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5G-XHaul

Dynamically Reconfigurable Optical-Wireless Backhaul/Fronthaul with Cognitive Control Plane for Small Cells and Cloud-RANs

D2.4 Network Topology Definition

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Executive Summary

The goal of this deliverable is to describe how a 5G-XHaul infrastructure provider may deploy the 5G-XHaul network architecture introduced in deliverable D2.2. It is worth noting though that there is no standardised model to deploy a transport network, but instead each operator follows a custom approach constrained by a variety of aspects such as its strategic decisions, legacy technologies, whether it owns fixed infrastructure or not, or its competitive environment. Therefore, this deliverable does not attempt to describe all the possible ways to instantiate the 5G-XHaul architecture, which would depend on each particular case, but instead we select an example scenario, in this case the city of Barcelona, and illustrate how the 5G-XHaul architecture can be deployed in that environment. We believe that this constitutes a representative example that can guide practical 5G-XHaul deployments.

Building on the case of Barcelona, we discuss physical deployment aspects, such as the best 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 controllers required for a city like Barcelona, whereby controllers can be deployed as software functions.

Finally, we conclude the document with a discussion about how the transport network of the two operators that participate in 5G-XHaul, Telefonica (TID) and COSMOTE (COS), could adopt the principles laid out in the 5G-XHaul architecture. The fact that the two considered networks differ significantly in their design, and that different operators have different strategic goals, proves the generality and the impact potential of the 5G-XHaul architecture.

The main contribution of this deliverable is to provide a quantitative evaluation of the dimensioning and deployment aspects of the 5G-XHaul architecture in a representative European city. In addition, the work in this deliverable is expected to feed the Techno-Economical analysis that will be carried out as part of WP6.

1. Introduction

This deliverable defines the 5G physical architecture corresponding to the logical architecture derived in deliverable D2.2 [1]. For this purpose, a 5G-XHaul network blueprint is derived, which defines the physical network elements of the 5G-XHaul system, the physical network architecture, and the forecasted network topology. Within this network blueprint, we identify the 5G-XHaul network elements and their associations in this physical architecture. Such physical architecture definition is especially important to identify strategies for the future physical deployments. We then detail the 5G-XHaul network elements by presenting their functionalities and their physical characteristics (size, components, etc.) and requirements (location, connectivity, etc.).

The objectives of the 5G-XHaul network blueprint are to devise physical deployment strategy projections, which can be used to i) derive the throughput requirements on different network segments and on corresponding network technologies, and ii) generate feasible topologies for network performance evaluations, e.g. calculate the signaling overhead of possible SDN solutions or evaluate failover scenarios. The network blueprint will build on the existing infrastructure (e.g. considering the Central Office (CO) site density, etc.) for a feasible and realistic output. In this deliverable, the technology candidates for different components of the network are also defined.

We then evaluate the derived network blueprint on a dense urban scenario, in line with the extreme Mobile Broadband (xMBB) use case defined in 5G-XHaul, which brings stringent constraints on the transport network. For such scenario, we take Barcelona city centre as a target area and provide an illustrative overlay of different 5G/5G-XHaul network elements. To define a feasible deployment scenario, we take the deployment characterisations (such as Inter Site Distances) for different network elements (such as Macro Cell Sites) from 5G-PPP projects including METIS, associations such as NGMN and technology providers. Finally, the compilation of the projections is evaluated by the operators involved in the 5G-XHaul consortium for their feasibility considering the existing deployments.

Hence, the derived deployment scenario defines the following information:

- Number of Small and Macro sites in the deployment and their inter-site distances.
- Number of fibre connection points.
- Locations or densities of compute and storage facilities (e.g. COs).
- Physical topology of the metro network.
- Locations/density of control plane elements.

In Section 2, we define the physical elements of a complete 5G-XHaul deployment and the physical architecture that describes the possible connections between these elements. Then, in Section 3, we present an illustrative Dense Urban Scenario topology for the Barcelona city. The possible deployment of functional elements of the 5G-XHaul control plane for the reference city of Barcelona is discussed in Section 4. In Section 5, the derived illustrative physical topology is used to calculate the throughput demands at different network elements to validate the support of the 5G-XHaul technologies at these network elements to carry such traffic loads. In Section 6, the control plane deployment is used to evaluate the resulting control traffic to validate the support of current technologies for such traffic. In Section 7, based on the derived physical 5G-XHaul architecture, the migration strategies of the existing systems to such solution is studied by the two operators of the 5G-XHaul consortium considering their existing deployments. Finally, Section 8 concludes this deliverable.

2. 5G-XHaul Physical Topology Elements and Architecture

In this section we define the physical elements of a complete 5G-XHaul deployment and the physical architecture that describes the possible connections between these elements.

The following group of elements are not part of the technologies being developed in the project, yet they are required for an overall system deployment.

- ***Macro Cell Sites*** are placements hosting a macro-cell. They consist of an antenna mast, and optionally a cabinet with cooling and power (if the baseband is hosted next to the antenna). A macro-cell site can host several sectors, normally 3. Typical placement is on a building roof.
- ***Macro Cells (MC)*****:** Each sector corresponds to a cell. The types of macro cells to be considered are 4G and 5G. Most or all of macro cells are expected to have a fibre attachment point.
- ***Small Cell Sites*** are placements hosting a small cell. Small Cell site may or may not have direct fibre connectivity. Alternative wireless connection is achieved through Sub-6 GHz backhauling, or millimetre wave (mmWave) backhauling/fronthauling.
- ***Small Cells (SC)*****:** Each small cell site is considered to have one sector of type 4G and 5G.
- ***5G-XHaul Central Office (5GX-CO):*** A CO inside a city managed by the 5G-XHaul infrastructure provider. This node can host 5G-XHaul network elements and/or compute/storage devices with virtualisation capabilities.
- ***Edge Cloud*****:** Compute/storage resources managed by the 5G-XHaul infrastructure provider and located close to the edge. Examples are servers located in macro-cell site cabinets, servers located in street cabinets, or compute/storage resources collocated with a small cell in a lamp post.
- ***Base Band Units (BBU)*****:** Radio processing unit located in the 5GX-CO, has optionally a CPRI interface to the RF unit located in the antenna. A softwarised and virtualised version of BBU (i.e. vBBU) can be run at edge cloud, at 5GX-CO or at the data centres (regional cloud, central cloud, etc.).

The following elements are required by the technologies developed in 5G-XHaul:

- ***WDM-PON*****:** Connectivity between the 5GX-CO and cell sites is achieved by means of the WDM-PON system, which consists of:
  - ***Optical Line Terminal (OLT)****:* Central unit of optical line cards mounted on a rack, preferably located in the 5GX-CO. A single OLT shelf can be scaled up to 40 individual and transparent optical channels, each of which is capable of relaying the data stream at the line rates of 1 Gbps to 10 Gbps, provisioning a virtual point-to-point tunnel between the OLT and the remote ONU. Notably, a centralised wavelength locker is also implemented in the OLT in order to control and stabilize the wavelengths of all the ONUs.
  - ***Electrical/Optical switch:*** to flexibly assign different resources delivered from the OLT to the Optical Network Units (ONUs), a cross-connect functionality can be implemented in the OLT by either an electrical or an optical switch [1].
  - **Remote node (RN)**: A passive WDM multiplexer/de-multiplexer with equivalent 40 channel ports routes every single wavelength to the corresponding ONU. Two possible field deployment options of the remote nodes, namely the star and drop line architecture, were proposed in deliverable D2.2 [1]. In case of the star topology, the RN should be installed in a street cabinet which is close to all the connected ONUs. It should be noted that, unlike the passive power splitter, the maximum distance and power budget is determined by the pluggables used at the OLT and ONUs. Due to the stringent latency requirement imposed by the *CPRI*, the distance between the OLT and the furthest ONU should be within 20 km. In addition, a WDM-PON network can be in principle amplified as it operates in C- and L-band.
  - ***ONU***: In the cell site, ONU directly interfaces the radio head for fronthaul setup and the BBU for backhaul setup, where the interface specification was defined in deliverable D2.2. Each ONU is able to adaptively select its transmission wavelength to fit the connected port of the multiplexer/de-multiplexer, thanks to the centralised wavelength locker at the OLT.
- ***TSON***: TSON solutions include two different types of nodes, the edge and the core nodes incorporating different functionality and level of complexity.

    - **TSON edge nodes** provide the interfaces between wireless, PON and DC domains to the optical TSON domain and vice versa. The ingress TSON edge nodes are responsible for traffic aggregation and mapping, while the egress edge nodes have the reverse functionality.
    - **TSON core nodes** switch transparently optical frames to the appropriate output port.
- ***mm-Wave Fronthaul/Backhaul (Xhaul) node*:**
    - Multiple mmWave radio transceivers integrated with a Network Processing Unit (NPU) into the same physical box (volume 5-10 litres), mounted on street furniture or building wall (typically same mounting platform as used by the small cell).
    - Phased array antennae are integral to the transceivers and can be steered in azimuth (for example over 90˚).
    - Powered and connected using Ethernet from small cell cell-site or macro site.
- ***Sub-6 Access/Backhaul (BH) wireless nodes*:**
    - Dimensions 30cm x 20cm x 10cm.
    - Comprising two wireless NICs working at the 5 GHz band (lower and upper parts of the band). These NICs feature 802.11ac and 3x3 MIMO.
    - One wireless NIC featuring 2x2 MIMO and 802.11n for the wireless access.
    - All wireless NICs are driven by an NPU controller with a programmable software switch acting as 5G-XHaul agent.
- ***Massive MIMO antenna*:**
    - Dimensions: 900x265x100 mm.
    - Deployment: Macro site tower mount or wall mount possible.
    - Interface
        - Up to 4 optical interfaces (typical is 2).
        - Up to 4 CPRI links (typical is 2), line rate 8, 40 Gbps total data rate (typical is 20 Gbps).
        - Up to 32 virtual ports, i.e., 32 independent IQ streams each carrying a 20 MHz signal (16 virtual ports is typical).

    - Radio Access
        - Band 7 (2.6 GHz FDD).
        - 40 MHz total RF bandwidth.
        - Contiguous carrier aggregation up to 40 MHz.

Figure 1 illustrates a 5G-XHaul physical network architecture, where the cell sites with fibre connections host an ONU for that connection, which is multiplexed/demultiplexed at RNs. The RNs connect to OLT at the 5GX-COs, where the inter domain transfer to TSON happens through a TSON Edge node. TSON nodes form a ring, which facilitates the connection to the core network and Internet through a TSON Edge Node. Small cell sites can be wirelessly connected to a Macro Cell Site or alternatively they can have fibre attachment points. For this, the feasible wireless connection technologies can be Sub-6 GHz or mmWave for Backhaul (BH) and mmWave for Fronthaul (FH) communication. The Edge Cloud, which includes compute/storage facilities are expected to be available mainly at Macro Cell sites as illustrated in the figure. Nevertheless, there can be cases where they are installed at small cells or street cabinets.

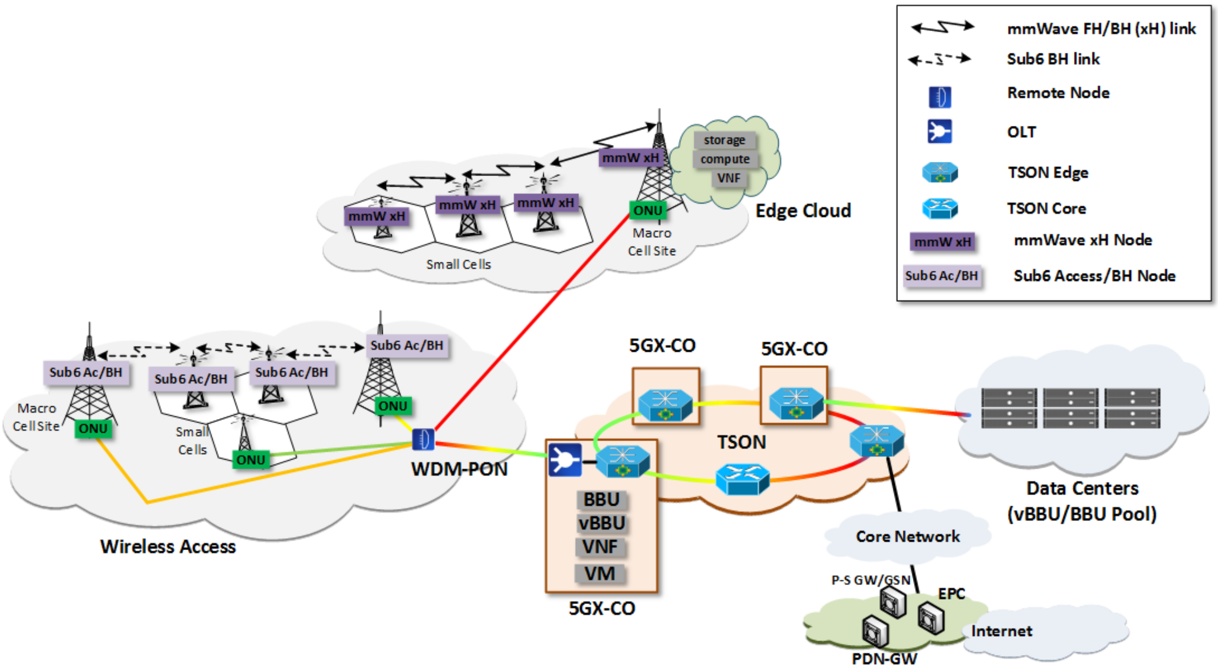

Figure 1: 5G-XHaul physical network architecture illustration.

In Figure 2, we detail the important components of a 5GX-CO. In 5G-XHaul, the 5GX-COs host OLTs and therefore are the data aggregation points from different cell sites. The communication technology used between the fibre attachment points of the cell sites and the 5GX-COs is WDM-PON, which interfaces with the TSON network at the 5GX-COs.

Because of a single-fibre working design, each WDM-PON channel is assigned one pair of wavelengths for the downlink and uplink, respectively. Given the fact that the downlink throughput is much higher than the uplink (for the load-dependent functional splits as considered in this deliverable), the required number of ONUs provisioning the macro cell sites and the small cell sites then depends on the aggregated ingress capacity at each cell. Since each ONU operates on a dedicated optical channel with up to 10 Gbps, as long as a single optical interface (i.e. a pair of optical transceivers between the ONU and radio equipment) does not exceed 10 Gbps, multiple ONUs can be installed in a single cell in order to meet the aggregated capacity need. On the other hand, if the total ingress capacity to the cell site is smaller than 10 Gbps, a 10GbE Ethernet switch can be utilised between the ONU and multiple radio equipment to aggregate the total capacity on a single ONU channel.

The compute/storage facilities at the 5GX-COs can run vBBU components or 5GX-COs can simply host physical BBU pools, in which way they can be an end point for fronthaul connections. Otherwise the fronthaul connections can be relayed to the data centres in the remote locations through TSON, after which point such connections are converted to BH connections and forwarded to the core network through TSON.

