5G Transport Network Blueprint and Dimensioning for a Dense Urban Scenario

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***Abstract*—In this paper, we provide a quantitative evaluation of the deployment aspects and dimensioning of the 5G transport architecture in a representative European city. In particular, we select an example dense urban city scenario based on the city of Barcelona, and illustrate how the transport network architecture defined by the 5G-XHaul project can be deployed in that environment. Building on the case of Barcelona, we discuss physical deployment aspects, such as the locations to deploy small cells, how many compute facilities should be scattered throughout the city, or where the control plane functions should be deployed. In addition, we provide a quantitative evaluation of the 5G-XHaul deployment in Barcelona, including the bandwidth required at the different segments of the architecture, i.e. the wireless segment, the WDM-PON access network, and the TSON metro network. We also evaluate control plane aspects, such as the number of 5G-XHaul SDN controllers required for a city like Barcelona.**

Keywords—5G transport network; network capacity planning; fronthaul/backhaul dimensioning.

I. Introduction

Albeit the existing studies defining 5G network architecture (e.g., [1]), there is a need to study physical deployment models for the 5G transport network to derive its capacity requirements and to assess the suitability of current networking technologies. To this end, we devise a network blueprint for the 5G-XHaul [2] transport network solution, by defining the transport network elements, the "physical" network architecture, and the network topology. 5G-XHaul is a European project working on the definition of converged Fronthaul (FH) and Backhaul (BH) networks for future 5G mobile networks. For this purpose, a logical transport architecture is defined in [3] that integrates various wireless and optical technologies under a common SDN control plane.

The physical deployment strategies studied in this paper for 5G transport networks can be used to i) derive the throughput requirements on different network segments and on the corresponding network technologies, and ii) generate feasible topologies for network performance evaluations, e.g. to calculate the signaling overhead of possible SDN solutions or to evaluate failover scenarios. In this line, we evaluate the derived 5G transport network blueprint for a dense urban scenario, based on city of Barcelona, considering the extreme Mobile Broadband (xMBB) use case defined in [4].

Using the traffic load projections for prospective 5G Radio Access Network (RAN) technologies from [5], we assess the bandwidth requirements in the wireless and optical segments of the transport network, and dimension the SDN control plane. The findings of this work can be used as a basis for mobile operators to already make strategic decisions towards 5G investments in a dense urban scenario.

This paper is organized as follows. Section II introduces the 5G-XHaul network elements and physical architecture. Section III describes the deployment of the 5G-XHaul elements in a dense urban area for the case of Barcelona city. Based on such deployment, Sections IV and V dimension the transport network data plane and control plane, respectively. Finally, Section VI summarizes and concludes the paper.

II. 5G-XHaul Physical Architecture

Fig. 1 illustrates a 5G-XHaul physical network architecture, which employs various optical and wireless technologies. The wavelength division multiplexing passive optical network (WDM-PON) is designed to deliver a wavelength-based point-to-point connectivity between cell sites and central offices. Each optical network unit (ONU) is attached to a Macro Cell site, and a dedicated wavelength is multiplexed/demultiplexed at the remote node (RN). The RNs connect to a WDM-PON Optical Line Terminal (OLT) at the 5G-XHaul Central Office (5GX-CO), which hosts compute resources and may host BaseBand Units (BBUs).

5GX-COs are connected to each other through a Time Shared Optical Network (TSON), defined in [6]. A WDM-PON OLT may interface a TSON edge node as defined in [3]. The TSON network facilitates the connection of the 5G-XHaul metro network to the operator's core network through a TSON edge node. In addition to the 5GX-CO, 5G-XHaul also contemplates the availability of compute resources in Edge Clouds, depicted in Fig. 1, which are located close to the wireless infrastructure.

