave (mmWave) frequencies, thus providing additional area capacity. While various RAN functional splits may be considered for the macro-cell layer, Small Cells will likely feature higher functional splits, thus relaxing the requirements on the transport.

The 5G-XHaul data plane architecture is depicted in Figure 1. A wireless transport segment, potentially including multiple hops, connects the Small Cells to the wired network. Macro-cells featuring Massive MIMO antenna arrays are connected to an optical transport segment comprising two different technologies: i) a passive high capacity WDM-PON network

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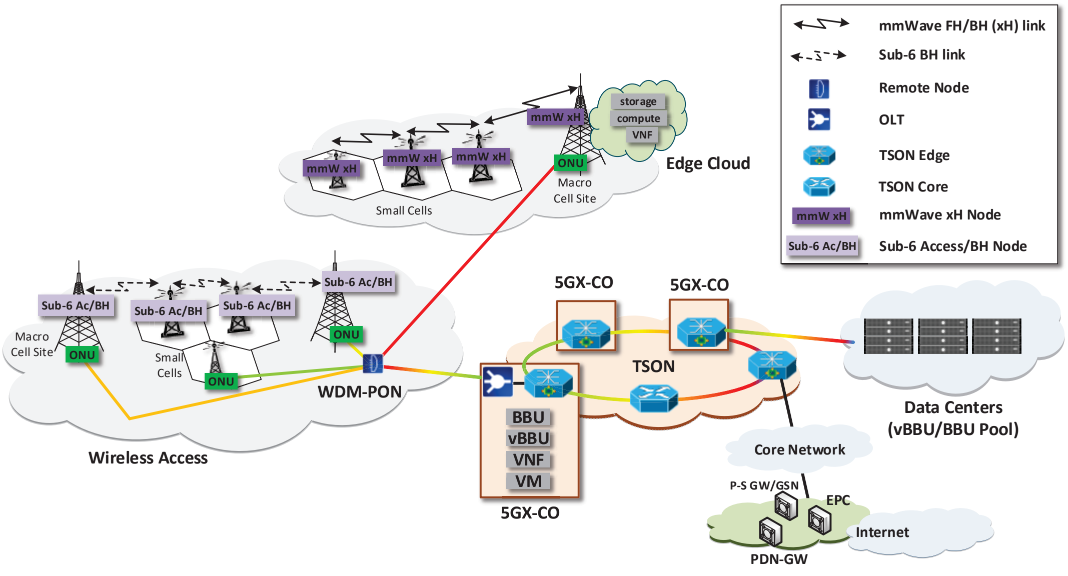

Fig. 1. 5G-XHaul data plane architecture

in the access, connecting the macro-cells to the central offices (5GX-CO in Figure 1); and ii) an active Time Shared Optical Network (TSON) in the metro segment, connecting 5GX-COs together, and with the core network. The 5GX-CO is seen as a virtualized environment where backhaul services and (virtual) BBUs are hosted. 5G-XHaul may be serving RAN networks from different tenants featuring different functional splits, e.g. a CPRI-based interface and a traditional IP-based backhaul interface. Thus, the 5GX-CO needs to be able to host the functions required to serve both types of interfaces. Nevertheless, the architecture also allows to concentrate backhaul services and BBUs in only a subset of the 5GX-COs, achieving then higher centralization gains [6]. To enable centralization, both the optical access and metro segments support the transmission of joint backhaul (Ethernet) and fronthaul (CPRI) connectivity services. The interested reader is referred to [7] for a blueprint deployment of the 5G-XHaul architecture in a typical European city.

The 5G-XHaul transport network considers the following wireless and optical technologies:

1) Scalable Massive MIMO: Large Massive MIMO arrays used by 5G macro-cells pose significant challenges in a CPRI-based C-RAN architecture. 5G-XHaul features a novel RAN functional split where antenna processing is offloaded to the Massive MIMO array [8]. This allows the transport network to scale with the number of spatial streams, rather than with the number of antenna elements as in traditional CPRI.