Hence, the TSON segment connects all 5G-XHaul 5GX-COs with each other in the metro network, accomplishing two main goals. First, given that 5GX-COs are connected and the multi-protocol nature of TSON, virtual or physical BBUs do not need to be present in all 5GX-COs, but they can be centralised in few 5GX-COs, which delivers larger pooling gains (c.f. Figure 2); in addition TSON also transports backhaul traffic coming from the (v)BBUs. Second, in 5G-XHaul TSON is the technology that will connect the ingress/egress access traffic available in each 5GX-CO, to the operator's transport core network. Without loss of generality, a particular implementation could be one where the core network of an operator uses IP/MPLS over WDM. In this concrete example a subset of the 5G-XHaul 5GX-COs in the metro domain would be equipped with IP routers connected to the operator core network. TSON would then be 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 (c.f. Figure 2).

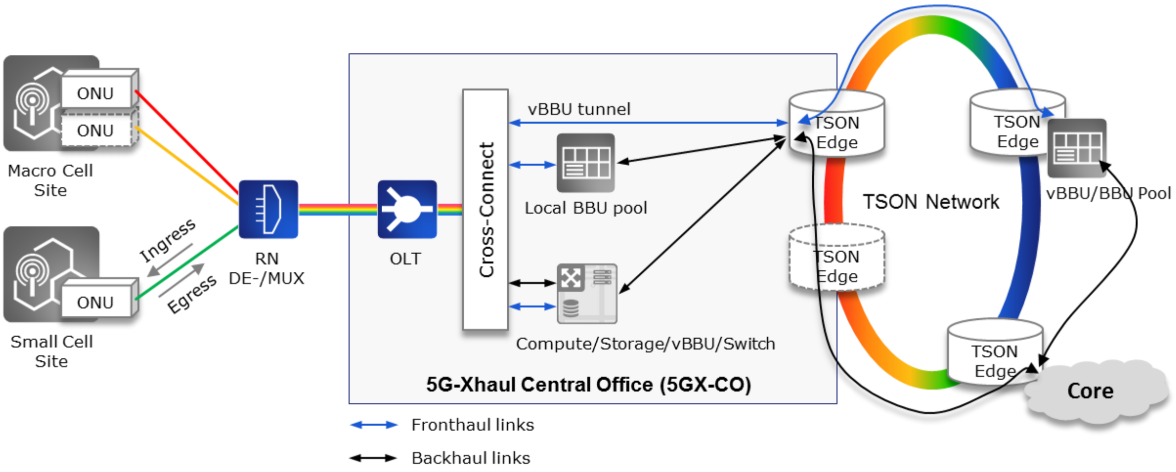

Figure 2: Prototype 5G-XHaul Central Office (5GX-CO).

3. 5G-XHaul Network Topology: Macro and Small Cell Layout in Dense Urban Scenario

To evaluate the traffic requirements of the physical architecture defined in Section 2 in a realistic scenario, we target a Dense Urban Scenario and choose the Barcelona city centre as a target location, where the example neighborhood (*Eixample*) consists of square shaped blocks that can be used to visualize the deployment of different network elements. For simplicity, unless explicitly stated, in our study we will take this reference area in Barcelona, depicted in Figure 3, and dimension the 5G-XHaul transport network as if the whole of Barcelona would be covered using a similar approach. Notice however that this represents a worst-case analysis, since in practice a city like 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) predictions of prior work for Macro Cell (MC) sites and Small Cell (SC) Sites. In [2], NGMN provides the projection of 200 m Macro ISD, and 3-10 small cells per Macro Cell in Dense Macro Scenario, whereas only a Macro ISD of 500 m is defined for Urban Macro Scenario. The 5G-PPP project METIS-II defines the Urban Macro and HetNet Scenario [3], where the Macro ISD is 200 m, and eight Small Cells (SCs) are defined per Macro Cell site. As a further detail, Small-Macro distances are defined to be >55 m, and SC-SC distances are defined to be >20 m. On the other hand, in their white paper [4], Nokia assesses the “Madrid” and the Tokyo deployment of METIS project, for which an ISD of 50-100 m of is foreseen for cmWave and mmWave access to achieve full coverage. In addition, mmWave radio is considered as a viable option for Small Cell backhauling in a mesh configuration with a maximum of two hops.

As a result, we choose the common assumption of 200 m ISD for Macro cells and 3-10 SCs per Macro Cell, and for a physical layout, look for a deployment in the downtown region of Barcelona city, specifically the *Eixample* neighborhood, where the blocks are regular square shaped (Figure 3).

Figure 3: Dense Urban Scenario: Target area snippet (*Eixample* neighborhood in Barcelona).

To provide the Macro and Small Cell layers in this neighborhood, we first translate the Macro Cell ISD into the blocks as: Each block has a 133.3 m edge, and hence, 1.5 blocks correspond to 200 m, which is the common Macro Cell ISD projections. Hence, 200 m is chosen as 5G-XHaul Macro Cell ISD for sake of simplicity in the illustrative layout. Accordingly, we lay out the Macro Cell layer for the target area (Figure 4). For the sake of simplicity, we leave the Macro Cell Sites that reside in the centres of the blocks, however a more realistic layout would not hinder the average ISD of 200 m.

Figure 4: Dense Urban Scenario: Macro Cell (MC) Layer layout.

The Small Cell layout will be based on the constraints defined by METIS-II (Macro-Small ISD>55 m) and the street light deployment approach, which currently is used for city-wide Wi-Fi access in Barcelona[1]. This then defines 3 Small Cells (unless there is a Macro Cell deployed at the target edge points) at each edge, with 70 m Macro-Small and Small-Small ISD (Figure 5).

Figure 5: Dense Urban Scenario: Small Cell (SC) Layer layout.

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[1] http://www.bcn.cat/barcelonawifi/en/

As seen in Figure 5, the number of SCs per MC is between 4 and 8, which complies with the NGMN projections [2]. Note that in a real deployment the SCs could use the same or different frequency bands than the macro. If they use the same frequency, then there could be self-backhauling. However, we do not consider this case here, and rather focus on the case where the SCs use a different frequency. This case is optimal to mitigate interference with the Macro Cell layer, and aligns with 5G-XHaul's focus on the transport network to connect these Small Cells.

Next, we consider the transport network technologies that this deployment employs. 5G-XHaul assumes three different 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 xH: SC in the lamp post connected to a mmWave node. There can be different configurations according to the number of mmWave radios the node has, e.g. two radios if a node only is connected to the lamp post in front and behind, or four radios, if the node is at an intersection.
3) SC+ Sub-6 Access/Backhaul: The SC can also be connected to a Sub-6 BH providing less capacity but more potential connections. In this case the SC can provide a hybrid Access/BH functionality, which can be configured by the SDN controller.

In addition to these SC types, we consider a single Macro Cell (MC) type, which is the one with the WDM-PON connection.

In Figure 6, an illustrative deployment using these transport technologies is provided. In addition, the physical wireless BH/FH connections 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 are switched off for energy cost or interference reductions), through backup paths with more hops as illustrated.

Note that the centre of square blocks might also have a SC for improved coverage, which might also provide transport functionality. This does not change the ISD calculated and the range of number of SCs per macro cell

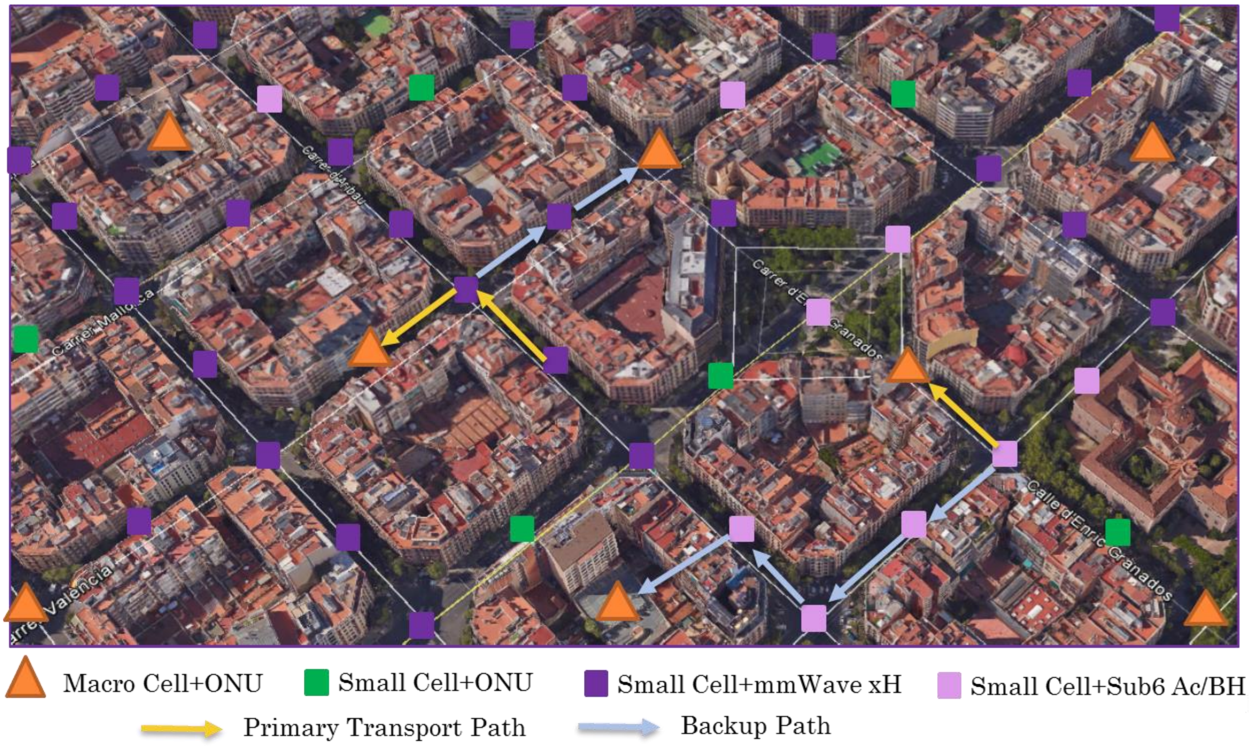

Figure 6: Dense Urban Scenario: Transport technology illustration.

4. Placement of Control plane elements

Taking as a reference the city of Barcelona, we discuss in this section where the different functional elements of the 5G-XHaul control plane will be deployed. The 5G-XHaul control plane architecture has been described in detail in deliverable D3.1 [5], however we include next a brief description.

4.1. Summary of 5G-XHaul control plane architecture

5G-XHaul targets a heterogeneous data-plane architecture composed of wireless and optical technologies (c.f. Figure 1). In order to enable a common control plane, the individual hardware components need to be abstracted into something that can be controlled by the control plane. In this regard, 5G-XHaul assumes a programmable "*match – action*" abstraction as the one proposed by OpenFlow [6]. This abstraction is provided by the wireless transport nodes, at the edge of the network, and the TSON edge nodes at the core of the metro network. The WDM-PON described in Figure 1 does not provide a programmable packet abstraction, but is instead treated as special type of transmission technology (i.e. a link) with some specific management capabilities (refer to deliverable D3.1 [5] for more details). Regarding the concrete "*match – action*" abstraction 5G-XHaul assumes a subset of OpenFlow 1.3 comprising L2 fields, and Provider Backbone Bridging (PBB), since this is the best way to integrate with Ethernet technology present in the data-centre and the network edge.

Having laid out the data plane abstraction, the 5G-XHaul control plane is built around two main concepts: 1) maintain per-tenant state at the edge of the network, and 2) enhance scalability and reliability by introducing control plane areas that divide the control plane responsibility across different controllers organised in a hierarchical manner.

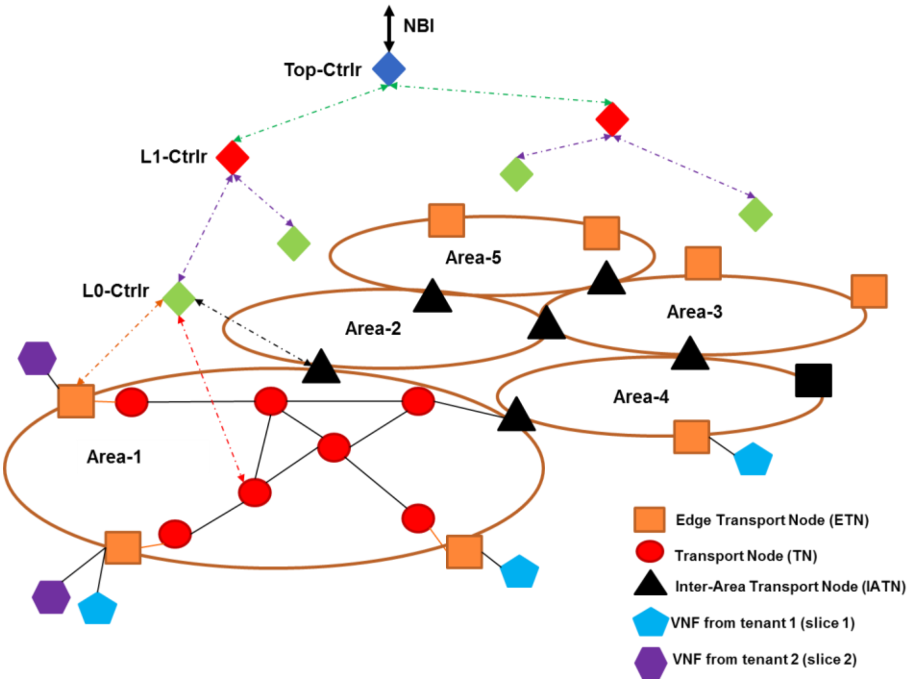

Figure 7: 5G-XHaul reference control plane architecture.

Figure 7 introduces three main functional entities in the 5G-XHaul control plane: 1) the Edge Transport Node (ETN), 2) the Inter-Area Transport Node (IATN), and 3) the Transport Node (TN).

In the framework of Figure 7 5G-XHaul can be understood as a network that connects geographically distributed Virtual Network Functions (VNFs) that belong to different tenants, which is one of the architectural principles of 5G according to the 5G-PPP Architecture Working Group [7]. For example, the purple hexagon, or the blue pentagon in Figure 7, represent VNFs that belong to different tenants. Thus, the ETN, depicted as orange squares in Figure 7, is an entity at the edge of the network with a connection to the tenant VNFs on one side and a connection to the 5G-XHaul TNs on the other side. The main function that the ETNs have to implement is to maintain a binding between the per-tenant state, e.g. the MAC address of a VNF belonging to a particular tenant/slice, and the ETN transport address, where that VNF is currently deployed[2]. A detailed description of the 5G-XHaul virtualisation solution is described in [5].

