5G Programmable Infrastructure Converging disaggregated network and compUte REsources

D4.1 State of the art and initial function design

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Executive Summary

This document corresponds to deliverable D4.1, “State of the art and initial function design” of the Horizon 2020 5G-PICTURE project. The aim of this deliverable is to provide a state-of-the-art review and the initial design of Physical and Virtual Network Functions (PNFs/VNFs) to be developed in Task 4.1, Task 4.2 and Task 4.3, in order to implement the functionalities required by the Disaggregated Radio Access Network (DA-RAN) concept proposed by 5G-PICTURE. These network functions will make use of the platforms for data plane programmability, programming models and hardware abstractions developed in WP3. Additionally, the designed network functions should be exposed and become available to be used by the orchestration and control plane comprising the 5G-PICTURE Operating System (OS) developed in WP5. More specifically, WP4 provides sophisticated PNF/VNF designs that can be allocated across different domains to fulfil end-to-end service requests from multiple tenants.

Corresponding to tasks Task 4.1, Task 4.2 and Task 4.3, three major domains are investigated in this deliverable: (1) Radio Access Network, (2) Transport Network and (3) Synchronisation Service. The PNF/VNF design for each domain, the methodology adopted towards integrating the developed PNFs/VNFs, and the approach for the end-to-end network service provisioning, are thoroughly investigated as the overall 5G-PICTURE solution.

A more complete design of the developed network functions and their key performance indicator evaluation will be extended in deliverable D4.2.

1 Introduction

There are two main architectures for 4G Radio Access Networks (RANs) deployments. The Distributed-RAN (D-RAN) architecture, consists of setting up macro-cell sites, usually on rooftops, which require an external pole to mount the antenna elements, and a co-located technical room with power and cooling facilities, to host the active elements including the Remote Radio Heads (RRHs), the Base Band Units (BBUs), and a conventional router or switch to connect to the transport network. D-RAN requires to provision complex sites, and to deliver power and cooling even if the macro-cell sites are not being used. To counter these drawbacks the Cloud-RAN (C-RAN) architecture consists of centralising the BBUs in a Central Office (CO), a location remote to the macro-cell site. In C-RAN, typically, the RRHs are mounted externally on the pole co-located with the antennas, hence eliminating the need for a technical room with power and cooling constraints. In addition, in C-RAN, where all the BBUs are centralised, it is easier to implement complex physical layer processing techniques where various bases stations operate in a coordinated manner to increase capacity. The drawback of the C-RAN architecture though, is that the interface between the RRH and the remote BBUs, usually based on the Common Public Radio Interface (CPRI) protocol, requires data-rates that are at least one order of magnitude higher than the transport requirements introduced by D-RAN. Hence, C-RAN is often deployed using a dedicated fibre between the RRHs and the BBUs.

Several studies have demonstrated that the traditional C-RAN architecture will not scale for 5G [1], given that the data-rates in CPRI increase linearly with the carrier bandwidth and the number of antennas in each macro-cell site. Therefore, several efforts in industry and academia have been devoted to architect the future 5G RAN network, carefully studying what functions and interfaces should be considered in each location (functional split), i.e., antenna pole, technical room, and central office. The latest vision, is that two types of functional splits will be deployed in 5G RANs. First, 3GPP is standardising a high level functional split between a Centralised Unit (CU), located in a central office, and Distributed Units (DUs), which could be deployed in various locations between the central office and the antenna pole. Second, the enhanced CPRI (eCPRI) standard has proposed various low level functional splits between the DU and the RRH, which provide a flexible trade-off between coordination gains in the wireless domain, and the introduced costs in the transport network.

In light of the previous industry trends, we posit that 5G RANs will be deployed in a variety of flavours (functional splits), depending on the constraints of each particular operator. Embracing this vision calls for advanced research on the following areas: i) a better understanding of the interactions between a particular functional split and the capabilities of the transport network, ii) mechanisms that deliver enhanced slicing capabilities in optical, packet and wireless transport technologies, and iii) mechanisms to effectively deliver synchronisation on demand to the various RAN functions deployed in a particular RAN architecture. The previous topics comprise the core of the work that will be carried out in WP4 and are introduced in detail in this deliverable.

