5G-XHaul

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

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Executive Summary

5G-XHaul focuses on developing a converged optical and wireless network solution supported by a flexible and scalable control plane with the aim to form a flexible transport infrastructure. This infrastructure will be able to jointly support the backhaul (BH) and fronthaul (FH) functionalities required to cope with the future challenges imposed by fifth generation (5G) Radio Access Networks (RANs).

In this context, a key aspect that needs to be addressed is the definition of an innovative heterogeneous network architecture adopting a variety of wireless and optical technologies able to support a wide range of 5G services. In view of this, this deliverable provides a high level description of a set of requirements and KPIs derived by the relevant use cases and services, reported in detail in the 5G-XHaul deliverable D2.1, and a description of the 5G-XHaul architecture that can support these requirements. More specifically, the converged optical-wireless 5G network infrastructure interconnecting computational resources with fixed and mobile users proposed by the 5G-XHaul project is presented. The proposed architecture aims at supporting both operational network (C-RAN) and end-user services. The 5G-XHaul overarching layered architecture, inspired by the European Telecommunications Standards Institute (ETSI) Network Function Virtualization (NFV) standard and the Software Defined Networking (SDN) reference architecture, supporting the required functions to effectively and efficiently provision these services is presented.

The development focus of 5G-XHaul involving both physical infrastructure and control plane activities is described in detail. The architecture of the physical infrastructure is defined including descriptions of the various wireless and optical technologies adopted as well as the data path interfaces required to enable integration across the greatly varying technology domains. The option of exploiting flexible functional splits is described and different transport classes (TCs) that the 5G-XHaul solution can support are discussed. In addition, the 5G-XHaul control plane responsible to provision transport slices instantiating the connectivity required by the 5G-XHaul tenants is described from both an architectural and a functional perspective.

Some initial considerations regarding the evaluation of the architecture is also provided through the description of a modelling tool that is being purposely developed. The evaluation focuses on the data plane performance as well as the trade-offs associated with the choice of TCs corresponding to different functional split levels. The novel modelling framework developed, adopts multi-objective optimisation to study a variety of FH and BH options, spanning from the traditional distributed RAN approach to solutions involving fully or partially converged FH and BH functions. Finally, some initial evaluation of the support of different TCs and the associate delay requirements is also provided.

1 Introduction

To meet the ever increasing growth of mobile traffic demands, the traditional wireless access network architecture based on single layer macro-cells is being currently transformed to an architecture comprising a large number of smaller cells with densely deployed access points (APs), combined with micro and macro-cells. In traditional Radio Access Networks (RANs), baseband units (BBUs) and radio units are co-located suffering several limitations including: i) increased Capital Expenditures (CAPEX) to acquire new base stations (BSs) and OPEX due to underutilised resources, ii) limited scalability and flexibility, iii) lack of modularity and limited density as the system is complex to resize after deployment, iv) increased management costs, and v) inefficient power delivery as the BSs processing power cannot be shared.

An alternative solution recently proposed is that of Cloud Radio Access Networks (C-RANs) where distributed APs, referred to as Remote Units (RUs), are connected to the BBU pool[1] through high bandwidth transport links known in as fronthaul (FH) (left part of Figure 1). FH is responsible to carry the RU wireless signals typically over the optical transport network using either digitised form based on protocols such as the Common Public Radio Interface (CPRI) the Open Base Architecture Initiative (OBSAI) and the Open Radio Interface (ORI), with CPRI currently being the most frequently used standard, or in analogue form through radio-over-fibre technology [1]. Recently, several solutions for wireless fronthauling have been proposed, as well [2]. The main advantage of digitised transmission is reduced signal degradation allowing data transmission over longer distances, enabling the adoption of longer reach optics offering higher degree of BBU consolidation. C-RAN's main disadvantages include increased transport bandwidth requirements to carry the sampled radio signals, and strict latency and synchronisation constraints [3]. For example, in a single Long Term Evolution (LTE) 20 MHz 2x2 MIMO sector, the required capacity for the RU-BBU interconnection is 2.46 gigabit-per-second (Gbps) and may increase up to 12.165 Gbps with CPRI line bit rate option 9 [4]. Given that existing optical transport solutions for APs are either based on Passive Optical Networks (PON), Gigabit-capable Passive Optical Networks (GPON) or 10GE technologies offering capacities up to 10 Gbps, it is obvious that the mobile BH network can rapidly become the bottleneck. To relax the stringent FH requirements of C-RAN architectures, while taking advantage of its pooling and coordination gains, alternative architectures proposing flexible splits have been proposed (Figure 2) [5], [6]. In addition to high bandwidth transport connectivity, this flexible split requires fine bandwidth granularity and elastic resource allocation.

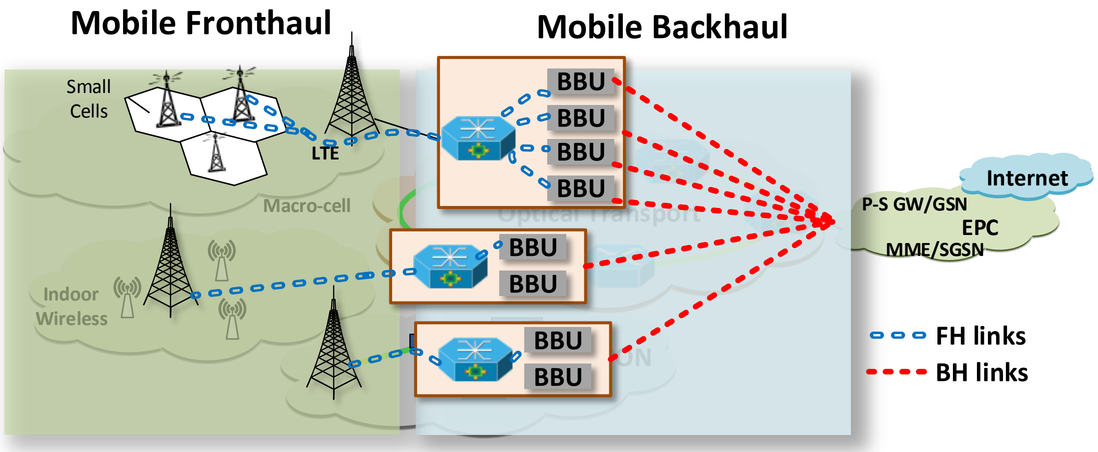

Figure 1: Mobile fronthaul and backhaul.

In this deliverable, the converged optical-wireless 5G network infrastructure interconnecting computational resources with fixed and mobile users proposed by the 5G-XHaul project is described. The relevant architecture aiming at supporting both operational network (C-RAN) and end-user services [7] is discussed. The corresponding overarching layered architecture, inspired by the ETSI Network Function Virtualization (NFV)

[1] In case of CPRI the Central Unit (CU) corresponds to the Baseband Unit (BBU) and the Remote Unit (RU) to the Remote Radio Head (RRH). In this document we will use CU and RU in general, BBU and RRH for CPRI.

standard [8], and the Software Defined Networking (SDN) reference architecture [9], is also presented. This architecture describes the required functions and their interactions, that 5G-XHaul proposes to effectively and efficiently provision both end-user and operational services over the proposed infrastructure.

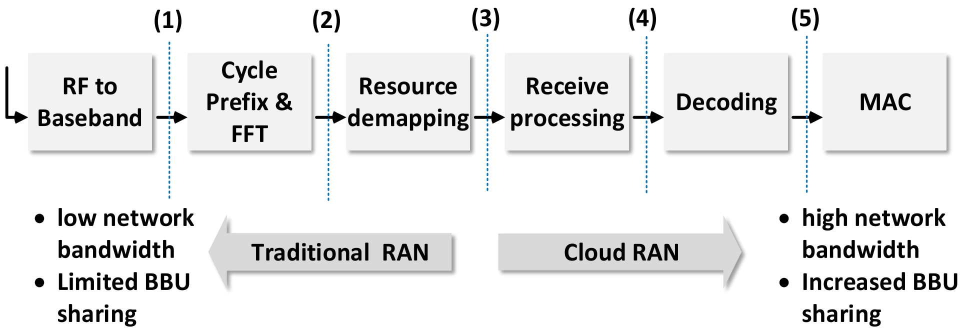

Figure 2: Functional split of BS processing [6],[11],[21].

Taking an architectural view the development focus of 5G-XHaul is presented in terms of both physical infrastructure and control plane. The physical infrastructure (data plane) architecture is defined. The various wireless and optical technologies adopted as well as the data path interfaces required to enable integration across the greatly varying technology domains are described. The option of exploiting flexible functional splits is described in the context of a selection of different TCs that the 5G-XHaul solution can support. In addition, the 5G-XHaul control plane that aims at allowing to provision transport slices instantiating the connectivity required by the 5G-XHaul tenants is described.

Some initial considerations regarding the evaluation of the architecture is also provided through the description of a modelling tool that is being purposely developed. This evaluation focuses on the data plane performance as well as the impact associated with the choice of TCs corresponding to different functional split levels. The novel modelling framework developed aims at evaluating the performance of this infrastructure. It includes a multi-objective optimisation service provisioning model used to study a variety of FH and BH options, spanning from the traditional approach where the two functions are supported separately to solutions involving fully or partially converged FH and BH functions.

Organisation of the document

This deliverable is structured in seven main sections. Following the introduction section, Section 2 provides a high level view of the requirements and key performance indicators that 5G-XHaul aims to support from a the user perspective. These are used as inputs that help to define the specific technical characteristics of the proposed solution. This section is produced taking as input deliverable D2.1 and consolidating the associated content. Section 3 concentrates on the presentation of the 5G-XHaul overarching architecture and its functional description. Section 4 describes the development focus of the 5G-XHaul project focusing on the data plane. From a data plane point of view the various technologies planned to be developed in the project are identified and described, while attention is paid to the description of the required interfaces given the high degree of heterogeneity of the proposed approach. In addition this section discusses the option of exploiting flexible functional splits TCs that the 5G-XHaul solution can support. Section 5 focuses on the second aspect of the 5G-XHaul development focus i.e. its control plane with emphasis in the control plane architecture and functionality. Regarding the control plane, architectural and functional information is provided. Section 6 concentrates on some initial architectural evaluation work focusing on the development of a suitable modelling tool and presenting some preliminary modelling results on the 5G-XHaul data plane, while some initial evaluation of the support of different TCs and the associate delay requirements is provided. Finally, Section 7 provides a summary and the main conclusions of the deliverable.

2 Requirements and Key Performance Indicators

The 5G-XHaul deliverable D2.1 [1] established the basis for the design process of the 5G-XHaul solution. In this context, the project adopted the usual top down approach methodology, also employed by other projects and Standards Developing Organizations (SDOs), of identifying relevant use cases, and deriving requirements to initiate the network architecture design process. However, there are two fundamental aspects that are specific of 5G-XHaul in the application of the use case based methodology.

Firstly, given that the 5G-XHaul solution focuses on the transport infrastructure of 5G networks, it is necessary to adapt the methodology. In this sense, two types of use cases have been identified, namely end-user use cases and operator use cases providing user requirements from two different "actor'" perspectives. In the former case "user" refers to the end-user (either a human being or machine) consuming 5G services, whereas in the latter case "user" refers to the operator, service provider or enterprise that utilizes the 5G-XHaul transport infrastructure and the related services.

Secondly, the requirements for the 5G-XHaul architectural design are not only derived from the end-user use cases and the operator use cases, but also take into consideration the physical layer performance characteristics, such as latency, jitter, and overall capacity, arising by the proposed Radio Access Technologies (RATs) for 5G systems, currently being designed by other 5G Infrastructure Public Private Partnership (5G-PPP) Phase 1 Projects, which are about to be standardised soon by 3GPP. For this reason, several potential 5G RATs technologies – like massive MIMO or millimetre wave (mmWave) – have been considered and analysed, both from a single transport link perspective as well as from an aggregation transport network point of view. To fulfil these requirements, important guidelines for the overall design of the 5G-XHaul transport network have been identified.

The 5G-XHaul deliverable D2.1 has also identified a **set of Key Performance Indicators (KPIs)** that will assist in the evaluation of the project progress towards its intended objectives, as well as the contribution of the project towards the envisioned 5G-PPP global performance KPIs expected by 2020.

The current deliverable, aims at also consolidating the functional requirements that are used for the definition of the architecture as well as the performance requirements that will be used for the validation of the 5G-XHaul solution. For these purposes, the requirements and KPIs from other relevant projects have been analysed. As stated in D2.1, the user of the 5G-XHaul system is not directly the end user consuming 5G services (either a human being or machine), but an operator, service provider or enterprise that obtains connectivity services from the transport infrastructure and services designed in 5G-XHaul. The requirements on the 5G-XHaul transport infrastructure from the network operator viewpoint will be driven, on one hand, by the characteristics and performance of the 5G radio interface and, on the other hand, by the functional requirements of the network architecture adopted.

2.1 Review of the approach from other relevant projects

Different projects have produced deliverables where they collect the use cases and requirements that they will use for the development of the different technological solutions they are addressing. Although other projects have also been considered (e.g, METIS II), the main ones to be considered are, as indicated above, the ones collected in the following sections, the two ones that are defining the air interface for high and low frequency bands, mmMAGIC and FANTASTIC-5G, and the one that is responsible of the 5G network architecture, 5G NORMA.

2.1.1 mmMAGIC

The mmMAGIC project (https://5g-mmmagic.eu/) main objective is to develop and design new concepts for mobile RATs for deployment in the 6-100 GHz range.

Although the methodology adopted is quite similar, it should be highlighted that the terminology used by the mmMAGIC project is different to that of 5G-XHaul. For mmMAGIC, a KPI is a "quantifiable measurement that reflects the critical success factors of a proposed solution; it reflects the goals captured by each use case. The KPIs are linked with the use case in order to link the proposed solutions with the usage driven test cases." On the other hand, a Requirement is defined as the quantified need for each KPI. For example: If the KPI is delay, the requirement could be 10 ms.

The mmMAGIC project considers four families of use cases [10]: broadband access in a dense area, broadband access everywhere, high mobility users and extreme real time or ultra-reliable communication. Several use cases are associated with each family, five with broadband access, and one with the other families, so a total of eight individual use cases have been analysed. For each individual use case a number of KPIs have been identified including:

- User data rate UL/DL.
- Connection density.
- Traffic density.
- Mobility.
- Availability.
- Latency.

For each use case the requirement is the value defined for each KPI.

2.1.2 FANTASTIC-5G

The objective of FANTASTIC-5G (http://fantastic5g.eu/) is to develop a new multi-service Air Interface (AI) for below 6 GHz through a modular design. To allow the system to adapt to the anticipated heterogeneity, the pursued properties are: flexibility, scalability, versatility, efficiency and future-proofness.

In IR2.1 [11], from an initial set of 24 use cases based on the output from different sources, like Next Generation Mobile Networks (NGMN) and METIS/METIS II, the project has identified a reduced set of seven use cases:

- Use Case 1: 50 Mbps everywhere Mobile Broadband (MBB).
- Use Case 2: High speed train MBB + Vehicle-to-X (V2X).
- Use Case 3: Sensor networks Multi Media Card (MMC).
- Use Case 4: Tactile Internet Mobile Cloud Computing (MCC).
- Use Case 5: Automatic traffic control / driving MCC + V2X.
- Use Case 6: Broadcast like services: Local, Regional, National Broadcast Microwave Services (BMS).
- Use Case 7: Dense urban society below 6GHz MBB.

It should be noted that the selection of the use cases is affected by other factors beyond the interest to address only 5G representative applications. These include e.g. the fact that use case simulations can be carried out using simulators that available in the framework of the project.

The project has also selected a set of KPIs:

- KPI 0: User experienced data rate.
- KPI 1: Traffic density (to achieve high system capacity).
- KPI 2: Latency.
- KPI 3: Coverage (to provide ubiquitous access).
- KPI 4: Mobility.
- KPI 5: Connection density.
- KPI 6: Reliability/availability.
- KPI 7: Complexity reduction.
- KPI 8: Energy efficiency.

For each of the use cases, FANTASTIC-5G has set the corresponding values for the KPIs and has also characterised them in terms of User Experience KPIs (0, 2, 3, 4, 6 in the list above) and System Performance KPIs (1, 5, 7, 8). The User Experience KPIs directly impact the Quality of Service (QoS) and the overall Quality of Experience (QoE) for the user of a given service, whilst the System Performance KPIs mostly relate to the service delivery efficiency from the mobile network operator's (MNO's) perspective.

2.1.3 5G NORMA

5G NORMA (https://5gnorma.5g-ppp.eu/) intends to develop a multi-service mobile network architecture that adapts the use of the mobile network – RAN and core network (CN) – resources to the service requirements, the variations of the traffic demands over time and location, and the network topology (including the available FH/BH capacity). The key idea behind 5G NORMA for achieving the above objective is to decompose the mobile network functions (including access and core functions) and adaptively allocate them to the access network or central cloud, depending on (i) the specific service and its requirements, e.g., bandwidth and latency; and (ii) the transport network capabilities (e.g., available FH/BH capacity).

In deliverable D2.1 [12], 5G NORMA has selected a number of use cases in order to derive functional and performance requirements from their analysis.

- Industry Control.
- Enhanced Mobile Broadband.
- Emergency Communications.
- Vehicle Communications.
- Sensor Networks Monitoring.
- Traffic Jam.
- Real-time Remote Computing.
- Massive Nomadic Mobile Machine Type Communications.
- Quality-aware Communications.
- Fixed-Mobile Convergence.
- Blind Spots.
- Open Air Festival.

From the analysis of each individual use case the following **groups of requirements** have been defined:

- Fast network reconfiguration within a network slice.
- Fast network reconfiguration between network slices.
- Device duality.
- Separation and prioritisation of resources on a common infrastructure.
- Multi-connectivity in access and non-access part of the 5G system.
- Massive scalability of protocol network functions.
- Highly efficient transmission & processing.
- QoE/QoS awareness.
- Adaptability to transport network capabilities.
- Low latency support.
- Security.

In terms of performance, 5G NORMA has identified KPIs for each individual use case and has classified these in three groups: very low latency and reliability for critical machine type communications; high throughput (compared to legacy networks) for massive broadband communication and the ability to support high volumes of devices for massive machine type communication. For the project, is of the utmost importance to validate the concept of flexibility, i.e., the capacity of supporting use cases with very different requirements using the same architecture.

2.2 Consolidation of 5G-XHaul requirements and KPIs

The objective of this section is to ensure that the requirements coming from other projects are consistent with those defined by 5G-XHaul, so the transport infrastructure proposed is able to meet the expectations of 5G operators (5G-XHaul users), both in terms of functionality and performance.

In terms of use cases, the set selected by 5G-XHaul covers most the applications of 5G that are considered by other projects or have similar requirements. In other words, no use case identified by these three projects includes requirements that are not covered by the requirements selected by 5G-XHaul. The use cases are also consistent with these considered by 3GPP and ITU-R.

With respect to the functional requirements posed on the transport infrastructure, 5G-XHaul shares some basic principles with other 5G-PPP projects and, specifically, with 5G NORMA, regarding the need to support multitenancy, network slicing and the flexible allocation of functionalities at different network levels. At this point in time it is premature to say that the 5G-XHaul transport solution is able to support all functional requirements associated with the network architecture proposed (given the level of detail in the description of the former available hitherto), but no inconsistency has been identified so far. Even more, some of the solutions proposed by 5G-XHaul may help to fulfil some of the functional requirements identified in a more effective way. The introduction of the concept of TCs in 5G-XHaul deliverable D2.1 [1], for example, may help to support the adaptability of the transport network capabilities requirement that has been identified by 5G NORMA. The main issue that may arise in the future is not that 5G-XHaul will not be able to provide the functionalities that the proposed network architecture requires, but that there may be incompatibilities in the solutions proposed in terms of, e.g. architecture, protocols or topology.

The performance requirements and KPIs defined by the projects analysed can be classified into two different groups:

- KPIs associated with the characteristics of the radio interface proposed. These KPIs translate into requirements related to the transport infrastructure. Given the spectral efficiency of the air interface and the spectrum availability (among other factors), it is feasible to derive the capacity requirements that the transport network must fulfil. The same reasoning can be applied to other KPIs like latency. However, it should be noted that the values indicated are, so far, targeted objectives to be achieved with the solution proposed.
- KPIs associated with the expected usage patterns of the different use cases. These KPIs translate into deployment options that must be feasible from both technical and economic viewpoints. For example, in some of the projects analysed, KPIs for traffic densities of the order of Gbps per square kilometre are proposed. For supporting these traffic densities, a high capillarity/high capacity cell deployment will be necessary, and the transport network should be able to support it in a cost affordable/sustainable way. For these purposes, it is necessary to ensure consistency in the evaluation scenarios used for the validation of the different solutions.

The main conclusions from the analysis carried out are the following:

- The set of use cases that 5G-XHaul has selected is sufficient, covering the main uses expected in the context of 5G.
- Functional requirements identified in 5G-XHaul are consistent with those coming from other projects referring to the transport network (there are functional requirements that are not relevant to 5G-XHaul). However, this does not guarantee necessarily that the solutions proposed will eventually be compatible – although the fact that the technical approaches adopted exhibit similarities (e.g., adoption of SDN and NFV to provide flexibility) will certainly help in avoiding potential compatibility issues.
- The consistency in terms of performance requirements and KPIs must be assessed during the validation process. However, the KPIs defined by other projects may help to define 5G-XHaul KPIs.

3 Overarching Layered Architecture

The overall 5G vision involves a converged heterogeneous network environment integrating a wide variety of network technologies for radio access with wireless and wired transport solutions interconnecting a huge number of vastly different end-devices and users, including compute and storage resources. These resources are called to support a combination of end-user and operational services, such as C-RAN, and the associated split options and can be hosted either by micro-Data Centers (DCs) referred to as Mobile Edge Computing (MEC), or at remote regional and central large scale DCs. Figure 3 presents the various relevant views on emerging 5G designs as they have been depicted in the 5G-PPP architecture white paper [13].

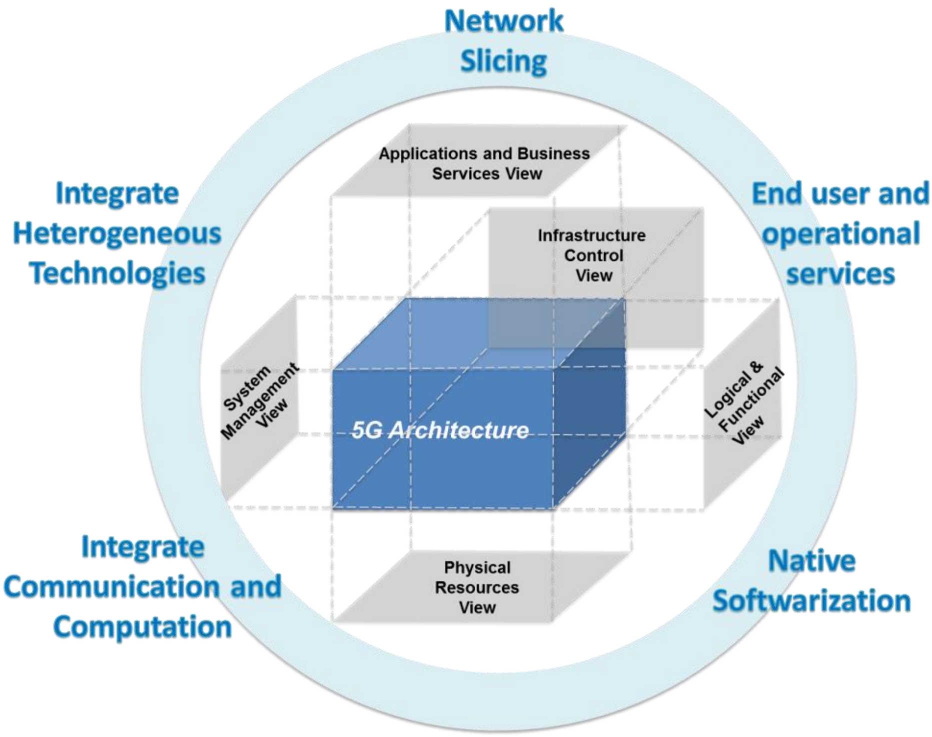

Figure 3: 5G Architecture Views [13].

In view of this, 5G-XHaul proposes a converged optical-wireless 5G network infrastructure interconnecting computational resources with fixed and mobile users, to support both operational network (C-RAN) and end-user services [7]. This infrastructure aims at addressing the limitations of existing solutions and take advantage of pooling and coordination gains improving efficiency in resource utilisation and providing measurable benefits in terms of cost, scalability, sustainability and management simplification. To address the flexibility, agility and adaptivity in the functions that a network can perform as required by the 5G environment, concepts such as network softwarisation provide a promising way forward [13]. In this context, the 5G-XHaul vision involves the adoption and integration of specific technical approaches supporting this paradigm, such as the SDN and NFV. More specifically in this section a layered architecture, inspired by the ETSI NFV standard [8] and the SDN reference architecture [9], is presented. This architecture has been also reported in [14].

The 5G-XHaul data plane considers an integrated optical and wireless network infrastructure for transport and access. The wireless domain comprises small cells complemented by macro cells. Backhauling can be supported through mmWave and Sub-6 wireless technologies or using a hybrid optical network platform combining both passive and active optical technologies. This platform can support demanding capacity and flexibility requirements for traffic aggregation and transport and, as such, a large variety of services envisaged for the 5G era.

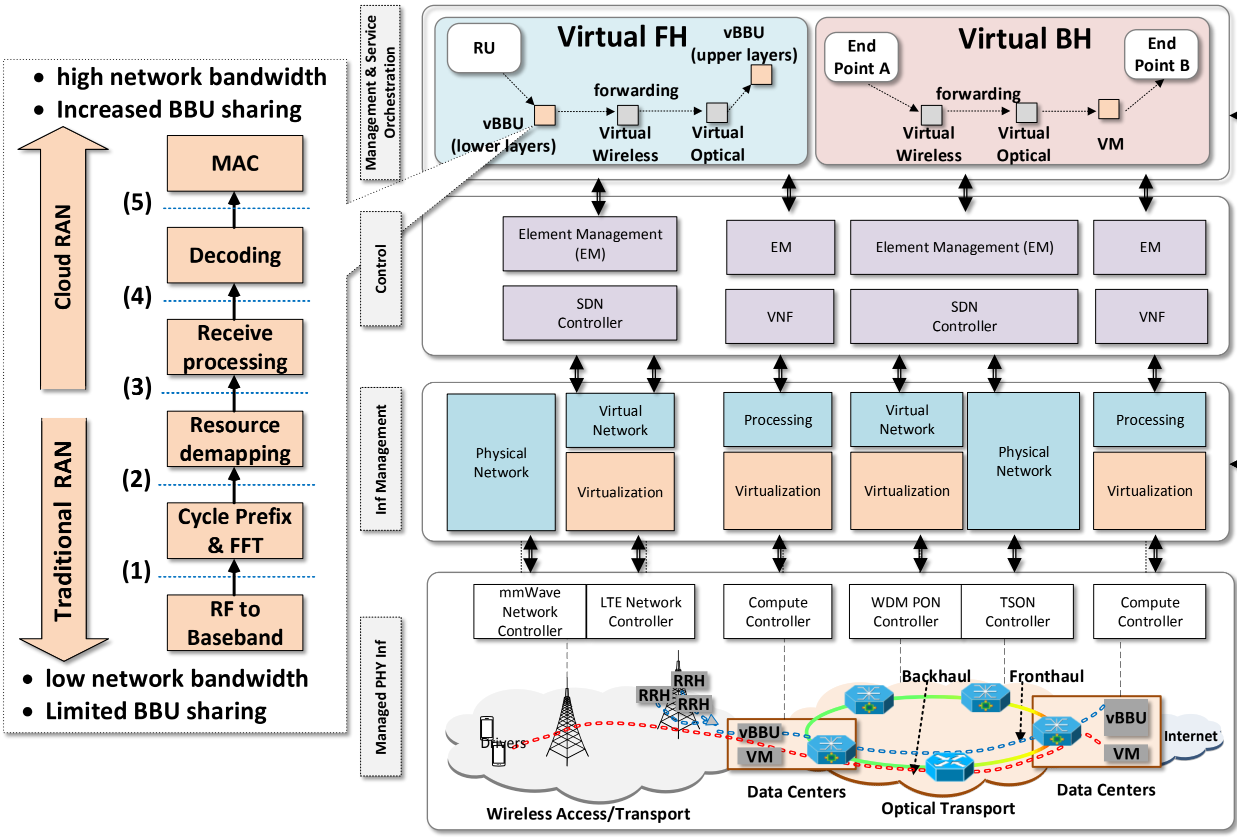

Figure 4: The overall overarching architecture.

A key architectural issue associated with this type of infrastructure is the placement of the Base Band (BB) processing with respect to the Remote Units (RUs). In 5G-XHaul, the concept of C-RAN, where RUs are connected to remote BB processing pools through high bandwidth transport links, is proposed as one solution that can be adopted to overcome the limitations of the traditional RAN approach. The inclusion of FH requirements in the 5G-XHaul infrastructure introduces new operational network services which need to be supported over the transport network. More specifically, the densely distributed RUs need to be connected to compute resources responsible for BB processing, with very stringent delay and synchronisation requirements. 5G-XHaul proposes to support BH and FH jointly in a common infrastructure, maximising the associated sharing gains, improving efficiency in resource utilisation and providing measurable benefits in terms of cost, scalability, sustainability and management simplification. In addition, 5G-XHaul proposes to split processing flexibly, with the aim to relax the stringent requirements transport capacity, delay and synchronisation. As illustrated in Figure 4, the range of “optimal split” options, spans between the “traditional distributed RAN” case where “all processing is performed locally at the AP” to the “fully-centralized C-RAN” case where “all processing is allocated to a CU”. All other options allow allocating processing parts at the RU, while the remaining processing is performed remotely at the CU. The optimal allocation of processing functions, executed locally or remotely, i.e. the optimal “split”, can be decided dynamically based on a number of factors such as transport network characteristics, network topology and scale, as well as type and volume of services that need to be supported.