The 5G-XHaul control plane introduces the concept of control plane areas in order to enable the scalability in both the data plane and the control plane. The idea is that a control plane area instantiates a single type of technology, e.g. wireless transport or TSON, and has a technology specific controller in charge of maintaining a set of “transport tunnels” across that control plane area. The SDN controller monitors the state of each tunnel, records relevant events, and reconfigures them if needed (e.g. if for energy reasons some node needs to be switched off or taken out for maintenance reasons). The ETNs residing in a particular control plane area classify per-tenant traffic into the transport tunnels instantiated in that area. Hence, the forwarding elements (TNs) inside a control plane area need to maintain enough forwarding state to ensure reachability between any pair of ETNs and IATNs in a given area. Consequently, a 5G-XHaul provider can use the size of a control plane area to suit the capabilities of its data plane technologies. If cheap network equipment that can hold a reduced number of flow entries in their Ternary content-addressable memory (TCAM) is used, then small control plane areas can be used, otherwise bigger control plane areas can be used. The trade-off is the number of controllers, since one Layer-0 controller (c.f. Figure 7) is needed per control plane area. In Section 6 we discuss several methods to dimension the 5G-XHaul control plane.

Finally, if a tenant deploys VNFs in ETNs located in different control plane areas, 5G-XHaul should support connectivity across these areas. However notice that for scalability reasons we limit the flows maintained in each Transport Node (TNs), depicted with a red circle in Figure 7, to the minimum required to implement forwarding within the area. Consequently, we introduce the notion of IATNs, depicted as black triangles in Figure 7, which belong to more than one control plane area and allow forwarding across areas by binding together tunnels from different areas.

A detailed description of the 5G-XHaul control plane can be found in deliverable D3.1 [5]. In deliverable D2.2 [1], a description of how the functional elements of the control plane architecture, i.e. ETNs, IATNs and TNs, map onto the physical architecture depicted in Figure 1 is also included. In addition, in the next section we discuss how the required control plane elements could be physically deployed in the city of Barcelona.

4.2. Physical deployment of ETNs

Edge Transport Nodes (ETNs) connect geographically distributed compute/storage resources with virtualisation capabilities through the 5G-XHaul network. We discuss next where ETNs could be deployed in the physical network:

- ETSI-MEC has defined a reference architecture for Mobile Edge Computing (MEC) [8], which collocates a MEC server in a macro-cell site. According to ETSI-MEC a MEC server can support virtualisation (through a hypervisor and VMs, or through containers). Hence, in 5G-XHaul we assume that compute/storage will be collocated with macro-sites, and in that case an ETN would run as a software agent inside the hypervisor running at the servers in the macro-cell site.
- Figure 8 depicts a typical street cabinet in Barcelona, and highlights in red the location of the many street cabinets deployed nowadays in Barcelona. Current initiatives tight to FOG computing are proposing to place IT infrastructure in those street cabinets, as has been recently demonstrated by Cisco in a Fog Computing PoC in Barcelona[3]. 5G-XHaul will consider that street cabinets will contain IT infrastructure with virtualisation support, hence an ETN implemented through a software agent would be embedded in the IT servers inside the street cabinets. A practical example of this could be a set of lamp-post with a Radio Unit (RU) installed comprising only low-level MAC and PHY functions, and the rest of the RAN protocol stack (e.g. PDCP, RRC) virtualised and instantiated in the compute/storage resources of a street cabinet located close to the lamp-post. In this setting, the virtual RAN functions could belong to different tenants, and would connect to the 5G-XHaul transport through an ETN.

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[2] Note that tenants may move their VNFs across different ETNs.

[3] https://www.youtube.com/watch?v=V6twynk_OB4

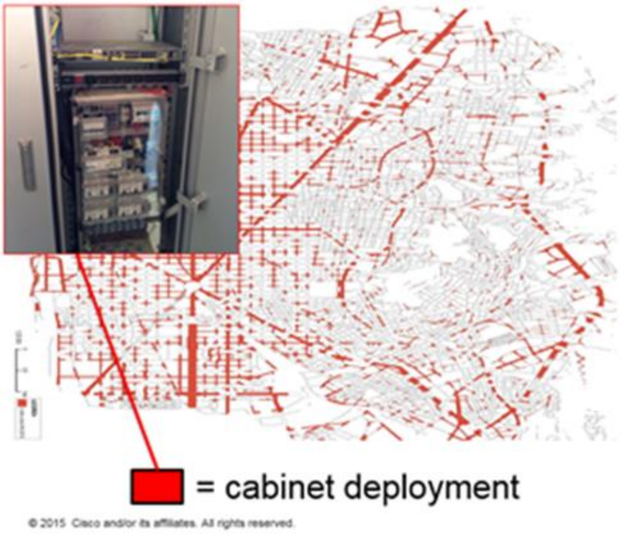

Figure 8: Barcelona 3300+ street cabinets deployment map.

- Small Cells are going to be deployed on lamp-posts or street furniture. Small Cells are typically based on embedded processors (ARM based), which also support virtualisation [9]. This means that if 5G Small Cells exist that support natively virtualisation, i.e. they can host Virtual Network Functions (VNFs), potentially belonging to different tenant/slices (for example a per-slice MAC function could be virtualised), then in the Small Cell hypervisor we would have an ETN providing access to the 5G-XHaul network. It is worth highlighting though that we do not expect all Small Cells to support natively virtualisation. Small Cells that do not support virtualisation will not embed an ETN, however this Small Cells still need to be reachable. For the sake of simplicity non-virtualised Small Cells can be understood as a Small Cell containing an ETN connecting a single function, namely the physical function.
- Finally, 5GX-COs will have compute/storage resources like a data centre (e.g. CORD architecture [10]). Thus, an ETN will be embedded in each of the bare metal servers offering virtualisation capabilities.

The following figure provides an exemplary deployment, where we highlight potential locations of ETNs in the network.

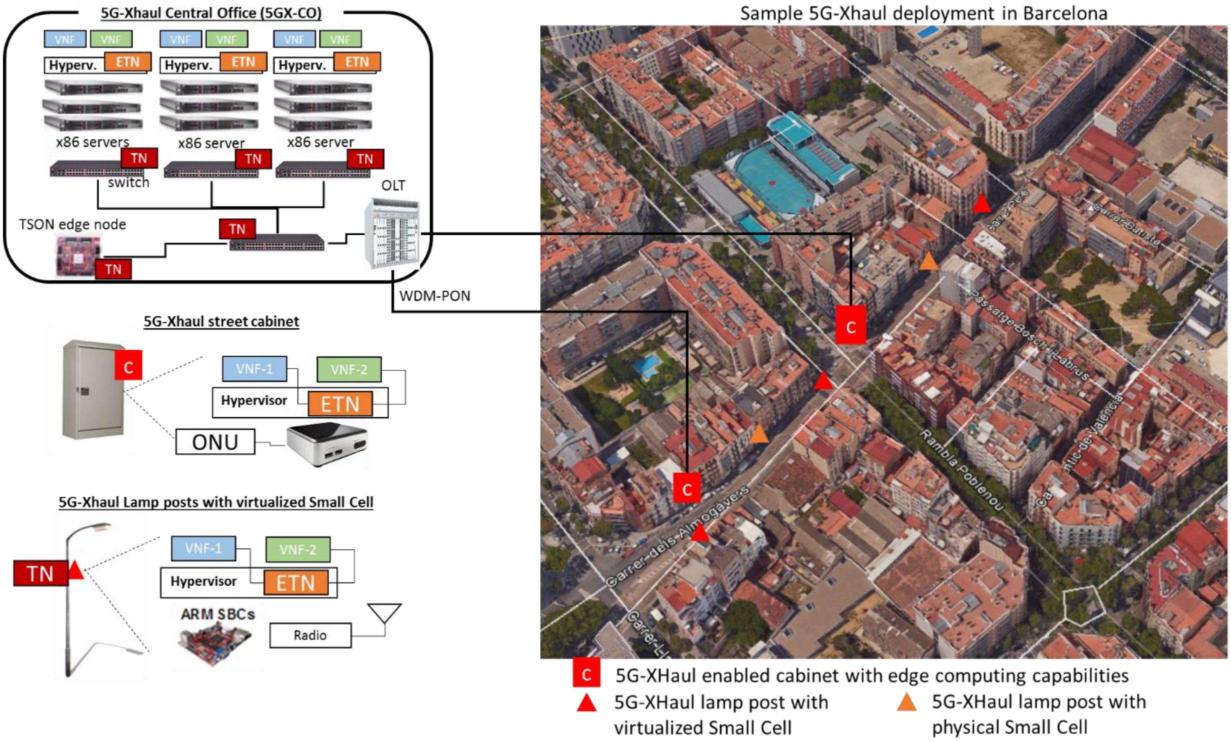

Figure 9: Example deployment of ETNs (software agents) in a sample 5G-XHaul physical deployment.

4.3. Physical deployment of IATNs and TNs

All network elements in 5G-XHaul that can store forwarding state are TNs. In particular, in the wireless domain, both mmWave and Sub-6 devices can hold forwarding state and be programmed by an SDN controller, so they are TNs. In the wired domain, TSON edge nodes are TNs, and Ethernet/OpenFlow switches providing connectivity inside the 5GX-CO are also TNs. It is worth highlighting that the WDM-PON OLT or ONU do not embed a TN function since forwarding in WDM-PON is not programmable, i.e. each ONU is “wired” to an OLT port. However, the cross-connect element can be considered as a TN with limited functionality since it allows programming the mapping of OLT ports to input cross-connect ports, but cannot hold per-flow state.

Inter-Area Transport Nodes (IATNs) are TNs that connect different control areas. In this regard, any network element acting as TN can also be configured to act as IATN if required.

4.4. Physical deployment of 5G-XHaul controllers

As defined in deliverable D2.2 [1], the 5G-XHaul control plane comprises in general a three level control plane hierarchy with a Top controller, Level-1 controllers and Level-0 controllers (c.f. Figure 7). The physical location of these controller is considered as follows:

- *Top controller*: Will be deployed on a data centre owned by the 5G-XHaul infrastructure provider and located in its core network (c.f. Figure 1).
- *Level-1 controller*: Will be deployed in a virtualised fashion in the 5GX-COs scattered through the city. Controllers will be replicated to increase reliability.
- *Level-0 controller*: Depending on the type of technology being orchestrated. For optical control areas, e.g. TSON, the Level-0 controller will be placed in a 5GX-CO. For wireless control areas, if enough compute resources are available on the macro-cell sites or on the street cabinets, the Level-0 controller can be deployed there. Otherwise the Level-0 controllers will also be deployed in the 5GX-CO.

5. Dimensioning the 5G-XHaul data plane for different functional splits

In this section we derive the transport network capacity requirements at different levels of the hierarchy for a city like Barcelona as defined in the following. Deliverable D2.3 [11] derives the final data rate requirements for the FH and BH architectures for the aggregation of a given number of cells. Furthering that study, the general requirements of D2.3 are used to dimension the network capacity at different network elements of the physical network layout devised in this deliverable. This dimensioning is studied on an exemplary network topology defined by projected ISDs of Macro and Small Cell sites as presented in Section 3 and a projected density of 5GX-COs in an urban scenario, which we obtain through discussions with the operators that participate in 5G-XHaul. In this study, we will focus on the mobile access traffic, yet, the 5G-XHaul architecture allows to incorporate fixed access traffic (c.f. Section 7 for an example of the fixed/mobile ratio for an operator in Spain). In addition, unless otherwise stated, the evaluation presented in this section is based on the worst-case assumption described in Section 3, which results from replicating the exemplary *Eixample* deployment to the whole of Barcelona.

Specifically, the required transport network bandwidth in WDM-PON (at Macro Cell Site and at 5GX-COs), in TSON (at the aggregation points of 5GX-COs for TSON ring topology) and in wireless segments (small cell backhauling) will be evaluated. The evaluation parameter will be the number of 5GX-COs within the city that is varied based on the projected 5GX-CO density numbers. In this regard, it is worth highlighting that currently operators offering fixed access have a high number of COs scattered through a city like Barcelona, due to the short range limitations of xDSL technology. A common desire among operators though is to cut OPEX reducing the number of COs, by migrating to fibre access technologies that have longer reach (e.g. PON based solutions like the ones proposed in 5G-XHaul). To cover the situation and strategy of different operators in this section we dimension the network for a wide range of 5GX-COs.

For the Barcelona city population of 1,4M inhabitants, distributed in 101.4 km^2, we derive the projected number of Macro and Small Cells, along with the number of 5GX-COs, and the resulting traffic loads on each component and link of the 5G-XHaul network topology as follows.

Number of Macro and Small Cells: For the calculated 22.68 Macro sites/km^2 dense urban scenario density, we find ~2,300 Macro sites covering Barcelona City along with 9,200 to 18,400 Small Cells, corresponding to 4-8 Small Cells per Macro Cell site[4]. Note that as explained in Section 3 this corresponds to a worst-case scenario. Later in this section, we will relax this assumption.

Number of 5GX-COs: To project the density of 5GX-COs in a dense urban scenario, first we look into the projections in the literature for the density of the COs. According to an Orange deployment [12], 15 cell site are served by a CO and according to another Orange data [13], up to 28 cell sites are connected to a CO. Since the number of 5GX-COs within a city is determined both by the capacity and the link distance constraints, we take a dense urban scenario from a city and derive the number of 5GX-COs per 1M habitant using real operator data, obtaining an average of 50 COs per 1M habitants. Note that the operators target to reduce the number of COs as the new technologies allow longer distances and higher capacities.

Assuming fibre connection between Macro sites and 5GX-COs, with the Orange's current approach of 15-28 cell site/CO, the resulting number of 5GX-COs for Barcelona area is 80-170 5GX-COs. Whereas the current 50 5GX-COs per 1M habitants corresponds to 70 5GX-COs in Barcelona. However, operators target to reduce the number of 5GX-COs in the future, which is enabled by the distances of fibre connections and increased optical network capacities. Hence we choose the range of 5-100 5GX-COs for our further calculations. Assuming 3 cells (sectors) per Macro Cell site, we then have 69-1380 Macro Cells per 5GX-CO, and 1 sector per Small Cell site gives 92-3,680 Small Cell per 5GX-CO.