2) Wireless Transport: The wireless transport segment in Figure 1 connects the Small Cells to the optical segment, and is dimensioned to support Ethernet backhaul services. This segment consists of two types of technologies: i) unlicensed mmWave technologies operating at V-Band (60 GHz), and ii) technologies operating in the unlicensed 5 GHz band (Sub-6). We expect these devices to be based on IEEE 802.11ad and IEEE 802.11ac/ax radios respectively, benefiting from the economies of scale associated to IEEE 802.11 technologies. Thus, in 5G-XHaul, high capacity 60 GHz links are combined with lower capacity but Non-Line of Sight (NLoS) capable Sub-6 radios to form a heterogeneous wireless mesh network.

3) Optical Transport: The optical segment of the 5G-XHaul data plane architecture involves WDM-PON in the access segment and TSON in the metro segment.

The 5G-XHaul WDM-PON solution encompasses an Optical Networking Unit (ONU), typically located in a macro-cell site; and an Optical Line Termination (OLT) located at the 5GX-CO. Up to forty different ONUs can be multiplexed over a single trunk fiber by means of a passive dense wavelength division multiplexing (DWDM) filter in the field. Each wavelength channel is capable of a symmetric data rate of 10 Gbps or 25 Gbps, depending on the reach and the optical modulation format used. An additional feature of this solution is the use of an inexpensive vertical-cavity surface-emitting (VCSEL) tunable laser in the ONU. The VCSEL is controlled by the OLT to autonomously tune to the correct wavelength, using an out-of-band communication channel between ONU and OLT. This solution has been standardized in the newly-consented ITU-T G.698.4 standard [9], lowering significantly the operational costs associated to WDM-PON. WDM-PON offers to 5G-XHaul a transparent interface that can deliver both Ethernet (backhaul) and CPRI (fronthaul) services on different wavelengths, using a transponder that receives the Ethernet/CPRI streams in colorless grey wavelength channels and converts them to DWDM wavelengths.

TSON is an active optical technology that provides sub-wavelength granularity [10], supporting natively the transport of both Ethernet and CPRI services forwarded through different wavelengths. TSON features TSON edge nodes, which collect/deliver Ethernet or CPRI traffic through a set of input/output optical interfaces; and TSON core nodes, which forward optical bursts multiplexed in time on each wavelength. Packets from each input interface are received at the TSON edge, and are aggregated into the different slots forming the