These joint FH and BH requirements are supported through the 5G-XHaul architecture as well as the advanced wireless and optical network technologies developed by the project. A key enabler of the proposed approach is the adoption of a high capacity, flexible optical transport comprising both passive and active solutions. The passive solution employs WDM-PONs, while the active solution adopts the Time-Shared Optical Network (TSON) [15], enhanced with novel features for improved granularity and elasticity. These can provide the required connectivity, capacity and flexibility to offer jointly FH and BH functions and support a large variety of end-user and operational services. A high level view of the 5G-XHaul infrastructure is provided in Figure 4.

The 5G-XHaul infrastructure exhibits a great degree of heterogeneity in terms of technologies. To address the challenge of managing and operating this type of complex heterogeneous infrastructure in an efficient manner, 5G-XHaul proposes the adoption of SDN and NFV that will be integrated in a seamless manner. In

SDN, the control plane is decoupled from the data plane and is managed by a logically centralised controller that has a holistic view of the network [16]. At the same time, NFV enables the execution of network functions on commodity hardware (general-purpose servers, standard storage and switches) by leveraging software virtualisation techniques [17]. Through joint consideration of SDN and NFV significant benefits can be achieved. For example, the separate control plane can be virtualised using NFV, and the SDN controller-related Virtual Network Functions (VNFs) may be deployed dynamically, having the ability to scale up and down on demand based on the associated workloads [16].

Examples of features that enable these benefits include the option to virtualize the separate control plane, using NFV and deploy Virtual Network Functions (VNFs) [18]. These are controlled by the SDN controller, to allow on demand resource allocation, able to support dynamically changing workloads [16]. SDN network elements can be treated as VNFs, since they can be implemented as software running on general-purpose platforms in virtualised environments [16]. Both SDN and non-SDN models can be supported by SDN network elements. On the other hand, network applications can include SDN controller functions, or interact with SDN controllers and can themselves provide VNFs. Service Chaining (SC), supporting orchestrated service provisioning over heterogeneous environments, is considered to be one possible network application. Network elements controlled by SDN controllers can provide either VNFs or Physical Network Functions (PNFs).

Taking advantage of the SDN concept and the benefits of cross-technology virtualisation, 5G-XHaul proposes an overarching layered architecture able to efficiently and effectively support 5G services presented in Figure 4. The **Managed Physical Infrastructure (PI) layer** is described in Section 4.

The **Infrastructure Management Layer (IML)** is responsible for the management of the different technology domains and the creation of virtual infrastructure (VI) slices, comprising heterogeneous resources. These VI slices enable multi-tenancy operator models providing both FH and BH services as mentioned in Section 2 and described in detail in the 5G-XHaul deliverable D2.1. This layer communicates with the various network and compute controllers that are responsible for retrieving information and communicating with the individual domains. Once the information has been collected, the resources are abstracted and virtualised. From the architectural and functional perspective, IML addresses all virtualisation and virtual resource management functions. Management of traditional non-virtualised physical infrastructures is also supported.

Cross-domain orchestration of the virtual and physical infrastructures, created and exposed by the IML to the higher layers, is carried out by the **Control Layer**. This layer has a holistic view of all network segments and technology domains and implements converged control and management procedures for dynamic and automated provisioning of end-to-end connectivity services (i.e. service chaining), according to specific QoS considerations. Configuration of virtualised (or non-virtualised) wireless and optical network resources, as well as legacy devices, is carried out by a set of distributed SDN controllers. Apart from network configuration capabilities, offered by the SDN controllers, further enhanced VNFs, running on top of the VIs, can be developed to operate the entire heterogeneous infrastructure in a seamless manner. The control plane developments in the framework of 5G-XHaul will be performed by Work Package 3 (WP3). More information on this layer can be found in Section 5.

Finally, converged orchestration of computation and network services can be provided through a **Management and Service Orchestration Layer**. This layer can support the composition and delivery of multi-tenant chains of virtualised network functions and should support interoperability with legacy software and hardware technologies and architectures. However, although architecturally 5G-XHaul has identified the functional purpose of such a layer, the project activities do not focus on or include relevant developments.

4 5G-XHaul Development focus: Data Plane – Converged FH BH

The 5G-XHaul data plane architecture considers an integrated optical and wireless network infrastructure. The wireless domain comprises a dense layer of small cells that are located 50-200 m apart [17]. This small cell layer is complemented by a macro cell layer to ensure ubiquitous coverage. Macro-cell sites are around 500 metres apart. Small cells can be wirelessly backhauled to macro-cell sites using a combination of mm-Wave and Sub-6 wireless technologies. Alternatively, the 5G-XHaul architecture allows small cells to be directly connected to a central office (CO) node using optical network technologies and, more specifically, PONs offering enhanced capacity through the deployment of Wavelength Division Multiplexing (WDM). In addition to WDM-PONs, 5G-XHaul adopts the use of a dynamic and flexible/elastic frame based optical network solution that can support more demanding capacity and flexibility requirements for traffic aggregation and transport. Through this architecture 5G-XHaul aims to efficiently support a large variety of end-user services as they are envisaged for the 5G era (e.g. as defined in 5G-XHaul deliverable D2.1 [1] and by the EU project METIS [17]).

As stated in Section 3, 5G-XHaul proposes to use a common network infrastructure to support jointly backhauling and fronthauling functions maximising the associated sharing benefits, improving efficiency in resource utilisation, and providing measurable benefits in terms of overall cost, scalability and sustainability objectives. As defined in [1], 5G-XHaul supports conventional fronthaul interfaces including CPRI, but also other types of functional splits referred to as TCs between RUs and CUs, such as those being studied in NGFI [20]. This can be practically supported through the proposed 5G-XHaul data plane architecture as well as the advanced wireless and optical network technologies that are developed internally within the project. It should be noted that a key enabler supporting the feasibility of the proposed approach is the adoption of a high capacity, flexible optical transport comprising both passive and active solutions. The passive optical network solutions will be based on WDM-PONs, while the active solution adopts TSON [15], TSON will be deployed after being enhanced with novel features for improved granularity and elasticity. These can provide the required connectivity, capacity and flexibility to offer jointly backhauling and fronthauling functions and support a large variety of end-user and operational services. It should be noted that the generic 5G-XHaul data plane architecture extends beyond wireless and optical transport solutions, and is also able to support other prominent technologies such as Ethernet, currently actively considered in standardisation bodies to support both FH and BH requirements [21]. A high level view of the 5G-XHaul data plane architecture is provided in Figure 5.

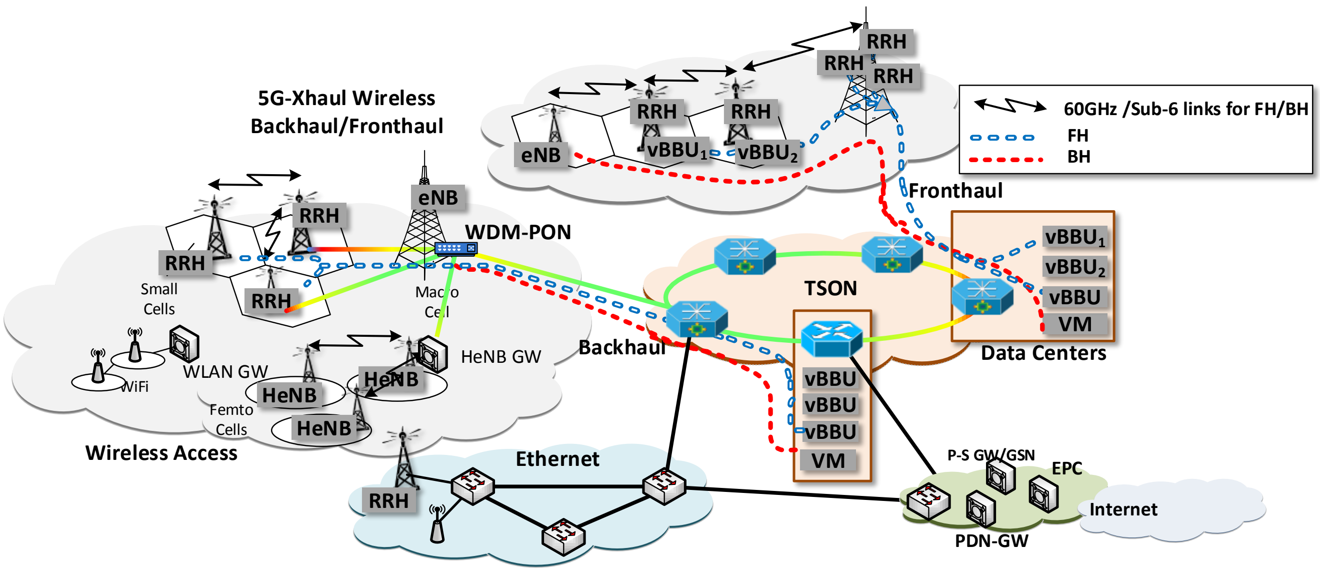

Figure 5: The 5G-XHaul Physical Infrastructure.

5G-XHaul supports the previously defined operational and end-user services adopting also the option of a set of TCs defined in [1]. In order to fulfil the requirements of the 5G environment and support the various TCs in the most efficient, future proof and scalable manner, 5G-XHaul focuses on developing novel programmability features on the data plane technologies shown in Figure 5. Some examples of these include: 1)

Flexibly allocating time and frequency resources in high capacity, flexible optical transport, 2) Dynamically turning off WDM-PON Optical Network Unit (ONU) transceivers to save energy, or 3) Reconfiguring beam directions in mmWave nodes to enable p2mp in the Small Cell wireless BH.

It should be noted that the 5G-XHaul physical infrastructure has been adopted as part of the 5G-PPP architecture, and is described in the relevant published White Paper [13] including both its functional structure as well as its design and technology approach. This is illustrated in Figure 6, where the 5G-XHaul solution is identified by the blue circle.

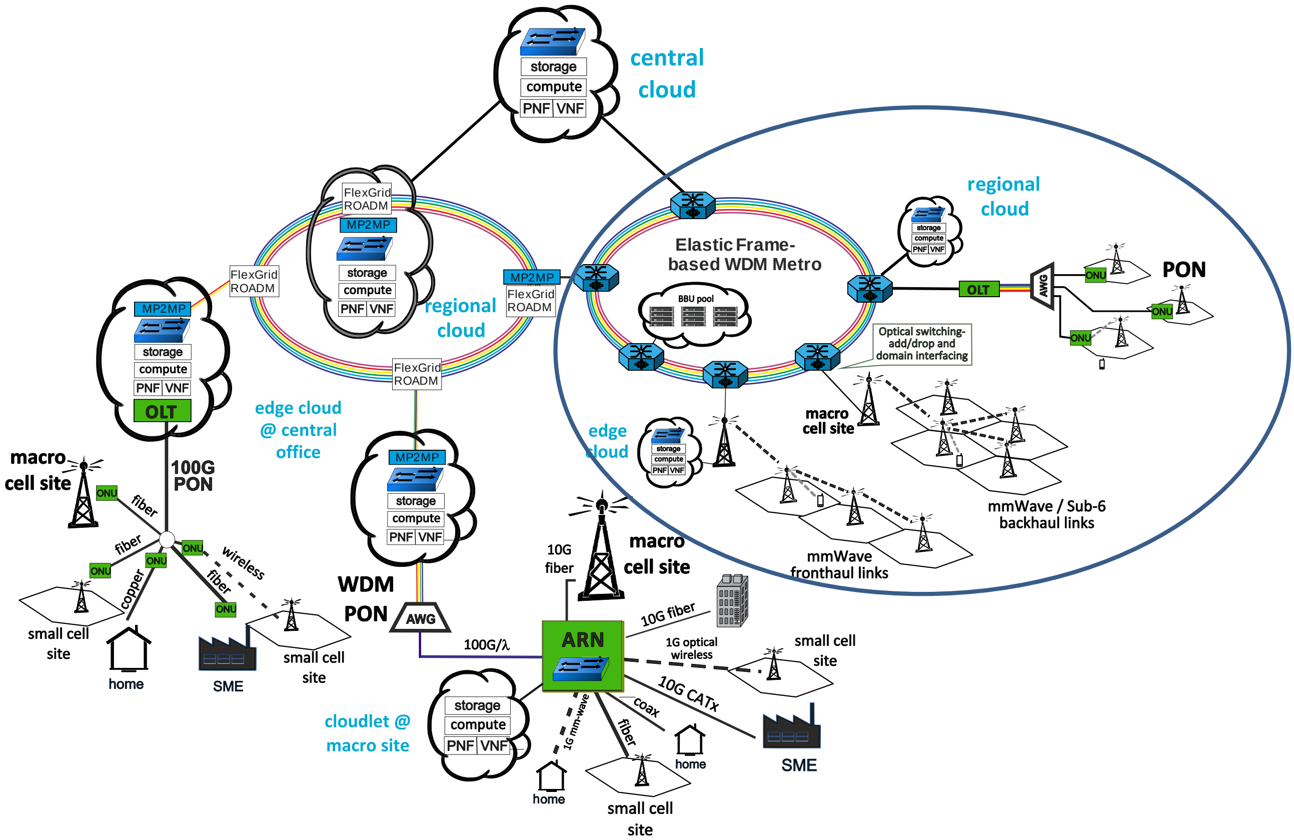

Figure 6: Physical architecture of a converged fixed-mobile network for 5G [13].

Throughout the next subsections, we introduce the technical details of each of the three main data plane technologies: wireless, optical and Ethernet. Moreover, a more detailed review of the data plane technologies are introduced and explained below, with the aim of extracting the performance they could offer in terms of data rate and latency. A more exhaustive revision of the technologies will be provided in planned technology-specific deliverables in the framework of WP4.

4.1 Wireless Architecture and Technologies

High capacity links, e.g. optical links, are widely available in urban environments but their deployment is still not fast enough to match the sheer number of small cells required to serve the upcoming demand in mobile data. Therefore, there is a need to bring up wireless broadband links which, in conjunction with dynamic network control, will provide the required flexibility and support the expected traffic growth. 5G-XHaul will provide the RAN with a highly compatible interface allowing the connection of new RAT (mmWave, LTE-A and 5G) as well as already known RATs as Wi-Fi (and hybrids), LTE Advanced plus wired connections.

In very dense RANs, multi-hop wireless transport topologies are required where wireless links will convey the aggregated traffic of several BSs. Seamless integration of mmWave BH technology with Sub-6 Non-Line-of-Sight (NLoS) technology is generally recognised as the technology providing the ideal combination of capacity and coverage by operators deploying wireless BH, particularly in complex urban deployments [31].

5G-XHaul proposes a wireless architecture encompassing different scenarios, by leveraging the wireless technologies developed in the project. Examples of this for the transport network are: **mmWave FH with point-to-point links**, **Sub-6 and mmWave BH mesh** (and co-located mmWave and Sub-6 mesh). Moreover, several concepts developed in the project for the transport network can be extended to the RAN, therefore as access extensions we propose a **joint access/BH mesh for mmWave and Sub-6**. An example of this could be self-backhauling. All these envisioned scenarios which impose a set of requirements to the 5G-XHaul wireless architecture are depicted in Figure 7. The 5G-XHaul's wireless architecture has been included as part of the 5G-PPP view on 5G Architecture in [13].

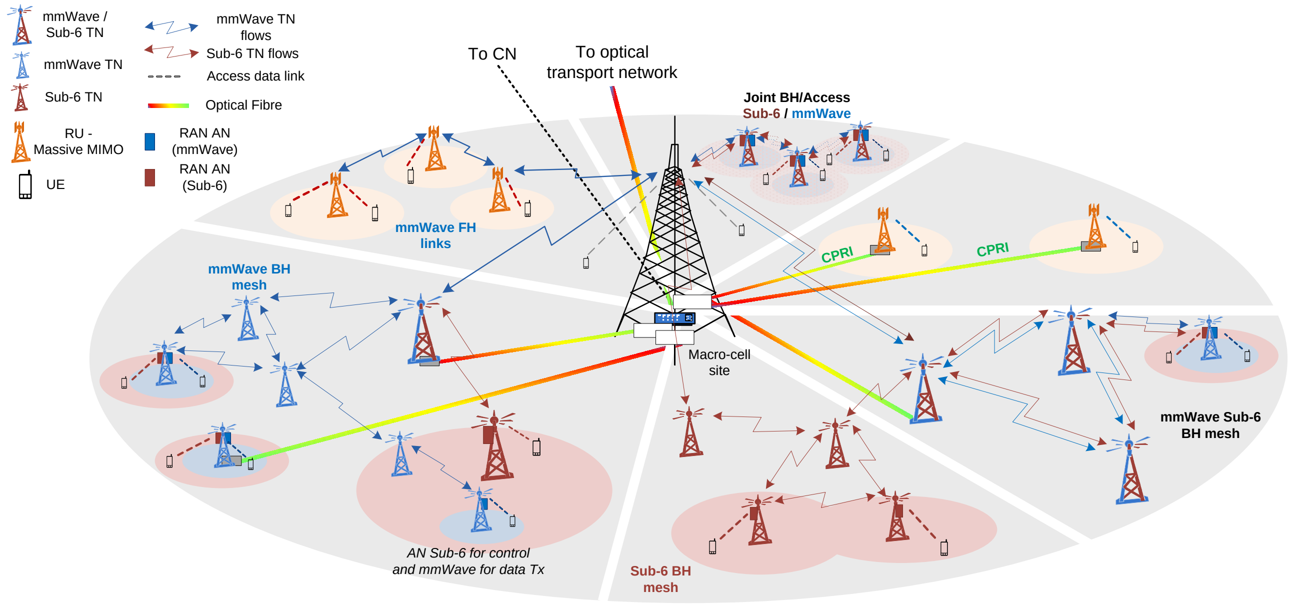

Figure 7: 5G-XHaul Wireless connectivity scenarios. TN stands for Transport Node, representing a device with transport functions; and AN for Access Node, representing a device with RAN functions.

In Figure 7, the macro-cell is connected to the optical metro network via fibre, which provides connectivity to the CN elements, typically deployed in a Data Centre (DC). We envision that, in practice, also the transport nodes (TN) may also have a direct connection to the optical transport network.

The densification of the envisioned 5G RAN requires multi-hop wireless topologies for the transport, where high capacity wireless links will transport the aggregated traffic of several BSs. Regarding wireless BH, the industry is currently considering mmWave solutions for delivering the required high capacities. On the other hand, Sub-6 solutions that allow NLoS operation also exist. Given that these solutions compete for spectrum with RAN technologies, they cannot provide alone the capacity required by BH future RAN architectures. However, Sub-6 nodes can complement mmWave nodes in situations where mmWave nodes face NLoS conditions. Therefore, 5G-XHaul will consider a **hybrid wireless BH network comprising both mmWave and Sub-6 technologies**. The street level mesh network for small cell coverage (BH) is represented in Figure 7 as TNs using either mmWave or Sub-6 communications. These TNs could also have co-located access nodes (ANs) to serve the users. The use of beam steering algorithms is envisioned, not only for establishing point-to-point links, but also for p2mp as well as forming mesh topologies. Section 4.1.1 provides an overview of this scenario, and introduces the enabling technologies proposed in 5G-XHaul.

5G-XHaul also proposes the transport of digitised radio signal transmission protocols like CPRI over fibre, as shown in the upper right part of Figure 7. This solution, however, limits the deployment of the C-RAN architecture in dense networks, where small cells are difficult to reach with fibre. Therefore, in the upper left part of Figure 7 we depict a possible scenario to overcome this limitation, which involves the use of high capacity **mmWave links for transporting C-RAN FH flows**. Enabling the transport of CPRI over mmWave technologies will greatly enhance the deployment opportunities for Cloud-RAN (for more details see Section 4.1.2).

As can be seen in Figure 7 there are obvious benefits integrating the transport and the mobile network and strengthening the interaction between them. In the converged scenario that 5G-XHaul proposes, the same wireless BH technology can be used for both BH and access links, making more efficient use of spectrum resources as they can be shared dynamically. The scenario that 5G-XHaul will tackle involves **joint access/BH mesh for mmWave and Sub-6**, described in detail in Section 4.1.3. The previous concept of beam steering for the BH can also be extended to the RAN. Therefore, there exists the possibility that TNs are dynamically configured either as TNs, or as ANs (or to perform both roles simultaneously) depending on the (instantaneous) needs of the network. As an example, a small cell based on Wi-Fi, acting as an AN, can be switched to the TN mode when traffic demands in its area relax, thus offering a new BH path. This is translated in extra link redundancy and relieves the load from other BH links.

4.1.1 Hybrid mmWave and Sub-6 BH

Faced with higher data traffic per cell, cellular network operators need to find ways to minimize the operating costs to transfer data to the CN. Concretely, the industry is currently considering means to alleviate the high deployment cost of fibre for the transport network as well as providing more flexible topologies. The higher data rates imposed by the various RATs in 5G require a more cost-effective technology able to convey such amount of traffic. For current BH networks, a study conducted in 2014 indicates that optical fibre BH is not available nationwide in Europe, and that current microwave replacements cannot sustain the traffic growth of LTE/LTE-A beyond 2017-2018 [23].

A combination of wireless technologies has been recently considered as a viable and cost-effective approach allowing operators to achieve end-to-end control of the network. The key wireless BH solutions exploit the mmWave spectrum in 60 GHz and 70–80 GHz bands, microwave spectrum between 6 GHz and 60 GHz bands, Sub-6 GHz band, TV white spaces, and satellite technologies. To select an optimal solution, the propagation environment, according to the location and deployment of the transport nodes, has to be studied and a decision must be taken.

Communication via mmWaves will be a key feature of 5G networks. Its operation at higher frequencies and wide spectrum availability at those frequencies allow reducing the solutions' form factor, and delivering Gbps data rates, respectively. Another important advantage of mmWave communications is low latency, which is crucial for 5G applications.

In the transport domain, mmWave transmission has already been successfully applied for backhauling purposes in the Ka-band (26.5-40 GHz), the license-exempt V-band (57-66 GHz), and the E-band (71-76, 81-86 GHz). In recent years, some of the mmWave transport products are able to fulfil the requirements for fronthauling as well. While the state-of-the-art (SotA) solutions reach multi Gbps data rates with ranges of up to 1 km, they are typically realised using relatively expensive technologies (III-V semiconductors, specialised antennas, etc.) and are mounted on low vibration poles. The next version of the 60 GHz WiFi standard, 802.11ay [24], is supposed to support wireless backhauling and mobile fronthauling among other new usage scenarios.

One of the key architectural features of mmWave communication systems is the availability of a large number of antenna elements forming antenna arrays at both transmitter and receiver sides. The antenna arrays have to provide array gain to obtain enough link margin for wide area operation. The mmWave links cast very narrow footprints (i.e. directional beams), diminishing significantly the effects of interference in a multi-user environment.

From Figure 7, the mmWave BH network consists of an ultra-dense 5G small cell network (small cells installed in street poles) with a considerable portion of BSs being served by mmWave backhauling links, either from a macro BS or in a multi-hop/mesh fashion. These mesh networks are very densely deployed and it is beneficial to dynamically turn BSs on and off as traffic demand varies. 5G-XHaul will design techniques to allow dynamic and autonomic reconfiguration of the mmWave BH, letting the control plane of the network to decide to which node to steer. The local mmWave node is the one who derives the appropriate BF weights to be used. Apart from allowing dynamic reconfiguration of the network topology, these techniques will also allow the implementation of different p2mp schemes over mmWave nodes.

Current and projected advances in Sub-6 technologies allow network operators start thinking on the deployment of wireless BH including both mmWave and Sub-6 technologies to benefit from an ideal combination of capacity and coverage – particularly in complex urban deployments. To exploit the available spectrum across the various frequency bands, a highly flexible communication interface is required that can support multiple RATs for various, possibly very different, services at the same time.

We propose to complement the use of mmWave for the BH mesh with an NLoS wireless technology operating below 6 GHz. The options 5G-XHaul is considering for this joint operation are the following:

- Scheduling of flows among mmWave and Sub-6, where mmWave can be used for heavy flows, whereas Sub-6 can be used for light flows, and
- Sub-6 for control and channel access, mmWave for data communication.

The following subsections introduce an overview of general aspects of wireless BH (scenarios, wireless channel, antennas, etc.) for both mmWave and Sub-6 technologies, and they provide an initial insight on the technologies to be developed in the project, which fall under WP4.

4.1.1.1 Millimetre wave BH - Envisioned scenarios, wireless channel and antennas

For the BH mesh scenario, we will consider the deployment of TNs located in street lamp posts in outdoor environments. Unlike in lower frequency bands, for these kind of scenarios, in the mmWave band one should consider the attenuation determined by conditions as rainfall, snowfall and fog, in addition to the normal free space attenuation. However, for distances of 200 metres or less, specific for small cells, the additional absorption loss is mild and the higher path-loss and resulting fragile link quality is largely due to weak diffractions in mmWave bands. To be able to achieve very high data rates, mmWave technologies mostly require LoS connectivity, although there exist recently studies that have dealt successfully with NLoS scenarios [25] in spite the high path loss.

5G-XHaul mmWave nodes will incorporate network programmable beam steering, a feature that will allow the 5G-XHaul control plane to steer the beams to the different mmWave nodes that belong to the mesh network. Programmable beam steering will be the basis to achieve network programmable p2mp connectivity, as illustrated in Figure 8. In particular, 5G-XHaul mmWave nodes will incorporate a Time Division Multiple Access (TDMA) Medium Access Control (MAC) based on 802.11ad, able to load different BF directions in different TDMA slots. Thus, by synchronising network nodes, dynamic p2mp topologies will be created where the bandwidth of each link can be controlled by the control plane by assigning a different number of slots to each link direction. The benefits of programmable p2mp in the mmWave BH are manifold. Firstly, reducing CAPEX is possible because fewer physical units will be required to interconnect the same number of Small Cell sites. Secondly, reliability, capacity and QoS can be improved by benefitting from additional paths. Finally, OPEX reductions can be achieved by intelligent algorithms that minimise network-wide energy consumption.

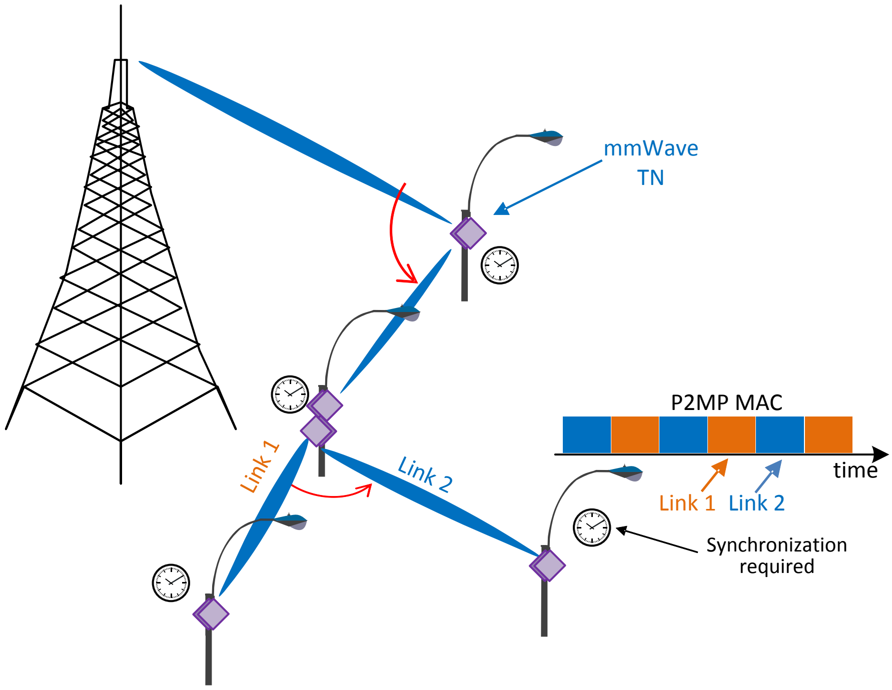

Figure 8: 5G-XHaul mmWave configurable MAC.

5G-XHaul aims at offering the 60 GHz mmWave band as a solution for the BH links (50 – 200 m). Table 1 presents the specifications this band has in different countries. The availability of 7–9 GHz of unlicensed spectrum at 60 GHz, advances in low-cost silicon technology, and high inherent interference rejection due to atmospheric loss, make 60 GHz an ideal solution for future 4G/5G small-cell BH links, where multi-gigabit rates are required.

Table 1 Current specifications for V-band in different countries.

Region	BW GHz	Tx power dBm	Max EIRP dBm	Min antenna gain dBi
US/Canada	7	27	43	33 @ 10 dBm
Japan	7	10	58	47
Korea	7	10	27	17
Australia	3,5	10	51,7	41,8
Europe	9	13	57	30

As can be seen from Table 1, the specifications for mmWave operation at 60 GHz differ between the existing ETSI specifications for operation in V band in Europe and those allowable in the USA under FCC Part 15.255. Specifically, in Europe, there are two ETSI specifications:

- EN 302 217 for Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas. This is generally used for point-to-point BH equipment and specifies minimum antenna gain of 30 dBi and max conducted power of +10 dBm up to an Equivalent Isotropically Radiated Power (EIRP) limit of +55 dBm.
- EN 302 567 for Broadband Radio Access Networks (BRAN); 60 GHz Multiple-Gigabit WAS/RLAN Systems (2012). This specifies a maximum EIRP of +40 dBm for outdoor and indoor operation and is therefore very similar to US FCC Part 15.255 – crucially the separation between gain and power is left open hence it is a better match for the use of an active phased array antenna – e.g. a +20 dBi gain array antenna with a +20 dBm conducted power from (e.g.) a 16 element array, each element with + 8dBm Tx power is technically and economically viable.