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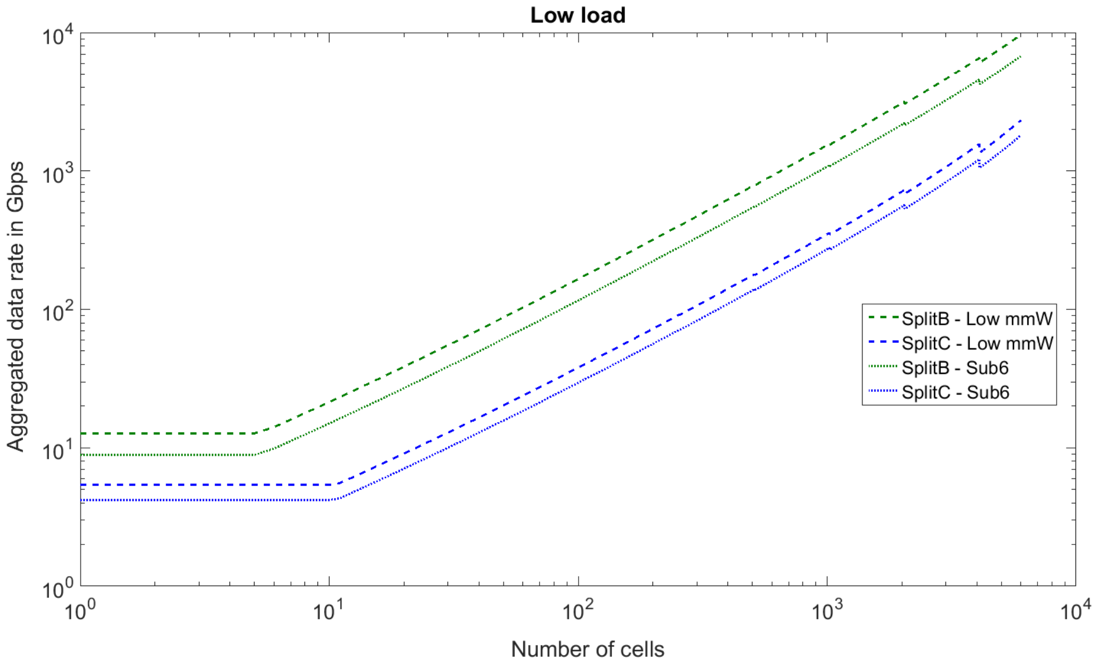
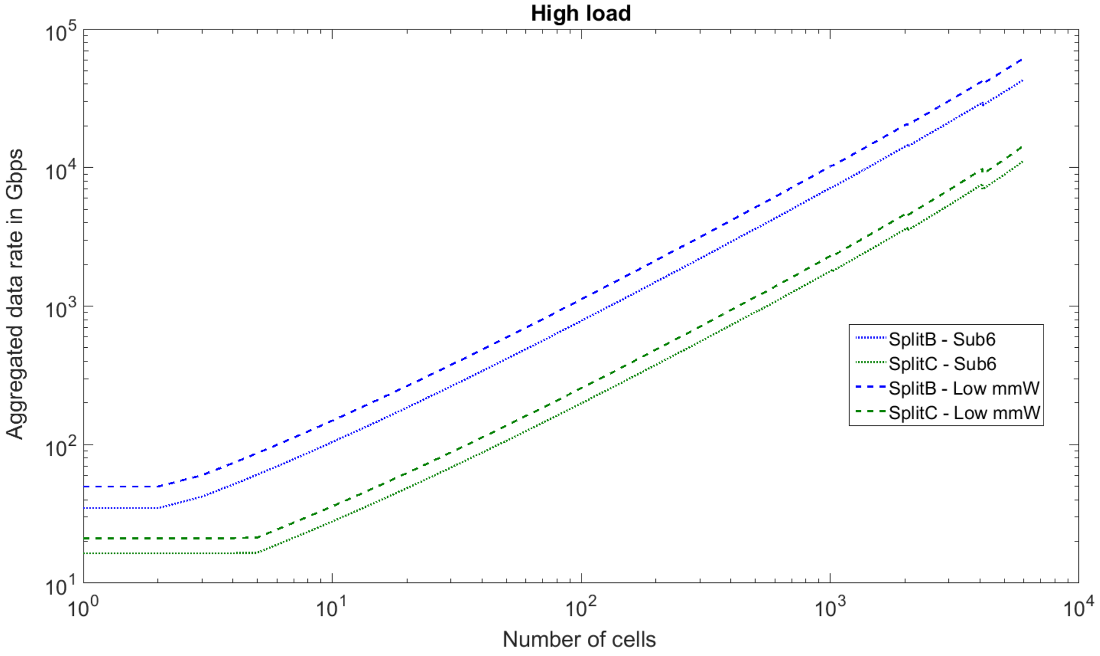
[4] Note that this projection assumes that all of Barcelona follows the lay-out of the *Eixample* quartier defined in Section 3, which as previously explained it is a worst-case assumption

Transport Network Capacity Provisioning:

Deliverable D2.3 [11], based on D2.1, considers the realistic case of varying load utilisation and statistical multiplexing among different cells and provides guidelines for the dimensioning of the transport network following suggestions from NGMN [14]. These projections are based on real network measurements obtained from an operational LTE network, which first requires deciding the busy hour of the day and then provisioning the network considering the Cumulative Density Function (CDF) of the traffic demands per cell for the busy hour and the resulting statistical multiplexing gains.



(a) Low Load Scenario.



(b) High Load Scenario.

Figure 10: Provisioned transport capacity for different RAN technologies and splits from D2.1.

In D2.3, aggregated traffic for a given number of cells for the busy hour is derived using traffic traces from an LTE network for a dense urban city area, with a projection of 5G traffic increase as detailed therein. Note that the provisioning is done to satisfy the 95% of the demand for that study, and considers statistical multiplexing gains. Figure 10 recalls the aggregated transport data rate for up to 6000 cells that will be required to map the results to the topology considered in this section. As described in D2.3, the projected per cell traffic generated for the Physical Resource Block (PRB) utilisations based on the 4G traces are represented as *Low Load Scenario*. Whereas, the traffic projections done using the scaled up utilisation levels for 5G are represented as *High Load Scenario*. Network dimensioning results in this section are given always for both the Low Load and the High Load scenarios. We expect realistic 5G utilisations to lay somewhere between the Low Load and High Load scenarios.

Given that the area covered by one LTE cell from the traces will in the future be covered by a Macro Cell and the SCs connected to it, we will assume that the traffic projected for one cell in D2.3 corresponds to the total traffic generated by Macro Cell and its SCs covering that cell area. Following the Small Cell Forum projections for offload ratios[5] between 56% and 75% for 4 to 10 small cells per macro cell, we assume the 70% of total traffic is generated by Small Cells and 30% by Macro Cell.

Out of the three RAN functional split types studied in D2.3, we evaluate the Split B (before resource mapping) and split C (above HARQ) in this section due to their dependence to the generated traffic and hence the possibility to exploit the statistical multiplexing gains. As per RAN type, we study the Sub-6 GHz (i.e. 2 GHz) for Macro Cells and both Sub-6 GHz and mmWave (30 GHz) options for SC access.

Finally, it should be noted that the traffic projections described in Figure 10 are based on downlink traffic only, and this is what will be used in the reminder of the section. The experimental LTE traces that were used to derive this study were highly asymmetric in DL and this is a trend expected to continue in the 5G eMBB 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.

5.1. Wireless Segment Capacity Provisioning

First, we focus on the traffic that would be carried at the wireless backhauling of the Small Cells. As shown in Figure 1, the wireless backhauling technology can be Sub-6 or mmWave. Note that based on NGMN guidelines [14], for capacity provisioning of n cells, the maximum of two metrics is taken: i) the highest single cell peak traffic at busy hour and, ii) the sum of average traffic of n cells at busy hour. Hence, as observed in Figure 10, this number is the same for 1 and 3 cell aggregation for low load scenario for any RAN technology and functional split type.

The per cell traffic values given in Figure 10 are projected using LTE cell traces, and hence, the per-cell traffic in Figure 10 is assumed to correspond to the total traffic generated by one Macro Cell (MC) and its associated SCs. Let's consider the area covered by a MC (and its associated SCs). Assuming the 70% traffic of this area is generated by the SCs, we can estimate the total SC traffic to be carried to the corresponding MC by simply multiplying the total traffic per cell by 70%.

Table 1 provides the resulting capacity requirement for the aggregation of SC traffic. Based on the aggregated traffic values of the wireless segment shown in Table 1, we can see the ~2x traffic increase in Split B in comparison to Split C, however the traffic increase using different RAN technology is less (<1.4x). Nevertheless, the High Load Scenario represents almost 4x higher traffic than the Low Load Scenario. We will, then, use the Low and High Load Scenarios to define an interval for the Urban Scenario traffic projections.

Table 1: Capacity Dimensioning (in Gbps) for SC-MC Wireless Links.

SC Split Type - SC RAN Technology	Split C – Sub-6	Split C - Low mmWave	Split B – Sub-6	Split B - Low mmWave
Low Load Scenario	2.9	3.8	6.2	8.9
High Load Scenario	11.5	14.8	24.4	34.9

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[5] http://www.smallcellforum.org/press-releases/report-finds-public-access-small-cells-quickly-carry-traffic-macros-urban-hotspots/

Recall that we expect realistic 5G utilisations to lay between the Low Load and High Load scenarios. As detailed in D2.2, current wireless backhaul/fronthaul technologies support up to 4.6 Gbps transfer rates, whereas studies such as IEEE 802.11ay currently being standardised and to extend the capability of 802.11ad are expected to offer data rates in excess of 20 Gbps. Hence, looking at Table 1 and at the current state and near-future projections of wireless technologies, we consider that only Split C seems feasible for the Small Cell layer if wireless backhauling is considered. This observation is in line with the RAN functional splits considered by other 5G initiatives [16].

5.2. WDM-PON Segment Capacity Provisioning

For the WDM-PON segment, connecting the Macro Cells to the 5GX-CO, we study the traffic to be carried by the WDM-PON through ONU-RN-OLT connections. First, we will provide the number ONUs required per cell site, then derive the aggregated traffic at the 5GX-COs, 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 fibre attachments and are composed of 3 sectors. All the SC traffic are fronthauled or backhauled to the MC sites.

Given the maximal capacity of an ONU and the transport capacity calculated in Figure 10 for different load scenarios, the required numbers of ONUs per cell unit and per cell sites (for three sectors) are summarised in Table 2 - Table 3. One cell unit corresponds to one MC and its associated SCs (for the purpose of these calculations we assume 1 MC cell has 2 SCs associated), whereas one cell site is 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 capacity envisioned for the ONU technologies in the near future, and a target of the WDM-PON technology research performed in 5G-XHaul.

In these evaluations, we only consider Split C for SC based on Section 5.1 findings, and we focus only on Sub-6 RAN for MC. This is because, as described in [17], the MC layer is envisioned to provide coverage and transport control plane traffic in 5G, for which, omnidirectional Sub-6 carriers are a better choice.

Table 2: Required Number of ONUs per Cell and Cell Site in Low Load Scenario.

Functional Split Type- RAN Technology	MC:SplitC - Sub-6 SC:SplitC - Sub-6	MC:SplitC - Sub-6 SC:SplitC - Low mmW	MC:SplitB - Sub-6, SC:SplitC - Sub-6	MC:SplitB - Sub-6 SC:SplitC - Low mmW
ONUs/cell (10 Gbps ONU capacity)	1	1	1	1
ONUs/site (10 Gbps ONU capacity)	1	1	1	1
ONUs/cell (25 Gbps ONU capacity)	1	1	1	1
ONUs/site (25 Gbps ONU capacity)	1	1	1	1

Table 3: Required Number of ONUs per Cell and Cell Site in High Load Scenario.

Functional Split Type- RAN Technology	MC:SplitC - Sub-6 SC:SplitC - Sub-6	MC:SplitC - Sub-6 SC:SplitC - Low mmW	MC:SplitB - Sub-6, SC:SplitC - Sub-6	MC:SplitB - Sub-6 SC:SplitC - Low mmW
ONUs/cell (10 Gbps ONU capacity)	2	2	3	3
ONUs/site (10 Gbps ONU capacity)	2	2	3	3
ONUs/cell (25 Gbps ONU capacity)	1	1	1	2
ONUs/site (25 Gbps ONU capacity)	1	1	1	2

Next, we derive the aggregated access traffic at 5GX-COs. We use the 70%-30% traffic split among SC and MC to evaluate separate types of functional splits for SC and MC. Figure 11 and Figure 12 show the calculated traffic per 5GX-CO for varying number of 5GX-COs for the evaluated Barcelona area for Low Load Scenario and High Load Scenario, respectively. As reasoned previously, the SC functional split is assumed to be Split C in these evaluations.

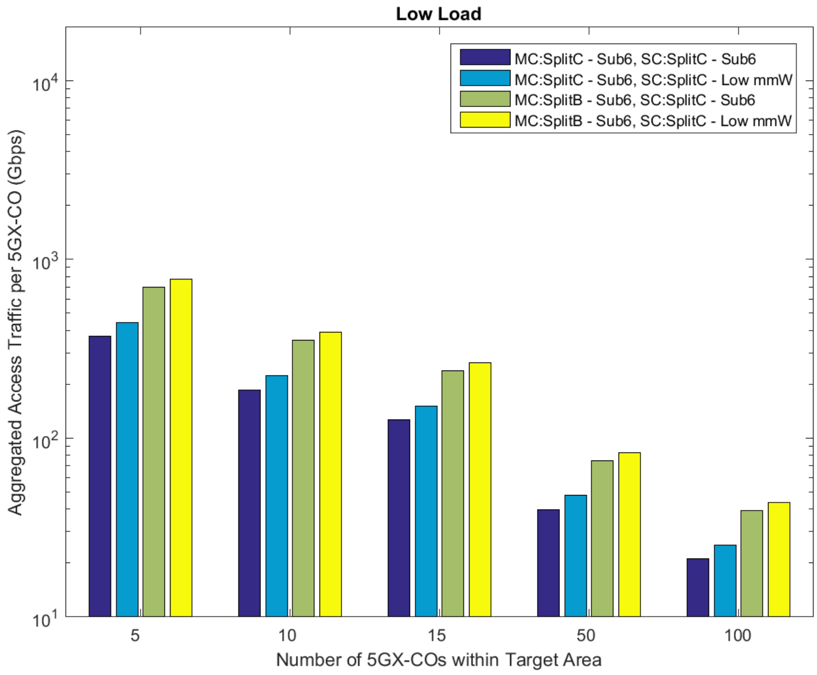

Figure 11: Aggregated access traffic per 5GX-CO for Low Load scenario.