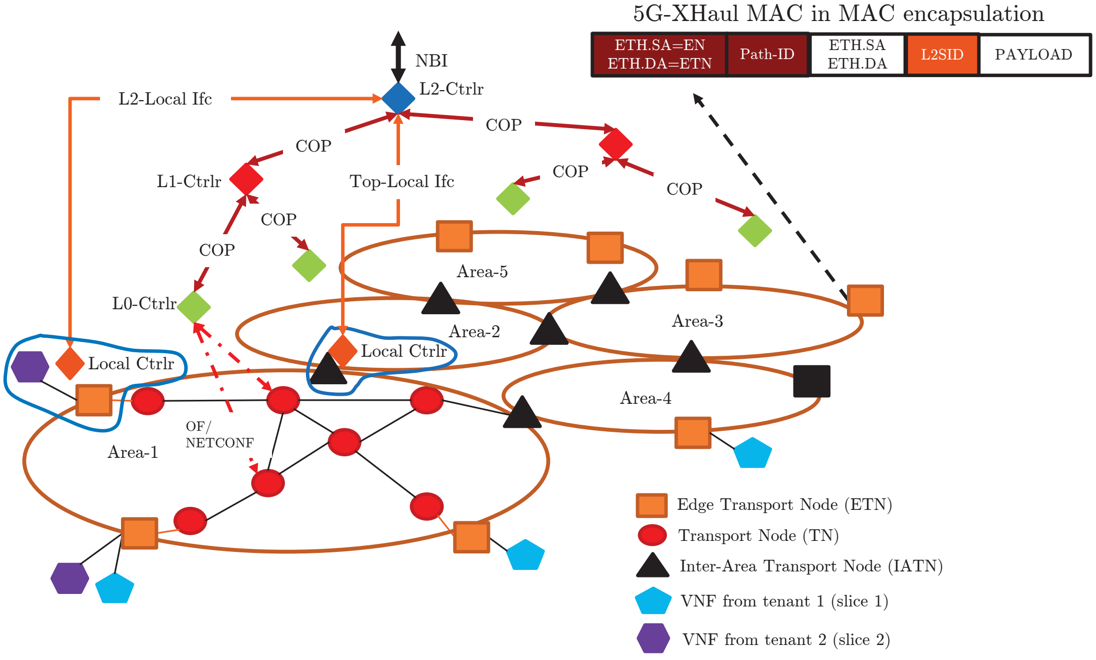

Fig. 2. 5G-XHaul control plane architecture

TSON frame. The reverse process is implemented at the receiver edge. TSON is currently prototyped on an FPGA platform providing programmability, not only in terms of the various parameters that define the TSON frame, but also in the logic mapping input ports to slots in the TSON frame. CPRI is natively supported in TSON edge nodes through a Xilinx GTH Transceiver IP core supporting CPRI protocol option 5.

B. 5G-XHaul Control Plane architecture

5G-XHaul features a multi-technology control plane built on the following design principles:

- *SDN architecture*. A logically centralized control plane is considered, offering higher level Application Programming Interfaces (APIs), enabling automation and easing the integration with other software systems, e.g. an NFV ETSI MANO system.
- *Hierarchical Control*. 5G-XHaul considers technology specific controllers for different transport network segments. For example, a wireless specific controller can allocate paths while considering cross-link interference, whereas a TSON controller derives the TSON TDM schedule depending on the allocated paths. In addition, to provide end-to-end connectivity services, a higher, technology agnostic, control layer is considered that provides forwarding across technology segments.
- *Scalable Virtualization and Multi-tenancy*. Multiple tenants may connect their physical or virtual network functions (PNFs/VNFs) through the 5G-XHaul transport network. To allow scalability, a layer 2 based overlay mechanism is used to enable network virtualization.
- *Two native forwarding abstractions: Ethernet and CPRI*. Ethernet is supported across the wireless and optical domains, where an active processing of the Ethernet header is performed in each hop. Native CPRI is supported only in the optical domain, being the CPRI interfaces mapped transparently between TSON and WDM-PON.

The 5G-XHaul control plane architecture is illustrated in Figure 2. Two main components can be distinguished: i) a data plane abstraction composed of three different transport functions, and ii) a hierarchy of SDN controllers.

The three transport functions are known as the *Transport Nodes* (TNs), the *Edge Transport Nodes* (ETNs), and the *Inter-Area Transport Nodes* (IATNs). TNs are grouped in control plane areas, controlled by a common Level-0 (L0) SDN controller (green diamond in Figure 2). L0 controllers proactively install in each TN a set of unidirectional label switched paths, which provide connectivity between all ETNs and IATNs within the control plane area. ETNs implement the binding between the per-tenant P/VNFs connected to the 5G-XHaul transport network, and the label switched paths available in each control plane area. Additionally, IATNs sit between areas and perform the required stitching between the corresponding label switched paths in each area. In 5G-XHaul, user plane traffic will flow mostly towards the 5GX-COs, whereas control traffic between nearby base stations may be local to a control plane area. To isolate TNs from per-tenant state, ETNs implement a MAC-in-MAC encapsulation (Figure 2). The outer VLAN tag included in the encapsulated frame is used by the TNs as forwarding label (Path-ID), whereas the inner VLAN tag (Layer 2 Segment ID L2SID) in the customer Ethernet frame is used to disambiguate different *slices* at the receiving ETN. Thus, although 5G-XHaul leverages MAC in MAC encapsulation, it does not use MAC learning, but instead it proactively establishes label switched paths. A slice in 5G-XHaul is the virtual layer 2 service connecting distributed functions of a given tenant. This slice can be isolated either logically and/or in terms of performance via: different priorities in the wireless segment, wavelengths in WDM-PON, or wavelength and TDM slots in TSON. The interested reader is referred to [11] for a detailed description of the 5G-XHaul approach to network virtualization.