In Europe, improved regulation for operation of 60 GHz systems is under study by the ETSI mWT ISG group [27], to which 5G-XHaul is contributing. The current practice is that OEM manufacturers self-declare which standard their equipment adheres to.

The 60 GHz band has been one of the most studied mmWave bands as it is currently used for unlicensed Wireless HD and Wireless Gigabit Alliance (WiGig) WLAN devices. A majority of measurements were conducted for indoor applications due to the earliest intended use cases (WLAN), and high oxygen absorption centred around 60 GHz [25]. 60 GHz outdoor communication for unlicensed BH applications has just recently gained great interest. Outdoor studies at 59 GHz were conducted in Oslo city streets, and showed that a majority of delay spreads were less than 20 ns over seven different street scenarios for LoS and obstructed environments [28]. Measurements and models showed that path loss in LoS environments behaves almost identical to free space, with a *path loss exponent* (PLE) of 2. This and other main characteristics of mmWave channel in the 60 GHz band are summarised in Table 2:

Table 2: mmWave channel parameters at 60 GHz [28][29][30].

Parameter	Values / Ranges
bandwidth	2.16 GHz
# antennas @ BS or AP	16-32 (orientative)
# antennas @ MS	16-32 (orientative)
delay spread	3 – 80 ns (indoor) 0,9 – 47 ns (outdoor)
angle spread	az. 12.7° - 28.4°, el. 16.1° -21.2° (indoor)

	mean: 14.5° , std. dev.: 7° [26]
# clusters	< 4
small scale fading	Minor[2]
large scale fading	distant dependent + shadowing
PLE *n*	1.7 – 3.3 (indoor) 2 – 4.6 (outdoor)
penetration loss	varies (40-80 dB bricks)
human blockage attenuation	20-30 dB
channel sparsity	more
Oxygen absorption	15-30 dB/km
Rain attenuation	5 dB/km @ 10 mm/h

There are several standards already available in the 60 GHz band. The WirelessHD consortium has developed a 60 GHz system for uncompressed High Definition (HD) video, and the IEEE 802.15 Task Group 3c developed a mmWave based alternative physical layer for the existing 802.15.3 WPAN standard. IEEE 802.11ad is a WLAN standard for 60 GHz band. Both IEEE 802.15.3c and IEEE 802.11ad support single carrier and multi carrier schemes.

The IEEE 802.11ad standard for 60 GHz defines three different PHY layers, namely control PHY, single carrier (SC) PHY, and OFDM PHY. Control PHY is designed for low SNR operation prior to BF. SC PHY supports data rates from 385 Mbps to 4.62 Gbps. The third, OFDM, PHY layer is not mandatory (it is optional), and it supports higher data rates, up to 6.75 Gbps. The standard supports a number of modulation and coding schemes (MCS) to adapt to different range-rate trade-offs. PHY rates are summarised in Table 1.

Table 3: IEEE 802.11ad PHY data rates.

PHY layers	Modulation	Coding rate	PHY rates
Control PHY	π/2-DBPSK	½+(32 spreading factor) =1/64	27.5 Mbps
SC PHY	π/2-BPSK, π/2-QPSK π/2-16QAM	1/2, 5/8, 3/4, 13/16 LDPC	385 – 4620 Mbps
OFDM PHY	π/2-BPSK π/2-QPSK π/2-16QAM	1/2, 5/8, 3/4, 13/16 LDPC	693 – 6756.75 Mbps

The 5G-XHaul mmWave BH mesh requires an antenna with high directive gain, bandwidth which covers the entire 60 GHz V-Band, high realised-gain, low cross-polarisation in the main beam direction and azimuth- and (desirable) elevation-steering capability. These antenna characteristics could be achieved in a technologically novel approach using a 3D built antenna array system. Such an antenna system will be built vertically using stacked 2D sub-modules (sub-arrays). Each 2D sub-module will be an 8x1 (and if needed 16x1) end-fire antenna element sub-array driven by one beam forming IC (BFIC) - (2D sub-module = 8x1 element sub-array + BFIC).

[2] Nakagami with factor from 3 to 5.

The mmWave antennas built for the communication in the 5G-XHaul mmWave mesh BH networks communication system should therefore meet the following specifications:

- wideband antenna - in order to cover multiple wide bandwidth channels.
- high directivity with low side-lobe levels – in order to facilitate an interference-free communication with other neighbor cells.
- high realised gain – in order to compensate the high frequency free space path loss.
- steerable in both azimuth and (desirably) elevation– in order to communicate with radios positioned in urban environment (or in case of spatial multiplexing – steerable sub-arrays in both dimensions).
- low cross-polarisation.

The small wavelength, specific to the mmWave band, means that at least theoretically a large number of antenna elements in a smaller form factor could be used to implement highly directional, steerable antennas [31]. On the other hand, the same short wavelength limits the distance between array elements and makes the implementation of the feed network very difficult. These geometrical limitations and high frequency losses in the feed network determined that the mainstream of development in academic and industry to be in the direction of integration of analogue front-end with antenna array (on-chip antenna, antenna-in-package and so on). The drawbacks of such integration are higher antenna losses and limited array size. Non-integrated mmWave phased antenna arrays were also part of research and development activities but usually the number of elements is drastically limited because of the technological challenges and limitations (see planar or slotted waveguide implementations). Another hybrid approach was an implementation solution where a sub-array antenna, either integrated with the beamformer or build as a sub-module together with the beamformer, was part of a larger and scalable planar antenna array where the sub-arrays were tiles of the antenna array. There is a lot of ongoing research in this direction in order to find the right balance between antenna system requirements and possible technological implementations [29][32].

4.1.1.2 General Overview of mmWave systems: Requirements and Architecture

For the sake of simplifying the exposition, we proceed by describing in Figure 9 a simplified, generic architecture of a mmWave transmitter, several instances of which will be in focus of 5G-XHaul (note that not all the blocks have to be used for a particular instance). In particular, this work will be carried out in WP4, under Task 4.2 The corresponding mmWave receiver can be analyzed in an analogous way.

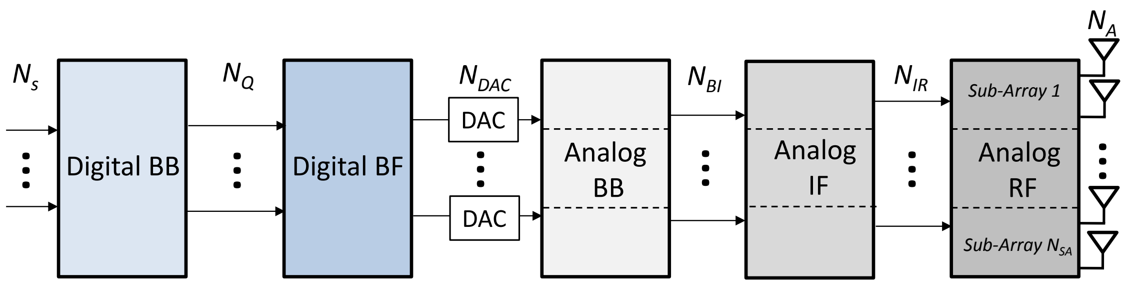

Figure 9: Generic architecture of a mmWave transmitter.

The notation in Figure 9 is as follows:

- N_S is the number of transported data streams in the system. While the current mmWave products typically operate with single-stream transmission, spatial multiplexing will be investigated in 5G-XHaul as well, under Task 4.2.1. The potential use cases to be analyzed range from SDMA-based p2mp backhauling (in addition to TDMA-based p2mp transmission), multiuser access, to LoS and NLoS MIMO transmission.
- Digital BB is performing waveform generation, and, in the case of multistream transmission, precoding. In general, $N_Q \geq N_S$, and the equality often holds in practice.
- Digital BF is the second stage of digital processing, which is typically frequency independent. In case the BF is realised in the digital domain, the interface denoted by N_Q can be considered as a new functional split corresponding to one of TC1 use cases from [1] (similar solutions are proposed for Sub-6 GHz massive MIMO system). In general, $N_{DAC} \geq N_Q$, and the equality often holds in practise.

- The Digital-to-Analogue Converters (DACs) and the Analogue-to-Digital Converters (ADCs) are of principal importance in mmWave transmission, as the ADC power consumption rises with the sampling speed and, particularly, with the resolution. For this reason, the practical solutions either assume that their number N_{DAC} is much smaller compared to the number of antenna elements N_A, or that their resolution is rather low.
- Analog operation in mmWave transmission often assumes BF which can be realised in BB, at an intermediate frequency (IF), or at RF. It should be noted that there are various realisations of beamformers including passive phase shifters, or vector modulators which can change both amplitude and phase. In addition to BF, operations of up-conversion and power amplification are performed.
- Regarding antenna arrays, there exist two principal architectural choices. The fully connected architecture assumes that any of the lines of the analogue interface N_{DAC}, N_{IR}, or N_{BI} can be connected to any of the antenna elements. As this might require very complex analogue circuits, the subbarray architectures, where each line is connected only to a part of the whole array (subarray) are of significant practical interest. Another design principle of interest is the lens antenna, consisting of an electromagnetic lens and a number of antenna elements in its focal region, with antenna selection reducing the number of required RF chains.

Some of the specific instances of the generic **mmWave transceiver architecture** of research interest for the 5G-XHaul project are:

- Multistream transmission: While the current mmWave products typically operate with single-stream transmission, spatial multiplexing will be investigated in 5G-XHaul, as well, as it is of significant interest for the work in IEEE802.11ay [24] and 3GPP 5G RAN [33]. The potential use cases are SDMA-based p2mp backhauling (in addition to TDMA-based p2mp transmission), multiuser access, LoS and NLoS MIMO transmission. The digital BB part operating on multiple streams can be followed by analogue or digital BF. This work will be carried out under Task 4.1.1 in WP 4.
- Single stream transmission following the IEEE 802.11ad standard, with analogue RF BF using vector modulators and a subarray antenna architecture. This architecture presents a baseline for the testbed and algorithmic research in the 5G-XHaul project. This work will be accomplished under Task 4.2.2 in WP4.
- Passive realisations of analogue BF: Here, fixed magnitude constraint on the phase shifters, and the losses of the passive components are considered (Task 4.2.1)
- Digital BF with low resolution DAC/ADCs, with 1 bit ADC being the extreme case (Task 4.2.1).

5G-XHaul mmWave transceiver solution

Given the focus of the project on configurable mmWave links and the expertise of the 5G-XHaul partners involved in the mmWave communication part, we now present our initial mmWave transceiver solution for reconfigurable transport links and detail its particularities. Some of the principal enablers to fulfil the requirements of the 5G-XHaul project are SiGe BiCMOS technologies and large, steerable antenna arrays.

From the general view of Figure 9, the 5G-XHaul mmWave solution only supports analogue BF, which is an approach that relies on RF domain processing to reduce number of RF chains and ADC/DACs. The BF is implemented using networks of digitally controlled analogue phase shifters or vector modulators. The former allows only change of phases of the signals feeding the inputs of antenna arrays to steer the transmit/receive beams in the desired directions, and the performance is limited by finite number of phase angles (i.e. quantisation of the phase angles). The latter one allows change of both phase and amplitudes of the signals feeding the antennas. The main drawback of this type of mmWave architecture is the support of only single stream MIMO transmission.

5G-XHaul will develop BF chipsets and design techniques to allow dynamic and autonomic reconfiguration of the mmWave transport under Task 4.2.2, enabling the network management to decide on the directions to steer, and the adequate BF weights derived by the individual mmWave nodes. The BF chip will work in both TX/RX Modes, with eight bidirectional channels. These techniques will also allow the implementation of different P2MP schemes over several mmWave nodes.

Antennas for p2mp wireless BH at 60 GHz have to be highly directive, with high gain enabling efficient BF and easy integration with the BF chipset. Planar (printed) antenna arrays are considered due to their small form factor, good reproducibility and low cost. Phased antenna arrays with patches or dipoles as basic antenna elements are investigated, with the target to enable scanning in both horizontal and vertical directions. The advantages and limitations of both types are being studied and the one with better properties (gain and complexity) will be chosen for implementation in the final demonstrator.

With all this, a particular instantiation of this work will be developed in WP4, under Task 4.2.2.

4.1.1.3 Sub-6 GHz wireless technology

The 5G-XHaul NLoS technology will be developed in WP4 under Task 4.3, and will incorporate an 802.11ac MAC and PHY, which will be extended to enable remote programmability. Consequently, the 5G-XHaul control plane will be able to measure the state of the Sub-6 BH, while controlling forwarding rules and MAC transmission parameters in order to provide transport flows with the required QoS. If 5G-XHaul Sub-6 nodes are collocated with 5G-XHaul mmWave nodes, the available synchronisation signal could be used for both kind of nodes, which will leverage synchronisation to mitigate contention and interference thus improving performance.

Furthermore, with the latest advances in the physical layer (i.e. aggressive modulations up to 1024-QAM, MIMO, etc.), this kind of networks are ready to offer throughput in the Gbps scale. Figure 10 shows an example of a mesh topology based on Sub-6 GHz TNs with multiple radios. In the example, TN2 and TN4 are co-located with ANs, which also make use of the same Sub-6 GHz bands.

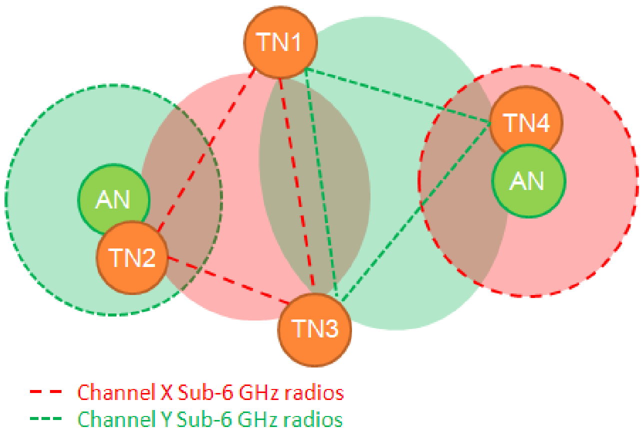

Figure 10: Example of mesh topology backhauling two Sub-6 GHz ANs consisting of four multiple-radio Sub-6 GHz TNs.

Due to the prevalence of IEEE 802.11-based radios within the Sub-6 GHz category, it is pertinent that we pay special attention to this family of technologies[3]. The latest commercial Wi-Fi devices support IEEE 802.11n and/or IEEE 802.11ac features, besides, the first IEEE 802.11ah-compatible devices [34] are expected to become available this year 2016, under the new Wi-Fi HaLow certification program by 2018 [35]

Table 4: Main characteristics of the PHY layer of the latest IEEE 802.11 specifications.

	IEEE 802.11ah	IEEE 802.11n	IEEE 802.11ac (Wave 2)	IEEE 802.11ac (Spec.)
Band	900MHz	2.4GHz & 5GHz	5GHz	5GHz
Antenna configuration	up to 4x4 MIMO (multi-user)	up to 4x4 MIMO (single user)	up to 4x4 MIMO (multi-user)	up to 8x8 MIMO (multi-user)

[3] Note that these technologies normally operate in ISM (i.e. unlicensed) frequency bands and, therefore, have to deal with heavy competition from many unpredictable sources of interference. In consequence, for the deployment of IEEE 802.11-based wireless backhaul networks, the use of licensed frequencies is recommended, especially in dense scenarios.

Highest modulation	256-QAM	64-QAM	256-QAM	256-QAM
Channel bandwidth (MHz)	1, 2, 4, 8 and 16	20 and 40	20, 40, 80 and 160	20, 40, 80 and 160
min/MAX PHY bitrate (Mbps)	0.15/347	6.5/600	6.5/3470	6.5/6933
(*)MAX coverage (m)	1500	200	150	150

(*) MAX coverage is achieved with the most robust modulation and coding scheme, i.e. at the slowest bit rate.

The IEEE 802.11 standard defines a distributed MAC, based on Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA), that is, stations transmit only after the shared medium has been sensed idle for a certain period of time; if the medium is busy, stations wait a random backoff time before trying again. The range of possible values for that random backoff time increases exponentially for each retransmission (e.g. upon a collision). The overhead introduced by the MAC layer can reduce throughput to ~65% of the nominal bitrate (shown in Table 4) or less, if the collision probability is high.

With CSMA, collisions occur frequently when the number of competing devices is high (i.e. tens of simultaneously active stations), degrading the performance of the radio links (increase delay, reduce throughput). Note that the number of neighbouring nodes participating in a mesh-like wireless BH and competing for the shared channel is expected to be low (cf. Figure 10). However, if both the RAN and the wireless backBH share the same frequency resources, then contention becomes an issue requiring careful attention.

The combination of CSMA with other multi-user techniques (SDMA through MU-MIMO from IEEE 802.11ac; OFDMA, under study for the future IEEE 802.11ax [36]; and even TDMA), highly configurable MAC and PHY layers and a smart resource management can mitigate, in part, the aforementioned drawbacks. Still, all this randomness hinders the identification of reliable upper bounds for time-related key performance indicators (access delay/jitter). As a consequence, IEEE 802.11-based radio links may not be suitable for transport classes with very strict time constraints. This study is presented in Section 4.5.

Sub-6 nodes are equipped with wide beam antennas and, thus, they can easily "see" multiple nodes in the vicinity, with which they can peer to form mesh-like topologies whereby redundant paths are offered to connect, wirelessly, the RAN with the CN.

In terms of node discovery, Sub-6 could assist in the creation of mmWave BH links, where mmWave directive antennas are equipped with motorised pan/tilt:

- Sub-6 (widebeam/omni, NLoS) discover other TNs in range.
- Sub-6 assess relative position of neighboring TNs (as per 802.11az [37]).
- Co-located mmWave interfaces use location information to point antenna towards most suitable peer to create/join a wireless BH.

A network controller may decide to change the topology of the BH links on demand to optimize data paths.

4.1.2 mmWave links for transporting C-RAN FH flows

As depicted in Figure 7, 5G-XHaul will enable the effective low-latency transport of digitised radio signal flows over multi-hop mmWave topologies. In particular maximum one way delays of 40 μs will be considered to allow the transport of CPRI over wireless links. However, the direct application of CPRI-like FH consisting of in-phase and quadrature (I/Q) samples for every antenna element leads to unacceptably high FH data rates.

While the current CPRI has a two way jitter requirement of 16.276 ns to comply with the 65 ns time alignment requirements of 2G/3G/4G systems, possibly tighter time alignment requirements in 5G might require amendments in FH standards or favor functional splits with less centralisation (Section 4.5 p.34 [13]).

Utilisation of large antenna arrays, both in Sub-6 GHz and mmWave bands, is expected to be a key component of the envisaged 5G air interface [45].

Figure 11 illustrates the joint operation of the mmWave wireless transport elements in 5G-XHaul. In a hybrid RAN deployment comprising Small Cell BSs and RUs, the mmWave FH can be dynamically used to forward the heavy flows (c.f Section 4.5 for more details on flows that can be conveyed via mmWave) connecting the RUand the CUs.

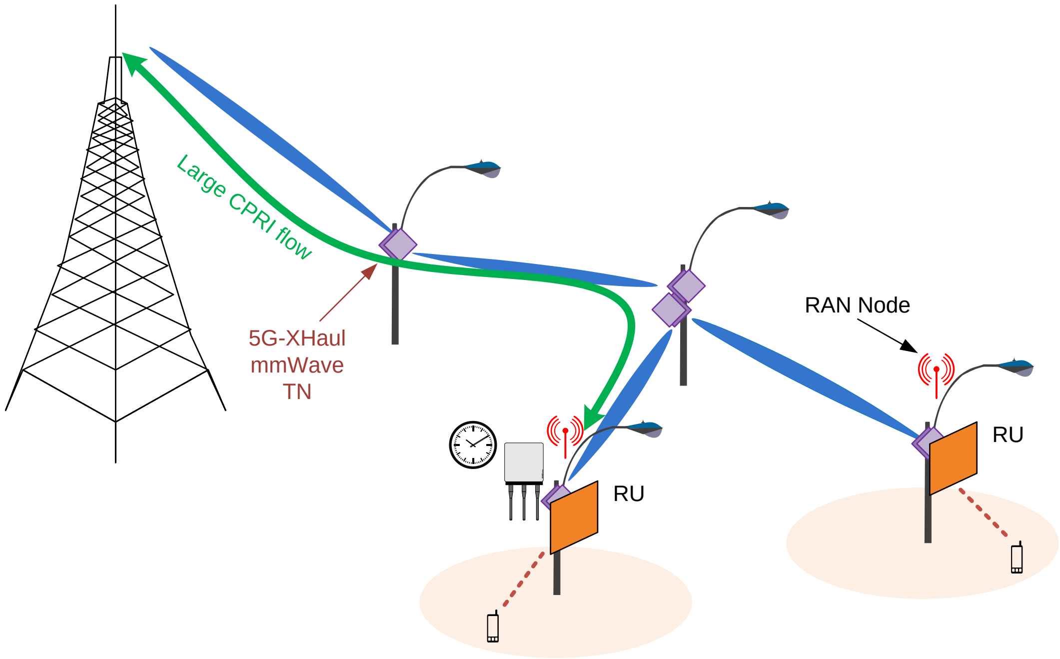

Figure 11: Transport of heavy flows over mmWave links.

As can be seen in Figure 11, 5G-XHaul proposes the use of massive MIMO technology for the AN (a RU using a much greater number of antenna elements) to strongly improve data rates, reliability as well as energy efficiency of the wireless access links. Performing for instance certain parts of the layer 1 processing at the RRU can substantially relax the requirement of feeding hundreds of antenna elements.

Wireless FH has inherent bandwidth limitations, which are especially relevant in the case of massive MIMO. For this purpose, 5G-XHaul studies massive MIMO with a new type of functional split that reduces transport requirements. Therefore, in this scenario we see Massive MIMO as an enabler to have wireless FH also given the possibility of including some processing capabilities at the RU which, in this case, will convey functional split suitable to the available mmWave technology. An initial idea of the requirements is shown in Table 9. This work will be carried out in WP4 under Task 4.3.2.

4.1.3 Joint access/BH mesh for mmWave and Sub-6

The convergence of optical and wireless network technologies, as well as their management cannot be investigated without considering the dynamic load generated in the RAN. 5G-XHaul will deliver an access agnostic transport network able to integrate any novel access technology designed for 5G. The transport network must scale in capacity to avoid becoming a bottleneck beyond the current data capacity shortage experienced by customers in the wireless access segment.

The inter-operation of the mobile network and the transport network is a promising trend to be able to cope with future 5G requirements. In these lines, in the converged scenario 5G-XHaul proposes, that the same wireless BH technology can be used for both the BH and the access link, making more efficient use of spectrum resources as they can be shared dynamically. The heterogeneous transport structure will also influence the operation of the RANs, e.g. latency differences on BH links could impact intercell coordination and cooperation algorithms. Therefore, both the mobile and the transport networks need to be aware of the limitations and capabilities of each other.

As depicted in Figure 7, wireless BH network elements can be dynamically configured either as TNs, or ANs – or to perform both roles simultaneously – depending on the (instantaneous) needs of the network. As an example, a small cell based on Wi-Fi (i.e. acts as AN) can be switched to a TN mode when traffic demand in its area relaxes, thus offering a new BH path (adds redundancy, relieves load from other BH links, etc.).

In ultra-dense deployments, access and BH convergence play a role in terms of sharing different types of resources (hardware, frequency, etc.) so they are utilised in a more efficient way. This convergence would also benefit from defining aligned PHY-level processing in the wireless access and transport/BH domains (frame structure, etc.), which provides the converged solution with full flexibility.

The concept of dynamic control of the wireless BH topology, where mmWave beam steering techniques are used to adjust the topology to the traffic demand can be used to extend the reach of 5G-XHaul transport network to the access segment. In particular, a moving end user device incorporating mmWave and Sub-6 technologies can be seen as an extreme case of dynamic wireless BH link, where due to user movement the device's point of attachment has to be often updated. This scenario is depicted in Figure 12.

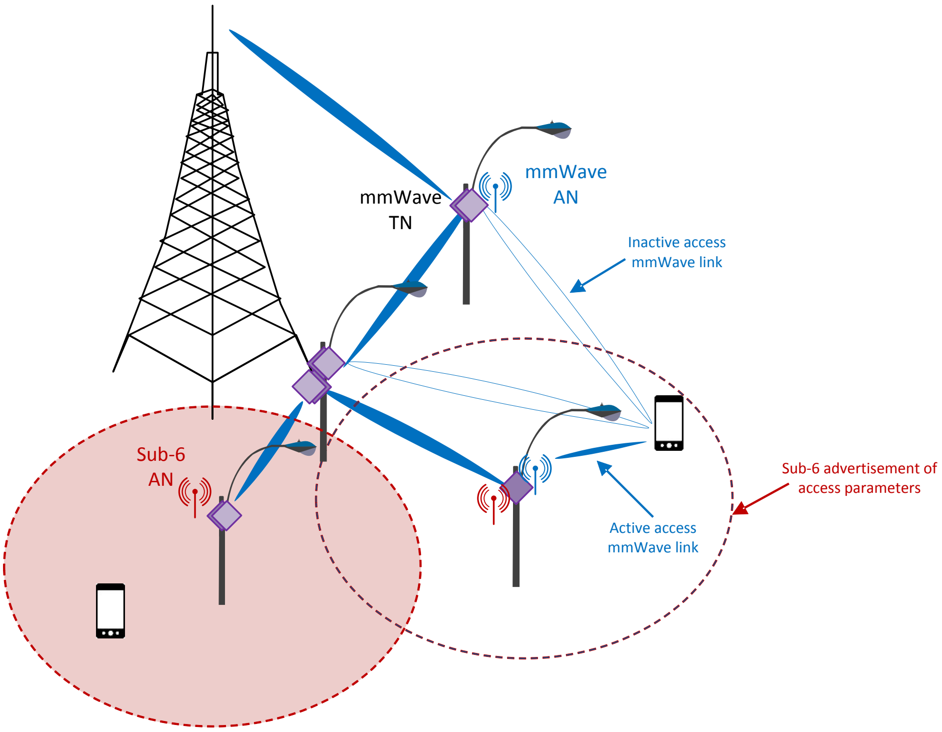

Figure 12: 5G-XHaul access extension.

Moreover, Sub-6 TNs, that are not deployed as densely as mmWave TNs, could be used for discovery of surrounding RAN elements, while the mmWave interface will be used to establish a high data rate communication with the RAN point of attachment. In a dense Small Cell network an end user device will have multiple network attachment possibilities, which will change in time as the user moves.

The work carried out here will be performed in WP4 under Task 4.3 and Task 4.4. In these tasks we will investigate the system wide benefits of co-locating nodes with Sub-6 capabilities together with mmWave nodes, and we will propose coordination methods for RUs and BSs, targeting a precise frequency, phase and time synchronization through either mmWave or Sub-6 links. The widely known methods for synchronisation will be complemented with offering these capabilities to the RAN.

4.2 Optical Technologies

To address the high bandwidth connectivity requirements of the 5G-XHaul solution the use of optical transport to support 5G networking will be demonstrated. The optical transport proposed will be based on two different WDM technologies, including an active and a passive solution. In terms of active technologies current commercially available solutions perform optical switching supporting wavelength switching granularity. However, given the very diverse requirements of operational and end-user services in the context of 5G, there is a need for new approaches, deploying more dynamic and flexible solutions that offer higher granularity at the sub-wavelength level and more elasticity in the optical domain. In view of these new requirements we propose an elastic frame-based WDM active solution in combination with a passive optical network (PON). The active solution adopts the TSON approach to provide variable sub-wavelength switching granularity and the ability to dynamically allocate optical bandwidth elastically [15], while low-cost point-to-point connections with limited flexibility, e.g. between the edge network and remote cells is supported through passive DWDM networks (WDM-PONs).

4.2.1 Time Shared Optical Network (TSON)

To support the varying degrees of bandwidth and latency requirements introduced by hybrid RAN deployments, we propose the use of the TSON optical network technology [38]. TSON is a multi-wavelength fully bi-directional synchronous and frame based flexible system. Its network implementation consists of FPGA optoelectronics platforms integrated with advanced optical components to enable high performance processing and transparent switching and transport [15][38][39]. The FPGA platforms are based on Xilinx Virtex 6 HXT boards (156.25 MHz clock frequency), supporting multiple 10 Gbps (for control and transport) DWDM SFP + transceivers. For the optical layer, TSON relies on fast optical ((Pb,La)(Zr,Ti)O_3) (PLZT) switches [39] having 10 ns switching speed as well as a set of active and passive components including Erbium Doped Fibre Amplifiers (EDFAs), MUX/DEMUXes etc. TSON is designed and implemented as a novel frame-based, time multiplexing network solution, offering dynamic connectivity with fine granularity of bandwidth. TSON is a contention-less solution through the deployment of a central resource allocation engine of route, wavelength, and time assignment, responsible to set-up the sub-wavelength paths. 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 domain and vice versa. The ingress TSON edge nodes are responsible for traffic aggregation and mapping, while the egress edge nodes having the reverse functionality. TSON edge nodes use FPGA platforms for processing of incoming data streams and to generate optical time-slices from them at the ingress TSON edge, and also to regenerate the original information from time-sliced optical bursts at the egress TSON edge node. In order to send and receive data, each TSON edge node (see Figure 13) uses four SFP + transceivers, two 1310 nm 10 km reach for end-point server traffic and control, and two DWDM 80 Km reach transceivers at 1544.72 nm and 1546.12nm. The 1310 nm interfaces can be used to support both data and control traffic either separately or combined depending on whether out-off band or in-band control is adopted. Although the current TSON configuration allows handling of Ethernet frames, it natively supports of broad range of framing structures and communication protocols including CPRI, OBSAI, 10GEthernet etc.