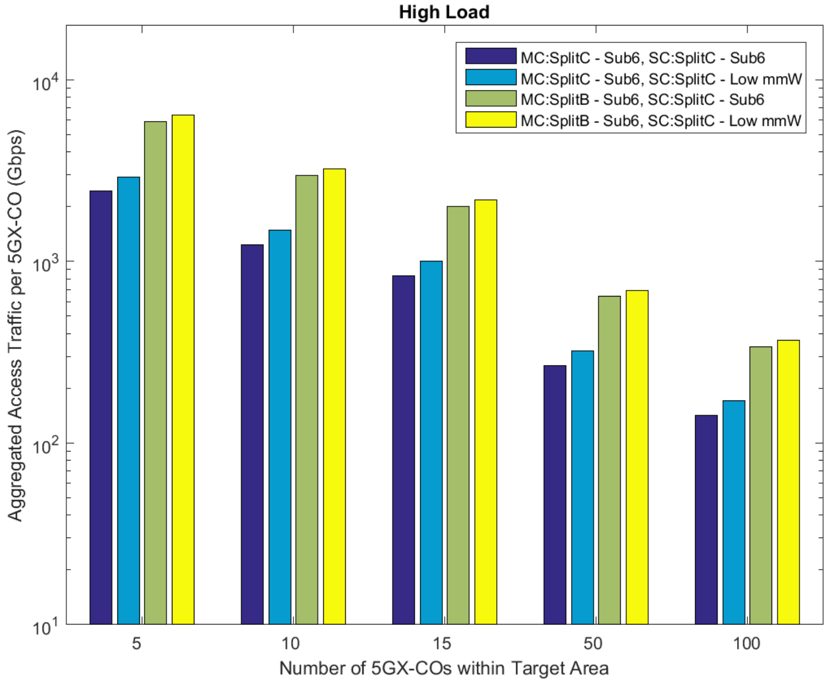

Figure 12: Aggregated access traffic per 5GX-CO for High Load scenario.

As seen in Figure 11 and Figure 12, 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. 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 here the required data rates scales almost linearly with the mean data rate. For example, reducing the 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, based on the results in Table 2 and Table 3, we can then determine the necessary number of OLTs with respect to the number of 5GX-COs, as shown in Figure 13 and Figure 14. Although the required amount of OLTs is in principle determined by the total number of macro cell sites, it can be seen that, with denser 5GX-COs within the target area, the more OLTs will be needed. This is because each OLT will have more unused channels if more than 15 5GX-COs are distributed in the area. It should be also noted that the WDM-PON system needs to be deployed to meet the high load demand, however, during the low load traffic period, the unused ONUs or OLTs can be in principle deactivated (i.e. sleep mode), in order to save the power consumption. Overall, from the WDM-PON perspective, it is preferable to use fewer 5GX-COs, such that the use of OLT equipment will be more efficient. This is, in fact, in line with the operators' 5G deployment strategies as detailed in Section 7.

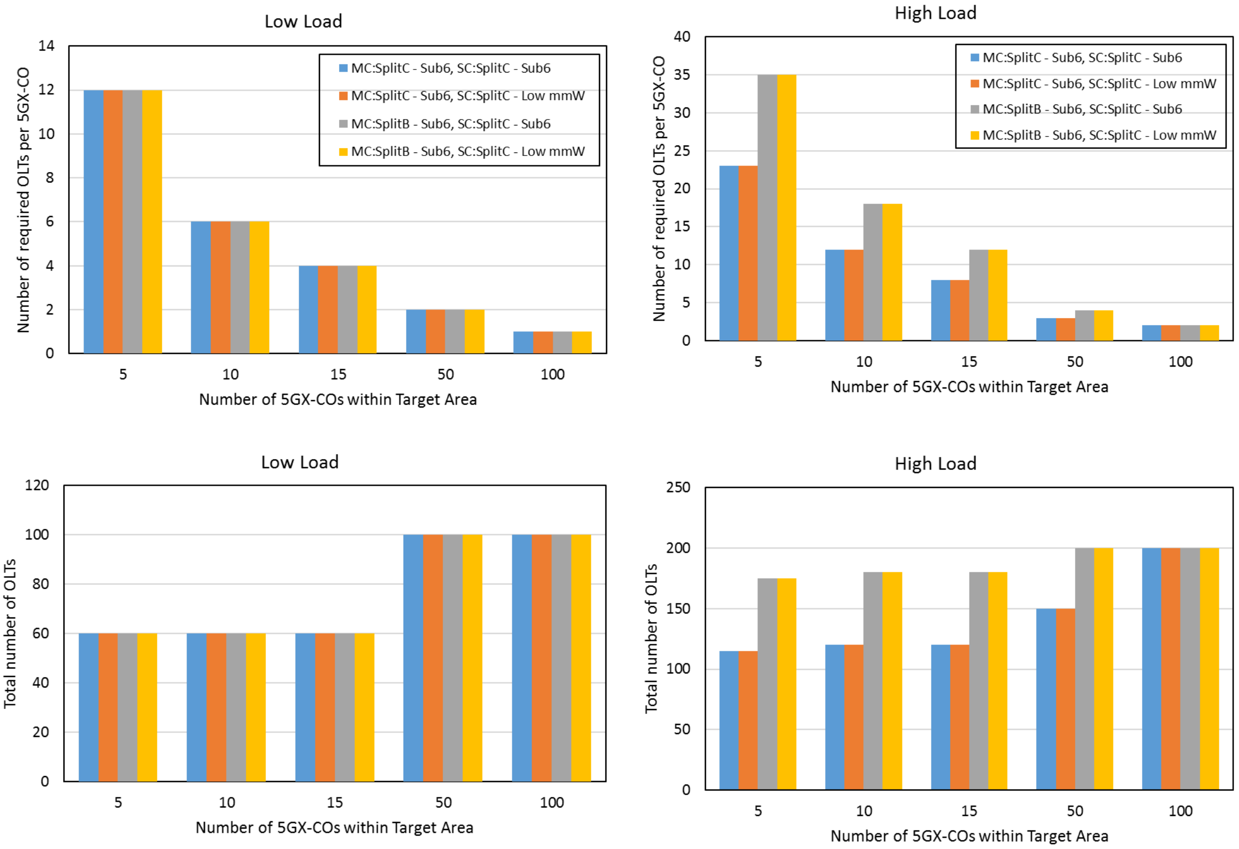

Figure 13. Number of OLTs per 5GX-CO and the total number of OLTs for the target area for maximal capacity of 10 Gbps per ONU.

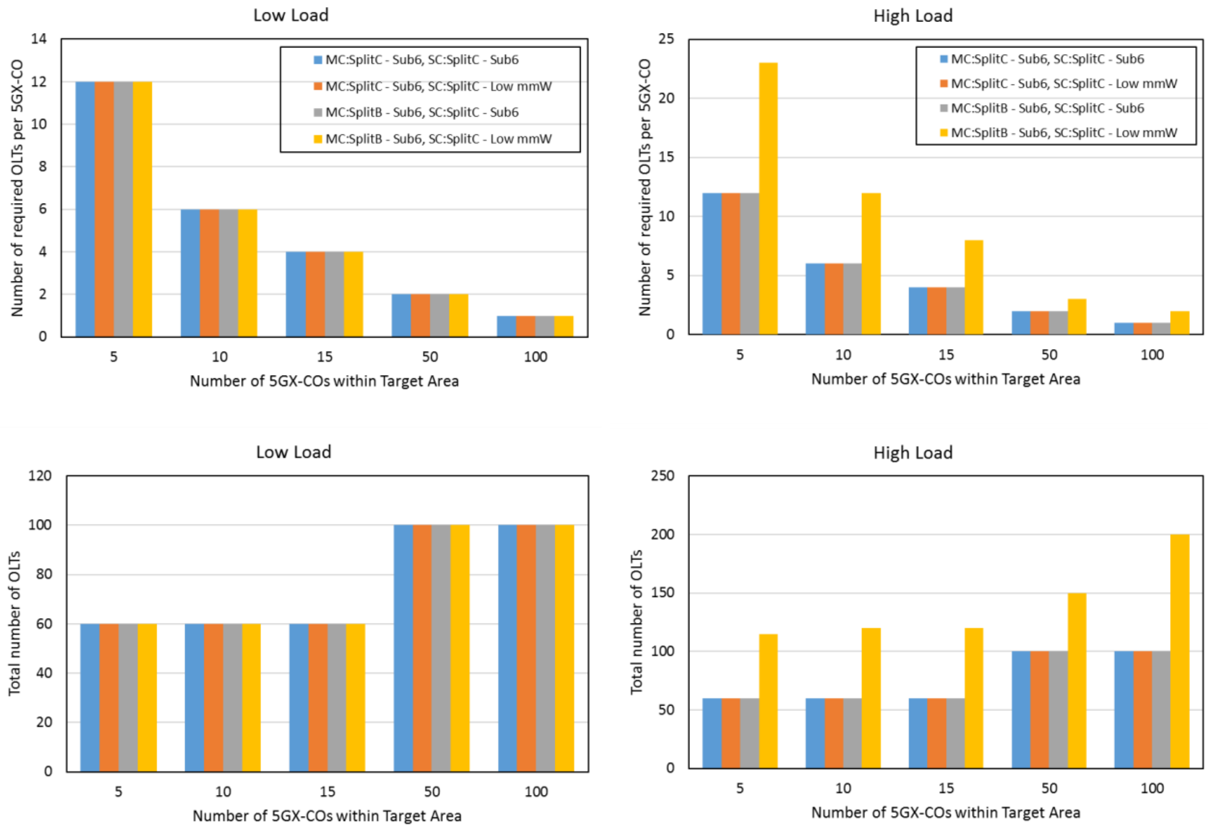

Figure 14. Number of OLTs per 5GX-CO and the total number of OLTs for the target area for maximal capacity of 25 Gbps per ONU.

5.3. 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 (IP/WDM) (c.f. Section 3 for more details), for example through an IP router. The interface between the TSON edge nodes and the node that connects to the operator's core transport network delimits the 5G-XHaul network. Among all the 5GX-COs, we let the subset of 5GX-COs that contains equipment connected to the operator's core network be called CoreNet-5GX-COs. Hence, the TSON network carries all the access traffic to/from these CoreNet-5GX-COs. We can thus repeat our experiments but computing the Ingress traffic at the CoreNet-5GX-COs, as a function of the number of CoreNet-5GX-COs, which we vary from 1 to 5.

In addition, we consider two different scenarios:

1) Local Processing: all 5GX-COs have BBUs. This means that Split B traffic is processed at the local 5GX-CO, and, therefore, TSON only transports Split C traffic towards the CoreNet-5GX-COs.

2) Remote Processing: Only the CoreNet-5GX-COs have BBUs, thus allowing for higher pooling gains. This means that the Split B traffic from the Macro Cells needs to be transported until the CoreNet-5GX-CO. Note that in this scenario only Macro Cells with Split B are considered, since Macro Cells with Split C would give the same results as the Local Processing scenario.

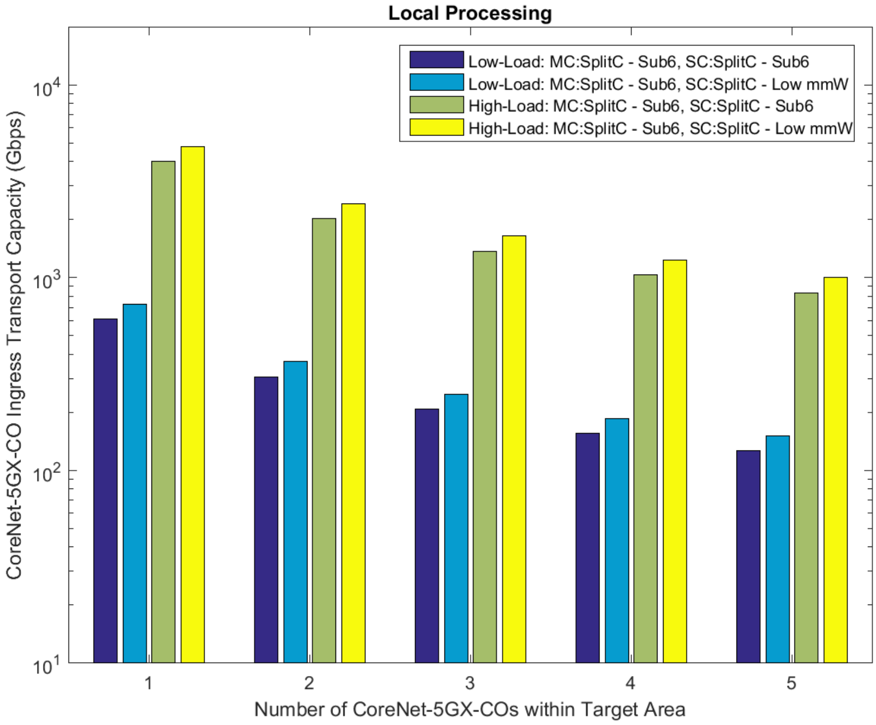

Figure 15: CoreNet-5GX-CO ingress traffic (assuming local BBU Processing is performed at each 5GX-CO).

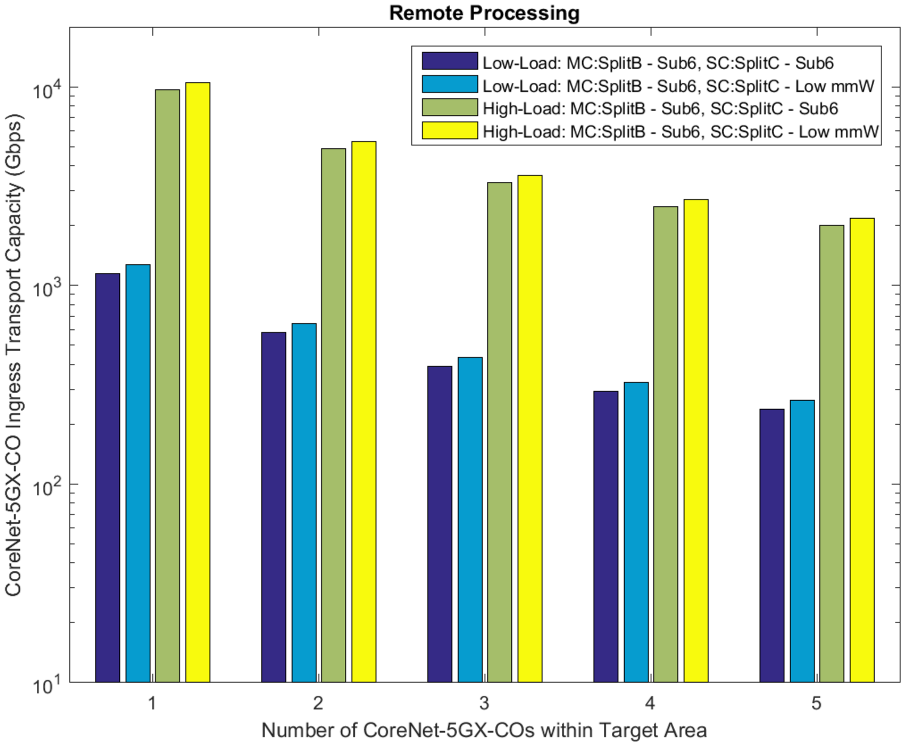

Figure 16: CoreNet-5GX-CO ingress traffic (assuming BBU processing at CoreNet-5GX-COs).

As expected, local processing capability, i.e., assuming BBU processing at each 5GX-CO, results in less aggregate traffic for the TSON segment.