Small Cell (SC) sites can be wirelessly connected to a Macro Cell site or alternatively they can have fibre attachment points through WDM-PON ONUs. The wireless transport network technologies considered in 5G-XHaul are Sub-6 GHz or mmWave for BH and mmWave for FH. Hence, 5G-XHaul defines three types of SCs regarding their BH/FH connection: 1) *SC+WDM-PON*: SC has an ONU and is connected to the OLT in the 5GX-CO, 2) *SC+mmWave*: SC in a lamppost connected to a mmWave transport node, and 3) *SC+Sub-6 Access/Backhaul*: The SC is connected to a Sub-6 GHz transport node, which can be used both for access and BH, providing less BH capacity but more potential connections. The choice of mmWave or Sub-6 BH/FH technology depends on several criteria such as the existence of Line-of-Sight (LoS) links between the SCs, the transport capacity requirement, etc. In addition to these SC types, we consider a single Macro Cell (MC) type, which is the one with the WDM-PON connection.

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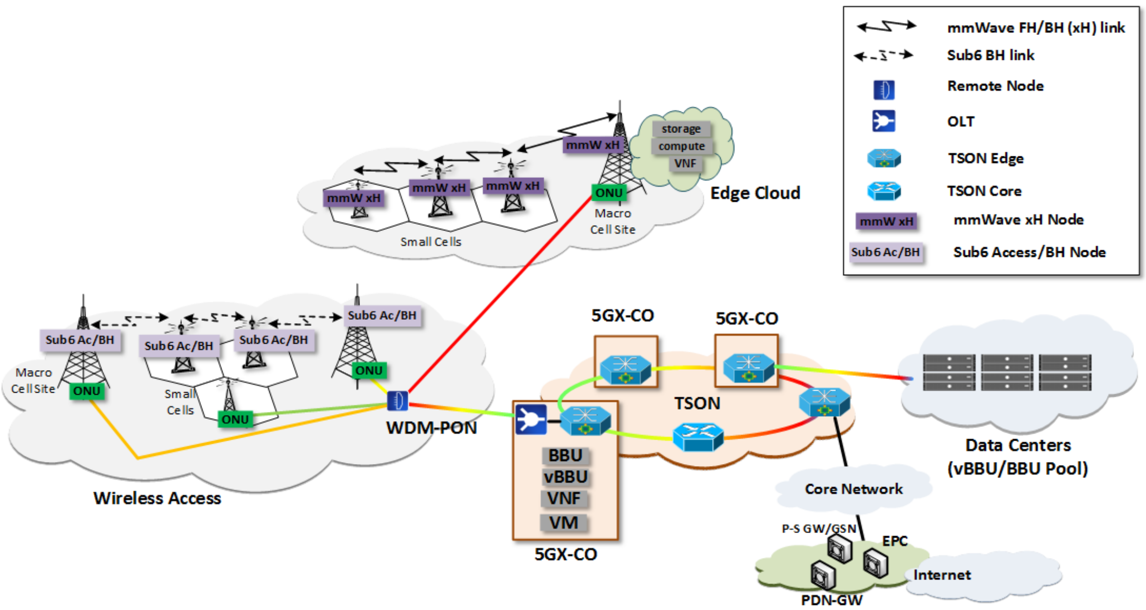

Fig. 1. 5G-XHaul physical network architecture illustration.

Each WDM-PON channel is assigned one pair of wavelengths for the downlink and uplink, respectively. Given the fact that in general the downlink throughput is much higher than the uplink, the required number of ONUs at a Macro Cell or Small Cell site mostly depends on the aggregated ingress capacity at the corresponding cell. Each ONU operates on a dedicated optical channel of at least 10 Gbps[1], and multiple ONUs can be installed in a single cell site to serve the aggregated capacity. On the other hand, if the total ingress capacity to the cell site is smaller than 10 Gbps, a 10GbE Ethernet switch can be utilized between the ONU and multiple radio equipment to aggregate the traffic from several cells on a single ONU, thus increasing efficiency.