In addition to this, it should be noted that as TSON supports Ethernet natively, it can transport CPRI and OBSAI either natively or through their packetised versions. As later detailed in Section 4.5.2 a Next Generation Fronthaul Interface (NGFI) based on additional functional splits that provide a range of trade-offs between transport requirements and centralization gains is being defined in IEEE 1904.3 [21]. In case that the future NGFI interface is packetised using Ethernet framing, it will be also natively supported by TSON.

For example, in Figure 13, if Ethernet traffic is considered at the ingress part of the edge node, the Ethernet frames received at the 10 Gbps receiver are passed to the 10GE MAC; Then the MAC discards the preambles and frame check sequence (FCS), transmits the data to the RX first in, first out (FIFO) and indicates whether the packet is good or not; The RX FIFO receives the data, waits for the good/bad indication from MAC, sends it to the DEMUX block if they are valid data. The DEMUX analyses the Ethernet frame information (i.e. Destination MAC address, Source MAC address and so on) and puts them in different FIFO. After that, the FIFO does not send any data until the AGGREGATION gives a command; the register file of AGGREGATION, containing the Time-slice Allocation information, is updated by the Lookup Table (LUT) (this table stores information related to time-slice Allocation and PLZT switching). The AGGREGATION module waits for the burst-length Ethernet frames ready in the FIFO and the time-slice allocation available, then transmits the bursts into a suitable wavelength TX FIFO. For the egress part of the edge TSON node, when the 10Gbps receiver receives the burst (time-slice), it drops it in the RX FIFO Lamda1/Lamda2; after the burst is completely received, the SEGREGATION block segregates the burst to Ethernet frames and transmits them to a TX FIFO. Every time the TX FIFO receives a complete Ethernet frame it sends it to the 10GE MAC. Finally, the MAC passes the data to the 10 Gbps transmitter and transmits them out.

On the other hand, when the ingress node receives CPRI traffic, the stream of radio data (I/Q samples) first traverses a pluggable I/Q module responsible for multiplexing and demultiplexing of I/Q samples and then the CPRI core that provides a set of interfaces having the following functionalities:

- *I/Q Interface*: Consists of a stream of radio data (I/Q samples) that is synchronised to the Universal Mobile Telecommunications System (UMTS) radio frame pulse.
  Synchronisation Interface: Provides the means for the client logic to synchronize to the network time by transmitting the UMTS radio frame pulse and clock frequency.
- High-Level Data Link Control (HDLC) Interface: Transports management information between master and slave. The HDLC interface is serialised and synchronous.
- Ethernet Interface: When configured to support speeds of up to 3072 Mbps.

Once CPRI frames reach the aggregation block then according to the LUT information of the Time-slice Allocation, the aggregation block calculates the frames needed to construct the burst, aggregates the frames, waits for the valid Time-slice, and finally sends the burst into a different wavelength FIFO. At this point, it should be noted that the I/Q module and the CPRI core are based on the Xilinx IP cores LogiCORE CPRI [4] whereas for the Ethernet MAC functionalities the LogiCORE 10-Gigabit Ethernet MAC and Xilinx GTH Transceivers are instantiated. A high level view of these function blocks of TSON edge nodes supporting Ethernet traffic together with the necessary extensions for CPRI traffic handling is provided in Figure 13:

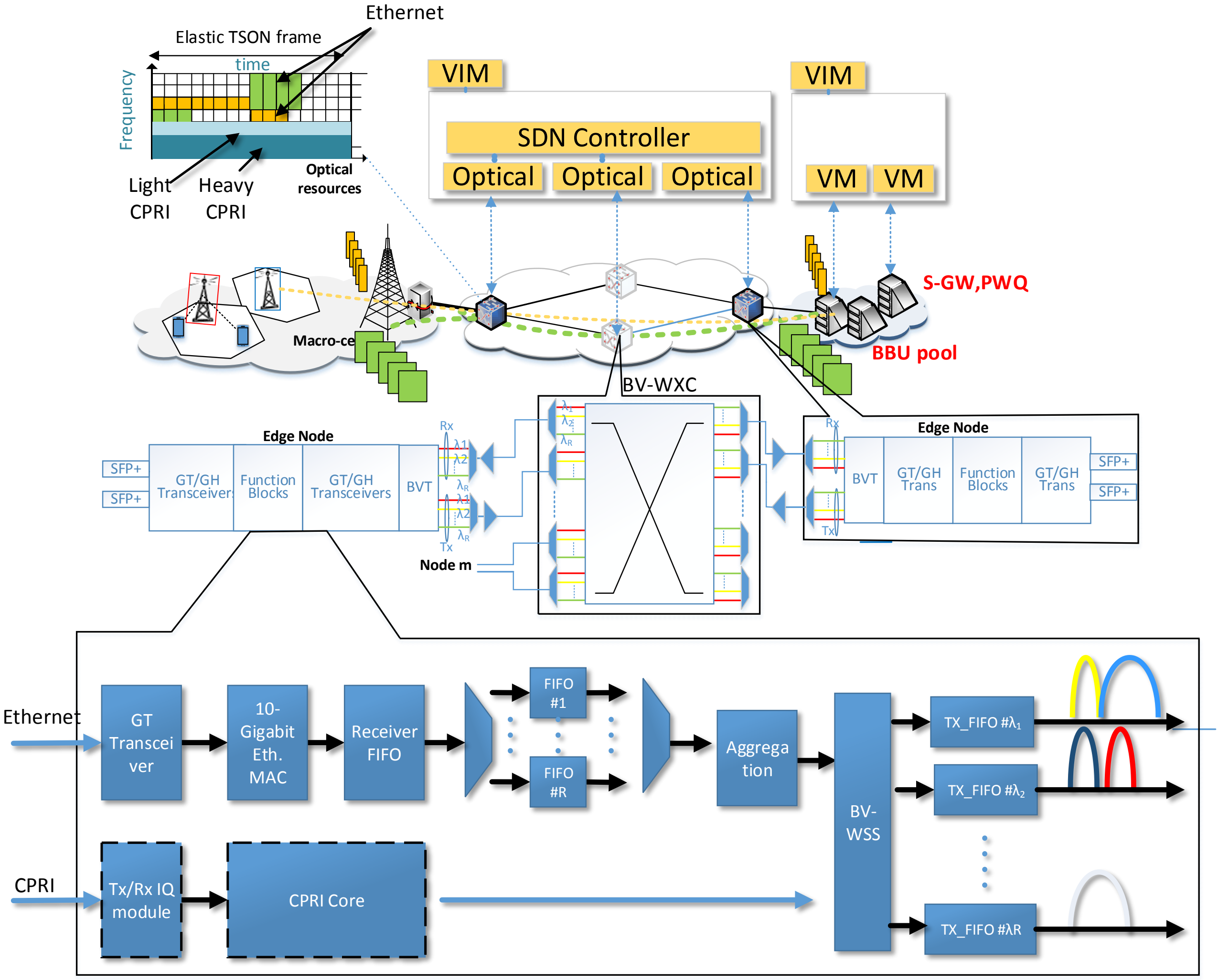

Figure 13: TSON edge function blocks with CPRI extensions.

The TSON core nodes switch transparently optical frames to the appropriate output port utilizing fast optical switching based on PLZT technology (Figure 13). The switching time of the core TSON nodes is 10 ns. These nodes adopt the wavelength selective architecture and as such require one switch per wavelength, to direct the incoming optical time-sliced signals towards the appropriate output ports, as defined by the control plane. The dimension of the space switch is defined by the number of fibres that are interconnected through the node. The TSON core node uses the same type of high performance FPGA boards for the PLZT control. The FPGA LUTs are filled from the control plane, through customised Ethernet communication carrying PLZT switching information, so to change the switching state per time-slice on the PLZT switches to establish and maintain optical paths across the TSON domain. The basic functions for the operation of TSON domains have been implemented in internal modules, within the SDN controller, that cooperates together for the on-demand provisioning of connectivity between TSON core and edge nodes. The interested reader can find a detailed description of the TSON control plane in the 5G-XHaul deliverable D3.1 [40]. Within the con-

[4] http://www.xilinx.com/support/documentation/ip_documentation/cpri/v8_2/pb012-cpri.pdf

text of 5G-XHaul, TSON will be extended in order to be capable of dividing the optical spectrum in a flexible manner and generating elastic optical paths, i.e. paths with variable bit rates. These TSON extensions will be carried out in WP4 within Task 4.1.

TSON synchronisation

The TSON network requires global frame synchronisation among TSON nodes to meet the precision needed in the 5G-XHaul environment. Currently, network-wise synchronisation is implemented connecting the FPGA boards to a statically selected master clock node via dedicated synchronisation links, and using a 3-way frame synchronisation protocol as shown in Figure 14, to tune and maintain a global frame.

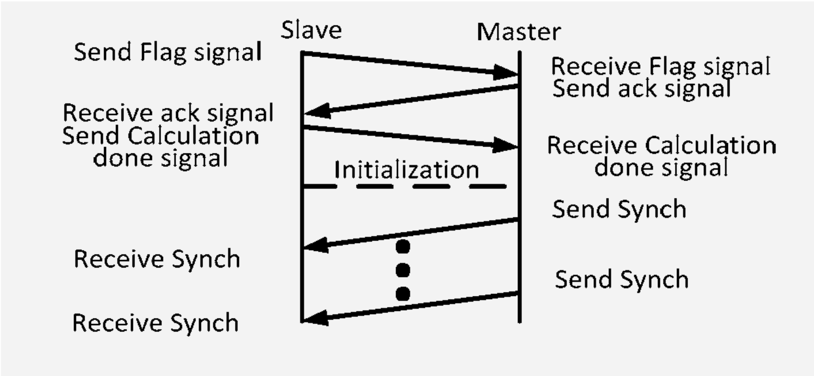

Figure 14: TSON data-plane synchronisation protocol.

The master clock node sends synchronisation frames – either in-band or out-of-band (OOB) modes – generated within just one FPGA clock-cycle (156.25 MHz → 6.4 ns) – with timestamps to the clock slave nodes regularly. The slave nodes use the timestamps and the known trip time between the slave and the master nodes to compensate for clock variations and drifts. The time-slice synchronisation in TSON is not needed since the link delay between network nodes is engineered to be multiple(s) of time-slice duration. As the network expands geographically, to maintain the synchronisation, the period of the regular synchronisation messages can be changed to avoid major drifts due to larger trip times. In addition to the above, more advanced synchronisation protocols (i.e. IEEE 1588) are natively supported by the FPGA edge nodes enabling 2-step precision time protocol (PTP) hardware timestamping through the instantiation of the Timer Synchronisation core module [41]. This core synchronises the time-of-day time from the system clock domain into the core clock domain. A high level view of the overall system with timer synchronisation capabilities is provided in Figure 15. The TSON synchronisation scheme that will be deployed will be designed and developed in detail in the framework of WP4 under Task 4.1.

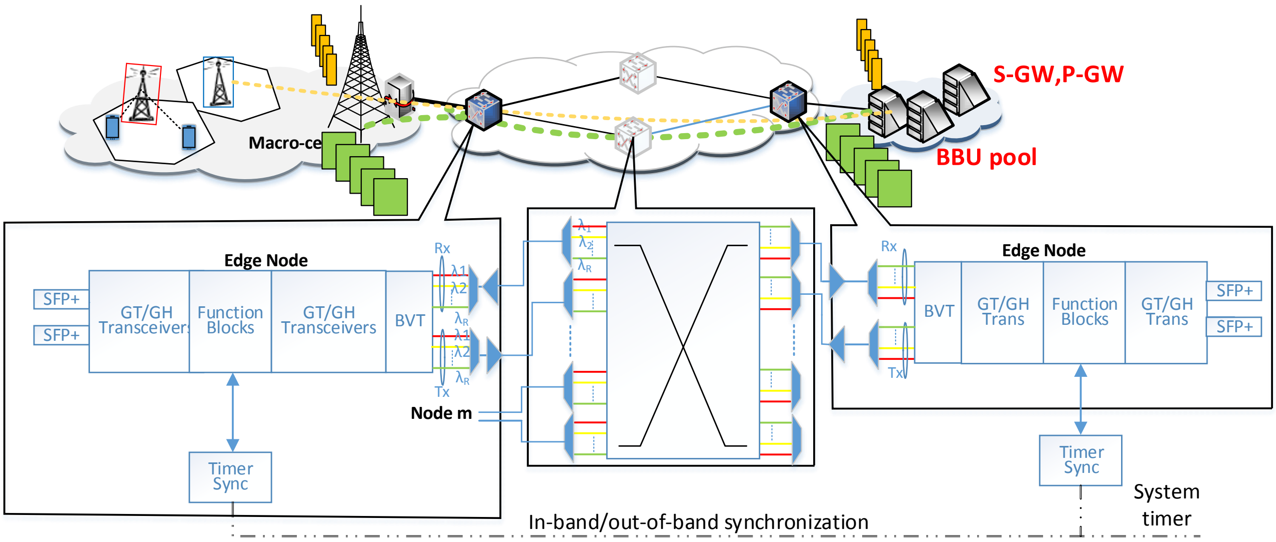

Figure 15: End-to-end TSON synchronisation.

TSON Resource Allocation Capabilities

Overall, the TSON network offers a hierarchy of three levels of resource granularity: connections, frames, and time-slices, as illustrated in Figure 16.

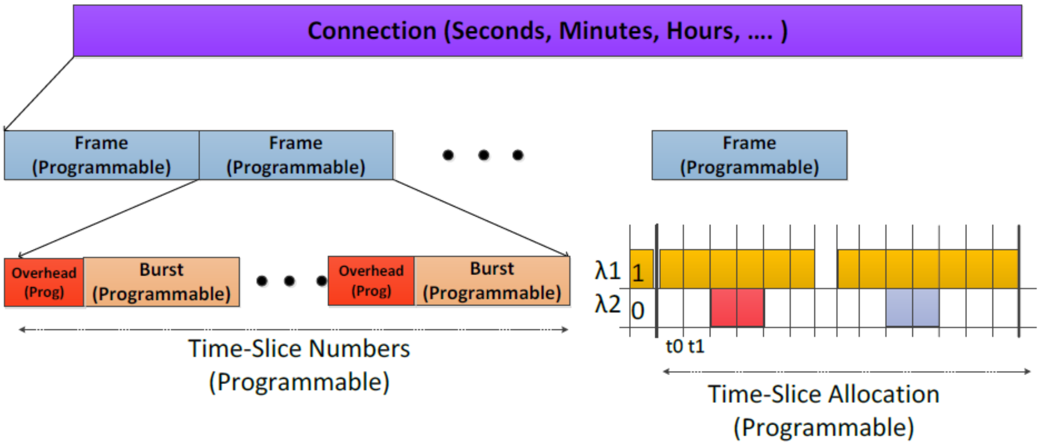

Figure 16: Structure of connection, frame and burst [15].

Connection refers to a sub-wavelength lightpath establishment between any two end points in the TSON domain. In order to improve statistical multiplexing of data units, each connection lasts for a number of frames with minimum size of 1 ms. Each frame is divided to time-slices as the smallest units of network resource, i.e. the actual sub-lambda resources. The frame length and the number of time-slices inside a frame define the minimum granularity achievable by the TSON network [14].The TSON framework offers a very flexible optical platform that supports sub-wavelength switching, frame lengths, varying from 64 ns to 25.6 μs and variable bit rates, spanning from of 30 Mbps up to several Gbps, with 30 Mbps step. As TSON's operational characteristics can be dynamically modified, varying service related requirements can be also supported. A typical example illustrating how a heavy CPRI flow can be embedded into the TSON framing structure is illustrated in Figure 17.

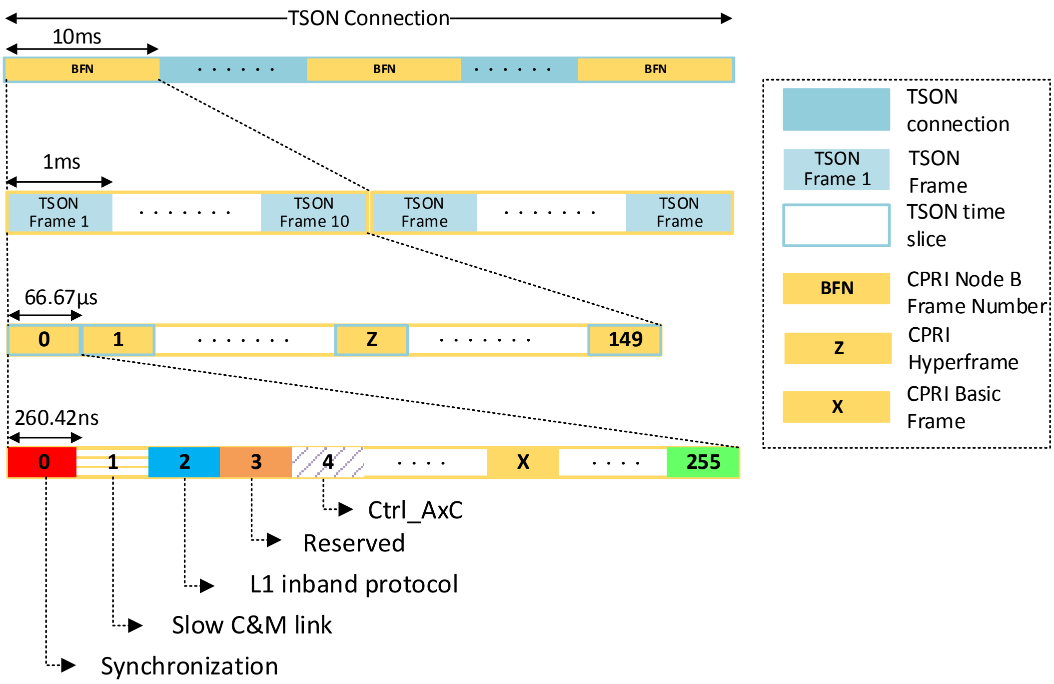

Figure 17: CPRI frame structure over TSON.

As already discussed TSON extensions are planned to be developed in the framework of 5G-XHaul and will include elastic bandwidth allocation (Figure 18) supporting continuous channels at various bit rate (i.e. heavy and light CPRI connections), as well all as sub-wavelength traffic.

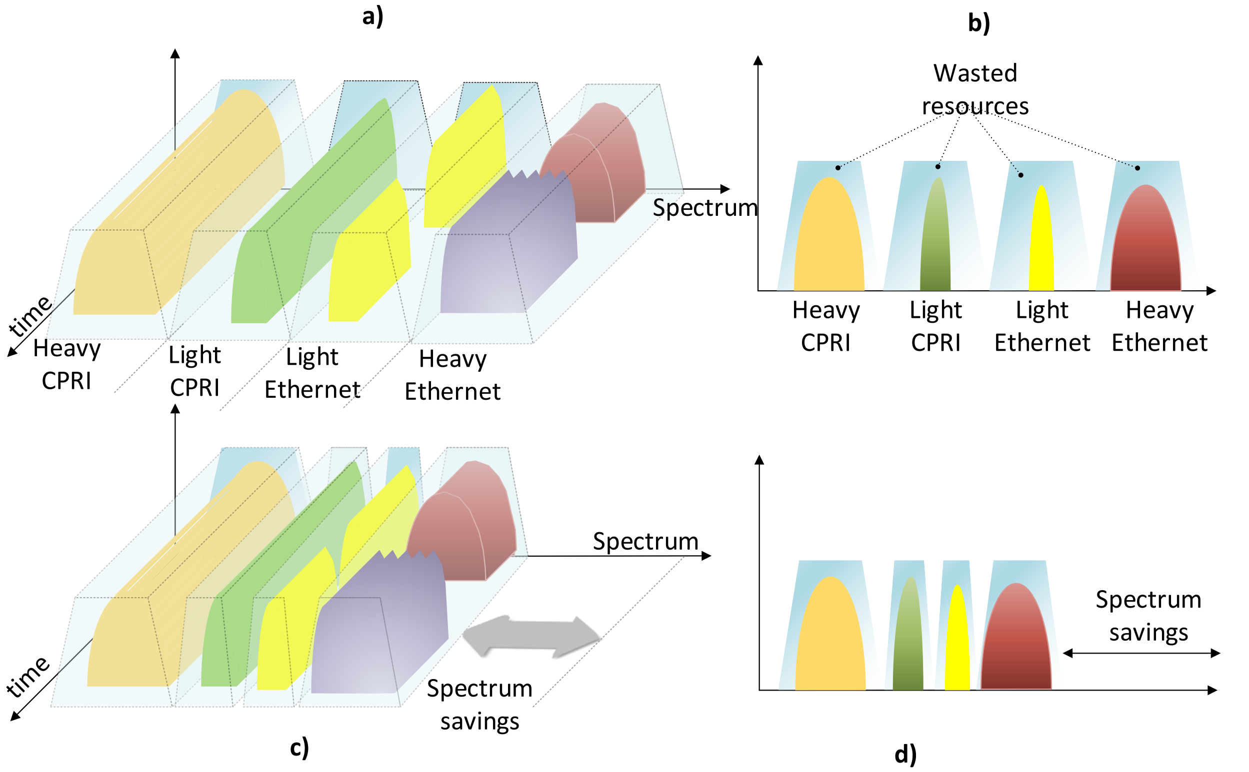

Figure 18: Joint BH/FH resource allocation without and with elastic bandwidth allocation: a-b) Fixed grid bandwidth allocation for fronthaul (Light, Heavy CPRI flows) and BH services (light and heavy Ethernet traffic, b) Support of the same services through flexible spectrum allocation.

4.2.2 WDM-PON

Connectivity between a central node and several distributed nodes is achieved using a WDM-PON system, terminating all wavelengths in an optical line terminal (OLT) and each individual wavelength in an ONU. Wavelength selective elements provide wavelength tunnels between the OLT and each ONU. The layout can be in a tree architecture with a trunk line between the OLT and a central filter node, from which individual drop lines connect to the ONUs, as shown in Figure 19a. An alternative architecture is the drop line structure, where individual wavelengths or groups of wavelengths are added and dropped at distributed filter nodes along the trunk line, as depicted in Figure 19b. In both cases, the OLT communicates with each ONU on a specific wavelength. Each ONU needs to adaptively select its transmission wavelength to fit the connected filter port. This is done with feedback from the OLT via an OOB communication channel.

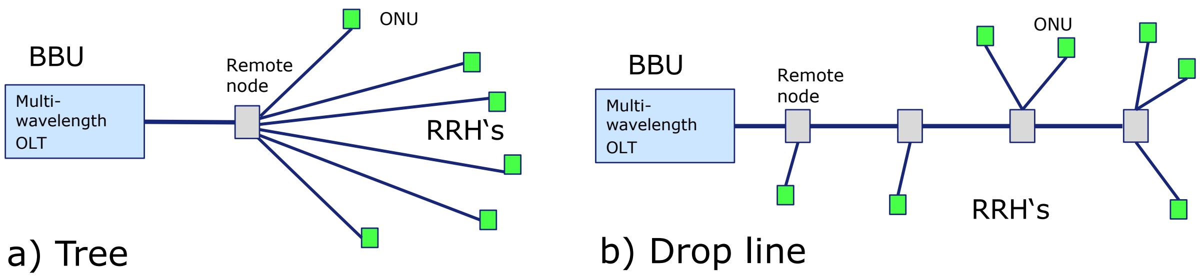

Figure 19: WDM-PON system architectures. a) tree structure, b) drop line structure.

While the optical layer of the WDM-PON provides a fixed connection between each fixed-wavelength transceiver in the OLT and a particular ONU, as determined by the remote node port, flexibility can be introduced into the system by using a cross-connect on the client side of the OLT. Different resources can thus be flexibly assigned to the network nodes connected to the ONUs. Figure 20 shows an example setup, where the WDM-PON system serves for FH applications by connecting BBUs at the OLT to RRHs attached to the ONUs. RRHs can be flexibly connected to different BBUs by changing the BBU - OLT transceiver connection in the cross-connect. Likewise, the system serves for BH applications by connecting ports of a 5G-XHaul Ethernet switch at the OLT to BBUs attached to the ONUs. This assignment is also reconfigurable via the cross-connect.

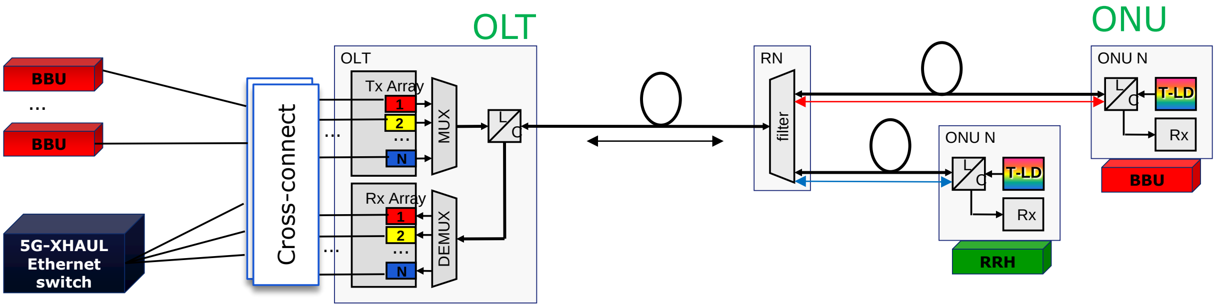

Figure 20: WDM-PON system architecture flexibly connecting nodes for FH and BH applications.

To realise the cross-connect a transparent solution can be provided, for instance, by an optical fiber switch. Figure 21 shows the working principle of a fiber-to-fiber switch based on optical beam steering. This type of switch is available with the size of up to 384 x 384 ports. For the application on the OLT side of a WDM-PON system, the size of 80 x 80 ports is sufficient. The advantage of an optical switch is data rate and format transparency, such that Ethernet as well as Optical Transport Network (OTN) or CPRI signals of any rates can be switched. Also, the switching power is typically low and does not depend on the rate of the signal.

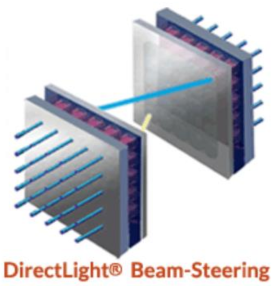

Figure 21: Working principle of optical beam-steering switch (Source: Polatis).

Alternatively, electrical switches can be utilized in the cross-connect. However, these switches are often rate or format specific, or they might terminate the protocol of the Layer-2 signal. On the other hand, they provide a lower cost solution and can be implemented with a smaller footprint.

4.3 Ethernet as a Physical Technology for BF/FH Convergence

Ethernet (referring to Ethernet PHY and forwarding) can be used for both FH and BH type of traffic, as illustrated in Figure 5. In the FH/BH over Ethernet paradigm, in principle, any optical fibre module that can be used on an Ethernet switch can be utilised. Some commonly used optical fibre modules include (not an exhaustive list):

- 10GBASE-LR (10km), XFP/SFP+
- 40GBASE-LR4 (10km) / FR (2km), CFP/CFP2
- 100GBASE-LR4 (10km), CFP/CFP2

Traditionally, Ethernet is used for best effort services. If Ethernet is used for FH, in order to meet the critical delay and jitter requirements, a path must be defined and bandwidth must be reserved along the path for a FH flow, to avoid congestion, delay, jitter, and packet losses.

From the data plane perspective, there are several approaches which can be of interest in enabling FH/BH over Ethernet, such as:

- Multiprotocol Label Switching – Transport Profile (MPLS-TP) over Ethernet
- Configuring Virtual Local Area Network (VLAN) (IEEE 802.1Q) in an Ethernet switch to address the FH/BH requirements, or any 5G-XHaul transport class in general. Here, the RRH sends out CPRI (over fibre) traffic, and the ingress Ethernet switch encapsulates the CPRI traffic over Ethernet. At the egress switch, the Ethernet encapsulation is removed. In order to guarantee bandwidth for a CPRI flow or CPRI flows from a RRH, a single VLAN ID should be configured end-to-end for the flow(s) with the bandwidth reserved, as illustrated in Figure 22.

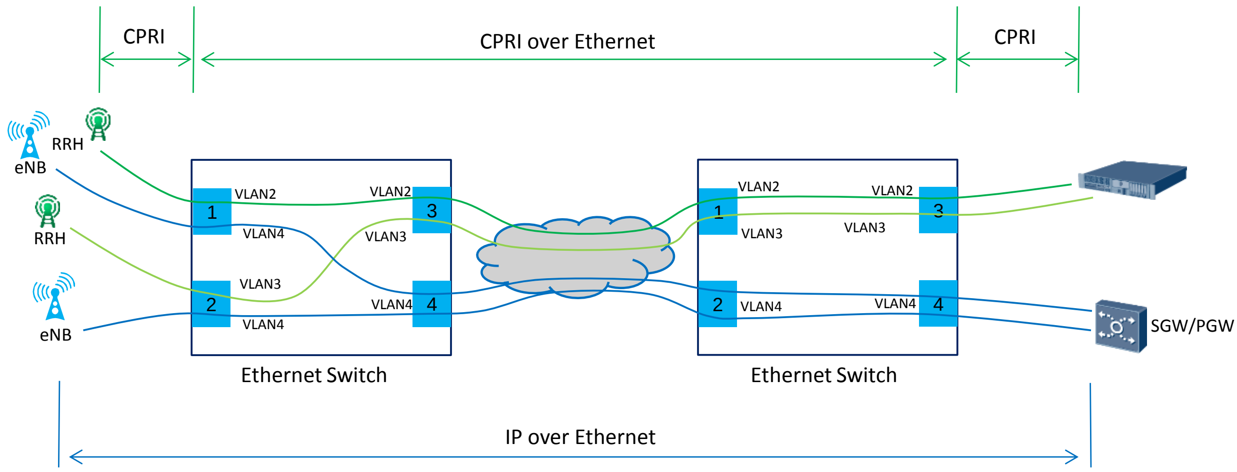

Figure 22: FH and BH over Ethernet by configuring VLAN.

A deeper analysis on the QoS features provided by Ethernet to support joint FH/BH can be found in [40]. However, even with methods for path/bandwidth reservation, several issues with Ethernet for FH/BH in terms of QoS remain to be resolved. In the sequel, some of the related research challenges are explained.