The current TSON implementation described in deliverable D2.2 [1] can support traffic volumes of the order of tens of Gbps. These capacity levels cannot accommodate the requirements derived in the worst case scenario described in Figures 15 and 16. 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 gigabit/s 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 to100 Gbps in networking solutions integrating high-capacity technologies which is below the Tbps capacity levels predicted in the worst case scenario under evaluation.

To provide further insight on the transport bandwidth required in practice, we recall that the cell site deployment shown in Section 3 and evaluated in this section corresponds to a worst-case scenario in terms of cell site density, since a regular and dense deployment is assumed throughout the whole city of Barcelona. In practice, due to physical restrictions and reduced population density areas, the overall cell site density is expected to be less, which will reduce the bandwidth transported at higher aggregation levels (e.g. TSON). To take this aspect into consideration, we evaluate reduced cell site densities by reducing the density derived in Section 3 by a given factor. To understand how cell site density affects transport requirements, in Figure 17, such evaluation is presented for the High Load scenario and for the most demanding functional split and RAN technology combination for the sake of brevity. In this evaluation, BBU processing is assumed to be done at CoreNet-5GX-COs, which signifies that TSON segment also carries FH traffic, again a worst-case assumption.

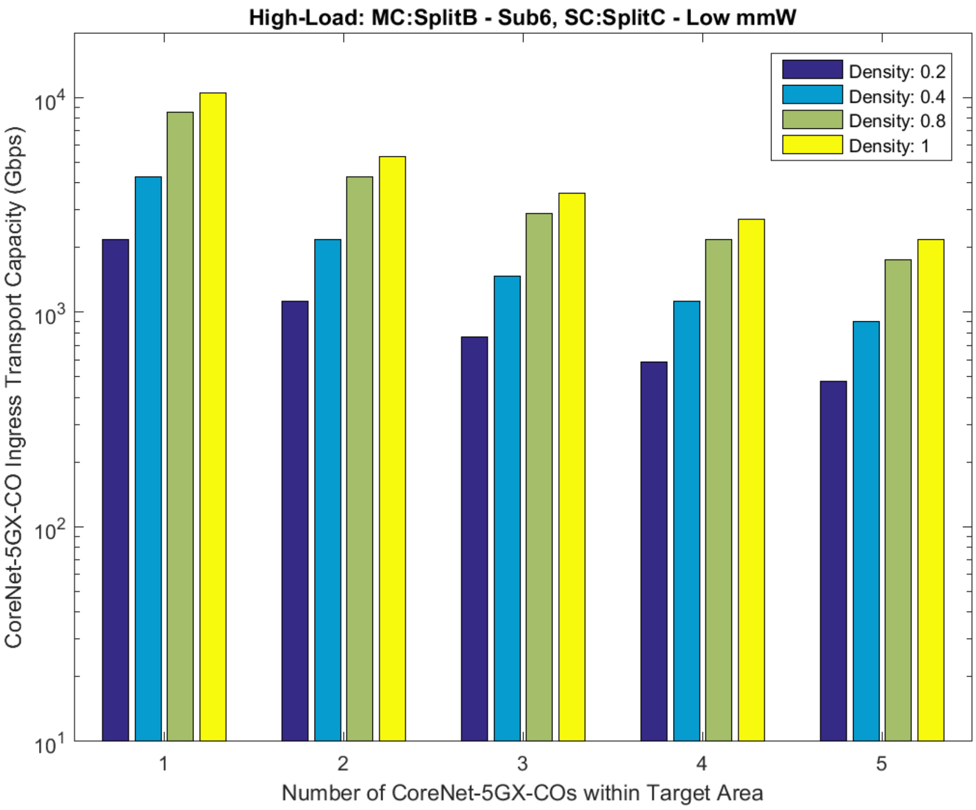

Figure 17: CoreNet-5GX-CO ingress traffic for varying cell densities (assuming BBU processing at CoreNet-5GX-COs and for high load scenario).

This section has illustrated the factors affecting the bandwidth requirements at different levels of the 5G-XHaul architecture. As expected, the required transport bandwidth depend on a variety of factors, such as the chosen RAN functional split, the actual 5G traffic demand, the density of cellular network, and the number of 5GX-

COs. These factors are very particular to each operator and intended service, and is therefore difficult to derive definitive conclusions. However, the derived figures demonstrate that the architecture, and the wireless and optical technologies developed in 5G-XHaul, are suitable to address a wide range of practical deployment scenarios.

6. Dimensioning the 5G-XHaul control plane

In this section we introduce a study to dimension the 5G-XHaul control plane for a city like Barcelona, which has been used as case study for this deliverable. In particular we are interested in deriving how many 5G-XHaul Tier-0 controllers need to be deployed in Barcelona, under the assumptions described in the previous sections.

Before describing the methodology used to dimension the control plane, we start by defining a Cell Site Area Unit (AU) as the geographical area covered by the Macro Cells (MCs) of a Macro Cell Site and their associated Small Cells (SCs). As detailed in Section 3, one MC Site covers an average of 8 access network elements, which are connected to the network through 8 5G-XHaul Transport Nodes (TNs). The interested reader is referred to deliverable D3.1 [5] for a full description of the entities that form the 5G-XHaul control plane.

There are two main system bottlenecks that should be used to dimension the control plane:

1. The capacity of the 5G-XHaul TNs in terms of the number of flows that can be kept concurrently in the fast memory of the switch, usually a CAM/TCAM. Maintaining flows in a fast memory is required to minimize switching delay in converged fronthaul/backhaul networks.
2. The capacity of the controller in terms of how many flows the controller can program per second. The 5G-XHaul Tier-0 controllers monitor the state of the network, and reconfigure the transport flows as needed in order to maintain per–tenant Service Level Agreements (SLAs).

6.1. Dimensioning the control plane based on switch capacity

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, namely a pessimistic one where network elements have 2K TCAM sizes, and an optimistic one with 10K TCAM sizes. Notice that the bottleneck in dimensioning the control plane will be the wireless network elements attached to the SCs and Macro-Cell of each AU, for which 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 a Tier-0 controller needs to guarantee reachability between all the ETNs and IATNs in a given control area. Thus, if there are N ETN+IATN in a control area, up to N*(N-1) unidirectional flows may have to be held in each network element. In addition, in deliverable D2.1 [19], 5G-XHaul defined a set of four basic Transport Classes (TCs) to hold different 5G transport services including FH and BH. Hence, up to 4*N*(N-1) flows per network element may be required in each TN inside a Tier-0 control area.

The key question hence, is how many ETNs/IATNs are going to be present in each control plane area. Recall that as described in Section 4, an ETN is a device with virtualisation support that can host Virtual Network Functions (VNFs) from different tenants, and could be embedded in a SC or in a server collocated with the macro-cell. Since it is difficult to come up with a specific number of ETNs/IATNs per control area, in this section 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 a Tier-0 control area is composed by an integer number of AUs and from here derive the total number of ETNs/IATNs in the control area, and the total number of flows to be held in each network element (TN). The number of flows to be maintained in each network element as a function of the Tier-0 control area size is depicted in Figure 18.

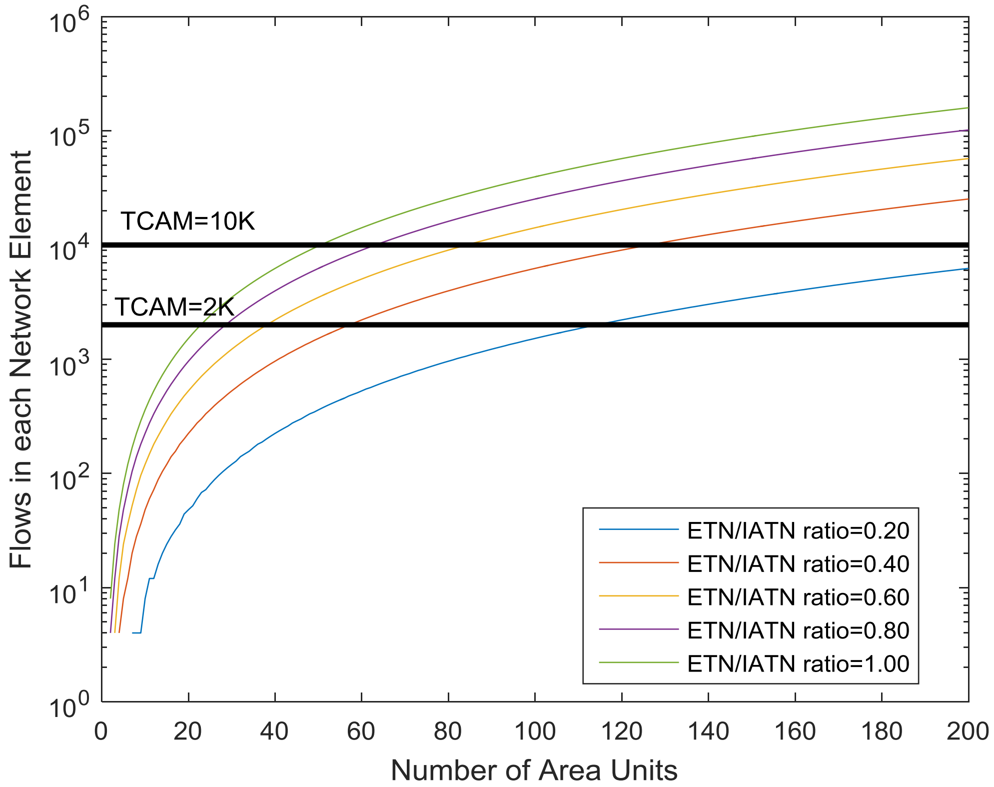

Figure 18: Flows to be maintained in each network element as a function of the control area size.

Figure 18 also marks two lines depicting TCAM sizes of 2K and 10K flow entries. Consequently, based on the TCAM size and on the ETN/IATN ratio one can derive the maximum number of AUs that can form a Tier-0 control plane area. In addition, as discussed in the previous sections, the city of Barcelona spans 101.4 Km2 and following the assumptions described in Section 3 would contain approximately 23 macro-cells per Km2, which results in approximately 2300 AUs in the whole city of Barcelona (in the worst-case).

Table 4 depicts the number of 5G-XHaul Tier-0 controllers that should be deployed in Barcelona, according to the different parameters described above.

Notice that although the number of Tier-0 controllers is high, controllers are themselves VNFs that can be deployed inside a virtual machine, making the deployment and operation of a high number of instances manageable using standard cloud platforms.

Table 4: Number of 5G-XHaul Tier-0 Controllers in Barcelona based on Switch Capacity.

ETN/IATN ratio	TCAM size	Num AUs	Tier-0 ctrlrs in BCN
0.4	2K	~ 60	~ 39
0.4	10K	~ 125	~ 19
0.8	2K	~ 30	~ 77
0.8	10K	~ 65	~ 36

6.2. Dimensioning the control plane based on controller capacity

Another factor that can limit the size of a Tier-0 control area is the capacity of the controller to process the events generated in that area, and to program the corresponding flow updates. In [20] a performance benchmark has been published about the OpenDayLight (ODL) controller, which we consider representative of other SDN controllers. The study analyses the performance of ODL with different southbound plugins, including OpenFlow. For the purpose of this study we take as reference the OpenFlow performance since as described in Section 5 of deliverable D3.1 [5] this is the SDN interface adopted by most of the network technologies considered in 5G-XHaul. The mentioned benchmark reflects an end to end flow programming capacity of ODL of 2000 flows/second. We consider this to be an upper bound, since in the mentioned benchmark dummy flows are programmed simply to test the maximum capacity of the associated APIs and protocols. In 5G-XHaul though, each flow update needs to be preceded by an algorithmic analysis of the network state and the computation of alternative paths. Therefore, in this study we consider two reference controller capacities in terms of the number of flows that can be programmed per second, of 1000 flows/second for a high end controller, and 200 flows/second for a low-end controller.

Our goal is to derive the number of flows that the controller needs to program per second, as a function of the Tier-0 control plane are size. Since the 5G-XHaul controller monitors the network and re-programs transport flows as a result of a varying network state, it is reasonable to assume that the number of programmed flows per second should be proportional to the number of events that the controller is processing per second. In particular we define a parameter *event2flow* ratio that defines how many new network events are required to trigger the controller to program a new flow, or re-program and existing one. In this study we set *event2flow* to *1/10* and *1/50*.

Hence, we need to derive the number of events per second processed by a Tier-0 controller as a function of the Tier-0 control area size. Assuming an OpenFlow interface, there are two main types of events, namely *port* events, which describe information related to a physical port, for example the available data-rate of a mmWave interface, and *flow* events, which describe information related to a flow, for example the amount of bytes transmitted by a flow in the last period. The number of flow events is proportional to the number of flows maintained in each network element, which has been derived in the previous section. The number of port events per second, is proportional to the number of ports present in each AU. Following the assumptions laid out in Section 3, we assume that in each AU half of the Transport Nodes (TNs) are pure mmWave TNs that contain *four* ports each, and the other half are mmWave plus Sub-6 TNs that expose *eight* ports to the SDN agent. The last assumption required to compute the number of flows per second to be programmed by a Tier-0 controller is an event (port & flow) generation rate, which is a parameter of the SDN interface. Notice that the higher the event generation rate the faster will be the reaction of the controller to the network state, and the higher the introduced overhead. In this study we consider three SDN event generation rates of 0.1, 1 and 10 events/sec.

Figure 19 describes the number of flows per second that need to be processed by a 5G-XHaul Tier-0 controller as a function of the Tier-0 control area size, defined as an integer number of AUs. In the same figure the two reference controller capacities of 1000 and 200 flows/second are also highlighted. Based on Figure 19, Table 5 computes the required number of 5G-XHaul Tier-0 controllers in Barcelona, assuming like in the previous section a total of 2300 AUs. As in the previous section it is worth highlighting that the required Tier-0 controllers can be deployed as VNFs in virtual machines.

In this section we have described two methods to dimension the 5G-XHaul control plane, and have applied them to the case study of Barcelona. In practice though, the most restrictive method will apply, i.e. the one requiring the higher number of Tier-0 controllers.