Organisation of the document

This deliverable is structured in six main sections.

Beyond this introduction, Section 2 introduces the terminology that will be used throughout the document and presents the overall system-level vision and methodology pursued by the different tasks included in WP4.

Section 3 introduces the work that will be carried out in Task 4.1 "*VNFs and PNFs for dynamic 5G-RAN deployments*". First, this section reviews the state of the art on 5G RAN architectures, considering the approaches defined in 3GPP and eCPRI. Second, we introduce the technical approaches that 5G-PICTURE will pursue in this domain, including both radio related aspects, such as the derivation of optimal functional splits, or the notion of flexible functional splits, and aspects related to the interaction between the transport network and a specific RAN architecture, such as the development of fronthaul compression techniques, or the suitability of wireless transport for different RAN architectures. Finally, the section concludes providing an initial design for a set of four technical innovations in this domain that will be further evaluated in deliverable D4.2.

Section 4 introduces the work that will be carried out in Task 4.2 "*Transport Slicing for converged wired-wireless FH/BH networks and integration with 5G-PICTURE orchestrator*". First, this section presents a review of the state of the art in transport networks, with a focus on transport slicing. In particular, 5G-PICTURE focuses on optical, Ethernet, and wireless transport technologies. Second, the section introduces the technical approach of 5G-PICTURE in the transport domain, which is to provide agility, assurance, and orchestration, across selected optical, Ethernet, and wireless technologies. Finally, the section provides an initial design for four technical components in the transport domain that will be developed in 5G-PICTURE. These technical components are: Flexible-Ethernet, Time-Share Optical Networks, wireless Small Cell networks with integrated access and backhaul capabilities, and the Open Packet Processor (OPP) technology to embed network functions in transport nodes. The presented technical components will be further evaluated in deliverable D4.2.

Section 5 introduces the work that will be carried out in Task 4.3 "*PNFs and VNFs to support synchronisation services in converged FH/BH networks*". Initially, the section reviews the state of the art on solutions to deliver synchronisation over packet networks, and derives the synchronisation requirements that will be imposed by 5G networks. Then it presents the technical approach adopted by 5G-PICTURE in this domain, which consists of the delivery of synchronisation "as a service" to the various RAN functions connected to the 5G-PICTURE transport network, and the adaptation of the 1588 protocol to some of the transport technologies developed in 5G-PICTURE, which were not originally designed to support transport synchronisation. Finally, this section presents an initial design for five different technical components in this domain that will be evaluated in deliverable D4.2.

Section 6 summarizes and concludes the deliverable.

2 Technical background information and relation with other WPs

Work Package 4 (WP4) deals with the development of physical and virtual functions that use the programmable platforms developed in WP3 and can be orchestrated by the operating system developed in WP5. Figure 1 illustrates the relations between WP4 and WP3 and WP5.

In this regard WP4 has identified three main focus areas where novel 5G functions will be required, namely:

- Development of physical and virtual RAN functions.
- Development of programmable slicing capabilities in heterogeneous transport networks, including wireless, packet and optical transport.
- Development of functions able to provide synchronisation on-demand to distributed RAN and transport functions.

The developments planned in each of these focus areas correspond respectively to Task 4.1, Task 4.2 and Task 4.3, and will be introduced in detail in Section 3, 4 and 5 of this document.