CPRI, a commonly used FH standard, requires $\pm$8.138 ns one way jitter and $\pm$16.276 ns round way jitter. It is very difficult for the existing Ethernet devices to meet the jitter requirements, even with enhancements such as IEEE 802.1Qbu frame pre-emption [42]. Namely, if 802.1Qbu is used, a maximum one-way jitter of 114.4 ns over a 10GE interface, or 11.44 ns over a 100GE interface, still exists [43].

One possible solution for this problem is retiming (cf. Figure 23), in which a timestamp should be put onto the packet at the network ingress node, and the egress node should check the timestamp and make sure all the packets traversing through the network should experience the same delay time.

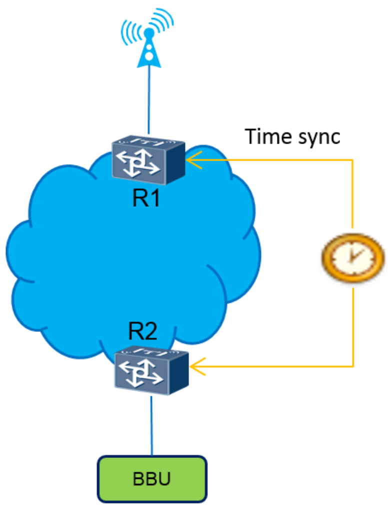

Figure 23: Re-timing architecture.

In order to achieve this constant delay time, packets may need to be buffered at the egress node for some time period and this constant delay must be long enough to cover all the forwarding delay, including the jitter. On the other hand, this constant delay value should be as small as possible, as the FH also has a critical delay budget. In other words, for large delays, the FH network can only cover a very short range.

The retiming solutions also require very accurate time synchronisation, precise enough to enable 8.138 ns retiming error. The existing synchronisation solutions typically do not provide this accuracy. A further study is needed to find out this time synchronisation accuracy requirement, and also develop a synchronisation solution to achieve it.

It should be noted that a solution without timestamping is possible in principle, with the egress node buffering and sending packets at a rate satisfying the jitter requirements. However, certain technical challenges such as the buffer dimensioning (jitter dependant), resolution, determining the constant rate, and packet loss issues must be resolved in this case.

Regarding the packet loss issues, there are further aspects to be considered. The uncompressed FH traffic is a Constant Bit Rate (CBR) stream, and for sporadic errors (i.e. BER), the FEC function in mobile technology, such as turbo coding in LTE, can resolve (most of) the BER issue.

However, the errors in FH traffic transmission over packet networks will cause packet drops due to the FCS in Ethernet, which means a single bit error will lead to 1500 byte or even 9000 byte (jumbo frame) data loss. This issue cannot be resolved by the Forward Error Correction (FEC) function, and the final resort is often retransmission , e.g. Hybrid Automatic Repeat Request (HARQ) in LTE.

The framing differences between CPRI, Ethernet, and mobile technologies make the problem worse, meaning that one Ethernet packet loss may lead to multiple CPRI frames damaged, and probably more LTE frames damaged. It should be noted that in case when the CPRI traffic is compressed and becomes a Variable Bit Rate (VBR) traffic, the problem still exists, with possibly more data being lost after a packet loss.

A possible approach to tackle this problem is a new header checksum mechanism which, however, extends the Ethernet header and changes the traditional forwarding behaviour.

4.4 Data Path Interfaces

5G-XHaul will enable seamless integration of future-proof technologies in the wired (optical) and wireless (mmWave, Sub-6) access/transport network domains providing the required backhauling and fronthauling services. Given the technology heterogeneity supported by the 5G vision, a critical function of the converged wireless-wired infrastructure is interfacing between technology domains. These domains may adopt very different protocol implementations and provide very diverse levels of overall capacity (varying between Mbps for the wireless domain up to tens of Gbps), granularity (varying between Kbps for the wireless domain and 100 Mbps), etc. Also, latency remains a critical parameter to be fulfiled in such a converged transport network. Finally, in order to enable performance gains achieved by cooperation between the mobile network and the transport network, the interfaces to future RAN technologies must be available.

A critical function in the converged infrastructure proposed is that of the interfaces between the different technology domains (optical and wireless). The interconnection of these domains involves interfacing both at the data plane and the control layer. For the data path (physical) interconnections, the two technology domains need to support common protocols to enable seamless traffic interchange between them. This introduces the requirement for the following interfacing functions:

- Bit-rate adaptation.
- Traffic aggregation/disaggregation.
- Protocol adaptation including appropriate framing.
- QoS mapping.
- Scheduling.

Interoperation between heterogeneous technologies requires a detailed agreement on the interfaces between the technology domains. In the following, we will concentrate on the interfaces in the data plane, especially the physical layer (OSI layer 1), and the data link layer (OSI layer 2). We assume that each technology domain is either a single-vendor environment with proprietary internal interfaces, or the technology has been standardized (e.g. by IEEE or ITU-T), such that a multi-vendor environment is based on standard (intra-technology) interfaces. Within 5G-XHaul, intra-technology interfaces will not be agreed upon, but contributions to standard organisations will be made to progress any pending standards (e.g. G.metro in ITU-T for the WDM-PON technology).

4.4.1 Interfaces between heterogeneous wireless domains

According to Figure 7, for both wireless transport and joint access/transport purposes, there must be an interface between the different wireless technologies developed in 5G-XHaul, namely mmWave and Sub-6.In most cases, Ethernet data will be transported in the 5G system. Therefore, this protocol should be considered as a main contender for the layer 2 specification.

Being IEEE 802.11ac/ax and IEEE 802.11ad/ay the most likely candidates to form the Sub-6 GHz and mmWave wireless parts of the BH, respectively, along with the fact that all IEEE 802.11 technologies share a common logical link layer (upper part of data link layer), make wireless bridges the most natural configuration to interface these two domains.

Those bridges consist of multiple radio interfaces (mmWave and Sub-6) physically attached to the same network node, which has the capacity to carry out transparent bridging of Ethernet frames between the different radio interfaces (usually at OS kernel level). OS level bridging is generally outperformed, in terms of forwarding speed, by dedicated hardware but, on the other hand, enables a seamless integration of QoS/scheduling policies.

Alternatively, the physical connection of different wireless domains can be achieved by means of wired links, provided that those links i) support data rates in the Gbps scale to avoid adding more restrictive bottlenecks in the data path and, ii) support transparent transport of Ethernet frames. These requirements allow the use of any 1000BASE and 10GBASE (and beyond) IEEE 802.3 families.

4.4.2 Interfaces between PON and wireless domains, PON and TSON domains

As an example, Figure 24 shows, in dashed lines, the interfaces between the WDM-PON technology and the 5G-XHaul switch at the OLT as well as the interfaces between the WDM-PON technology and the wireless technologies at the ONU. To enable flexible architectures, the interface specifications should be agnostic to the technologies connected. This means, for instance, that a connection between the WDM-PON and the TSON should be based on the same interface specification as between the WDM-PON and the mmWave. Furthermore, the interface specification should be agnostic to the technology implementation. This means, for instance, that a WDM-PON system with an optical implementation of the cross-connect at the OLT side should meet the same interface specifications as a WDM-PON system with an electrical cross-connect implementation. Any variation of the WDM-PON system, like the location of the optical inter-technology transceiver, must not affect the interface.

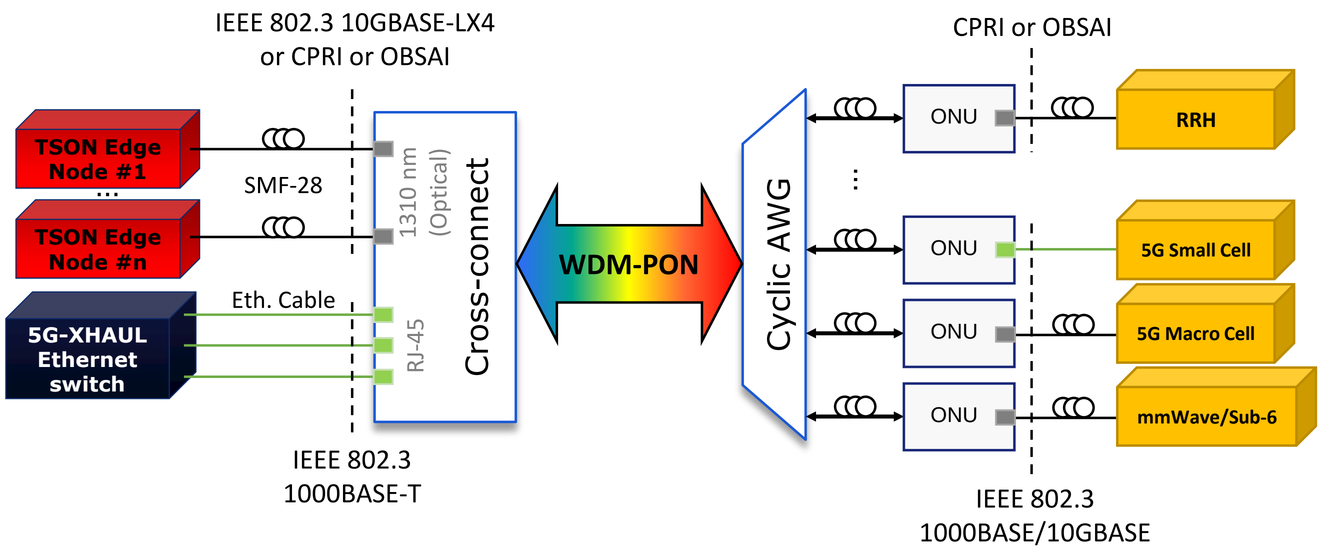

Figure 24: Interfaces (dashed lines) between WDM-PON technology and wireless or switch technologies.

Physical layer interface

The connection between equipment of different technologies in a 5G system is typically very short. However, high data rates will potentially be required. Therefore, it is reasonable to use a low-cost optical connection based on an ultra short reach (USR) or short reach (SR) interface specification. The IEEE 10GBASE-USR and 10GBASE-SR standards define interfaces at a data rate of around 10 Gbps over some hundred meters of multimode fiber.

One important agreement required for the interface definition is on the maximum data rate of the interface. The physical implementation of an interface, i.e. the transceiver module, typically allows data rates up to a maximum rate with increasing cost for higher maximum rates. Some transport technologies are limited in the achievable data rate. Therefore, it might be sensible to define different interface classes to account for the capabilities of different technologies.

While standard optical interfaces will leave larger implementation flexibility for each technology area, double signal conversion at every interface might not be cost effective. An option would be to specify electrical signals at the interfaces and physical integration of the devices for different technologies. As an example, the physical form factor of the ONU in a WDM-PON system can be implemented as a small form factor (SFP) module, which can be plugged into an Ethernet switch or a mmWave device with an SFP cage. The interface specification would in this case be based on a SERDES framer interface (SFI) standard. While reducing system cost, however, this interface type would limit the implementation options of the connected technologies.

At the both OLT and ONU, as shown in Figure 24, we assume that the interfaces comply with IEEE 802.3 1000BASE-T, 10GBASE-LX4, as well as CPRI and OBSAI standard. Regarding the physical links, for instance, the balanced copper cable and optical SFP/SFP+ pluggable transceiver operating at 1310 nm would be the feasible between the PON and wireless domains, as well as between the PON and TSON domains.

Data link layer interface

While the physical layer interface specifications are mainly considering the physical properties of a signal transported between different technologies, the data link layer, or layer 2, specification define the bit level properties (e.g. protocol) of the transported data. While some technologies are agnostic to the data framing, because the technology is transparent to the data (like the WDM-PON technology with optical cross-connect), other technologies or implementations of technologies will terminate the data protocol (like the WDM-PON with electrical cross-connect or the TSON). Therefore, in general a precise framing specification is required.

In most cases, Ethernet data will be transported in the 5G system. Therefore, this protocol should be considered as a main contender for the layer 2 specification. In some cases, however, other formats are required. For instance, for a pure FH architecture with signals between the BBU and the RRH framed in CPRI format, the transport of this format over Ethernet might not be feasible. Therefore, other layer 2 formats than Ethernet might need to be specified for some inter-technology interfaces. The supported layer 2 interfaces at the both OLT and ONU are summarised in Table 5.

Table 5: Specification of supported interfaces in WDM-PON.

Client Data Rate	Service
1000.0 Mbps	1GbE
1228.8 Mbps	CPRI (2x)
2457.6 Mbps	CPRI (4x)
3072.0 Mbps	CPRI (5x), OBSAI (4x)
4915.2 Mbps	CPRI (8x)
6144.0 Mbps	CPRI (10x), OBSAI (8x)
9830.4 Mbps	CPRI (16x)
10137.6 Mbps	CPRI (20x)
10312.0 Mbps	10GbE

Note: CPRI (2x) means CPRI double rate, etc.

4.4.3 Interfaces between wireless, PON, DC and TSON domains

TSON relies on a set of serial interfaces for optical-to-wireless, optical-to-optical and optical-to-compute data transfers. These interfaces rely on high speed serial links for the physical interconnection of the various technology domains supporting up to 10 Gbps per transceiver. This interface is primarily composed of the following components:

- Physical Medium Dependent (PMD) that is an electrical module performing serial signal transmission.
- Physical Media Attachment (PMA): responsible for the serialization/deserialization of data.
- Physical Coding Sublayer (PCS): responsible for the encoding/decoding of the data streams.

These enable the support of a variety of protocols such as, Ethernet and PCI Express, with data rates ranging from few Mbps up to several Gbps. A key characteristic is that these protocols share common blocks in the PCS as well as common coding schemes i.e. 8b/10b coding. A typical example of the architecture of the serial interface for the Ethernet use case is provided in Figure 25.

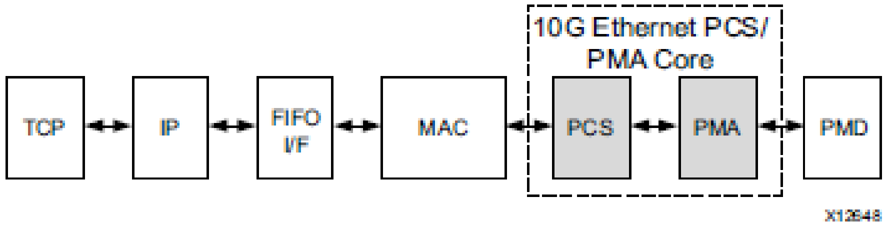

Figure 25: Edge TSON nodes addressing interfacing requirements across Wireless-TSON and DC domains.

In addition to Ethernet and PCI Express, wireless protocols such as CPRI and OBSAI are also supported. To achieve this, the PCS blocks need to be carefully adopted to make the link delay variations deterministic and compliant with the CPRI/OBSAI Physical Layer. A summary of the protocols supported is provided in Table 6.

Table 6: Communication protocols and achievable rates.

Protocol	Rate (Gbps)
GE	1.25
10GE	3.125 6.125 10.3125
CPRI	1.228 3.072 6.144
PON	BPON, GPON, GEPON, 10GGPON, 10GEPON

4.5 Support of different transport classes

Next generation mobile networks need to support diverse set of use cases, requirements and applications. These requirements and challenges have imposed stringent requirements on the 5G RAN and, hence, several radio access technologies such as mmWave, massive MIMO are proposed and widely investigated. A centralised RAN architecture provides pooling gains but on the other hand it also imposes challenging requirements on transport networks. Hence, to utilize the centralization gains provided by C-RAN and at the same time relax these stringent requirements, a more flexible and dynamically configurable transport network is proposed in 5G-XHaul.

4.5.1 Functional splits

One way of reducing the requirements is to divide the signal processing chain between the RU and CU, utilizing the so-called functional split. These splits have a considerable impact on the transport network and were hence analyzed in 5G-XHaul deliverable D2.1 [1]. Three of those splits were selected as being representative options to be further investigated by 5G-XHaul and are being shortly summarised in the following. Figure 26 shows the signal processing chain of an air interface and indicates the three splits selected.

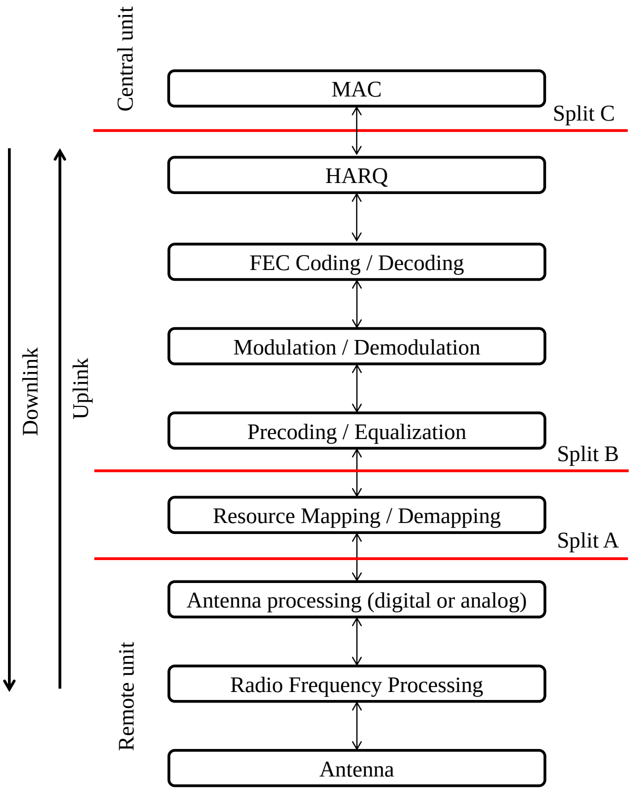

Figure 26: Functional split options.

Split A corresponds to classical FH split in C-RAN which utilizes CPRI to facilitate full centralisation gain. The only difference to CPRI is that the antenna mapping is decentralized at RU to enable large antenna arrays for BF. The data forwarded between RUs and CUs consists of time-domain I/Q samples which scales with number of antennas, sampling frequency, quantizer resolution and number of ADC chains. Split A requires stringent requirement in terms of data rate, latency and synchronisation. One of the major disadvantages of this split is that the FH data rate is load-independent, meaning full FH data rate needs to forwarded even at the time of low user traffic.

In split B, resource mapping is decentralized to RU, and other PHY layer processing such as channel equalisation/precoding, modulation/demodulation and coding/decoding are still centralised. In this case, only those resources which are currently utilised need to be forwarded. The data exchanged in split B corresponds to frequency domain samples.

In split C only the higher MAC-layer functionalities such as scheduling are centralised, whereas HARQ, channel equalisation/precoding, modulation/demodulation and coding/decoding are decentralised. Since the HARQ is performed locally at RU, this relaxes the latency requirements. This functional split is similar to the classical BH.

Having studied all those splits, it is worth noting that while a particular split might be best suited for a certain scenario; it is expected that multiple splits will coexist within the same 5G network according to different use cases, air interfaces, and deployments.

In particular, In 5G RAN dense urban scenarios with multitude of RATs (e.g. mmWave, Sub-6 GHz), multi-connectivity and RAN-level protocol harmonisation would be crucial to ensure high coverage and capacity, due to the spotty coverage of mmWave bands. METIS II [45] investigates the 5G RAN functional architecture and design. Given that different Air inter-face Variants (AIVs) might be good candidates for different use cases – and might be more applicable for certain bands (e.g. mmWave, Sub-6 GHz) –, it is widely investigated to which extent data plane instances related to different bands can be logically aggregated on certain layers.

To this end, there can be many possible aggregation possibilities among 5G AIVs, e.g in upper PHY, lower / upper MAC, Radio Link Control (RLC), or Packet Data Convergence Protocol (PDCP) level, given that the AIVs are harmonised on and above the protocol layer of aggregation. Two possible aggregation options were discussed in METIS II [44], assuming different air interfaces can be shown in Figure 27. Note here that the aggregation in a certain layer requires harmonisation (e.g. similar functions and parameterisation) in this layer and above.

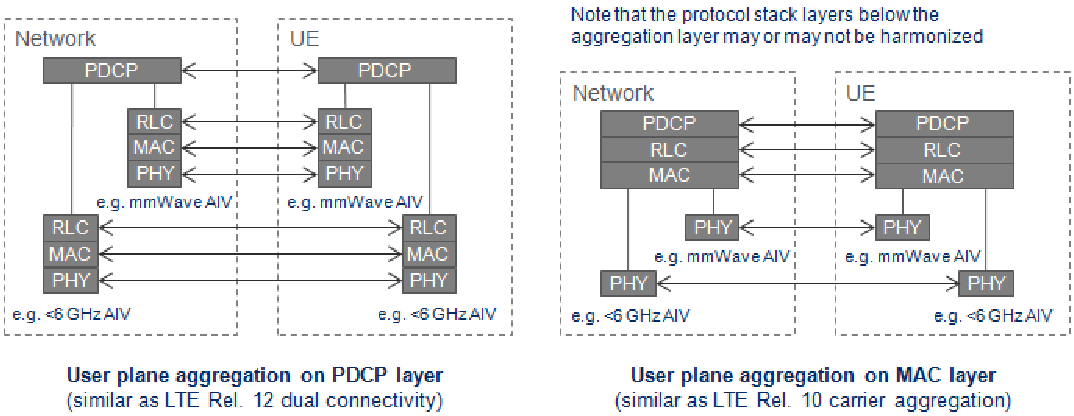

Figure 27: Potential options for user plane aggregation (source: METIS II White Paper - Preliminary Views and Initial Considerations on 5G RAN Architecture and Functional Design).

- **MAC-level aggregation:** MAC layer aggregation can offer tighter integration among different AIVs since MAC would be harmonised between different air interfaces and functions like cross-carrier scheduling could provide optimised performance. Nevertheless, this scenario will likely require co-location of nodes, due to the dynamic coordination which is required at MAC level. Moreover, this may be challenging among AIVs in Sub-6 GHz and mmWave bands since we may have PHY layers with very different frame structure.
- **PDCP-level aggregation:** PDCP-level aggregation is the case when two or more AIVs have harmonised PDCP layers. This could be achieved in case of having PDCP (e.g. independent or master-slave) in both macro and small cells or to split the radio bearer in PDCP level. In both cases, S1-like interface (e.g. S1*) will terminate at macro and Xn-like interface (see options 3A-3C, as introduced in [45] for Dual connectivity) will be between macro- and small cell.

For different levels of aggregation, different deployment scenarios could necessitate different split of functions. In heterogeneous D-RAN architectures (with small cells under the macro-cell or local-Cloud), protocol aggregation at MAC and PDCP layer would require at least Split C (note that there might be further split options in upper layers as discussed also in [6]). Splits A and B would be highly required when the aggregation of multiple AIVs is performed in upper /lower PHY. This is applicable mainly for the C-RAN deployments, where splitting CRPI could potentially provide even higher pooling gains.

An exemplary deployment, which is in line with the Joint BH/Access scenario, as illustrated in Figure 5, can be seen in Figure 28, where a macro-cell site is wirelessly connected to TNs and can support multiple AIVs (one for mmWave and one for Sub-6 GHz). User traffic can be transferred through TNs and we can have different splits and protocol configurations based on the AIV. In this example, PDCP can be common for both AIVs, whereas lower layers can be tailored for different AIVs. For mmWave AIV, the centralisation can be higher due to the ultra high capacity and low latency BH that mmWave bands can offer. On the other hand, for Sub-6 GHz TNs, only PDCP can be centralized due to the relatively low rata and latency requirements imposed by this split.

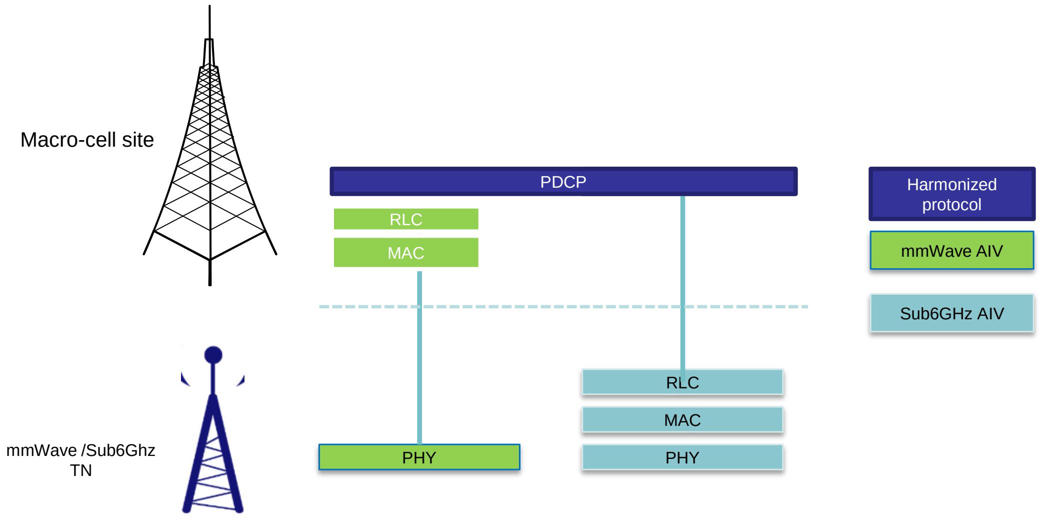

Figure 28: Macro-TN protocol split for multiple AIVs.

4.5.2 5G-XHaul Transport Classes

Each functional split will have its own set of distinct requirements in terms of data rate, latency and synchronisation. At the same time, end-user application such as tactile internet or vehicular communications can impose their own requirements on the overall RAN. Hence, 5G-XHaul transport network needs to be flexible enough to transport data traffic of various types according to their end-user use cases and functional split. In order to reduce the number of possible requirement combination and hence to simplify the overall network management, 5G-XHaul has proposed four basic TCs [1], which are summarised in Table 7. Latency is the main requirement that has driven the definition of the different TCs and, hence, main differentiating parameter among these TCs is latency.

When employing Split A or B, synchronisation is the key requirement, hence TC 0 is introduced to carry synchronisation packets utilizing packet based synchronisation such as the precision time protocol [46]. The typical data rate in this TC is expected to be the least among the different TCs.

TC 1 is introduced to support low latency traffic imposed by RAN requirements, e.g., legacy CPRI and low latency application traffic, e.g., tactile internet traffic. A maximum latency of 200 µs round trip is proposed for this TC that could meet both the CPRI requirements as well as 1 ms end-to-end latency requirement for tactile internet applications [1]. Compared to the TC 0, the expected traffic in TC 1 would be very high.

TC 2 needs to support similar traffic as TC 1, but with relaxed latency requirement. TC 2 proposes maximum latency of 2 ms and this latency is suitable for the functional splits where the HARQ-induced latency requirement is relaxed.

Lastly, the TC 3 is introduced that is intended to support non-critical traffic such as classical IP-based BH or control signaling. This TC will have maximum latency among all the TCs. On the other hand, the traffic flow would be asynchronous.

Table 7: Transport classes proposed for converged transport networks.

	Use case	Transport latency (round trip)	Synchronisation	Typical data rate per access point
TC 0	• Synchronisation	Very low variance	Enabler	10 Mbps
TC 1	• Split A FH traffic • Split B FH traffic without relaxed HARQ • Tactile user traffic • Failover signaling • SDN in-band control signaling	≤ 200 µs	Synchronous, time aligned	100 Gbps
TC 2	• Split B traffic with relaxed HARQ • Split C traffic with coordinated BF • Relaxed tactile user traffic	≤ 2 ms	Synchronous, time aligned	50 Gbps
TC 3	• Split C traffic without coordinated BF • Conventional BH/ fixed access traffic • Control signaling	≤ 20 ms	Asynchronous, not time aligned	10 Gbps

The purpose of the TCs is to indicate the basic properties and requirements of an associated traffic flow. This is necessary in order to keep the complexity of management low in an SDN-enabled network. Network nodes like routers and switches utilize forwarding rules to prioritize packets, select paths or assign bandwidth. However, the network nodes can only keep a limited number of rules due to their limited Ternary Content-addressable (TCAM) memory [47]. If the traffic does not match the rules, new rules have to be installed on the nodes by a centralised SDN controller. This induces additional latency, thereby impeding the strict constraints and also adding to the variability of the queueing delay, which could impede the accuracy of delay estimations required for synchronisation. Reducing the number of practically applied TCs could limit the number of different rules and serves as an easy way to indicate the priority of a packet.

Furthermore, the TCs can help in an SDN controller to abstract the network state and optimise the network accordingly. To give an example, in case of a switch outage, TC 3 traffic could be re-routed via a long, high latency route, as it is insensitive to latency. However, if the switch in outage was serving a TC 1 flow, as well as the supporting TC 0 flow, this traffic would need to be rerouted via a low latency route, and synchronisation would need to be organised on the new route. Without the utilisation of TCs, each flow with its respective requirements would have to be analysed separately and accounted for in the optimisation.

Latency is the main differentiator of the different TCs. Recently, 3GPP agreed on latency requirements for 5G RANs. Table 8 shows how these different requirements can be achieved using the proposed TCs. Note that 3GPP considers as latency also the BB and Layer-2 processing, which is not considered in the TCs. Still, it can be seen that the TCs are aligned with 3GPP requirements, leaving enough delay budget for the aforementioned processing.

Table 8: Comparison of 3GPP latency requirements and 5G-XHaul Transport Classes.

Traffic type	3GPP L2 latency [33]	5G-XHaul TC transport latency
Control plane	10 ms	TC 2: 2 ms
UL Logical Link Control (LLC)	0.5 ms	TC 1: 0.2 ms

eMBB	4 ms	TC 2: 2 ms
Legacy traffic	-	TC 3: 20 ms

In order to assess which physical technology is suitable for which transport class, Table 9 compare the different technologies against the TC requirements.