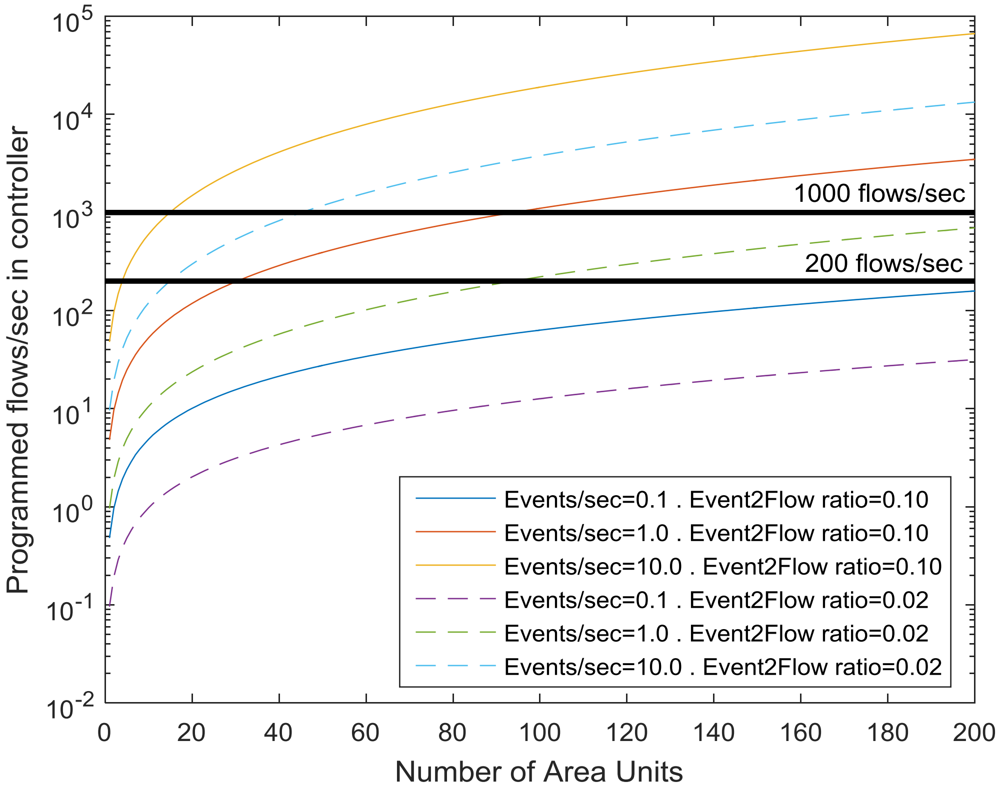

Figure 19: Flows/sec to be programmed by a 5G-XHaul Tier-0 controller.

Table 5. Number of 5G-XHaul Tier-0 Controllers in Barcelona based on Controller Capacity.

Ctrlr capacity (flows/sec)	Network events/sec (ev-sec/ev2flow ratio)	Num AUs	Tier-0 ctrlrs in BCN
200	1/0.1	~ 30	~ 77
200	1/0.02	~ 100	~ 23
1000	1/0.1	~ 100	~ 23
1000	1/0.02	~ 220	~ 11

7. Migration from legacy to 5G-XHaul architecture

5G-XHaul aims to be an enabler for the deployment of the next generation mobile systems that will provide ubiquitous access to novel applications/services to heterogeneous devices, ranging from smartphones and tablets to sensor-type devices. It is envisaged that these novel applications and services will address diverse vertical markets including health, assisted living, smart cities, ITS, factories of the future, etc. and as such will have a significant societal and economic impact. Hence, the 5G-XHaul transport network has a key role in guaranteeing the desired QoS/QoE of the offered applications/services. The most important generic requirements for the transport network include the following: (a) adequate and upgradable capacity according to site requirements, (b) adaptability to future capacity and service needs, (c) re-use of existing infrastructure (own or group e.g. fibres) to minimize OPEX/CAPEX, (d) low time to market, etc. In this section, we analyze how the 5G-XHaul architecture can be built on the existing infrastructure to fulfil these requirements, studying the transport network solutions from the two mobile operators that participate in 5G-XHaul.

7.1. Telefónica transport architecture's potential migration to 5G-XHaul

Telefónica's strategic viewpoint for the evolution of the transport network in the following 3-5 years is based in three main objectives from an architectural viewpoint:

1. Progressing towards a network architecture where control and data plane elements would be separated, following the approach of the SDN architectural framework.
2. Reducing the hierarchical levels of the network, as well as the network elements deployed and the protocols that should be supported, taking advantage of long range transport technologies.
3. Achieving a true fixed and mobile transport network convergence, maximizing the reuse of both data plane and control plane elements, in order to optimize both CAPEX and OPEX. It also contemplates the support of hybrid access in order to improve the Quality of Experience (QoE) of broadband services for the customers and/or increase reliability. At the end of the process, it is expected to reach also a functional convergence, which may allow for the unification of common functions in order to provide more efficient operation and management (e.g. combining a P-GW and a B-RAS in the same network element).

These objectives, mainly driven by simplification and economic efficiency, should be compatible with some technological and operational trends for the future, like

- Moving towards higher capillarity radio access networks (RANs), with high capacity per radio point (especially when high frequency bands are being used).
- Support of multiconnectivity with legacy RAT and Wi-Fi networks.
- Support of network slicing, and associated requirements, like network slice isolation, very low latency or increased reliability.
- Support of an increase in the total traffic volume to be transported of the order of x3-x10 by 2020, associated not only to the increase of end-user traffic but to other factors, like increased IoT traffic or support for functional splits. Current mobile traffic volume is around 20 PB per month (compared to 390 PB per month for fixed access, which includes mobile traffic offloaded to Wi-Fi) for Telefónica Spain, 23 PB for Telefónica UK and 26 PB for Telefónica Germany[6].

In order to achieve these objectives, it is necessary to accelerate the end of life of some legacy technologies (closure of the copper based PSTN, switching off the 2G and potentially 3G mobile networks). This may allow for a reduction of the points of presence of the network, which in the case of Spain may result in the elimination of close to 75% of the existing COs. The resulting transport network will be composed by four hierarchical levels (identified as HLx), defined as:

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[6] However, mobile traffic per user is higher in Spain (around 1.8 GB per month) than in UK (1.7 GB) and in Germany (less than 1 GB).

- HL1: Interconnection level. Provides interconnection with other packet data networks.
- HL2: Backbone level. Provides regional connectivity and reliability for the interconnection of service level (HL3) nodes.
- HL3: Service level. Provides access to service level capabilities, like security platforms, CDN caching, video platforms, etc.
- HL4: Capillarity level. Provides the connectivity to reach the end user.

The current transport architecture incorporates up to eight different levels, in some cases with loops between nodes of different hierarchical levels. In terms of points of presence, for the case of Spain, the number of nodes/points of presence foreseen by 2019 for each hierarchical level are the following:

- HL1: 6.
- HL2: 10.
- HL3: 70.
- HL4: 2000 (current figure is around 8000 local COs).

The 5G-XHaul proposed architecture provides a viable alternative in order to achieve the indicated objectives in the context of the evolution towards 5G. Among the main advantages identified are:

- Separation of the control plane and the data plane.
- Integrated support of BH and FH over the same transport solution.
- Definition of transport classes that allow for an efficient support of different functional splits and technological solutions like massive MIMO, based on the capabilities (capacity, latency) of the transport infrastructure.
- Support of multitenancy (as Telefonica is not an integrated fixed and mobile operator in all the countries it operates).
- Support for both wired and wireless transport alternatives, both at mmWave frequency bands and Sub-6 GHz frequency bands.
- Support for the reuse of future FTTH technologies, like WDM-PON, the transport network.
- Ethernet based access/capillarity network.

According to the Telefonica's proposed transport architecture, mobile packet core control functionalities should be connected to HL2 level, while edge cloud functionalities and data plane functionalities should be located at nodes of the HL3 level – this would correspond to the 5GX-COs defined in the 5G-XHaul architecture. The migration process from the current architecture will start with the elimination of access nodes and their consolidation at HL4 nodes. It should be noted that this would result into the extension of the average length of the access infrastructure (understood as the connection from the user equipment to the first HL4 node) from an average of 400 m to more than 2 km. It may also result as well in the potential elimination of aggregation levels in the transport network.

There are some particularities of Telefonica's strategy that may impact on the evolution towards 5G, like the decision of moving service control platforms to HL2 level, which may not be compatible with use cases that require extremely low E2E latency. However, there is no blocking factor that may preclude to implement some control functionalities also at HL3 level.

7.2. COSMOTE transport architecture's potential migration to 5G-XHaul

In this section, a BH network evolution paradigm is presented with view to the 5G-XHaul innovations by referring to network migration aspects of a COSMOTE-like mobile network operator. The reference mobile operator operates a 2G/3G/4G/4G+/5G mobile nationwide network over a highly mountainous and island terrain offering ~100% population coverage (11 million population), having ~50% market share. Moreover, the mobile operator belongs to the same group as the national incumbent telecom operator (in the case of COSMOTE being OTE), offering fixed telecommunication services nationwide (operating a copper/fibre network).

For this operator paradigm (COSMOTE) the existing BH network blueprint is presented and network evolution (5G-XHaul-related) aspects are discussed: (a) the substitution of obsolete technologies with newer ones dealt with in 5G-XHaul, (b) the possible topology modifications of existing backhaul network that are facilitated by 5G-XHaul, (c) the evolution of nodes' functionality towards the adoption of Cloud-RAN solutions with reference to 5G-XHaul's functional splits and (d) the consolidation/ convergence of fixed and mobile networks.

Legacy Network Architecture

A generic layout of COSMOTE's legacy mobile BH transport network is depicted in Figure 20, while a more detailed view is presented in Figure 21. As observed, COSMOTE's legacy network comprises one Core Layer and three BH/transport Aggregation layers:

- The 1st aggregation Layer includes 40 Aggregation Locations connected to DWDM rings and 10Gb Ethernet Rings using the MPLS-TP aggregation protocol. A small number of cell-sites are connected directly to these aggregation nodes either via microwave or via fibre/copper.
- A 2nd Aggregation Layer involves the aggregation of the majority of cell sites via microwave links, while a substantial number of fibre/copper connections (based on 10G Ethernet) exists.
- The rest of the cell sites are aggregated at a 3rd layer mainly using microwave links and in some cases fibre/copper.

In all aggregation layers MPLS-TP is selected as a routing protocol.

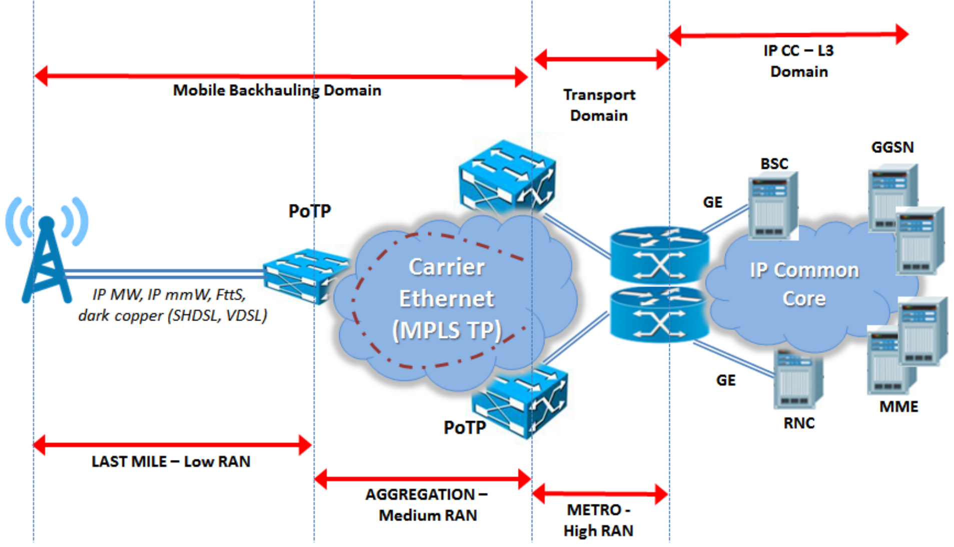

Figure 20: Backhaul/Transport Network Generic Layout.

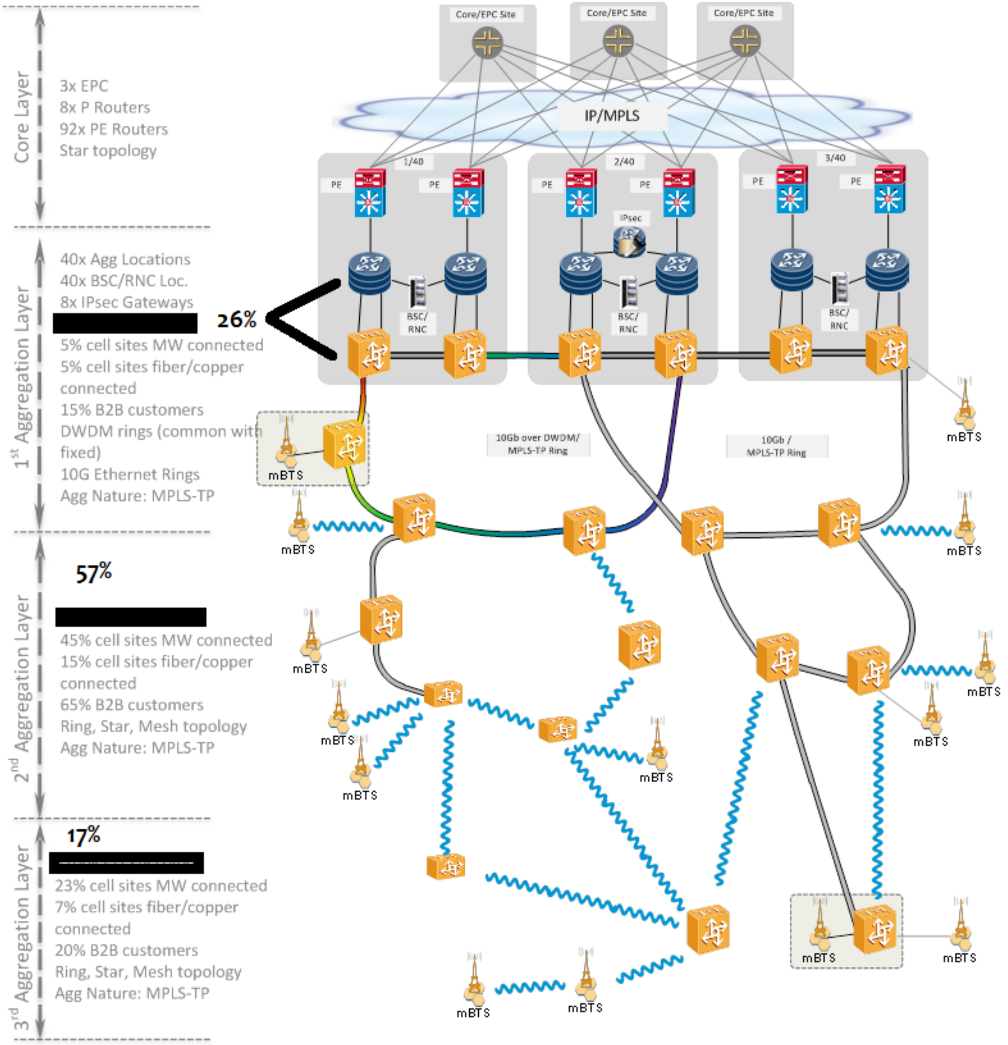

Figure 21: Backhaul/Transport Network Layout – Blueprint.