5G-XHaul supports Cloud-RAN (C-RAN) by deploying physical or virtual BBUs in the 5GX-CO that serve the Macro Cell sites connected to that 5GX-CO through WDM-PON. Alternatively, the BBUs can also sit in a more centralized location (e.g. a remote 5GX-CO), and the FH connections can be relayed through TSON. Note that the latter approach enables larger pooling gains. Thanks to its multi-protocol support, TSON also relays the BH traffic generated after BBU processing until the operator's core network. TSON is in charge of creating dynamic connections in the optical domain to balance the access traffic against the subset of 5GX-COs connected to the operator core transport network. The interested reader is referred to [3] for the details of the FH/BH support in TSON and WDM-PON.

III. 5G-XHAUL NETWORK TOPOLOGY IN A DENSE URBAN SCENARIO

We start dimensioning the RAN topology choosing the Barcelona city centre as a target location, in particular the Eixample neighborhood consisting of square shaped blocks that can be used to visualize the deployment of different network elements (c.f. Fig. 2). In our study we will take this reference area in Barcelona, and dimension the 5G-XHaul transport network as if the whole of Barcelona would be covered using a similar approach. Note that this represents a worst-case analysis, since in practice a city such as Barcelona contains areas with reduced demand for mobile data. We consider this worst-case scenario because realistic future 5G traffic demands are difficult to derive at this stage, and a worst-case analysis can help drive strategic investment decisions.

To derive a realistic topology of the cell sites, we first consult the inter-site distance (ISD) projections of prior work for Macro Cell (MC) sites and Small Cell (SC) sites [2], [3],[4] in dense urban scenarios for 5G. For example in [2], NGMN provides a projection of 200 m Macro ISD, and 3-10 Small Cells per Macro Cell. In the Eixample neighborhood (c.f. Fig. 2), each block edge is 133.3 m, and hence, 1.5 blocks correspond to an ISD of 200 m. Further, based on the constraints defined by METIS-II (MC-SC ISD>55 m) in [7], we assume 3 Small Cells (unless there is a Macro Cell deployed at the target edge points) at each edge, with 70 m MC-SC and SC-SC ISD. This deployment is illustrated in Fig. 2, which results in 4-8 SCs per MC complying with NGMN projections [2].

In Fig. 2, an illustrative deployment using different transport technologies is depicted. In addition, the wireless BH/FH connection examples are also provided for both wireless technologies considered. Such wireless BH/FH connections are expected to define paths of maximum 1-2 hops until a fibre attachment point. However, the resiliency and the dynamicity of the system is achieved (e.g. cells/transport nodes are switched off for energy cost or for interference reductions) through backup paths with more hops as illustrated.

Regarding 5GX-COs, we assume that the Central Offices(COs) that exist in Barcelona today that provides fixed broadband access (xDSL, fibre) can be re-used to serve 5G-XHaul traffic. However, the WDM-PON technology used in

[1] 5G-Xhaul targets the design of a WDM-PON solution with 25Gbps per wavelength.

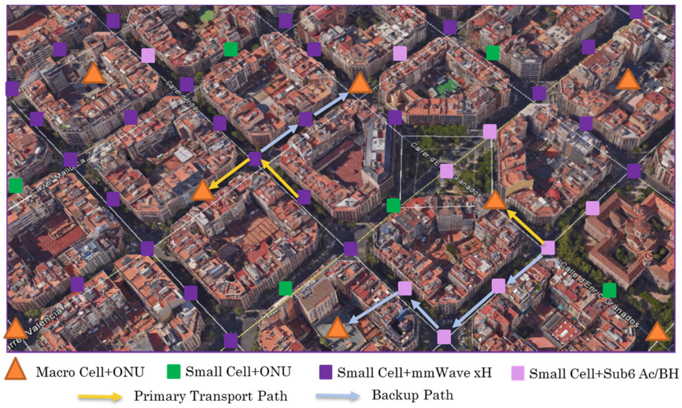

Fig. 2. 5G-XHaul Dense Urban Scenario topology illustration in Barcelona Eixample neighborhood.