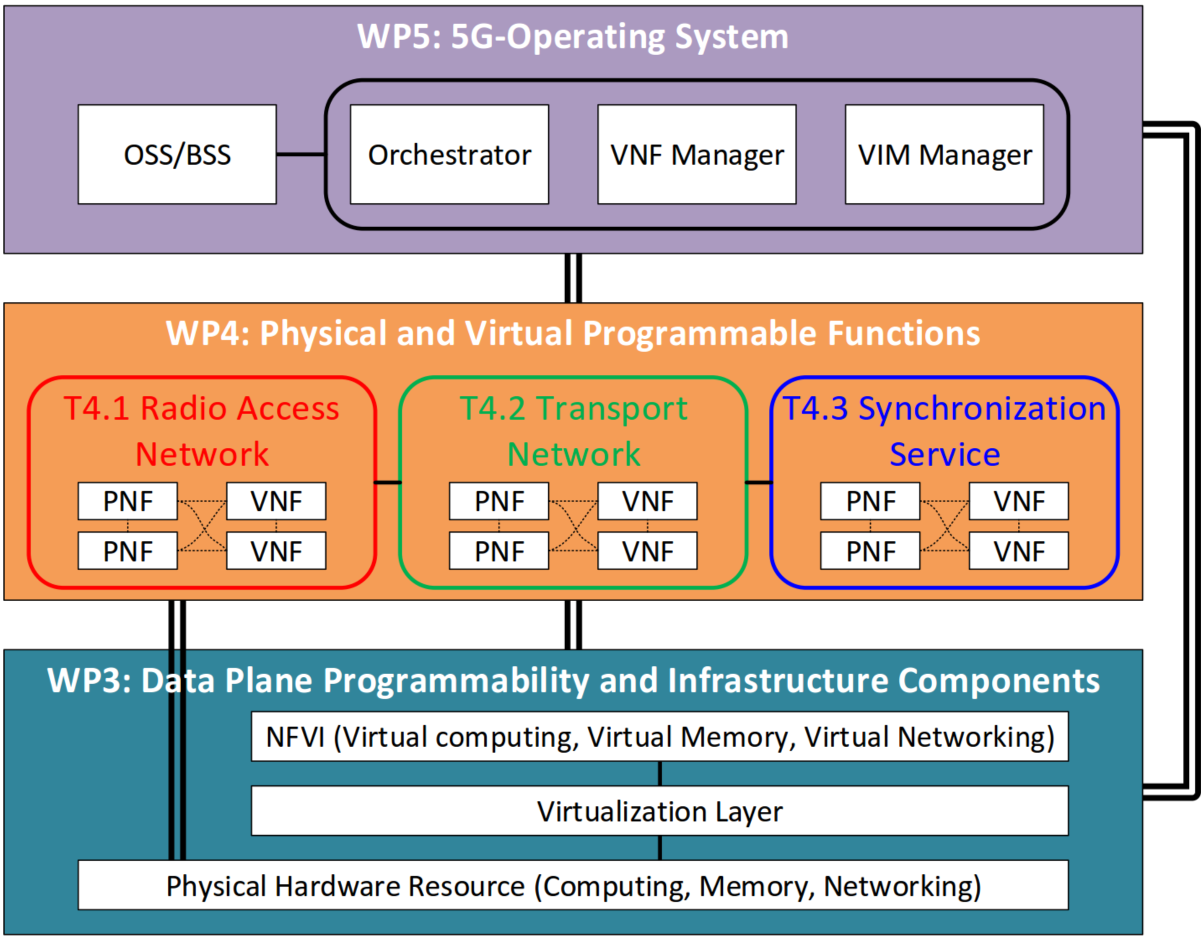


Figure 1: Interdependencies of WP4 with WP3 and WP5.

2.1 Terminology used

In the context of WP4 we will use the following terminology. These terminologies are aligned with the vertical, stakeholder and roles analysis included in deliverable D2.1 [2]:

- **5G-PICTURE Operator**: The role of operating the 5G-PICTURE solution/framework and having access to the Hardware/Software (HW/SW) pool of resources to enable (instantiate) the dynamic provisioning of infrastructure resources to various Tenants based on their needs and requirements. The role of the 5G-PICTURE Operator can be undertaken either by the infrastructure owner(s), such as a Mobile Network Operator (MNO), a private 5G network owner (e.g., Stadium owner), or by a third party having access to Infrastructure Providers' resources under specific agreement (terms and conditions).