Table 9: Support of Transport Classes by transport technologies.

mmWave	Data rate	Latency
Base parameters	4.6 Gbps [48]	50-200 µs one way mean latency per hop (depends on traffic load and directionality, see Section 6)
TC 0 support	IEEE 1588 and SyncE	
TC 1 support	Typical data rate of 5G RAT not supported, CPRI up to line rate 4 supported	hop (under reduced throughput and other conditions, see Section 4.1)
TC 2 support	Typical data rate of 5G RAT not supported, 4G RAT supported	≤ 5 hops
TC 3 support	1 cell (single hop)	≤ 50 hops
Sub-6 wireless	**Data rate**	**Latency**
Base parameters	6.9 Gbps (802.11ac)	~ 0.4 ms per hop
TC 0 support	IEEE 1588 and SyncE	
TC 1 support	Typical data rate of 5G RAT not supported, CPRI up to line rate 6 supported	Not supported
TC 2 support	Typical data rate of 5G RAT not supported, 4G RAT supported	Not supported
TC 3 support	~ 1 cell	≤ 50 hops
PON	**Data rate**	**Latency**
Base parameters	1-10 Gbps per wavelength (G.metro draft) (25 Gbps per wavelength is still under development)	Fiber latency ~10 µs/km Active equipment: typically sub-us in total
TC 0 support	IEEE 1588 and SyncE	
TC 1 support	4-10 wavelength per typical cell; max. 10 cells for 40 channels (100 GHz spacing)	Optical propagation delay (distance) + round trip processing delay of FH active equipment
TC 2 support	2-5 wavelengths per typical cell; max. 20 cells for 40 channels (100 GHz spacing)	
TC 3 support	1 wavelength per typical cell; 40 cells for 40 channels (100 GHz spacing)	
TSON	**Data rate**	**Latency**
Base parameters	8.68 Gbps per wavelength	To be defined (dependent on TSON extensions)
TC 0 support	IEEE 1588 and SyncE	
TC 1 support	12 wavelengths per typical cell	1 hop

	6 cells for 80 channels (50 GHz spacing)	
TC 2 support	6 wavelengths per typical cell 12 cells for 80 channels (50 GHz spacing)	≤12 hops
TC 3 support	2 wavelengths per typical cell 40 cells for 80 channels (50 GHz spacing)	≤120 hops
Ethernet	**Data rate**	**Latency**
Base parameters	10G, 40G, 100G	Frame/backplane based device / 20~40 µs Single chip device / box: 3~5 µs
TC 0 support	IEEE 1588 and SyncE	
TC 1 support	100G or 2*40G interface	≤ 5 hops; ≤ 30hops (assuming 100 µs for fiber propagation delay)
TC 2 support	100G or 40G interface	≤ 47 hops
TC 3 support	10G interface	≤ 50hops (usually the network is not so complex)

As can be seen from Table 9, the very high data rates potentially required for TC 1 and TC 2 – due to the high degrees of centralization and large air interface bandwidth – impose the requirement of fibre technology. However, wireless technologies are a valid option for legacy BH traffic as well as for highly centralized C-RAN based on the current air interface in combination with CPRI. From the latency perspective, all technologies have the potential to support the different TCs. The only exception here is Sub-6 wireless, which currently cannot meet the stricter latency requirement of TC 1 and TC 2.

Within the WDM-PON based FH, latency is mainly determined by the distance-dependent fiber propagation delay. Apart from this, the delay imposed by the WDM-PON terminal equipment is typically sub-*microseconds.* Regarding the cross-connect function at the OLT, the latency is negligible in case of using an optical beam steering based switch, while an electrical ultra-low latency switch could be also feasible with only less than 5 ns latency [1]. Hence, PON would be able to support all TCs.

For synchronisation (TC0), it was assumed that all technologies will be packet-based and, hence, PTP and SyncE can be utilized for alignment in time and frequency, as discussed in Section 4.3. TSON already includes synchronisation functionality to synchronise the different TSON edge nodes. This functionality will be upgraded to be compliant with the IEEE 1588 protocol.

It should be noted that the four TCs provide only a very basic proposal, which highlight the need to consolidate requirements on the transport. In general, more traffic classes can be defined, and the support by different PHY technologies can be evaluated accordingly. Also, as described in deliverable D2.1 [1], the data rate actually required on a certain transport link depends on many factors, such as the air interface bandwidth, the split type, the load, and the number of cells. Similarly, the total transport latency depends on the distance to be covered, the latency induced by intermediate nodes like routers or switches, and the latency induced by PHY and MAC layer protocol functionalities such as framing, buffering, or retransmissions. Hence, the numbers given in the table above should serve only as guidelines. However, it can still be concluded that in general, wired technologies and little protocol overhead are necessary for high-capacity and low latency traffic, while wireless technologies and more complex protocols should be only considered for less demanding TCs.

In addition, the values utilized above refer to currently available technologies; however, it can be expected that these technologies will advance during the development of 5G networks. In this regard, IEEE 802.11ax task group [36] is developing the next generation of Wi-Fi technology targeting a four-fold increase in throughput by the year 2019. As a matter of fact, the group already announced 10.53 Gbps data speed using Wi-Fi in the 5 GHz band during lab trials. Controlled contention through Hybrid TDMA/CSMA methods and the use of licensed bands in Sub-6 will allow to limit per-hop delays in the range of 200 us. Hence, we foresee full support of TC 3 with the Sub-6 technologies in the near future, and a limited support of TC 2 in BH paths with a small number of hops. As for mmWave, IEEE 802.11ay [24] is currently being standardised and will extend the capability of 802.11ad to offer data rates in excess of 20 Gbps by using a combination of channel bonding, MIMO and higher order 64-QAM modulation. The standard is expected to be completed in 2019. This would bring the data rate closer to the support of TC 2 as well.

The utilization of TCs is coupled with the topology of the network, as it determines the possible splits and which transport technologies can be employed. Three basic topologies need to be considered (see Figure 5):

- Decentralized deployments: The RUs are full BSs.
- Local cloud: CUs are deployed in proximity to RUs.
- Global cloud: The CUs are located in a few large DCs.

For decentralised deployments, the transport traffic is similar to 'classical' BH traffic in terms of data rate and latency. As the transport data rates are comparable to those on the access links, all transport technologies can be employed, especially also mmWave and Sub-6 GHz. For legacy BH traffic it is assigned TC 3, due to its relaxed data rate and latency constraints. Hence, all transport technologies have to support TC 3. Due to the unavailability of a CU close to the user, low latency applications need not be considered for this deployment.

Local cloud deployments can be used for two scenarios (or a combination of those): centralised RAN processing or user application processing. The former could implement any split, from full centralization in Split A to centralized MAC in split C. Both for the lower splits and for ultra-low latency user processing low FH latencies are required. Accordingly, technologies employed here have to support TC 1. In case of centralised RAN processing, synchronisation is required, hence TC 0 needs to be supported as well. Due to the close proximity of CU and RU, all transport technologies can be employed in theory. However, Sub-6 GHz can be assumed to provide too little bandwidth to be considered for low layer splits. Accordingly, it does not need to support TC0. Depending on the distance of CU and RU, propagation latency might be too high to support TCs 1 and/or 2.

In a global cloud deployment, the CU is located too far away from the RU to allow either centralised RAN processing or ultra-low latency application processing. Accordingly, the long-range transport technologies do not have to support TCs 0-2. However, it should be noted that if a physical link is shared to transport both local and long range traffic, it should support the lowest TC required for the respective traffic. A more detailed analysis of the latency induced by the transport network can be found in Section 6.3.

5 5G-XHaul Development focus: Control Plane

In this section we introduce the 5G-XHaul control plane architecture. The main goal of the 5G-XHaul control plane is to instantiate the Infrastructure Management Layer (IML) of the 5G-XHaul overarching architecture introduced in Section 3. Hence, the 5G-XHaul control plane will allow a 5G-XHaul provider to provision transport slices instantiating the connectivity required by the 5G-XHaul tenants, while providing tenants the ability to control their transport slices (c.f Control Layer in the overarching 5G-XHaul architecture).

In order to achieve the aforementioned goals, the 5G-XHaul control plane is designed according to the following design principles:

- The 5G-XHaul control plane will be logically centralised following the SDN architecture [40]. The goal of this logical centralisation is to minimise the operational complexity required to control and monitor a heterogeneous transport network composed of multiple technology domains.
- It is assumed that 5G-XHaul tenants will instantiate Virtual Network Functions (VNFs) across a set of geographically distributed compute and storage facilities connected by means of the 5G-XHaul infrastructure. The main task of the 5G-XHaul control plane will thus be to provision on-demand connectivity between the tenant's VNFs. The interested reader is referred to Section 3 for an explanation of how the 5G-XHaul architectural views are aligned with the 5G-PPP community.
- The 5G-XHaul control plane will be able to provision connectivity across the heterogeneous transport technologies introduced in Section 4. For this purpose a common forwarding plane abstraction will be used across technologies, preferably based on an Ethernet interface, which as described in Section 4 is supported by all technologies considered in 5G-XHaul.
- Scalability is a key aspect for the 5G-XHaul control plane design. For this purpose, whenever possible the network state will be pushed to the edge, i.e. to the compute and storage facilities hosting the tenant's VNFs.

5.1 Overall Control Plane Architecture

Figure 29 illustrates the 5G-XHaul control plane architecture that is based on the following design principles:

- Full address space virtualisation is offered through an overlay, implemented using encapsulation at the edge of the transport network. This means that different tenants can use overlapping L2 or L3 address spaces.
- Data plane scalability is addressed in the control plane design by isolating the forwarding tables of the transport network elements inside the 5G-XHaul infrastructure from any tenant related state (overlay). This is again achieved by encapsulating tenant frames at the edge of the network into transport specific tunnels.
- Scalability of the SDN control plane is achieved introducing the concept of *areas*. An area defines a set of transport network elements that are under the control of a logically centralised SDN controller[5]. A control plane hierarchy is introduced whereby higher level controllers are used to coordinate the actions of area level controllers.
- Finally, the vision of a converged multi-technology transport network is enabled by: i) the previously introduced areas, which embody a single type of transport technology (e.g. wireless mesh, optical or Ethernet), and ii) a transport adaptation function (TAF) that maps the per tenant traffic at the edge nodes to the transport specific tunnels of a given area.

In order to support the previous principles, three types of transport nodes are defined in 5G-XHaul that are depicted in Figure 29. First, *Edge Transport Nodes* (ETNs), connect the tenant Virtual and Physical Network Functions (VNFs/PNFs) to the 5G-XHaul transport network, maintain the corresponding per-tenant state, and

[5] In practice we could have a controller cluster with a mechanism to synchronize state between instances.

encapsulate tenant traffic into transport specific tunnels. Second, *Inter-Area Transport Nodes* (IATNs), support the necessary functions to connect different areas, which may be implemented using different transport technologies. Finally, regular *Transport Nodes* (TNs), support an area specific transport technology, and provide forwarding services between the ETNs and IATNs of that area.

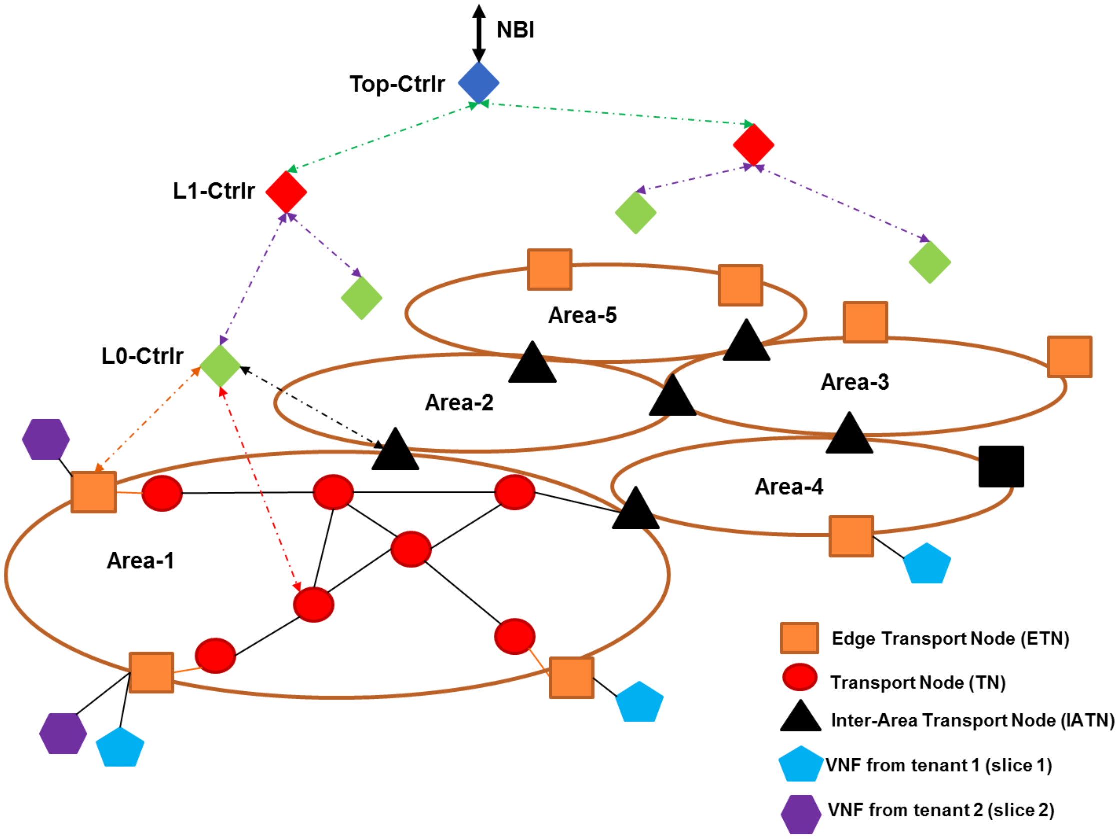

Figure 29: 5G-XHaul Control Plane architecture.

Figure 30 illustrates an example of how the logical control plane architecture described in Figure 29 could be mapped on the physical multi-technology architecture described in Section 4. In particular, Figure 30 depicts a hierarchical architecture, where compute and storage facilities that can potentially host tenant VNFs are geographically distributed. Concretely, tenant VNFs could be hosted in: i) compute facilities collocated with Small Cells, ii) Edge data centres, or cloudlets, collocated for example with macro-cell sites or with street cabinets, which may also have optical or Ethernet connectivity, iii) regional level data centres, and iv) centralised data centres. Figure 30 illustrates how ETNs are always assumed to be located within one of the previous compute facilities, since ETNs provide connectivity to the tenant's VNFs.

Figure 30 also illustrates the concept of multi-technology control plane areas used in 5G-XHaul. In particular, Figure 30 depicts an outer layer of Small Cells connected using any of the wireless technologies developed in 5G-XHaul and introduced in Section4. This outer layer of wirelessly connected Small Cells is partitioned in multiple 5G-XHaul control plane areas, where the TNs of each area are controlled by a Level-0 controller. Thus, this is an example of having multiple contiguous 5G-XHaul areas embodying the same type of transport technology. In order to provision connectivity across area boundaries IATNs are required to connect these areas. In addition, 5G-XHaul areas may also embody different transport technologies. For example, Figure 30 illustrates how some edge DCs, contain an IATN connecting a wireless control plane area, with a control plane area embodying an optical technology, i.e. WDM-PON+TSON, or a control plane area embodying an Ethernet technology. IATNs feature the appropriate interfaces introduced in Section 4.4 in order to connect heterogeneous technology domains.

Note that the control plane introduced in Figure 29, i.e. the controller hierarchy, is not depicted in Figure 30 for clarity reasons. However, forwarding in each of the areas highlighted in Figure 30 would be under the control of a standalone (cluster of) controller(s), which would coordinate with each other through the previously introduced controller hierarchy.

The distributed compute and storage facilities depicted in Figure 30 are assumed to be equipped with an appropriate virtualization infrastructure to host the tenant VNFs. Regarding the infrastructure required to provide network virtualisation, this is the main task performed by the ETNs, and will be described in detail in the upcoming sections. The distributed compute and storage facilities will be also be used to host the SDN controllers that implement the 5G-XHaul control plane. The exact deployment of these controllers though, will depend on the technology that is being controlled, and is at the moment an open research topic. It is worth noting that as 5G-XHaul proposes a distributed network, SDN control traffic will be transmitted in-band and needs to be appropriately protected. In addition, 5G-XHaul tenants interact with their own slices by communicating with the 5G-XHaul controllers, which in turn communicate with the respective network elements using the corresponding control plane connection. The interested reader is referred to deliverable D3.1 [40] for a detailed introduction to the reliability aspects of the 5G-XHaul control plane

In the next sections we describe in more detail the functions of the different nodes introduced in the 5G-XHaul control plane architecture, i.e. ETNs, IATNs and TNs. A more elaborate description of these nodes is included in deliverable D3.1 [40].

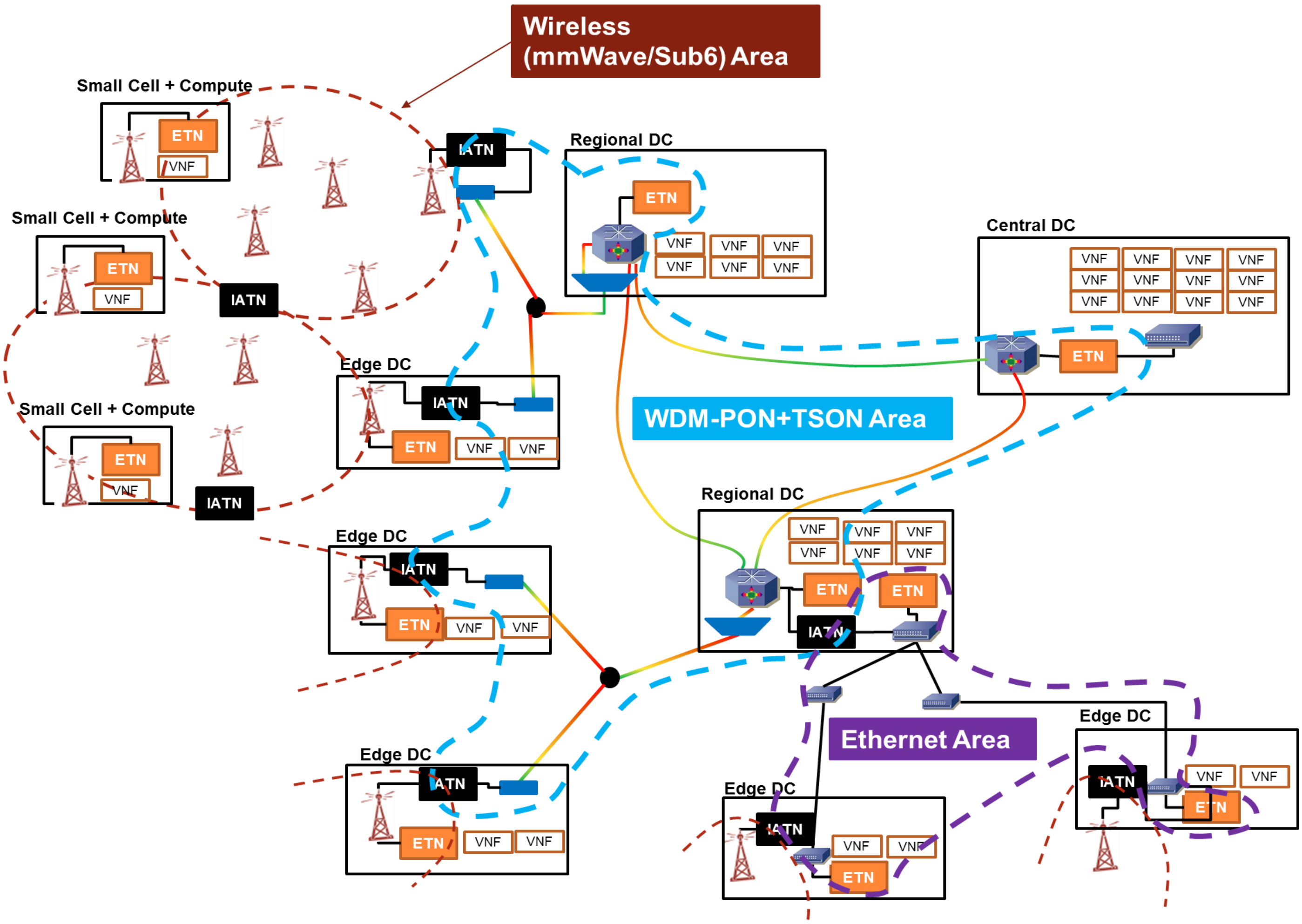

Figure 30: Relation between physical architecture and control plane functions.

5.2 Overlay: ETNs

ETNs maintain per-slice state providing 5G-XHaul tenants the required abstraction to operate on their slices. To address this requirement, we introduce the notions of *tenant ID* (T-Id) and *slice ID* (S-Id), which are globally unique identifiers for the end-to-end slices instantiated by a tenant, as later discussed in Section 5.5; e.g. *opA.slice1*, where *opA* is the tenant ID for operator *A* and *slice1* is the slice ID of a slice that operator *A* wants to deploy for a specific service. There is thus a 1:N relationship between tenant and slice IDs.

While the above identifiers need to be globally unique in the control plane, in the data plane different local transport slice IDs may be used in each 5G-XHaul area, namely a *Transport Slice ID* (TrSlice-Id) is used to represent in the data plane a given *T-Id.S-Id*, where *TrSlice-Id* may be different in each 5G-XHaul area (c.f. Figure 29). Notice that having a notion of slice ID at the data plane is useful in order to easily deploy policies at the tenant or slice level, e.g. deploying an Access Control List (ACL) that binds all the traffic for a tenant to a given QoS class, or that drops all the traffic of a malfunctioning slice. Thus, a function is embedded in the ETNs that performs the mapping between the global slice IDs of the control plane and the local Transport Slice ID in the data plane. In particular, an ETN embeds three major functions that are discussed next, namely: i) per-tenant Logical Datapaths, ii) a Forwarding Information Base (FIB), and iii) a TAF. These components are illustrated in Figure 31.

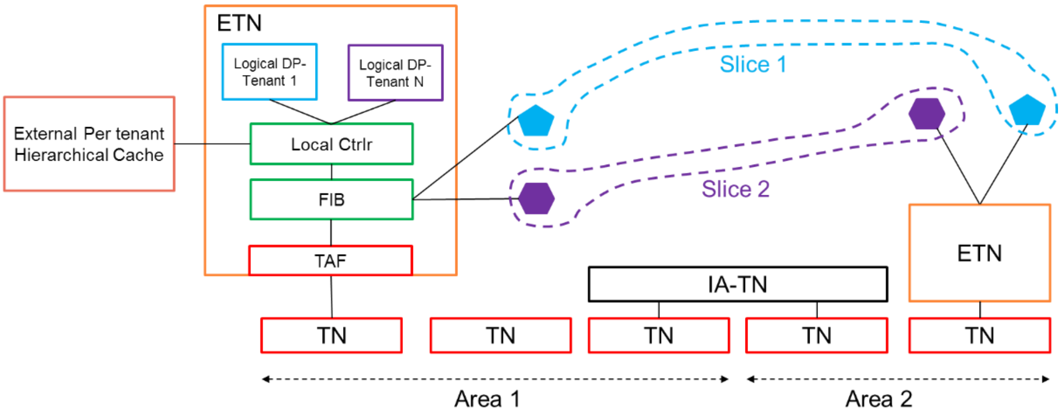

Figure 31: Detailed view of an ETN.

On the control plane, an ETN instantiates a logical datapath for each tenant having VNFs/PNFs connected to that ETN. Logical datapaths receive high level control policies from the tenant's own control plane, and push those policies to a local SDN controller in the ETN. Notice that this represents an implementation of the Control Layer in the overarching 5G-XHaul architecture introduced in Section 3, whereby tenants may operate a separate control plane against the virtual resources offered by the IML. The local controller in the ETN obtains the rules from each logical datapath, adds appropriate context, and pushes the rules to the ETN FIB. Introducing multi-tenancy support at this last controller layer, which runs on the actual forwarding element, leaves intact the underlying performance-centric multi-stage FIB architecture design that performs the actual packet forwarding [49]. Hence, a critical aspect in the design of the ETN is the datapath delay introduced by the ETN FIB. In order to minimize this delay, tenant-specific rules are often evicted, resulting in a small number of simultaneous rules hosted in the FIB. Consequently, a hierarchical structure of rule caches is used to scale up to a large number of rules coming from different tenants. Finally, the per-tenant FIB matches tenant-specific rules and inserts packets into transport-specific tunnels, which are pre-instantiated and it is expected that traffic from multiple slices can be combined into a single transport tunnel.

As mentioned in Section 5.1, an ETN uses encapsulation to isolate transport network elements from per-tenant related state. A TAF is included in the ETN that pushes the corresponding transport header before injecting the packets into the transport network. The transport header signals three major pieces of information: i) the path to be followed by a transport tunnel in the area, the ii) local Transport Slice ID, and iii) the QoS allocated to that tunnel. Each ETN features a TAF corresponding to the transport technology used in the 5G-XHaul area where the ETN is located. At the moment, we consider Ethernet as the unique TAF.

The Ethernet TAF provides MAC-in-MAC encapsulation as defined in Provider Backbone Bridging (PBB) [50]. In the Ethernet TAF the path to be followed by a packet is signaled using the MAC address of the destination ETN, or IATN (as explained in Section 5.5) within the same area, together with the outer VLAN field, which can be used for load balancing when multiple paths are available to the destination ETN/IATN. The Transport Slice Id is signaled in the Ethernet TAF using the *24* bit I-SID field in the outer MAC header. Finally, QoS classes can be signaled using the priority bits in the outer VLAN tag.

The interested reader can find a more accurate description of the virtualisation mechanisms included in the ETNs in Section 3 of Deliverable D3.1 [40].

5.3 Underlay: TNs and IATNs

TNs connect ETNs and IATNs within a given 5G-XHaul area (c.f. Figure 29). The concept of a TN is technology agnostic, thus a TN could be represented by a mmWave wireless node at the street level, by an Ethernet switch at the metro segment, or by an active optical node at the CN (e.g. TSON [15]). Regardless of the actual technology, in 5G-XHaul a TN offers a dataplane abstraction where forwarding, along with some other primitives like bandwidth provisioning or reliability, can be programmed by a logically centralised control plane.

Since the set of ETNs and IATNs available in a given area are fairly static, 5G-XHaul assumes that transport tunnels between ETNs/IATNs in an area are pre-provisioned. A pre-provisioned transport tunnel means that the ETNs and IATNs in that area have an interface representing such tunnel, and that the required TNs have the corresponding entries in their FIBs. Notice however that pre-provisioned transport tunnels do not need to be static, as tunnels can be reconfigured by the control plane in case of network situation changes. For example, the control plane may switch down a set of TNs for energy saving, while relocating all the affected transport tunnels to other TNs; the ETNs would be agnostic to such relocation. In addition, pre-provisioned tunnels may be point to point tunnels, or multicast trees connecting a set of ETNs/IATNs in a given area. In the case of a multicast tree, the transport technology in the 5G-XHaul area needs to support packet replication along the interfaces participating in each multicast group. In 5G-XHaul multicast group membership is managed by the logically centralised control plane. In the case of a 5G Mobile Network a multicast tree can be useful for example to connect base stations implementing a cooperative transmission scheme. Finally, transport tunnels are associated to the set of TCs described in Section 4. These TCs are dimensioned to transport FH traffic, BH traffic, as well as traffic resulting from other functional splits. Thus, multiple transport tunnels to a given ETN/IATN may be pre-provisioned representing the different TCs.

IATNs provide connectivity between neighbouring 5G-XHaul areas (c.f. Figure 29). As illustrated in Figure 31, an IATN can be understood as an interconnection function sitting above one TN for each area being connected by the IATN. The different areas can use the same or different transport technologies. The IATN interconnection function contains a control plane function and a data plane function that are described next.

In the control plane, an IATN needs to discover the areas that it has access to, and convey these areas to the 5G-XHaul control plane. In addition, a unique identifier is required for an IATN that also needs to be conveyed to the control plane. This information is required by the control plane to allocate paths at the area level. More detail on control plane functions are discussed in Section 5.5.

In the data plane, an IATN needs to implement the forwarding principle used in each of its connected areas. Thus, an IATN includes the corresponding TAF (described in Section 5.2) for each area it connects. IATNs maintain their own FIB function that maps tunnels from one area to tunnels of another area. In case, an IATN interconnects areas belonging to the same technology, technology specific optimisations are possible to accelerate the datapath that are currently being investigated.

5.4 5G-XHaul Tenant Abstraction

A network virtualization technology allows a tenant to instantiate a virtual network connecting its virtual or physical network functions, hereafter referred to as VNFs and PNFs. Notice that in the case of 5G-XHaul a VNF/PNF could also represent a base station. Thus, a typical virtual network abstraction is that of a Layer-2 switch directly connecting the tenant's VNF/PNFs, as e.g.in [51]. This abstraction although simple for the tenant, comes at a cost for the infrastructure owner, who needs to accommodate for each tenant unconstrained *any to any* communication patterns enabled by this abstraction, thus consuming significant resources on the physical substrate. In [52] it is shown that a more efficient embedding is possible if the tenant abstraction declares information about the expected communication patterns between its VNFs.

The goal of 5G-XHaul is to define a transport network architecture connecting the VNF/PNFs of tenants offering 4G or 5G connectivity services. To effectively support multi-tenancy in this environment, the communication patterns imposed by the mobile network should be exploited. For example, in 4G, most of the traffic generated by base stations is addressed to the packet gateways in the CN, however low delay direct connections between neighbouring BSs may be beneficial for handover or interference coordination signalling. In 5G we expect the following changes in the communication patterns: i) the amount of local traffic between neighbouring base stations will increase to enable more demanding interference coordination techniques, ii) native support for multicast to a group of base stations may be beneficial to support cooperative transmission schemes, and iii) core packet gateways will be virtualised and possibly distributed to regional data centres, which will result in a more distributed traffic matrix over the transport network.