5G-XHaul enables longer reach and thus a reduction on the number of COs is possible. In Section IV, we will dimension the 5G-XHaul data plane for a varying number of 5GX-COs.

In addition to the data plane elements depicted in Fig. 2, the 5G-XHaul architecture also defines control plane elements, such as SDN controllers (organized hierarchically in three tiers), and control agents embedded in the network elements called Edge Transport Nodes (ETNs), Inter-Area Transport Nodes (IATNs), and Transport Nodes (TNs). The interested reader is referred to [8] for a description of the 5G-XHaul control plane. TNs and IATNs are functions embedded in the data plane elements, for example those depicted in Fig. 2. An ETN however is software function instantiated in the hypervisor of virtualized IT equipment (like a VTEP in VXLAN [9]), and could be deployed in the servers of the 5GX-CO or in the Edge Clouds (c.f. Fig. 1). In the case of Barcelona, an excellent candidate to host Edge Clouds are a multitude of street level cabinets, which are currently used for controlling public lighting and traffic lights, and which have already been used to demonstrate Fog computing applications [10]. Finally, in 5G-XHaul data plane elements are grouped in control plane areas under the control of an SDN controller. Thus, the SDN controllers responsible for traffic engineering in the SC layer could also be deployed in the Edge Clouds (cabinets), and the TSON SDN controller in a 5GX-CO. The interested reader is referred to [11] for further detail on the 5G-XHaul deployment scenarios.

IV. Dimensioning the 5G-XHaul Data Plane

For the Barcelona city population of 1.4M inhabitants, distributed in 101.4 km^2, and assuming the calculated 22.68 Macro sites/km^2 dense urban scenario density (c.f. Fig. 2), we find ~2,300 Macro sites covering Barcelona along with 9,200 to 18,400 Small Cells, corresponding to 4-8 Small Cells per Macro Cell site. Note that as explained in Section III this corresponds to a worst-case scenario.

Regarding the number of 5GX-COs, several works from Orange declare 15 [12] and 28 [13] cell site served by each CO in operational networks. Applied to Barcelona for the number of MC sites, this would result in 80-150 5GX-COs. However, operators target to reduce the number of 5GX-COs, which is enabled in 5G-XHaul through WDM-PON. Hence we choose to study the range of 5-100 5GX-COs in our evaluation.

A. *Aggregated RAN Traffic Projections*

To dimension the transport network we need to assume a traffic model for the 5G RAN, i.e. how much transport traffic is generated per cell. For this, we utilize the study from [5], where we derived aggregated transport traffic requirements to serve a growing number of 5G cells. This study is based on the analysis of the busy hour from an operational LTE network in a dense urban city area, while provisioning the transport network for the 95% demand and considering statistical multiplexing gains. As described in [5], two scenarios are considered. A *Low Load Scenario* assuming for 5G the same resource utilization levels measured in the LTE network, and a *High Load Scenario* where the LTE utilization levels are scaled up following NGMN guidelines. Network dimensioning results in this section are given always for both the Low Load and the High Load scenarios. We expect realistic 5G utilizations to lay somewhere between the Low Load and High Load scenarios. The considered LTE traces provide traffic generated per Macro Cell, but our 5G-XHaul reference deployment contains both Macro and Small Cells. Following the Small Cell Forum projections for offload ratios between 56% and 75% for 4 to 10 Small Cells per Macro Cell [14], we assume the 70% of total traffic is generated by Small Cells and 30% by Macro Cell.