- **5G-PICTURE Infrastructure Provider**: Provides infrastructure resources (network resources, storage space, and compute resources) to third parties (to be utilised in a dynamic way in the 5G-PICTURE framework) by exposing programmable interfaces to the 5G-PICTURE operator for the support of the 5G-PICTURE framework. Two providers are identified as Telecommunication Infrastructure Providers and Cloud Infrastructure Providers in deliverable D2.1 [2]. The former provides network resources for connectivity purposes, while the latter provides cloud-compute and storage resources.
- **5G-PICTURE Tenant**: Refers to the entity who requests the provisioning of network and compute/storage resources of the 5G infrastructure in the dynamic and efficient way that the 5G-PICTURE framework allows, to be able to offer the services that fall into its business (activities of interest). A 5G-PICTURE tenant could be an MNO, an Internet Service Provider (ISP), a Vertical, a third party providing services to a vertical, etc.
- **End Users**: These are stakeholders who enjoy 5G services while being static or on the move. End users are considered to be the subscribers (corporate or individuals) of a Telecom operator or a Vertical, or the Verticals themselves in case they make use of 5G services in support of their specific business activities.
- **5G-PICTURE Transport Network**: Heterogeneous transport networks leveraged in the 5G-PICTURE framework potentially consist of wireless, packet and optical technologies providing connectivity between distributed compute/storage resources.
- **Radio Access Network (RAN)**: Served through the 5G-PICTURE Transport Network. Long Term Evolution (LTE), Wi-Fi, NarrowBand-Internet of Things (NB-IoT) or 5G New Radio (NR) are example Radio Access Technology (RATs) considered in 5G-PICTURE. Different types of RATs can be connected to the same 5G-PICTURE Transport Network.
- **RAN Functional Split**: A RAN functional split is an implementation of the base station element in a particular RAN technology, where such Base Station (BS) is divided in three main components, namely: the Radio Unit (RU) that comprise simple antenna, the Radio Frequency (RF) front-end, and some baseband processing functionalities; the Distributed Unit (DU) located next to the RUs; and the Central Unit (CU), typically located on a compute location. As detailed in Section 3, in 5G-PICTURE we consider various types of functional splits. In this document when the context allows, we may refer directly to the functional split instead of using the generic term RAN.
- **Central Unit (CU)**: Upper part of the protocol stack in the BS of a particular RAN technology. The CU receives IP packets on its northbound interface, and outputs a different data representation in its southbound interface. For example, in a particular RAN implementations, the CU may implement all the digital processing and output on its southbound interface time domain radio signals transported by the CPRI protocol. On another implementation a CU may consist of the Packet Data Convergence Protocol (PDCP) layer in the LTE protocol stack and output the PDCP Protocol Data Units (PDUs) towards the Radio Link Control (RLC) layer located in the DUs.
- **Distributed Unit (DU):** Lower part of the protocol stack in the BS of a particular RAN technology. On the southbound interface a DU is connected to RUs that comprise RF front end and outputs radio signals. The northbound interface of a DU is variable depending on the particular type of the RAN implementation. For example, in one implementation a DU may receive time domain radio signals using the CPRI protocol, while in another implementation it may receive IP packets that contain the PDCP PDUs.
- **Radio Unit (RU)**: A passive or active element with much smaller footprint than the traditional BS. The RU can include solely simple components like antennas, RF front-end, analogue-to-digital converter circuit or some baseband operation functionalities like (Inverse) Fast Fourier Transform (FFT/IFFT), to be configured by the DU.
- **Packet Gateway**: A packet gateway is a functional element belonging to the mobile packet core network of the 5G-PICTURE tenant. The packet gateway interfaces with the CU to receive packets from the mobile users and forward packets coming from the Internet. IP protocols are used to communicate between the CU and the packet gateway.

- **X-Haul**: Refers to a transport infrastructure that is able to support transport services belonging to different RAN functional splits. For example, the 5G-XHaul infrastructure defined in [3] is able to transport CPRI and IP packets, thus being an example of an X-Haul implementation.
- **Dedicated/shared Network Functions**: The former ones are dedicated to specific services and can be customised to the need of the service. By contrast, the shared network functions refer to the ones that are shared and can be multiplexed between more than one service.