<u>Generic Backhaul/Transport Network Evolution</u>

The factors affecting the BH/transport network design/evolution include the following:

- Access network evolution, which includes the following:
    - Traffic increase per existing BS coming from:
        - New (bandwidth hungry) services.
        - Increase in usage of existing services.
        - Increase in number of subscribers (seasonality, new subs, etc.).
        - Deactivation of a nearby BS.
        - The introduction of new access technologies (4G+ and MIMO 4x4, hybrid access[7], etc.).
        - New spectrum.
    - Traffic profile of each BS (traffic during the day, BH traffic).
        - Activation of new BSs (macro, micro, small cells) and deactivation of old or “problematic” ones (mainly due to licensing issues).

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[7] Provides dual backhauling for pool fixed connections in order to increase their BW to acceptable levels and provide an adequate broadband experience (https://www.cosmote.gr/fixed/en/cosmote-home-double-play/internet-at-home/cosmote-home-speed-booster?lastLayoutId=8)

    - Access network technologies per site (2G/3G/4G).
    - Introduction of traffic off-loading techniques/mechanisms (WiFi APs, femtos).
    - Fibre availability for each BS site.
- New core network architectures including:
    - Network Functions Virtualization.
    - Software-Defined Networking.
    - Cloud core.
    - Control and user plane separation.
    - Information-Centric Network.
- Other / new trends including:
    - Protection strategy: implementation of a dual path topology per each and any aggregation and/or pre-aggregation node (acc. to traffic criteria).
    - Tight synchronisation requirements (due to introduction of LTE Advanced): Packet synchronisation is an essential (key) factor on developing a full packet mobile transport network. Going to LTE-A specific features, frequency and time (phase) requirements are getting extremely tight, requesting a specific consistent strategy.
    - QoS e2e management for advanced service provisioning.
    - Small cells new architecture.
    - Coordinated and cloud RAN.
    - OPEX minimization, Cost efficiency & TCO.

The main factors that will determine the reference (COSMOTE-like) operator's access network evolution – having impact on its BH/transport network evolution- are the following:

- The company's roll-out plans regarding the activation of new sites to serve the predicted traffic demand increase – especially in big cities, touristic places, etc.
- The company's roll-out plans regarding the upgrade of existing BSs/repeaters from legacy technologies (2G/3G) to HSPA+/LTE/LTE-A.
- The usage of the company's spectrum allocations for LTE (currently at 800, 1800 and 2600 MHz); e.g. the increase of spectrum usage from 10 to 20MHz to provide services up to DL/UL 150/50 Mbps.
- The adoption of carrier aggregation techniques (using the 800, 1800 and 2600 MHz allocations) in order to provide maximum throughputs >350 Mbps.
- The adoption of high order MIMO schemes (4x4), which in combination with carrier aggregation (1800/2600 MHz) can reach nominal speeds up to 600 Mbps.
- The introduction of the Small Cells concept; gradually, depending on traffic demand with Small Cells supporting 3G/4G technologies. New micro/small cells will be deployed for a) the 3G/4G capacity relief, b) the non-covered spots especially in touristic areas (i.e. hotels, resorts, beaches, etc.) and c) areas with permanent site acquisition problems (i.e. VIP residential areas, historical cities, etc.).

To this end, the reference mobile operator's transport/backhaul network evolution comprises the following:

A. Substitution of obsolete technologies with newer ones (in order to support higher traffic, better QoS/QoE for existing and future telecom services, etc.).
B. Topology modifications of existing transport/transmission network (shorter network and shorter hops, fronthaul & CPRI transmission, etc.), including simplification of network architecture by reducing the hierarchical/aggregation layers.
C. Evolution of nodes' functionality towards the adoption of Cloud-RAN solutions.
D. Consolidation/Convergence of fixed and mobile networks (common network topology/architecture, harmonised network configuration and policies) to achieve CAPEX-OPEX minimisation.

A. Substitution of obsolete technologies with newer ones

Considering the Low RAN deployment, the following existing technologies will remain as options for a COSMOTE-like BH/transport network.

1. Microwave (1+0): It will be used for the minority of terminal BS since it supports throughputs up to 500 Mbps.
2. Microwave (2+0): This is the enhanced IP MW technology that can support up to 1 Gbps.
3. Microwave (1+1): To be used in special cases like islands with difficult site access etc.
4. FttS: It will be used at sites where dark fibre is available or small extensions to the fixed NGA layer are required.

5. Copper Bonding (SHDSL, VDSL): Could be utilised to support LTE eNBs layer in cases for up to 600-800 m distances.

At the same time, in line with 5G-XHaul propositions, modern BH/transport network technologies will be also widely used for deployment such as:

1. mmWave / E-Band: To be used for urban macro for achieving more than 1 Gbps backhauling capacity.
2. mmWave / V-Band: To be used for small cells and micro Base Stations in dense urban areas for achieving rates in the order of 500 Mbps.
3. Point-to-Multipoint (P2MP) Street Node (@ 26 and 28 GHz). To be used also for SCs and micro BTSs in dense urban areas for achieving rates 30 Mbps.
4. Sub-6 Non-Line-of-Sight (NLoS): To provide basic connectivity on micro layer for cases where non cable or MW/mmWave solutions could be made available.

Considering COSMOTE, the operator has already conducted a number of trials to assess the performance of emerging backhaul technologies such as:

- Sub-6 NLoS.
- mmWave / E-Band – achieving data rates of 4 Gbps at 7,5 km (with Super-Dual-Band (SDB)) and at 5 km (without SDB), with 10 Gbps E-Band.
- mmWave / V-Band – achieving data rates of 500 Mbps at 300 m.

The aim is to maximize the number of sites capable of supporting 1 Gbps. This can be achieved either by using dark fibre or mmWave which are “equivalent” technologies in terms of throughput.

Considering a COSMOTE-like mobile operator’s strategic goals, we can assume that:

- Emphasis will be given on the utilisation of new Low RAN technologies for connecting new sites in the coming years, while, in short term, existing sites’ backhauling will remain as is.
- In the long term, the obsolete transmission technologies will be gradually substituted by newer ones – following the new sites’ transmission deployments.

So, during the forthcoming decade, as far as COSMOTE Low RAN network evolution for connecting **new sites** is concerned the following are envisioned:

- Low RAN will be based predominantly on Sub-6 and V-Band technologies within the forthcoming decade, as their use is expected to rise gradually from less than 5% currently up to 65% by year 2025, which is in line with the developments carried out in 5G-XHaul.
- Last Mile mmWave technologies will be used in 10% of the new sites – steadily over the 10-year Low RAN network deployment.
- About 30% of new sites’ backhauling will be based on Fibre Optic Network technologies -such as the WDM-PON as proposed by the 5G-XHaul-, for the next 10-year Low RAN network deployment (the percentage seems to fall to 27% by year 2025 which is only due to the increase of Sub-6 and V-Band usage.
- The use of Last Mile microwave (1+0) will gradually phase-out within the forthcoming 5-years.
- The use of Last Mile microwave (2+0) and xDSL Modem Pairs will gradually phase-out within the forthcoming 10-years.

The aforementioned figures can be explained by Greece’s highly mountainous and island terrain which introduces restrictions to a Greece-wide Fibre Optic Network deployment.

As far as the “small cells” trend is conserned, it is assumed that a 3 to10 small cells per macro cell will be gradually deployed. For the small cells backhauling, DSL, fibre, p2p and wireless (V-band, Sub-6, p2mp, etc.) technologies will be considered. More specifically, throughout the years 2017-2025:

- V-Band and Sub-6 technologies will be deployed for backhauling about 50% of SCs.
- DSL sub-loop bonding of Fibre Optics will be deployed for backhauling about 30% of SCs, and
- p2mp wireless will be deployed for backhauling about 20% of SCs.

According to mobile network topologies development strategy, pre-aggregation and aggregation nodes deliver the traffic towards a higher level node following two different paths, via MPLS-TP techniques and/or an SDN-based control plane. Paths are implemented via fibre - MRS (Medium Range Span), WRS (Wide Range Span), Fibre tails - and via NG MW with physical link aggregation techniques (PLA). Aggregation at all Layers is based on MPLS-TP. T-SON could initially be adopted at the 1st aggregation Layer, and depending on the size of the rings (in terms of capacity/number of nodes aggregated) at the 2nd aggregation Layer.

B. Topology modifications

Simplification of network architecture can be achieved by utilizing 1 Hop Towards Fibre (1H2F), targeting 1 Gbps for sites connected to a fibre site/node. Note also that although further simplification can be achieved by reducing the number of aggregation layers, in COSMOTE-like cases this is not applicable since only 3 aggregation layers exist; it is impossible to further reduce this number mainly due to Greece's mountainous and island terrain.

C. Evolution towards Cloud-RAN solutions

Considering the evolution of COSMOTE-like networks' aggregation nodes' functionality towards the adoption of Cloud-RAN solutions, it is possible that C-RAN could utilize the nodes of the Aggregation Layers (1st and 2nd mainly, and possibly 3rd) to accommodate vBBUs so as to ensure the less possible complexity and the maximum possible OPEX/CAPEX savings without compromising the network performance. Of course the selection of nodes and the roll-out plan will take into account the LTE/LTE-A and 5G (in future) access network roll-out, so that the aggregation nodes that support LTE/LTE-A/5G BSs will be the first ones upgraded to accommodate vBBUs/VMs.

Considering the functional splits proposed by 5G-XHaul since functional splits B and C achieve high multiplexing gains they will be preferred for aggregation nodes serving large BSs' clusters (high number of SCs, hotspots, etc.). For BSs located in sites with no space or with inappropriate hosting conditions for BBU equipment, split A could be considered.

Of course the final roll-out of C-RAN will be determined by the availability of equipment offered by the operators' selected/cooperating vendors.

D. Fixed-Mobile Networks Convergence

COSMOTE belongs to the OTE Group[8], being also a member of the Deutsche Telekom Group. Since 2013, the two companies (COSMOTE and OTE) have been merged at operational, network and commercial/marketing levels. In the context of network convergence, COSMOTE's 1st aggregation layer DWDM rings are being utilised in common with OTE for the provision of mobile and fixed telecommunication services, thus achieving CAPEX-OPEX reductions at OTE Group level. For COSMOTE and COSMOTE-like operators, 5G-XHaul innovations will be applicable to all aggregation layers thus achieving higher grade (fixed and mobile) convergence towards network edges.

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[8] OTE, the Hellenic Telecommunications Organization, is the largest telecommunications provider in the Greek market, and, together with its subsidiaries, forms one of the leading telecom groups in South-eastern Europe. OTE Group offers the full range of telecommunications services: from fixed-line and mobile telephony, broadband services, to pay television and ICT solutions.

8. Summary and Conclusions

In this deliverable we have provided an in-depth analysis of the physical deployment aspects of the 5G-XHaul architecture introduced in D2.2, taking as a reference the city of Barcelona. Specifically, we discuss how to deploy the Small Cell (SC) and Macro Cell (MC) layers to deliver the expected 5G capacity, how to backhaul/fronthaul SCs and MCs using respectively the wireless and optical technologies developed in 5G-XHaul, and how to deploy the control plane functions defined in the 5G-XHaul control plane introduced in D3.1.

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.

Finally, we have described how Telefonica and COSMOTE could incorporate the principles laid out in the 5G-XHaul architecture in their transport network evolution strategies. In particular, we have shown that 5G-XHaul is well aligned with the strategies of these operators by: i) connecting the dense SC layer using wireless technologies (V-Band and Sub6), ii) enabling a reduction of the number of Central Offices through the use of long reach optical technologies like WDM-PON and TSON, and ii) enabling the convergence of fixed and mobile traffic again through the 5G-XHaul optical technologies.

Summarizing, this deliverable has illustrated a practical realisation of the 5G-XHaul architecture introduced in D2.2 in a representative European city, and has validated that the 5G-XHaul architecture is aligned with the network evolution strategies of major mobile operators. We believe that this deliverable can become a useful guide for operators interested in taking up some of the technologies developed in 5G-XHaul.

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10. Acronyms

Acronym	Description
3GPP	Third Generation Partnership Project
5G	Fifth Generation Networks
5GPoA	5G Point of Access
5G-PPP	5G Infrastructure Public Private Partnership
5GX-CO	5G-XHaul Central Office
ADC	Analogue-to-Digital Converter
API	Application Program Interface
ARPU	Average Revenue Per Unit
ARQ	Automatic Repeat Request
BER	Bit Error Rate
BB	Baseband
BBU	Baseband Unit
BH	Backhaul
BS	Base Station
CAPEX	Capital Expenditures
CCDF	Complementary Cumulative Distribution Function
CDF	Cumulative Distribution Function
CO	Central Office
CoMP	Cooperative Multipoint
CP	Cyclic Prefix
CPRI	Common Public Radio Interface
C-RAN	Cloud Radio Access Network (aka Cloud-RAN)
DAC	Digital-to-Analogue Converter
DC	Data Centre
DL	Downlink
e2e	end-to-end
eNB	Evolved Node B
EIRP	Equivalent Isotropically Radiated Power
EPC	Evolved Packet Core
FH	Fronthaul
HARQ	Hybrid Automatic Repeat Request
ICN	Information-Centric Networking
ISP	Internet Service Provider
IT	Information Technology

ITS	Intelligent Transport Services
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LLR	Log-Likelihood Ratios
LoS	Line-of-Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MBB	Mobile Broadband
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
mmWave	Millimeter Wave
MNO	Mobile Network Operator
MPLS	Multiprotocol Label Switching
MTC	Machine-Type-Communications
MVNO	Mobile Virtual Network Operator
NBI	North-Bound Interface
NFV	Network Function Virtualization
NGFI	Next Generation Fronthaul Interface
NGMN	Next Generation Mobile Networks
NloS	Non-Line-of-Sight
OBSAI	Open Base Station Architecture Initiative
OOB	Out-of-band
ORI	Open Radio Interface
OS	Operating System
OTN	Optical Transport Network
OTT	Over-The-Top
p2p	Point-to-Point
p2mp	Point-to-Multipoint
PBB	Provider Backbone Bridge
P-GW	Packet Data Network Gateway
PDCP	Packet Data Convergence Protocol
PON	Passive Optical Network
PTZ	Pan–tilt–zoom
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology

RATN	Radio Access Transport Network
RB	Resource Block
RF	Radio Frequency
RLC	Radio Link Control
RRH	Remote Radio Head
RU	Remote Unit
SDN	Software Defined Networking
SDO	Standards Developing Organizations
S-GW	Service Gateway
SINR	Signal to Interference plus Noise Ratio
SLA	Service Level Agreement
TC	Transport Class
TDD	Time Division Duplex
TETRA	Terrestrial Trunked Radio
TSON	Time-Shared Optical Network
UC	Use Case
UE	User Equipment
UHD	Ultra High Definition
UL	Uplink
VM	Virtual Machine
VN	Virtual Network
VNO	Virtual Network Operator
VNP	Virtual Network Provider
vCN	virtualised Core Network
vRAN	Virtualised RAN
WDM	Wavelength Division Multiplexing
WRC	World Radio Conference