Another factor that impacts the transport capacity is the type of RAN functional split, which defines the degree of centralization of baseband processing. Following the recommendations in [5], we evaluate Split B (before resource mapping) and Split C (above HARQ) due to their dependence on the generated traffic and hence the possibility to exploit statistical multiplexing gains. The transport traffic for Split B only depends on the current air interface load, while the Split C traffic in addition varies with the channel quality of the individual users. In the following evaluations, we only consider Split C for Small Cells, due to the capacity limitations of current and near-future wireless backhaul technologies. This observation is in line with the RAN functional splits considered by other 5G initiatives [15].

For the RAN technology, we study the Sub-6 GHz (i.e. 2 GHz) for Macro Cells (MC) and both Sub-6 GHz and mmWave (30 GHz) options for Small Cell (SC) access. Note that only Sub-6 RAN is considered at the MC for coverage purposes. Therefore, our evaluation will consider four configurations representing four types of RAN configurations depending on the functional split and frequency used in MCs and SCs:

a. *Cg.1*: MC – Sub6 (Split C), SC – Sub6 (Split C),
b. *Cg.2*: MC – Sub6 (Split C), SC – mmWave (Split C)
c. *Cg.3*: MC – Sub6 (Split B), SC – Sub6 (Split C)
d. *Cg.4*: MC – Sub6 (Split B), SC – mmWave (Split C)

Finally, it should be noted that our traffic projections are based on downlink traffic only. The experimental LTE traces that were used to derive the projections were highly asymmetric in DL and this is a trend expected to continue in the 5G xMBB service, which will be powered by video and immersive experiences [15]. The interested reader can extrapolate the effect of significant UL traffic ratios by linearly scaling the results provided in this section.

B. *Wireless Segment Capacity Provisioning*

We evaluate the traffic that would be carried at the wireless segment connecting SCs and MCs. Table I provides the resulting capacity requirements for the aggregation of SC traffic in our considered scenarios. Note that these values correspond to the aggregation of the 70% traffic from a 5G MC coverage area, i.e., from all SCs of a MC. For the wireless segment, we see that mmWave RAN SCs require ~1.4x transport capacity as Sub6 RAN SCs. In addition, High Load scenario requires almost 4x the traffic of Low Load scenario.

TABLE I. Dimensioning for SC-MC Wireless Links (Gbps)

Scenarios	Cg.1, 3	Cg.2, 4
Low Load	2.9	3.8
High Load	11.5	14.8

Recall that we expect realistic 5G utilizations to lay between the Low Load and High Load scenarios. As detailed in [3], current wireless BH/FH technologies support up to 4.6 Gbps transfer rates and are expected to offer in the near future data rates in excess of 20 Gbps, which are sufficient to cover the projections in Table I.

C. *WDM-PON Segment Capacity Provisioning*

For the WDM-PON segment, we first provide the number of ONUs required per cell site, then we derive the aggregated traffic at each 5GX-CO, which in turn is used to define the number of OLTs required per 5GX-CO. For the sake of simplicity, in these calculations we assume all the MC sites have three sectors, and that the SC traffic wirelessly backhauled through the MC sites. Thus, we define one cell unit as one MC and its associated SCs, and one MC site as the aggregation point of three cell units (i.e., three sectors). In the calculations, two ONU capacities are used: i) 10 Gbps, which is the capacity available through the current technologies, and ii) 25 Gbps, which is the target ONU capacity in 5G-XHaul. Table II depicts the required number of ONUs in each MC cell/site for our four RAN configurations and the High Load utilization scenario. In the Low Load scenario only one ONU is required regardless of the RAN configuration.

TABLE II. Required Number of ONUs per Cell and Cell Site in High Load Scenario

Required ONUs	Cg.1	Cg.2	Cg.3	Cg.4
ONUs/cell (10 Gbps)	2	2	3	3
ONUs/site (10 Gbps)	2	2	3	3
ONUs/cell (25 Gbps)	1	1	1	2
ONUs/site (25 Gbps)	1	1	1	2

Next, we derive the aggregated access traffic at a 5GX-CO, based on the 70%-30% SC-MC traffic split and our four SC-MC RAN configurations. Fig. 3 shows the calculated traffic per 5GX-CO for varying number of 5GX-COs in Barcelona area, for Low and High Load scenarios. As seen in Fig. 3, the use of Split B for MCs increases the traffic carried by the WDM-PON significantly. As expected, reducing the number of 5GX-COs within the area increases the aggregated traffic per 5GX-CO.