In order to address the previous communication patterns, 5G-XHaul proposes tenant abstraction, or slice definition, depicted in Figure 30. A tenant defines a set of layer two segments, $S = \{s_1 \dots s_N\}$,, where each segment in S is meant to directly connect a subset of the tenant's VNFs. Figure 30 illustrates layer two segments in different colors, and assigns to each segment a unique identifier referred to as layer two segment ID (L2SID). Each segment $s_i \in S$ is associated with QoS parameters, such as a peak bandwidth B_i and maximum latency L_i, defining the constraints of that layer two segment. Each VNF in the tenant slice, depicted with hexagon shapes in Figure 30, is associated to a single layer two segment $s_i \in S$. In addition, the tenant abstraction allows to define *logical datapaths* (DPs), illustrated with solid pentagon shapes in Figure 30, which may have multiple interfaces, each interface connecting to a different layer two segment $s_i \in S$. Logical DPs are used to control the forwarding state between VNFs in the tenant slice, according to the tenant's own control logic. In particular, logical DPs host the custom control state defined by each tenant's control plane, thus implementing the *Control Layer* described in the 5G-XHaul overarching architecture introduced in Section 3. Figure 32 provides an example of the control rules that can be pushed by the tenant's control plane into the logical DPs.

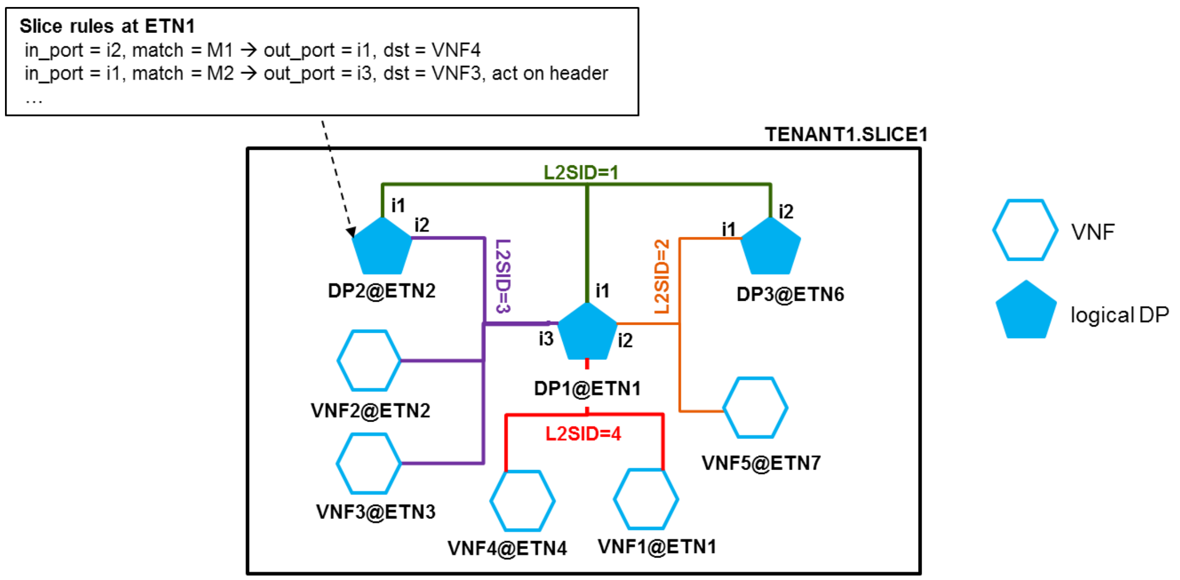

Figure 32: Tenant abstraction proposed in 5G-XHaul.

For more details on the proposed tenant abstraction and an initial implementation design the interested reader is referred to [40].

5.5 Hierarchical SDN controller design

In 5G-XHaul the control plane is composed of a hierarchy of controllers as illustrated in Figure 29. The top level controller, hereafter referred to as the *Top* controller is responsible to provision per tenant slices, and to orchestrate the required connectivity across different 5G-XHaul areas and domains (e.g., optical transport domain, wireless transport domain). At the lowest level of the hierarchy we find the *Level-0* controller that is responsible for the provisioning and maintenance of transport tunnels between ETNs and IATNs of a given 5G-XHaul area; a Level-0 controller operates at the level of individual network elements. A set of Level-0 controllers are logically organized under a Level-1 controller, which is in charge of maintaining connectivity between the corresponding Level-0 areas, and operates with a higher level of abstraction, namely maintains state at the area level instead of maintaining state for each network element as Level-0 controllers do. Note that the proposed architecture is recursive in the sense that a Level-*i* controller can be defined to coordinate a set of Level-(*i-1)* controllers. Hereafter, and without loss of generality, we assume a three level hierarchy consisting of Level-0, Level-1 and Top controllers.

Dimensioning the number of network elements under a Level-0 controller, or the number of Level-0 controllers under a Level-1 controller depends on many factors and is an area of active research. A Level-0 controller is assumed to be in charge of an area instantiating a single type of transport technology, i.e. a mmWave area, an Ethernet area, or an active optical area. Thus, the number of elements under a Level-0 controller will be very dependent on the particular technology. For example, for scalability reasons a large number of mmWave transport nodes deployed at the street level can be partitioned into a plurality of areas and Level-0 controllers, whereas the optical switches composing the metro network and the corresponding Ethernet clients could be controlled respectively by a different Level-0 controller. A deployment example has been provided in Figure 30. Notice that having technology specific controllers allows to develop solutions tailored to the control plane of each technology. Upper level controllers, i.e. Level-1 and Top controllers do not need to be technology specific since they operate at a higher abstraction level (the area level). In practice for scalability reasons controllers at each level will be deployed in clusters of synchronised controllers.

The major functionality carried out at each controller level is illustrated through an example. Consider a tenant defining a slice according to the abstraction described in Section 5.4. The tenant indicates the ETN where each VNF/PNF included in the slice is connected, where the selected ETNs may be located in different 5G-XHaul areas (c.f. Figure 29). Thus, once defined, the slice is submitted to the 5G-XHaul Top controller through a north bound interface (NBI). The responsibility of the 5G-XHaul control plane is then to wire the transport tunnels connecting the ETNs involved in the tenant's slice. The first task of the Top controller is to look up the Level-1 controllers in charge of the ETNs included in the layer two segments defined in the received slice. Once the Level-1 controllers are identified, the Top controller runs a path allocation algorithm to establish a path between all the ETNs participating in the same layer two segment. The path determined by the Top controller is expressed as a set of Level-1 controller areas, whereby a Level-1 controller area is composed of all the 5G-XHaul areas (c.f. Figure 29), where the corresponding Level-0 controller is controlled by the Level-1 controller. For each determined path, the Top controller requests the involved Level-1 controllers to allocate a transport connection between ETNs under their control, or between an ETN and a neighbouring Level-1 area. In order to determine these paths, the Level-1 controllers run a path allocation algorithm that returns the set of 5G-XHaul areas composing the path, along with the corresponding Level-0 controllers in charge of each area. Consequently, for each path, the Level-1 controller submits a request to the corresponding Level-0 controller, which runs a path allocation algorithm to identify the transport tunnels and paths connecting each involved ETN and IATN within the 5G-XHaul area under its control. Once the process completes the tenant slice is fully connected and communication may begin.

An initial design describing the functions allocated at each controller level can be found in [40].

5.6 Interactions between the Transport Network and the Mobile Network

The goal of 5G-XHaul is to create a transport infrastructure destined to serve 5G Mobile Network operators. Therefore, in most cases the slices instantiated by the 5G-XHaul tenants will be connecting mobile related VNFs, for example base stations with elements of the mobile packet core. In this context, we envision that an important service provided by 5G-XHaul to a mobile network slice is the ability to interact with the transport network in a more tightly coupled way than what is possible in 4G, in order to improve QoE.

In fourth generation (4G), and previous generations, the Mobile Network is composed of RAN and the CN. In the case of 4G, RAN and CN communicate over a transport network, but the only assumption about the TN is that it is an IP network. Thus, the TN is unaware that it is transporting packets between base stations in the RAN and packet gateways in the CN. In particular, base stations and packet gateways set up IP tunnels over the transport in order to communicate with each other. Such tunnels need to be updated for example when a mobile device hands over between BSs. For security reasons the IP tunnels used in the Mobile Network are often encrypted, which refrains the TNs from becoming aware of the type of radio traffic being carried in the tunnel in order for example to deliver a tailored treatment. Instead, 4G defaults to standard IP QoS mechanisms such as Differentiated Services Code Point (DSCP) markings. In 5G-XHaul we advocate that more open interfaces between the Mobile and Transport Network can be beneficial for a number of reasons, which we discuss next.

5.6.1 Use cases for information exchange between the Mobile and Transport networks

Unlike in 4G, where it is assumed that the transport network can be overprovisioned, in 5G the Mobile Network and, in particular, the RAN design, needs to consider the performance of the transport network. Concretely, the characteristics of the transport network will dictate the optimal allocation of RAN signal processing functions between a RU and CU [1], which is critical to implement cooperative and interference mitigation techniques that increase spectral efficiency. Thus, parameters like the transport network available rate and latency are key in the selection of the RAN configuration to be used.

We next present a set of use cases that motivate the need for a RAN and transport information exchange:

- *Proactive congestion avoidance*: Lack of coordination between RAN and transport may result in the mobile network triggering a handover to a target base station that is then connected to a congested link in the transport network. In order to avoid these situations, the mobile network must be aware of the transport network congestion levels when triggering handovers between cells.
- *Load balancing*: Information about the RAN, enables the transport network to more effectively balance the traffic load between BSs and mobile network functions across different paths. This results in a better utilisation of resources within the transport, as well as in an overall improvement of QoE.
- *Fairness*: Currently, transport networks do not offer the same granularity in QoS profiles as the RAN provides. Transport networks are therefore unable to distinguish among different types of traffic, which may result in unfairness, or policy violations, upon congestion. A mobile network and transport network information exchange would for example allow to appropriately re-classify mobile traffic into transport QoS classes in order to comply with the policies defined by the mobile network operator at all times.
- *Self-backhauling*: Early 5G deployments require means for incremental deployment as initially the density of 5G BSs with dedicated backhauling would be limited. A useful technique which can be beneficial in future systems is self-backhauling. The support of wireless self-backhauling is a technique studied by some 5G RAN proposals. If such capabilities are available, mobile and transport networks should coordinate to decide when it is best to make use of self-backhauling.
- *Energy Saving*: If operating in isolation, the mobile and transport networks may take conflicting decisions when trying to minimize energy consumption by independently switching off RAN and transport nodes. Energy efficiency is a clear example where mobile and transport network coordination is required for a global system optimisation.
- *Cell-less RAN architecture*: Some 5G RAN proposals operating at very high frequencies, where blockage and path loss due to NLoS are very significant, are studying the possibility of not having a mobile device exclusively attached to a single BS, but rather be able to receive/transmit data from/to different BSs according to channel measurements performed by the mobile device [44]. Changing points of attachment at such short time scales requires a very tight coordination between the Mobile Network and the transport network in order to quickly reconfigure the downlink and uplink paths.

5.6.2 Envisioned types of interfaces between the Mobile and Transport networks

The proposed 5G-XHaul transport network relies on a mix of legacy and new technologies. The information regarding the type of resources and how to share this information between the mobile and transport network depends on the specific transport service, the deployment scenario, the radio deployment architecture, and the choice of the transport technology. Hence, it would be desirable to achieve an information-sharing model, where each domain (mobile network and transport) manages the information to be shared with the other, and prescribes how to use that information.

The trend towards adopting a logically centralized control plane in 5G, both for the transport and the mobile network, is a step towards enabling this information exchange, because an SDN controller naturally collects information about the network state that can be shared with other domains.

Three main types of mobile network-transport interfaces depicted in Figure 33 are identified to support the use cases introduced in Section 5.6.1:

- An interface between the transport controller and the Mobility Management Entity (MME[6]). The MME is an entity in the CN that is aware of the current position of mobile devices at the cell level, for Radio Resource Control (RRC) connected devices, and at the tracking area level, for RRC idle devices. The MME is also involved in handover preparation. Hence, the MME could provide the transport controller with statistics about aggregate mobility behaviors in the RAN, or about the cell level trajectory of a given mobile device.

[6] Or equivalent entity in 5G

- An interface between the transport controller and a RAN controller (e.g. a SON controller [53]). Unlike the MME, a RAN controller is aware of radio conditions and is in charge of managing cooperative and interference coordination techniques, for which the support of the transport network may be required. In principle, the information exchanged through this interface has a shorter lifespan than the information exchanged with the MME.

An interface between the centralised MAC scheduler[7] of a given (group of) BSs, and the transport controller. The information exchanged through this interface has the shortest life span. This interface would be for example required to support a cell-less RAN architecture.

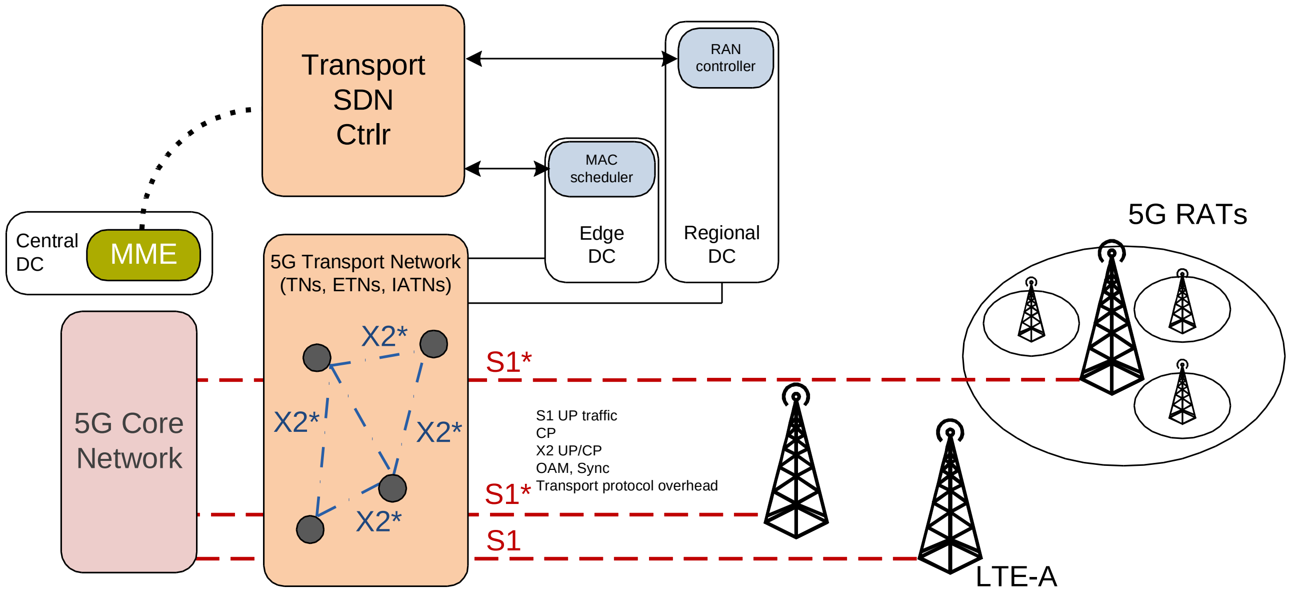

Figure 33: Envisioned interfaces between mobile network and the transport network.

The interested reader is referred to deliverable D3.1 [40] for an initial design of the aforementioned interfaces.

[7] In 4G, the MAC scheduler is a function inside the RAN protocol stack in charge of scheduling packets from different radio bearers on the available radio resources. An equivalent meaning is assumed for 5G

6 5G-XHaul Architecture Evaluation

In this section we summarise some initial considerations regarding the evaluation of the proposed data plane architecture. In addition, some initial evaluation of the support of different TCs and the associate delay requirements is provided. However, more detailed evaluation results and discussion will be provided as part of the upcoming deliverable D2.3.

6.1 Evaluation of the data plane architecture

More specifically, we consider a physical infrastructure (PI) that interconnects RUs and end-users with a set $\mathcal{S}$ of S geographically distributed general purpose servers through a heterogeneous frame-based WDM optical metro network [54].

The proposed provisioning model takes a holistic view considering jointly mobile FH and BH functions to ensure appropriate allocation of the required resources across all domains. Its objective is twofold: i) to minimise the operational expenditure of the FH in terms of power consumption under strict delay constraints achieved through the optimal functional split of BS processing as well as through optimal BBU placement [55], and ii) to minimise end-to-end service delay in the BH.

To address these issues we have developed a MOP optimisation model that aims to identify the optimal resources (i.e. wireless, optical network and computing resources) and policies (i.e. optimal split option and traffic offloading strategies) that can support the required services in terms of both topology and resources. Part of this work has been reported in [14].

To achieve this goal, the PI is represented as a weighted graph $\mathcal{G} = (\mathcal{N}, \mathcal{E}, \mathcal{D})$ where $\mathcal{N}$ represents the set of PI nodes, $\mathcal{E}$ the set of PI links and $\mathcal{D}$ describes the set of demands. $\mathcal{D}$ is partitioned into $\mathcal{D}_F$ and $\mathcal{D}_B$ i.e., $\mathcal{D} = \mathcal{D}_F \cup \mathcal{D}_B$, where $\mathcal{D}_F, \mathcal{D}_B$ are the set of demands originating from the FH and BH, respectively. In order to abide to the strict latency constraints of the various TCs (i.e. CPRI flows), the FH is modeled using network calculus theory, where each transport flow $d \epsilon \mathcal{D}_F$ is constrained by an arrival curve a_{r_d,b_d} and a service curve β_{c_d,T_d}. Arrival curves of the form a_{r_d,b_d} allow sources d to transmit bursts with size b_d bits at once, but no more than r_d bps in the long run [56]. Service curves β_{c_d,T_d} can serve traffic with rate c_d after T_d time delay. Arrival curves a_{r_d,b_d} depend primarily on the functional split options of the BS processing and the characteristics of the LTE system. As already discussed, assuming an LTE system with transmission bandwidth B_w=20 MHz, sampling frequency 30.72 MHz, bit resolution per I/Q 2, oversampling factor 2 and 2 antennas, $r_{d(1)}$ under split option (1) will be 2.46 Gbps. However, when employing split option (2) this is reduced to $r_{d(2)}$=720 Mbps, assuming 1200 subcarriers and Fast Fourier Transform (FFT) period of 66.67 μs [5], [55].

In the general case, the joint FH/BH problem is solved taking into account a set of constraints that guarantee the efficient and stable operation of the resulting infrastructures. The basic constraints that are included in the analysis are summarized as follows:

Demand, split option constraints:

Let Σ_d be the set of split options for demand d and σ_{di} a binary variable taking value equal to 1 if split option $i \epsilon \Sigma_d$ is adopted, 0 otherwise. The following demand and split option constraints should be satisfied: $\sum_{s\epsilon\mathcal{S}} \sum_{p\epsilon\mathcal{P}_d} \wp_{ds} x_{dp_s} = \sum_{i\epsilon\Sigma_d} \sigma_{di}\, a_{r_{d(i)},b_{d(i)}}, \; d\epsilon\mathcal{D}_F \;\; (1), \;\; \sum_{i\epsilon\Sigma_d} \sigma_{di} = 1, \; d\epsilon\mathcal{D}_F \;\; (2)$ where $\mathcal{P}_d = 1,2,\ldots,P_{ds}$, is the set of paths transferring FH demands $d \,\epsilon\, \mathcal{D}_F$ to DC $s\epsilon\mathcal{S}$, $\wp_{ds}$ is a binary coefficient taking values equal to 1 if $d\epsilon\mathcal{D}_F$ is processed at server $s, s\epsilon\mathcal{S}$, 0 otherwise and x_{dp_s} is the non-negative capacity allocated to path p supporting demand d.

Network capacity constraints:

Summing up the paths through each link $e\,(e\epsilon\mathcal{E})$, capacity constraints expressed through $\sum_{d\epsilon\mathcal{D}_F} \sum_{s\epsilon\mathcal{S}} \sum_{p\epsilon\mathcal{P}_d} \delta_{edp} x_{dp_s} \le u_{FH,e}, \; u_{FH,e} \le \mathcal{U}_e \;\; e\epsilon\mathcal{E}$ should be satisfied, where, δ_{edp} indicates a binary coefficient with value 1 if link e belongs to path p for traffic flow d and 0 otherwise, $u_{FH,e}$ is the link e capacity allocated for FH functions and $\mathcal{U}_e$ is the total capacity of e.

Latency constraints:

x_{dp_s} is viewed as the arrival curve for flow d using path p to reach server s. The aggregated arrival curve for all flows $i\epsilon\mathcal{D}_F, i \neq d$ at e, denoted as $a_{-d,e}$, is given through $a_{-d,e} = \sum_{i\epsilon\mathcal{D}_F, i\neq m} \sum_{s\epsilon\mathcal{S}} \sum_{p\epsilon\mathcal{P}_d} \delta_{eip} x_{ip_s}$. Now, let β_{u_e,T_e} be the service curve of e, where T_e is the propagation delay. According to network calculus, for a flow traversing a system with arrival curve a and service curve β, the upper delay bound is $h(a,\beta) = \inf\{t \geq 0 : (a \oslash \beta)(-t) \leq 0\}$, where $\oslash$ is the in min-plus deconvolution operator. The upper bound $\hat{t}_{de}$ of the delay introduced by link e for flow d can be evaluated through $\hat{t}_{de} = h\left(x_{dp_s}, \left[\beta_{u_e,T_e} - a_{-d,e}\right]^+\right)$. Once $\hat{t}_{de}$ has been determined, the total delay introduced across all links forming the path is evaluated. To ensure seamless operation of the CPRI protocol, this delay should be limited below a specific threshold, usually, between 100-200 μs.

Processing capacity constraints:
Besides network capacity, FH requires specific computing resources allocated for BBU processing. The processing power per demand depends on the sub-components of the BBU (Figure 2) including FFT, Error Correction, processing-resource mapping/demapping etc. calculated in Giga Operations per Second (GOPS) via an equation of the form [59], [60]: $P_{\mathcal{I}_{BBU},d} = \sum_{c \epsilon \mathcal{I}_{BBU}} P_{c,d}(\mathcal{X}_{act}, \mathcal{X}_{ref}, s_{c,x})$. $\mathcal{I}_{BBU}$ is the set of BBU subcomponents, P_c is the processing power required to execute tasks related to component c and $\mathcal{X}_{act}, \mathcal{X}_{ref}, s_{c,x}$ are reference parameters [60]. These parameters depend on the configuration of the LTE system (i.e. number of antennas, bandwidth, modulation, coding, number of resource blocks). Based on the functional split adopted, part of the processing can be performed either at a local BS with cost w_d per GOPS or at a remote server s with cost w_s per GOPS $(w_s > w_d)$. The total information to be processed by server s for FH is $\pi_{FH,s} = \sum_{d \epsilon \mathcal{D}_F} \sum_{i \epsilon \Sigma_d} \mathcal{p}_{ds} P_{\mathcal{I}_{BBU(i)},d}$, while at the local BS d it is $\pi_{FH,d} = \sum_{i \epsilon \Sigma_d} P_{\mathcal{I}_{BBU(-i)},d}$. $\mathcal{I}_{BBU(i),d}$ is the subset of components processed at the remote BBUs in case of split $i \, \epsilon \Sigma_d$ and $\mathcal{I}_{BBU(-i),d}$ is the subset of the remaining components processed locally. During this process, the servers' capacity constraints should not be violated: $\pi_{FH,s} \leq \mathcal{C}_s$ $(s \epsilon \mathcal{S})$ and $\pi_{FH,d} \leq \mathcal{C}_d$ $(d \epsilon \mathcal{D}_F)$.

Objective:
Assuming that the cost per link e is w_e, the optimal FH network is identified through the minimisation of the cost: $\min \sum_e w_e \, u_e + \sum_{s \epsilon \mathcal{S}} w_s \pi_{FH,s} + \sum_{d \epsilon \mathcal{D}_F} w_d \, \pi_{FH,d}$ subject to capacity, functional split and demand constraints. Due to the inherent energy efficient operation of the optical network, improved performance is achieved, in terms of power consumption for higher degree of centralisation i.e. C-RAN compared to traditional RAN approach. However, this comes at the expense of overloading the optical transport to support the FH requirements, leaving limited resources for the BH functions. To address this issue, the secondary optimisation objective is to minimise the end-to-end delay in the BH:

$$min \sum_{e \epsilon \mathcal{E}} \left[\mathcal{U}_e - u_{FH,e} - u_{BH,e}\right]^{-1} + \sum_{s \epsilon \mathcal{S}} \left[\mathcal{C}_s - \pi_{FH,s} - \pi_{BH,s}\right]^{-1}$$

subject to demand processing and capacity constraints in the BH, where $u_{BH,e}$, $\pi_{BH,s}$ represent the network and server capacity allocated to the BH, respectively.

Numerical Results

The proposed MOP scheme is evaluated using the Bristol 5G city infrastructure (Figure 34) [64] that will host the final proof-of-principle 5G-XHaul demo. This infrastructure covers a 10x10 km2 area over which 50 APs are uniformly distributed and comprises TSON nodes in the optical segment, and microwave point-to-point links for backhauling the APs. TSON deploys a single fiber per link, 4 wavelengths per fibre, wavelength channels of 10 Gbps each, minimum bandwidth granularity of 100 Mbps and maximum link capacity of 40 Gbps. The TSON power consumption model is provided in [57]. The microwave transceivers considered, support maximum bandwidth of 2 Gbps and their typical power consumption is 45 Watt (Huawei OptiX RTN310). Furthermore, a 2×2 MIMO transmission with adaptive rank 10 MHz bandwidth adjustment has been considered, while users are distributed and generate traffic over the serviced area according to real datasets reported in [58]. This traffic, corresponding to wireless access traffic, needs to be processed by specific compute resources. Figure 35 presents the evolution of the average traffic per BS for the wireless access domain, respectively. This traffic needs to be processed by specific computing resources.

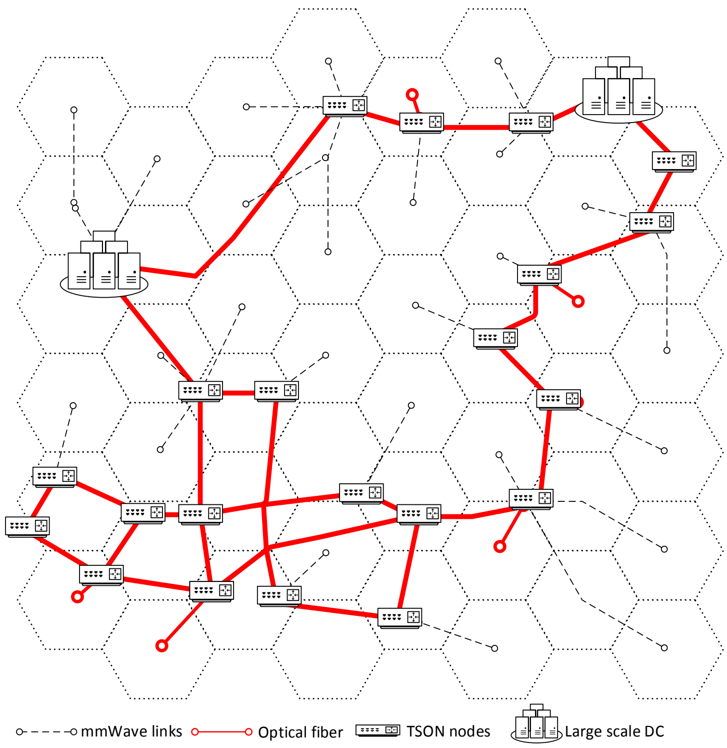

Figure 34: Bristol 5G city network topology with mmWave backhauling.

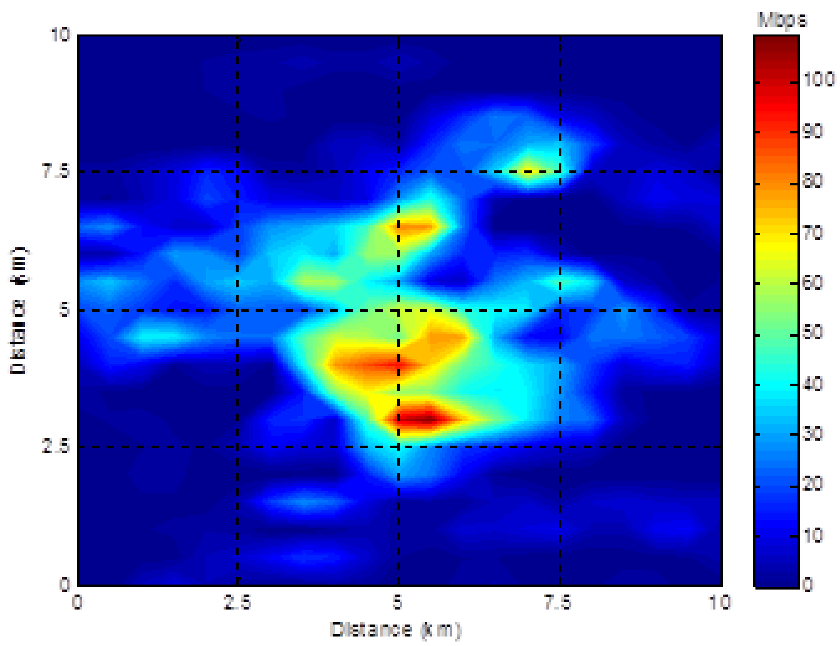

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Figure 35: Snapshot of spatial traffic load.