Figure 2 depicts a first layer of technology specific (wireless and optical) SDN controllers (L0 controllers) that use OpenFlow and NETCONF to control and manage the network devices. They interface with Level-1 (L1) controllers by means of the Control Orchestration Protocol (COP) [12], where the *service-call* model has been extended to accommodate unidirectional VLAN-based label switched paths, and the *service-topology* model has been extended to accommodate the 5G-XHaul ETN and IATN functions[13]. The L1 controller receives an end-to-end connectivity service request to connect two ETNs from the Level 2 (L2) controller, again through a COP-based interface, and decides how to instantiate an end-to-end connectivity service spanning multiple control plane areas. The L2 Controller programs ETNs and IATNs via the *L2-Local* interface.

Finally, it is worth noting that the aforementioned control functions (L0, L1, and L2 controllers) can be virtualized and deployed as VNFs using a MANO service platform.

III. EXPERIMENTAL EVALUATION OF THE 5G-XHAUL ARCHITECTURE

The 5G-XHaul architecture was evaluated in a city-wide testbed deployed in Bristol, UK, whose physical topology is illustrated in Figure 3. The deployed infrastructure features all novel 5G-XHaul wireless (Sub-6 and 60 GHz) and optical (WDM-PON and TSON) technologies.

The topology consists of a high-speed Wi-Fi Access Point (AP) backhauled through a multi-hop hybrid wireless mesh network spanning several sites in the Bristol waterfront. The multi-hop network comprises four 60 GHz links, operating in LoS conditions, and one Sub-6 link operating in NLoS conditions. Link distances spanned approximately between 120 and 220 meters. The wireless segment terminates at the WeTheCurious science museum, where dark fiber was made available connecting to the Bristol University building, where the optical segment of the 5G-XHaul architecture is deployed. The optical segment consists of: i) WDM-PON ONUs connecting to WeTheCurious, ii) the corresponding WDM-PON OLT, and iii) two back-to-back TSON nodes. Fiber spools were used between the TSON nodes and between the OLT and the ONUs to emulate alternative deployment distances.

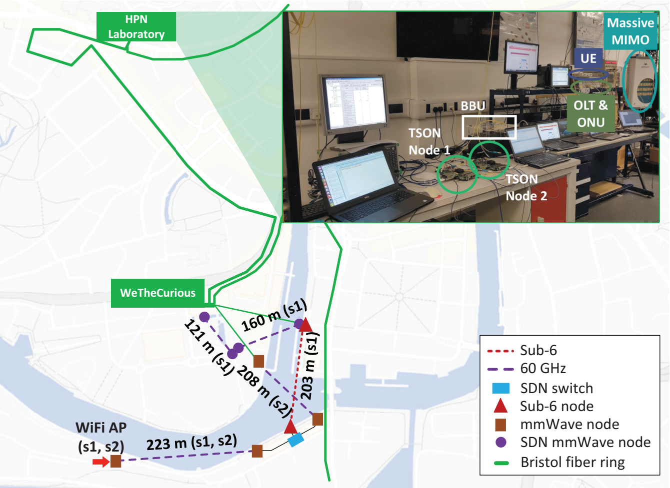

Fig. 3. 5G-XHaul BiO testbed overview. Wireless SDN and Optical Network at HPN laboratory.

The previous infrastructure was controlled using two L0 SDN controllers, one per segment (wireless and optical). L1 and L2 controllers were used to coordinate the two domains, being hosted on Virtual Machines (VMs) instantiated on an OpenStack cluster (not shown in Figure 3). The control plane provisions the label switched paths that support backhaul services.