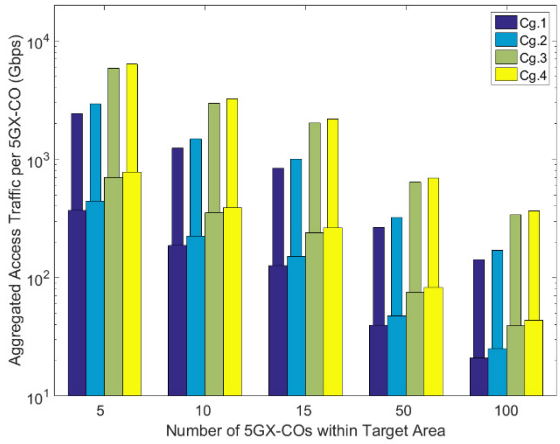

Fig. 3. Aggregated access traffic per 5GX-CO for Low Load scenario (wider bars) and High Load scenario (narrower bars).

However, this increase is close to be inversely proportional to the decrease in the number of 5GX-COs. This is because for the large numbers of cells being aggregated in our scenario the required data rates scales almost linearly with the mean data rate. For example, reducing the number of 5GX-COs from 100 to 5 (20x reduction) results in traffic increase of between 17.2x and 17.4x.

Next, we calculate the number of OLTs required at each 5GX-CO. As each OLT can enable up to 40 individual wavelength channels in the WDM-PON link [3], we can determine the number of OLTs with respect to the number of 5GX-COs based on the number of ONUs on each site. We can see in Fig. 4 that for a higher number of 5GX-COs, more OLTs are needed. This is because each OLT will have more unused channels if more than 15 5GX-COs are distributed in the area. Thus, from the WDM-PON perspective, it is preferable to use fewer 5GX-COs, which is in line with the OPEX reduction targeted by operators. For the sake of space, Fig. 4 only shows the results for a 25 Gbps ONU capacity, however similar trends are observed with 10 Gbps ONU capacity.

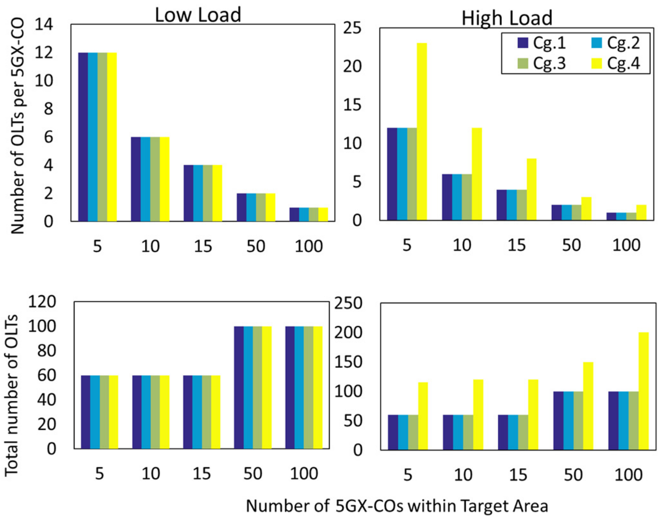

Fig. 4. Number of OLTs per 5GX-CO and the total number of OLTs for the target area for maximal capacity of 25 Gbps per ONU.