The proposed optimisation scheme is focusing on three different scenarios:

a) "*Traditional RAN"* giving emphasis on the optimisation of the cloud services supported by the BH. Power consumption per BS ranges between 600 and 1200 Watt under idle and full load conditions, respectively. Small scale commodity servers are deployed for user cloud services.

b) *"C-RAN with fixed BBUs"* where remotely located specialised hardware is used for BBU processing with 200 GOPS capacity/BBU and 1.2 Watts/GOPS power consumption. In this scenario, cloud computing demands originating from the end-users are processed at small scale servers as before.

c) *"C-RAN with virtual BBUs (vBBUs)"* where large-scale commodity servers are used to support both BBU processing (through the creation of vBBUs [4][61]), and user cloud services.

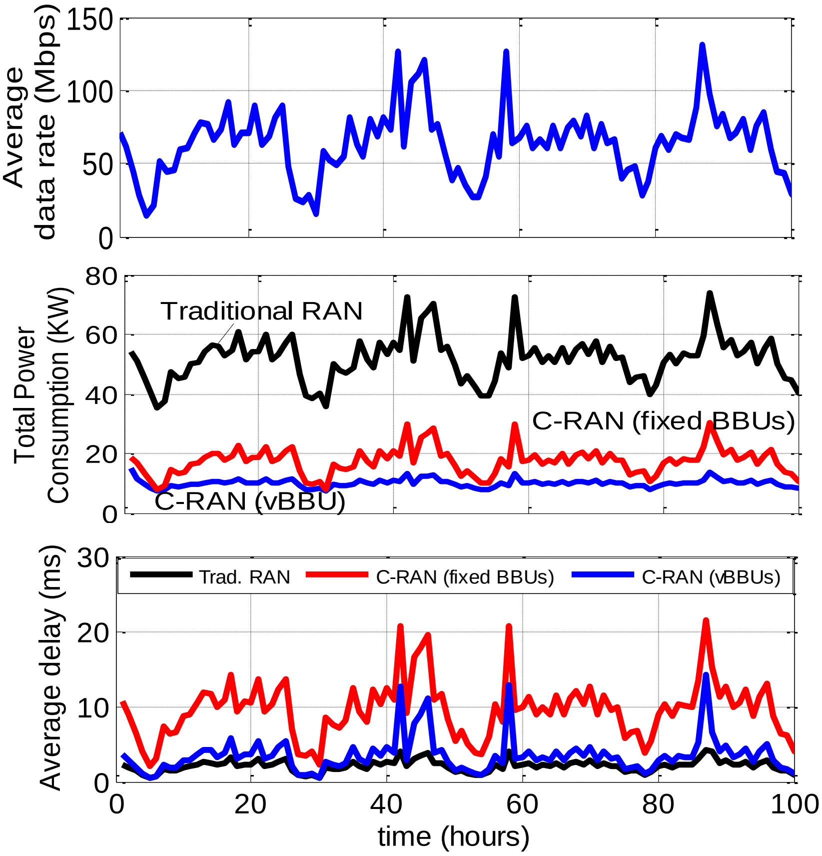

Figure 36: a) Average traffic/BS based on the dataset [10] during 8/2012, b)-c) Total power consumption and delay over time for the traditional RAN and the C-RAN with fixed and vBBUs.

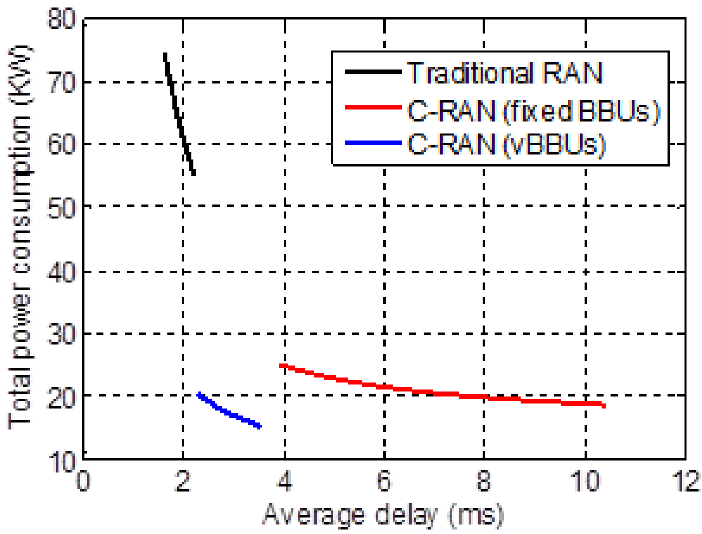

Figure 37: Pareto front of the MOP.

When adopting the C-RAN approach over the proposed integrated wireless-optical infrastructure, and comparing it with the traditional RAN approach, significant energy savings (ranging between 60-75%) can be achieved (Figure 36b). However, due to overloading of network resources to support FH requirements, C-RAN leads to an increase of the end-to-end service delay in the BH (Figure 36c), which however remains below 20 ms for a 100 Mbps flow request. It is interesting to note that the BH service delay calculated for the C-RAN vBBU case is lower compared to the delay calculated for the C-RAN fixed BBU case. This is due to the fact that in the C-RAN vBBU case lower processing times are required by the large commodity servers to execute the user cloud services.

Figure 37 shows the Pareto front indicating optimal operating points of the proposed MOP framework, in terms of energy consumption and end-to-end service delay, for all three scenarios considered. The C-RAN scheme with vBBUs achieves the optimal balance between energy consumption and end-to-end service delay. Traditional RAN provides minimum end-to-end service delays as its functions do not consume any BH bandwidth, but suffers high energy consumption due to the lack BBU sharing. The C-RAN with fixed BBUs scheme, offers relatively low energy consumption, but higher delays as execution of end users services is not exploiting the benefit of fast processing times available through the large scale servers.

6.2 Support for the different TCs using IEEE 802.11ad wireless mesh

In this section we summarise an initial evaluation of the support of different TCs when a mmWave mesh employs IEEE 802.11ad technology. The mesh node construction and the assumed 802.11ad MAC scheduler operation are described in [40].

TC 0

In principle IEEE 1588-2008, aka PTP Version 2, can operate over a meshed wireless BH. It exploits “transparent clock” in which special packets are timestamped and these timestamps may be corrected according to the delays through the mesh. MAC to MAC delays for an 802.11ad Personal Basic Service Set (PBSS) may be initially determined by the transmitter MAC at the point in time when the packet is allocated a transmission time. The degree of accuracy is subject to the implementation of the receiver PHY and MAC layers. Packets errored on the air interface may be discarded. If a packet is held in a receiver buffer reordering queue the timestamp can be adjusted by the receiver MAC before sending it further into the mesh – but an implementation would probably assign the 1588 packets to a dedicated TID (traffic identifier) which has its own sequence number space and hence not blocked by other data re-tries.

Note that since the TC 1 and TC 2 assume synchronous delivery, jittered packets need a play-out buffer (like CPRI over Ethernet) and some of the delay budget must be reserved for this part. If we assume no packets are discarded for late arrival, then the maximum delayed packet should have a delay less than the delay budget (and if equal to the delay budget it would pass through the play-out buffer with no additional delay).

TC 1

The round-trip latency requirement for TC 1 is 200 µs. Even with a single-hop network this would require a scheduling interval of approximately 0.1 ms, negligible scheduler advance and switching delay. For an MCS12 link the sustainable rate would be approximately 1.5 Gbps in each direction, and a mean round trip latency without errors of 240 µs. There would be no time to retransmit MAC Protocol Data Units (MPDUs) so this seem impractical given the reliability of real-world radio links. Even with a 0.05 ms scheduling interval the mean round trip latency would be 75 µs, 95-percentile latency approximately 130 µs, and worst-case 240 µs, in these ideal conditions, and the data rate would only be 800 Mbps in each direction.

Conclusion: support for TC 1 latency with Gbps rates is not practical.

TC 2

The round-trip latency requirement for TC 2 is 2 ms. This can be maintained if the number of hops is limited and the aggregate downstream and upstream rates per small cell are constrained. For example, if the network is a binary tree of depth 3, if each cell sources and sinks at rate *r*, the sum load on the two PBSSs that terminate at the gateway would be 6*r* (each). If the last link supports MCS12 then *r* would be of the order of 0.5 Gbps.

TC 3

The latency requirements are relaxed here and synchronous delivery is not expected, so the mesh links can run close to peak data rates. The rate per small cell depends on the radio conditions (MCS per link) and the topology of the mesh.

6.3 Evaluation of Transport Class Latencies

In deliverable D2.1 [1] we analyzed the data rate requirements of different RATs. In the following, additional latency analysis is provided, which is the second metric that differentiates the TCs. The total latency is the sum of the following contributions:

- Propagation latency: $t_{prop} = \frac{2d}{c_{fiber}}$, with d being the distance and c_{fiber} being the speed of light in fiber $c_{fiber} = 2 \cdot 10^8 \frac{m}{s}$.
- FH processing latency: $t_{proc,FH} = 5\ \mu s$, this being the maximum allowed processing time for current CPRI implementations.
- FH node switching latency: $t_{proc,switch} = 2N \cdot t_{switch}$ with N being the number of switches transgressed and $t_{switch} = 1\ \mu s$ being the moderate estimation of the switching time of a single switch from [62].
- RAN processing time: $t_{proc,RAN} = 2.7\ \mu s$, being the currently assumed BBU processing time in a BS [63].

Note that a factor of 2 is included where appropriate to account for the round trip. Figure 38 illustrates the total latency over distance for different numbers of switches with and without the BB processing time at the BBU, $t_{proc,RAN}$ (note the double-logarithmic scale). In general, the latency is composed of constant contributions ($t_{proc,FH}, t_{proc,switch}, t_{proc,RAN}$) and the fibre propagation time, t_{prop}, which linearly depends on the distance. For comparison, the maximum latencies of the different TCs, as well as the channel coherence times for different RATs from D2.1 are shown. Several facts can be observed, which are listed below.

First, baseband processing dominates over the FH latency in the current implementation up to a distance of about 20 km. In addition, the BB processing is currently too high to support low latency applications requiring sub-ms latencies. This issue needs to be addressed in the BB implantation for ultra-low- latency applications. However, BB implementation is not the focus of 5G-XHaul.

Next, it can be observed that with the current BB processing times, centralized RAN processing is impossible for high speeds, and even for low speeds in case of the 80 GHz RAT.

Regarding the TCs, the latency without BB processing is of relevance, as they already consider a margin for BB processing. As can be seen, TC 1 can be supported up to a distance of 20 km (which is in line with current CPRI deployments), TC 2 up to 200 km (which is suitable for a local cloud deployment), and TC 3 up to 2000 km (which is suitable for a global cloud deployment). With the considered switching time, the number of switches on the route is also irrelevant, as the propagation latency dominates. Hence, a packet-based architecture can be assumed to be feasible even over large distances.

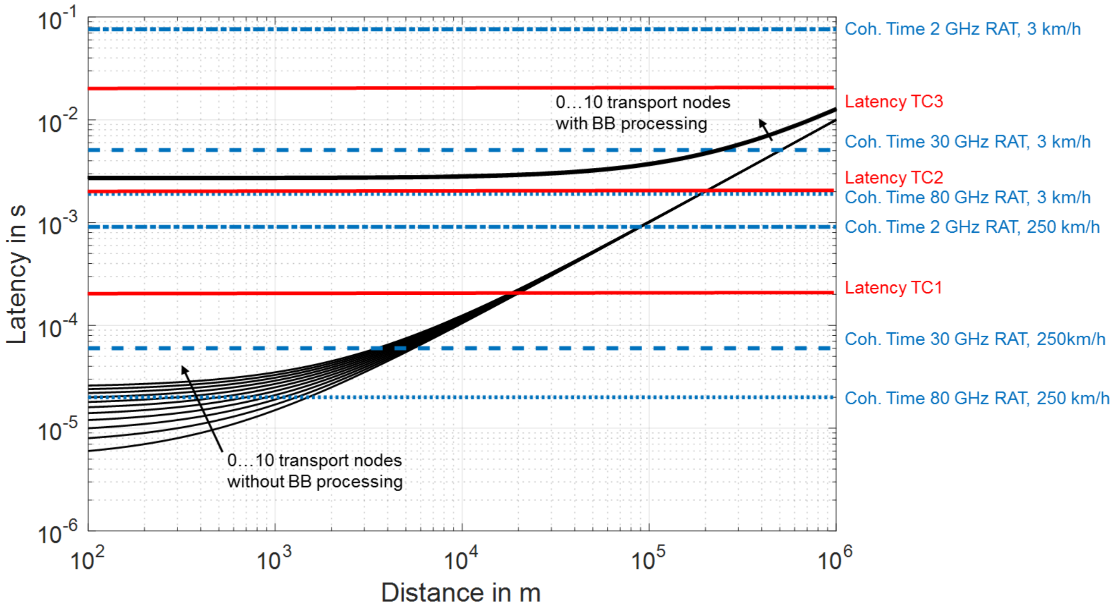

Figure 38: Latency over distance for different number of switches with and without BB processing.

7 Summary and Conclusions

In this deliverable, the converged optical-wireless 5G network infrastructure interconnecting computational resources with fixed and mobile users proposed by the 5G-XHaul project is described. The proposed architecture aims at supporting both operational network (C-RAN) and end-user services. A summary of a set of requirements and the associated KPIs, derived through a use case and 5G service analysis, is provided. The corresponding overarching layered architecture, inspired by the ETSI NFV standard and the SDN reference architecture that can support these requirements is also presented. This architecture describes the required functions that 5G-XHaul proposes to effectively and efficiently provision both end-user and operational services.

The development focus of 5G-XHaul is presented in terms of both physical infrastructure and control plane. The architecture of the physical infrastructure is defined in detail including descriptions of the various wireless and optical technologies adopted as well as the data path interfaces required to enable integration across the greatly varying technology domains. The option of exploiting flexible functional splits is described and different transport classes that the 5G-XHaul solution can support are discussed. In addition, the 5G-XHaul control plane, responsible to provision transport slices instantiating the connectivity required by the 5G-XHaul tenants, is described from both an architectural and a functional perspective.

Some initial considerations regarding the evaluation of the architecture is also provided through the description of a modelling tool that is being purposely developed. This evaluation focuses on the data plane performance as well as the impact associated with the choice of transport classes corresponding to different functional split levels. The novel modelling framework developed aims at evaluating the performance of this infrastructure. It includes a multi-objective optimisation model used to study a variety of FH and BH options, spanning from the traditional approach where the two functions are supported separately to solutions involving fully or partially converged FH and BH functions. Finally, some initial evaluation of the support of different TCs and the associate delay requirements is also provided.

8 References

[1] 5G-XHaul Project, Deliverable D2.1 "Requirements Specification and KPIs Document", submitted on March 1st, 2016.

[2] J. Chen et al "Demonstration of Analog Millimeter-wave Fronthaul Link for 64-QAM LTE Signal Transmission" in Proc. IEEE VTC, Fall 2015

[3] D. Bladsjo, et.al., "Synchronization aspects in LTE Small Cells," IEEE Comm. Mag., vol.51, no.9, pp.70,77, Sep. 2013.

[4] C-RAN. The Road Towards Green RAN. White Paper 3.0 (Dec. 2013), http://goo.gl/Sw6bfw

[5] U. Dötsch et al., Quantitative Analysis of Split Base Station Processing and Determination of Advantageous Architectures for LTE, Bell Labs Tech. J, vol. 18, no.1, pp. 105-128, May 2013.

[6] D. Wubben et al., "Benefits and Impact of Cloud Computing on 5G Signal Processing: Flexible centralization through cloud-RAN," IEEE Signal Proc. Mag., vol.31, no.6, pp.35-44, Nov. 2014

[7] Mobile Fronthaul: Transmode's unique active and passive solution enables mobile operators to migrate to Cloud-RAN architecture.

[8] http://www.etsi.org/technologies-clusters/technologies/nfv

[9] https://www.opennetworking.org/

[10] mmMAGIC D1.1 Use case characterization, KPIs and preferred suitable frequency ranges for future 5G systems between 6 GHz and 100 GHz, https://bscw.5g-mmmagic.eu/pub/bscw.cgi/d54427/mmMAGIC_D1.1.pdf

[11] FANTASTIC-5G IR2.1 Use cases, KPIs and requirements, http://fantastic5g.eu/wp-content/uploads/2016/01/FANTASTIC-5G_IR2-1_final.pdf

[12] 5G NORMA D2.1 Use cases, scenarios and requirements, https://5gnorma.5g-ppp.eu/wp-content/uploads/2016/01/5G_NORMA_D3.1.pdf

[13] 5G-PPP View on 5G Architecture – (White Paper), accessed on July 05, https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-5G-Architecture-WP-For-public-consultation.pdf

[14] A. Tzanakaki et al., "5G infrastructures supporting end-user and operational services: The 5G-XHaul architectural perspective," 2016 IEEE International Conference on Communications Workshops (ICC), Kuala Lumpur, Malaysia, 2016, pp. 57-62.

[15] Y. Yan, Y. Qin, G. Zervas, B. Rofoee and D. Simeonidou, "High performance and flexible FPGA-based time shared optical network (TSON) metro node," 2012 38th European Conference and Exhibition on Optical Communications, Amsterdam, 2012, pp. 1-3.

[16] ETSI GS NFV-SWA 001 V1.1.1 (2014-12), "Network Functions Virtualisation (NFV); Virtual Network Functions Architecture", 2014.

[17] METIS Project D6.1 [Online] http://tinyurl.com/joohwkt

[18] M. Savi, M. Tornatore, G. Verticale, "Impact of processing costs on service chain placement in network functions virtualization," in proc. of IEEE NFV-SDN, 2015 pp.191-197, 18-21 Nov. 2015

[19] Bo Han; Gopalakrishnan, V.; Lusheng Ji; Seungjoon Lee, "Network function virtualization: Challenges and opportunities for innovations," IEEE Commun. Mag., vol.53, no.2, pp.90-97, Feb. 2015.

[20] China Mobile NGFI White paper: China Mobile, ALU, Nokia, ZTE, Broadcom, Intel, "White Paper of NGFI (Next Generation Fronthaul Interface) Version 1.0", October 4, 2015.

[21] IEEE 1904.3 Task Force, Standard for Radio Over Ethernet Encapsulations and Mappings http://grouper.ieee.org/groups/1904/

[22] J. Bartelt *et al.,* "The Impact of 5G Radio Access Technologies on a Converged Fronthaul and Backhaul Network," submitted to *IEEE Wireless Comm.,* Feb. 2016.

[23] J. Allen and F. Chevalier, ``Report for Vodafone_Mobile backhaul market: Phase 1 report,'' Analysys Mason, Cambridge, U.K., Tech. Rep., 2014.

[24] Rob Sun et al "IEEE 802.11 TGay Use Cases", Sep. 2015.

[25] T. S. Rappaport et al., "Millimeter wave mobile communications for 5G cellular: It will work!" IEEE Access, vol. 1, pp. 335–349, May 2013.

[26] mmMAGIC D2.1 Measurement Campaigns and Initial Channel Models for Preferred Suitable Frequency Ranges, https://bscw.5g-mmmagic.eu/pub/bscw.cgi/d94832/mmMAGIC_D2-1.pdf

[27] ETSI mWT Group, https://portal.etsi.org/tb.aspx?tbid=833&SubTB=833

[28] L. Verma, M. Fakharzadeh and S. Choi, "Backhaul need for speed: 60 GHz is the solution," IEEE Wireless Communications, Dec 2015, Vol. 22, No. 6, pp. 114-121, doi: 10.1109/MWC.2015.7368832.

[29] Yong Niu, Yong Li , Depeng Jin, Li Su, Athanasios V. Vasilakos, "A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges", Wireless Networks, Nov 2015, Vol. 21, Is. 8, pp 2657-2676

[30] S. Kutty and D. Sen, "Beamforming for Millimeter Wave Communications: An Inclusive Survey," IEEE Communications Surveys & Tutorials, SQ 2016, Vol. 18, No. 2, pp. 949-973, doi: 10.1109/COMST.2015.2504600

[31] S. Rangan, T. S. Rappaport and E. Erkip, "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," in Proceedings of the IEEE, vol. 102, no. 3, pp. 366-385, March 2014.

[32] Y. Kim et al., "Feasibility of Mobile Cellular Communications at Millimeter Wave Frequency," in IEEE Journal of Selected Topics in Signal Processing, vol. 10, no. 3, pp. 589-599, April 2016.

[33] 3GPP TR 38.913, "Study on Scenarios and Requirements for Next Generation Access Technologies", March 2016.

[34] IEEE Draft Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment: Sub 1 GHz License Exempt Operation," in IEEE P802.11ah/D8.0 April 2016.

[35] M. Alleven, "Wi-Fi Alliance introduces Wi-Fi HaLow technology for Internet of Things". "FierceWirelessTech". Questex, LLC, Jan. 2016.

[36] IEEE 802.11 Task Group AX, "Status of Project IEEE 802.11ax High Efficiency WLAN (HEW)"; accessed July 2016, www.ieee802.org/11/Reports/tgax_update.htm

[37] IEEE 802.11 Task Group AZ Next Generation Positioning (NGP) http://www.ieee802.org/11/Reports/tgaz_update.htm

[38] G. S. Zervas, J. Triay, N. Amaya, Y. Qin, C. Cervelló-Pastor, and D. Simeonidou, "Time Shared Optical Network (TSON): a novel metro architecture for flexible multi-granular services," Opt. Express 19(26), B509–B514 (2011).3GPP TS 23.402: Technical Specification Group Services and System Aspects; Architecture enhancements for non-3GPP accesses, Release 10, V10.5.0, September 2011.

[39] K. Nashimoto, K. Kudzuma, and D. Han, "Nano-second response, polarization insensitive and low-power consumption PLZT 4×4 matrix optical switch," in conference of Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011.

[40] 5G-XHaul Project, Deliverable D3.1 "Analysis of state of the art on scalable control plane design and techniques for user mobility awareness. Definition of 5G-XHaul control plane requirements", submitted on July 15th, 2016.

[41] http://www.xilinx.com/support/documentation/ip_documentation/axi_10g_ethernet/v1_1/pg157-axi-10g-ethernet.pdf

[42] IEEE, 802.1Qbu - Frame Preemption, http://www.ieee802.org/1/pages/802.1bu.html

[43] IEEE, 802.1CM, Applicability of Qbu and Qbv to Fronthaul, November 2015, http://www.ieee802.org/1/files/public/docs2015/cm-farkas-applicability-of-bu-and-bv-1115-v02.pdf

[44] March. P., et.al., Preliminary Views and Initial Considerations on 5G RAN Architecture and Functional Design, March 2016. Online. Available here: https://metis-ii.5g-ppp.eu/documents/white-papers/

[45] METIS II, “5G RAN Architecture and Functional Design White Paper”, March 2016, https://metis-ii.5g-ppp.eu/wp-content/uploads/5G-PPP-METIS-II-5G-RAN-Architecture-White-Paper.pdf

[46] Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, IEEE Standard P1588-2008, 2013. [Online]. Available: https://standards.ieee.org/develop/project/1588.html. Accessed Sep. 1, 2015.

[47] M. Dong, H. Li, K. Ota and J. Xiao, "Rule caching in SDN-enabled mobile access networks," *IEEE Network*, vol. 29, no. 4, pp. 40-45, July-Aug. 2015.

[48] Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band, IEEE Std 802.11ad-2012, IEEE Standards Association.

[49] Pfaff B, Pettit J, Koponen T, Jackson E, Zhou A, Rajahalme J, Gross J, Wang A, Stringer J, Shelar P, Amidon K. The design and implementation of open vswitch. In12th USENIX Symposium on Networked Systems Design and Implementation (NSDI 15) 2015 (pp. 117-130).

[50] Salam, Samer, and Ali Sajassi. ”Provider backbone bridging and MPLS: complementary technologies for next-generation carrier ethernet transport.” Communications Magazine, IEEE 46.3 (2008): 77-83.

[51] Mudigonda, Jayaram, et al. ”NetLord: a scalable multi-tenant network architecture for virtualized datacenters.” ACM SIGCOMM Computer Communication Review. Vol. 41. No. 4. ACM, 2011.

[52] Ballani, H., Costa, P., Karagiannis, T., and Rowstron, A. (2011, August). Towards predictable datacenter networks. In ACM SIGCOMM Computer Communication Review(Vol. 41, No. 4, pp. 242-253). ACM.

[53] Self-configuration and self-optimization in LTE-advanced heterogeneous networks." IEEE Communications Magazine 51.5 (2013): 36-45.

[54] A. Tzanakaki et al., “Virtualization of heterogeneous wireless-optical network and IT infrastructures in support of cloud and mobile cloud services," IEEE Commun. Mag. , vol.51, no.8, pp.155-161, Aug. 2013

[55] N. Carapellese, M. Tornatore, A. Pattavina, "Energy-Efficient Baseband Unit Placement in a Fixed/Mobile Converged WDM Aggregation Network," IEEE JSAC , vol.32, no.8, pp.1542-1551, Aug. 2014.

[56] J.-Y. Le Boudec, P.Thiran, “Network calculus: a theory of deterministic queuing systems for the internet”, Springer, 2001

[57] B. R. Rofoee, G. Zervas, Y. Yan, M. Anastasopoulos, A. Tzanakaki, S. Peng, R. Nejabati, and D. Simeonidou, “Hardware Virtualized Flexible Network for Wireless-DataCenter (invited)” , IEEE/OSA J. Opt. Commun. Netw., March 2015, vol. 3, pp A526 - A536.

[58] X. Chen et al., “Analyzing and modeling spatio-temporal dependence of cellular traffic at city scale,” in proc. of IEEE ICC, pp.3585-3591, 2015

[59] C. Desset et al., “Flexible power modeling of LTE base stations,” in proc. of IEEE WCNC 2012, pp.2858-2862, 1-4 April 2012

[60] T. Werthmann, T., "Approaches to adaptively reduce processing effort for LTE Cloud-RAN systems," in proc. of ICCW, pp.2701-2707, 8-12, 2015.

[61] http://tinyurl.com/nlfup2l

[62] J. Bartelt et al., “Fronthaul and backhaul Requirements for Flexibly Centralized Radio Access Networks”, IEEE Wireless Comm., Vol. 22, no. 5, pp 105-111, October 2015.

[63] H. J. Son and S. M. Shin, “Fronthaul Size: Calculation of maximum distance between RRH and BBU”, Netmanias Tech-Blog, 2014. [Online]. Available: http://www.netmanias.com/en/?m=view&id=blog&no=6276 . Accessed Apr. 6, 2016.

[64] Bristol Is Open, http://www.bristolisopen.com/overview/

9 Acronyms

Acronym	Description
3GPP	Third Generation Partnership Project
5G	Fifth Generation Networks
5G-PPP	5G Infrastructure Public Private Partnership
ACL	Access Control List
ADC	Analogue-to-Digital Converter
AIV	Air Interface Variant
API	Application Program Interface
ARPU	Average Revenue Per Unit
BER	Bit Error Rate
BB	Baseband
BBU	Baseband Unit
BFIC	beam forming integrated circuit
BH	Backhaul
BMS	Broadcast Microwave Services
BS	Base Station
CAPEX	Capital Expenditures
CBR	Constant Bit Rate
CN	Core Network
CoMP	Cooperative Multipoint
CP	Cyclic Prefix
CPRI	Common Public Radio Interface
C-RAN	Cloud Radio Access Network (aka Cloud-RAN)
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DAC	Digital-to-Analogue Converter
DC	Data Centre
DL	Downlink
DP	Data Path
DSCP	Differentiated Services Code Point
e2e	end-to-end
EDFA	Erbium Doped Fibre Amplifiers
EIRP	Equivalent Isotropically Radiated Power
ETN	Edge Transport Node
ETSI	European Telecommunications Standards Institute
FCS	Frame Check Sequence

FEC	Forward Error Correction
FFT	Fast Fourier Transform
FH	Fronthaul
FIB	Forwarding Information Base
FIFO	first in, first out
GE	Gigabit Ethernet
GOPS	Giga Operations per Second
HARQ	Hybrid Automatic Repeat Request
IATN	Inter-Area Transport Node
IML	Infrastructure Management Layer
I/Q	in-phase and quadrature
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LLC	Logical Link Control
LoS	Line-of-Sight
LTE	Long Term Evolution
LUT	Lookup Table
MAC	Medium Access Control
MBB	Mobile Broadband
MCC	Mobile Cloud Computing
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MMC	Multi Media Card
MME	Mobility Management Entity
mmWave	Millimetre Wave
MNO	Mobile Network Operator
MPDU	MAC Protocol Data Unit
MPLS	Multiprotocol Label Switching
MTC	Machine-Type-Communications
NBI	North-Bound Interface
NFV	Network Function Virtualisation
NGFI	Next Generation Fronthaul Interface
NGMN	Next Generation Mobile Networks
NLoS	Non-Line-of-Sight
OBSAI	Open Base Station Architecture Initiative
OLT	Optical Line Terminal
ONU	Optical Network Unit
OOB	out-of-band

ORI	Open Radio Interface
OS	Operating System
OTN	Optical Transport Network
p2p	Point-to-Point
p2mp	Point-to-Multipoint
PBB	Provider Backbone Bridging
PBSS	Personal Basic Service Set
PDCP	Packet Data Convergence Protocol
PCS	Physical Coding Sublayer
PLZT	((Pb,La)(Zr,Ti)O_3)
PMA	Physical Media Attachment
PMD	Physical Medium Dependent
PNF	Physical Network Function
PON	Passive Optical Network
PTP	Precision Time Protocol
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RLC	Radio Link Control
RRC	Radio Resource Control
RRH	Remote Radio Head
RU	Remote Unit
SDN	Software Defined Networking
SDO	Standards Developing Organisations
SotA	State-of-the-Art
TAF	Transport Adaptation Function
TC	Transport Class
TCAM	Ternary Content-addressable
TN	Transport Node
TSON	Time-Shared Optical Network
UC	Use Case
UE	User Equipment
UL	Uplink
USR	Ultra Short Reach
V2X	Vehicle-to-X
VBR	Variable Bit Rate

VLAN	Virtual Local Area Network
VNF	Virtual Network Function
WDM	Wavelength Division Multiplexing
WP	Work Package