Our goal was to benchmark the performance of the 5G-XHaul architecture and to demonstrate the joint provision of backhaul and fronthaul services in a multi-tenant fashion. For the former we instantiate two backhaul slices, each consisting of: i) a virtual Wi-Fi AP instantiated over the physical AP, ii) two unidirectional end-to-end label switched paths, and iii) a VM delivering an HD video service. To provide isolation, each backhaul slice is forwarded through a different path in the wireless mesh (see section III.B for detailed information). To provision a fronthaul service, a Massive MIMO antenna array and a BBU were also deployed at the Bristol University site. The Massive MIMO antenna array was connected to a WDM-PON ONU, the BBU to a TSON node, and CPRI was used to fronthaul the time domain radio samples between the BBU and the antenna array.

A. Benchmarking 5G-XHaul wireless and optical segments

Figure 4 depicts the latency and throughput performance of the wireless segment and of the end-to-end backhaul slices respectively. The solid lines of Figure 4 plotted against the lower x-axis, show all wireless links introducing a worst case round trip delay below 10 milliseconds. The end-to-end round trip delay experienced by each slice is below 15 milliseconds for 80 % of the packets, but shows a long-tail behavior of almost 100 milliseconds. This is due to the varying performance delivered by the Wi-Fi AP used in the access network, which is subject to interference.

The crossed lines in Figure 4 plotted against the upper x-axis, show how the 60 GHz links provide a stable performance between 600 Mbps and 800 Mbps, which is determined by the Modulation and Coding Scheme (MCS) allowed by the existing propagation conditions. The Sub-6 link, featuring an IEEE 802.11ac radio operating with a bandwidth of 80 MHz, delivers a throughput between 100 Mbps and 250 Mbps, with variations again introduced by the use of a dynamic MCS. The end-to-end performance of each backhaul slice is, however, significantly smaller (20 Mbps), and is limited by the wireless access technology in use (IEEE 802.11g Wi-Fi).

To assess the performance of the optical segment, we first validate the error-free provision of Ethernet services up to 10 Gbps and CPRI line rate 5 (4.9 Gbps), using the integrated

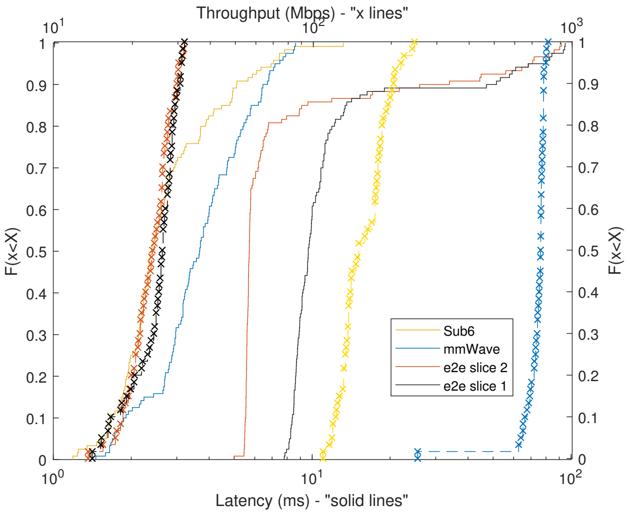

Fig. 4. Benchmark of the 5G-XHaul wireless segment. Latency shown with solid lines on lower x-axis. Throughput shown with crossed lines on upper x-axis.

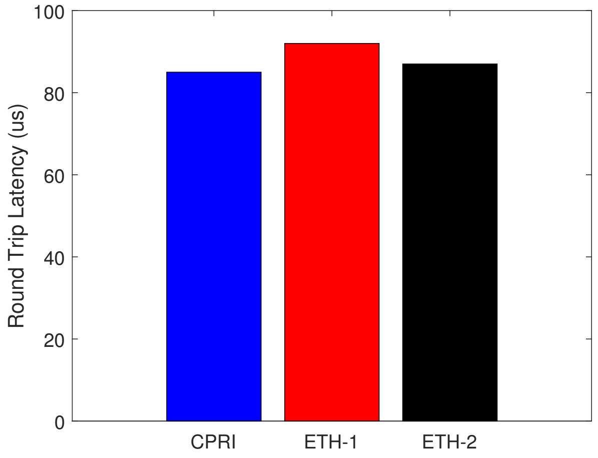

Fig. 5. CPRI and Ethernet services over 8 km fiber

TSON and WDM-PON technologies. To deliver the required services, one of the TSON edge nodes features three SFP+ interfaces connected to the WDM-PON OLT. Two OLT ports deliver the Ethernet traffic flowing through each backhaul end-to-end slice, and the other port delivers the CPRI samples to the Massive MIMO antenna array. The other TSON edge node features two SFP+ interfaces, one connected to an Ethernet switch that serves backhaul traffic, and another one connected to the BBU.