D. TSON Segment Capacity Provisioning

Next we assume that the TSON nodes form a ring topology, interconnecting the 5GX-COs scattered in Barcelona through TSON edge nodes. We further assume that a subset of these 5GX-COs connect to the operator's core transport network, which we call CoreNet-5GX-COs. Hence, the TSON network carries all the access traffic to/from these CoreNet-5GX-COs. We consider two different scenarios: i) *Local Processing*, where all 5GX-COs have BBUs, and ii) *Remote Processing,* where only the CoreNet-5GX-COs have BBUs. In case of *Local Processing,* Split B traffic is processed at the local 5GX-CO, and, therefore, TSON only transports Split C traffic towards the CoreNet-5GX-COs. On the other hand, *Remote Processing* allows higher BBU pooling gains, by carrying the Split B traffic to the BBU pools at CoreNet-5GX-COs.

In the following, only Cg.3 and Cg.4 (i.e., Split B for MC traffic) are evaluated. However, note that, for *Local Processing*, Split B traffic is converted to Split C; hence Cg.3 and Cg.4 would give the same results as Cg.1 and Cg.2, respectively, for the *Local Processing* scenario. The resulting TSON segment transport capacity as a function of the number of CoreNet-5GX-COs, which we vary from 1 to 5, is shown in Fig. 5. As expected, local processing capability, i.e., assuming BBU processing at each 5GX-CO, results in less aggregate traffic for the TSON segment.

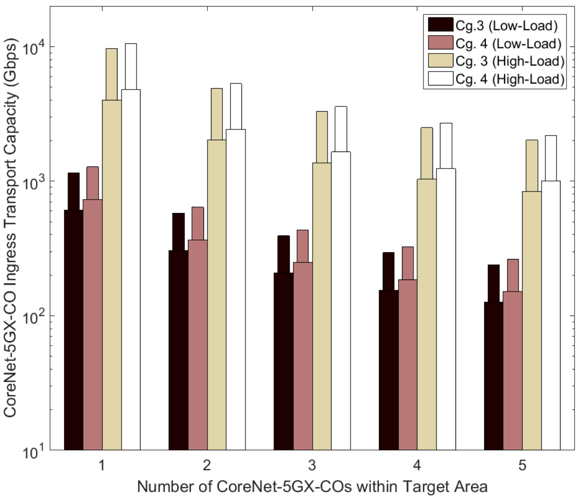

Fig. 5. CoreNet-5GX-CO ingress traffic for BBU processing only at CoreNet-5GX-COs (narrower bars) and at any 5GX-CO (wider bars).

The current TSON implementation described in [3] can support traffic volumes of the order of tens of Gbps. However, TSON technology can be extended to enable higher capacities through increased data rates per wavelength channel and increasing the number of channels that can be supported per fibre adopting scalable switching architectures. Taking such an approach can in principle lead to increased capacity levels reaching Tbps. However, a challenging issue that remains to be solved relates with the fast-path (wire speed) processing for multi-Gbps links at the edge. Specifically to satisfy the very tight 5G end-to-end delays, processing functions (i.e. packet transactions) should be executed at wire-speed. Currently processing rates appear to reach up to 100 Gbps in networking solutions integrating high-capacity technologies, which are below the Tbps capacity levels predicted in the worst-case scenario under evaluation. Lower transport capacities are obtained if a less dense RAN deployment is considered for Barcelona; recall from the introduction of Section IV that we are considering a worst-case deployment density. The interested reader is referred to [11] for the required transport capacities in the less dense deployment cases.

V. DIMENSIONING THE 5G-XHAUL CONTROL PLANE

In this section, we derive how many 5G-XHaul Tier-0 controllers [3] need to be deployed in Barcelona, for the deployment described in the previous sections. For this purpose, we define a cell site Area Unit (AU) as the geographical area covered by a Macro Cell (MC) and its associated Small Cells (SCs).

In order to dimension the control plane, we consider as the bottleneck the capacity of the 5G-XHaul Transport Nodes (TNs) in terms of the number of flows that can be kept concurrently in a fast memory, usually a (Ternary) Content-Addressable Memory, i.e., CAM/TCAM. A complementary method to dimension the control plane is described in [11].