The next performance measure is the round trip delay through the 5G-XHaul optical segment, for both the Ethernet and CPRI services. The overall delay includes TSON and WDM-PON propagation delays, as well as the delay stemming from the various fiber deployment lengths. For WDM-PON, the delay is introduced by the OLT and ONU transponder cards and by the WDM filters. For TSON, being an active technology, processing delays are introduced by a PHY IP core in the case of CPRI, and by the PHY+MAC IP core, plus the additional processing required to analyze label switched paths, in the case of Ethernet.

In the case of Ethernet we observe: i) A round trip of 3.241 μs for the Back-to-Back (B2B) scenario, ii) 86.144 μs for the 8 km fiber, and iii) 169.175 μs for the 16 km fiber. To understand the contribution of the WDM-PON and TSON segments to the round trip latency, we measure for the B2B case a TSON PHY+MAC IP Core delay of 2.974 μs, a TSON processing delay of 0.167 μs, and a WDM-PON delay of 100 ns. Notice that fibre introduces a propagation delay of 5 μs per km. In the case of CPRI the following round trip delays are measured: i) 0.99 μs in the B2B case, ii) 84.19 μs for the 8 km fiber, and iii) 166.86 μs for the 16 km fiber. These results validate that the 5G-XHaul optical segment is able to cope with 4G and 5G fronthaul requirements.

B. Evaluation of SDN features for Backhaul services

To evaluate the impact of the SDN control plane on the reliability provided to backhaul services, each backhaul slice runs through a different path in the wireless segment. Figure 3 depicts how slice 1 traverses first a 60 GHz hop, then a Sub-6 hop, and two more 60 GHz hops before connecting to the optical segment; whereas slice 2 traverses two 60 GHz hops and connects to the optical segment (cf. labels s1 and s2 in Figure 3). For each slice we run an H.264 HD video between the VM and a tablet device attached to the slice's virtual AP through the optical and wireless segments. Each HD video requires approximately 3-4 Mbps to run smoothly.

To provide reliability in the wireless backhaul, we use an SDN feature called Fast Local Link Reroute (FLRR) [14], which involves: i) the L0 controller proactively installing a *main* and a *backup* label switched path for each slice, and ii) having a fast recovery agent installed in the wireless devices that detects the link failure and diverts affected packets towards the backup path. The backup label switched path for slice 1 is configured through the same links used by slice 2. To evaluate this feature, we start playing the HD videos, and then break the Sub-6 link traversed by slice 1.

In [8] we report a traffic trace captured while streaming the HD video for slice 1, including the break of the Sub-6 link. There, it can be seen how right after the link break the TCP based video stream enters Slow Start, but traffic keeps flowing at all times. Indeed, no glitch was appreciated in the HD video of slice 1 while rerouting the traffic. The HD video[1] for slice 2 also played flawlessly throughout the experiment.

C. Evaluation of joint Fronthaul and Backhaul services

We now analyze the ability of the 5G-XHaul optical segment to jointly deliver backhaul and fronthaul services. To operate at the full capacity provided by the optical segment, we loopback the fibers between WeTheCurious and the laboratory at Bristol University, thus disconnecting the wireless segment. An 8 km fiber spool is used in this experiment introducing a base delay of 80 μs. We evaluate Ethernet services using an Ethernet analyzer that generates two 4.9 Gbps streams with

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[1] https://www.youtube.com/watch?v=NExIMi5tozU

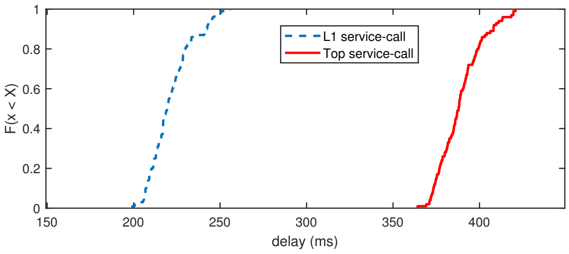

Fig. 6. Control plane latency to set-up multi-domain connectivity service.

the VLAN tag corresponding to the label switched paths for slice 1 and slice 2. Concurrently to the Ethernet traffic, we generate a CPRI line rate 5 stream (4.9 Gbps) between the BBU and the Massive MIMO antenna array.

We verify in the Ethernet and CPRI analyzers that the correct 4.9 Gbps are delivered for each Ethernet slice and for the CPRI service while operating concurrently. Additionally, Figure 5 depicts the round trip delay experienced by each service. We observe that the CPRI service and the two Ethernet slices experience respectively a round trip delay of 85 μs, 92 μs, and 87 μs. The processing introduced by TSON explains the slightly higher delay in the case of Ethernet. In addition, we verified the correct reception of a 16-QAM constellation over the CPRI service by tapping into one of the antenna elements of the Massive MIMO array [8]. Generalized Frequency Division Multiplexing (GFDM) [15] was used to modulate the RF signal between the BBU and the SDR. The correct reception of the 16-QAM constellation, while concurrently transporting error-free Ethernet traffic, validates the ability of the 5G-XHaul architecture to jointly transport backhaul and fronthaul services.

D. Evaluation of 5G-XHaul hierarchical Control Plane

We conclude our evaluation studying the time required by the 5G-XHaul hierarchical control plane to instantiate an end-to-end connectivity service. The following process is required:

i. The L1 controller receives a COP service-call request through its northbound interface issued by the L2 controller.
ii. The L1 controller derives the L0 controllers that need to be involved in this particular service-call, and issues the corresponding COP service-calls.
iii. L0 controllers return the details of the (pre-)provisioned label switched paths to the L1 controller in their COP response.
iv. The L1 controller builds the COP response to the L2 controller, including the information of the IATN functions involved in the end-to-end service.
v. The L2 controller contacts the involved ETN and IATNs to install the necessary bindings to perform the MAC-in-MAC encapsulation in the ETNs, and the stitching of label switched paths between domains in the IATNs.

To increase statistical confidence we instantiate 100 different connections and measure the Cumulative Distribution Function (CDF) of the aggregated results. The solid red line in Figure 6 represents the overall connection provisioning time when the 5G-XHaul L2 controller establishes a connection between two ETN functions located in two different control plane domains. We can see that in the worst case, the overall service provisioning time is well below 500 ms. To understand the contribution of the L1 controller in the overall connection provisioning time, the dashed blue line in Figure 6 represents the CDF of the time between the moment the L2 controller issues the service-call request to the L1 controller (step i.), until the time when the label switched paths in each domain are provisioned and the L2 controller receives the response from the L1 controller (step iv.). The measured provisioning time as a result of these two steps is 250 ms. These service provisioning times are orders of magnitude smaller than the times required in current networks to set up multi-domain connectivity services, and can be considered a stepping stone towards fully automating control and management functions in future transport networks.

IV. CONCLUSIONS

The upcoming deployment of 5G RANs leads to an increased variety of the transport interfaces required to connect base stations to the core network. It is of key importance to design transport networks able to serve all these interfaces in a cohesive way. In this paper we presented 5G-XHaul, a novel wireless-optical transport network architecture that supports concurrent backhaul and fronthaul services, under a unified SDN control plane. We have used a city-wide testbed in Bristol to characterize the performance of the 5G-XHaul architecture, and to demonstrate the ability to concurrently support backhaul and fronthaul services. We claim that the features delivered by 5G-XHaul are an important step to support the deployment of 5G mobile networks.

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