According to [18], typical data-centre switches have embedded TCAMs which can hold between 2K and 10K flow entries. In the context of 5G-XHaul we will consider two scenarios, network elements with 2K TCAM sizes, and with 10K TCAM sizes. Note that the bottleneck in dimensioning the control plane will be the SCs of each AU, for which it is reasonable to assume limited TCAM sizes. In order to derive the number of flows that need to be kept in each network element (TN), it should be noted that the SDN controller needs to guarantee reachability between all the ETNs and IATNs within its control plane area (c.f. Section III and [3]). Thus, if there are N ETN+IATN under an SDN controller, up to 4×N×(N-1) unidirectional flows may have to be held in each network element, where 4 corresponds to the number of Traffic Classes considered in 5G-XHaul [16].

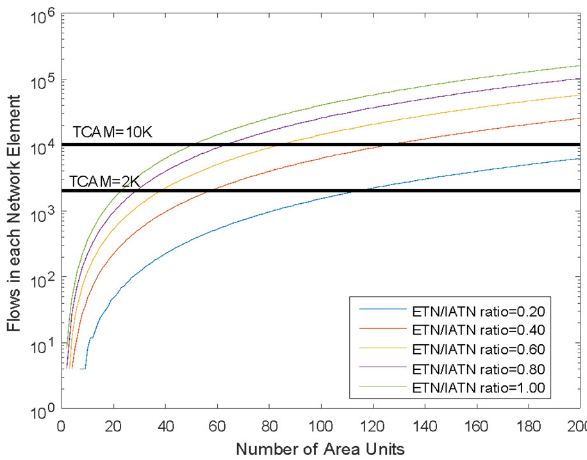

Fig. 6. Number of flows to be maintained in each network element as a function of the control area size (given in AUs).

Since it is difficult to come up with a specific number of ETNs/IATNs under each SDN controller, we assume that a ratio (0<r<1) of network elements in each AU are ETNs or IATNs. Consequently, if we know the number of ETN/IATN in each AU, we can consider that an SDN controller manages the devices of an integer number of AUs and from that derive the total number of ETNs/IATNs in its control area, and the total number of flows to be held in each network element, which is depicted in Fig. 6. Note that control area sizes are varied in the units of AUs.

As depicted in Fig. 6, based on the TCAM size and the ETN/IATN ratio, one can derive the maximum number of AUs under an SDN controller, and from there the number of SDN controllers required in Barcelona area; under the worst case assumption of the uniform deployment described in Section II. These results are described in Table III. Note that although the number of controllers is high, controllers can be deployed inside a virtual machine, making the deployment and operation of a high number of instances manageable using standard cloud platforms.

TABLE III. Number of 5G-XHaul Tier-0 Controllers and Maximum Control Area Sizes (in AUs) in Barcelona based on Switch Capacity

ETN/IATN ratio	TCAM size	# AUs	# Ctrlrs BCN
0.4	**2K**	~ 60	~ 39
0.4	**10K**	~ 125	~ 19
0.8	**2K**	~ 30	~ 77
0.8	**10K**	~ 65	~ 36

VI. CONCLUSIONS

In this paper, we have provided an analysis of the physical deployment aspects of the 5G-XHaul architecture. Building on the example of Barcelona, we have dimensioned the bandwidth required at different levels of the transport network while considering different 5G RAN deployment implementations featuring multiple functional splits in the SC and MC layers. We have evaluated the bandwidth required at the 5G-XHaul Central Offices, and shown that the WDM-PON and TSON optical technologies developed in 5G-XHaul can be appropriately dimensioned to handle the required traffic. We have also looked at the control plane, and dimensioned the number of SDN controllers that should be deployed in a city like Barcelona. As a result, this paper has illustrated a practical realisation of the 5G-XHaul architecture in a representative European city and the resulting transport network requirements.

ACKNOWLEDGMENTS

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