Throughout the document the following terminology is used for Network Slicing, aligned with 3GPP documents in [4], [5] and [6]:

- **Service Instance:** An instance of an end-user service or a business service that is realised within or by a Network Slice.
- **Network Slice Instance (NSI):** It is a realisation of a slice. Also, it is a set of network functions and the resources for these network functions which are arranged and configured, forming a complete logical network to meet certain network characteristics required by the service instance(s). The resources comprises of physical and logical resources. A NSI may be composed of sub-network Instances, which as a special case may be shared by multiple network slice instances. The NSI is defined by a network slice blueprint.
- **Network slice subnet instance (NSSI)**: It is a set of network functions and the resources for these network functions which are arranged and configured to form a logical network. The Sub-network Instance is defined by a sub-network blueprint. A sub-network instance is not required to form a complete logical network. A sub-network instance may be shared by two or more network slices. Resources comprise both physical and logical resources.

Regarding the specifics of the transport network, 5G-PICTURE builds on the transport network model defined by the 5G-PPP 5G-XHaul project (http://www.5g-xhaul-project.eu/). The interested reader is referred to [3] for a detailed description of the 5G-XHaul transport network. Thus, we introduce the following terminology:

- **Transport Node (TN)**: Refers to a network element in the transport network able to forward packets through the 5G-PICTURE Transport Network.
- **Technology Domain**: A set of interconnected Transport Nodes that communicate using the same transport technology. For example, in the framework of 5G-PICTURE, we can have a Time Shared Optical Network (TSON) technology domain or a Flex-Ethernet technology domain.
- **Datapath**: Refers to a programmable packet processing pipeline embedded in a Transport Node. This packet processing pipeline may be programmed by an external control plane, for example using protocols like OpenFlow.
- **Control Plane**: Set of procedures used to configure the datapath in a Transport Node. The Control Plane may be distributed, e.g., co-located with the Transport Nodes, or centralised, e.g., integrated in an external Software-Defined Networking (SDN) controller.
- **Control Plane area**: Represents a group of Transport Nodes that operate under a common control plane, e.g., using a common SDN controller. Nodes within a control plane area belong to the same technology domain, i.e., wireless, optical or packet.
- **Transport tunnel**: A transport tunnel represents a unidirectional path between two Transport Nodes in the same control plane area. A transport tunnel is signalled by a set of fields carried in the header of the packets processed by the datapath. Different control plane areas may use different tunnel identifiers. Transport Tunnels are provisioned by the control plane.

The following terminology is adopted specifically with regard to synchronisation:

- **Precision Time Protocol (PTP)**: The protocol that is defined within IEEE 1588 for clock synchronisation over a network. In the context of this document, specifically the protocol as defined in IEEE 1588-2008, also known as IEEE 1588v2.
- **Synchronous Ethernet (SyncE)**: It is an ITU-T standard that adds support for clock frequency transport from one node to another by relying on the timing of the individual bits within the physical layer signal transmitted via an Ethernet interface. A SyncE receiver recovers frequency from the physical layer bit timing and uses the recovered frequency to clock any downstream transmission, effectively establishing a frequency transport chain.

- **Synchronisation Service**: Traffic configured and instantiated between a master node and slave nodes (for example CUs, DUs or edge nodes) with the purpose of transporting a time reference or solely a frequency reference to which the slave nodes can synchronise.
- **Master Clock**: A node that provides the time reference to which slaves synchronise. In the specific context of PTP, the Master Clock is the node that sends periodic synchronisation packets towards slaves and whose internal clock is not disciplined (operates free-running).
- **Boundary Clock (BC)**: A PTP-capable transport node whose ports may either be in master or slave mode. In its typical usage, one of its ports is connected to an upstream Master Clock, being therefore a slave, while the other ports are connected to downstream slaves and, therefore, are in master mode. This way, the BC synchronises to master time and passes this synchronised reference to downstream slave nodes.
- **Transparent Clock (TC)**: A PTP-capable transport node that has the ability to measure the so-called residence time of a PTP message, namely the time that the message takes to traverse the node from ingress port to egress port. In contrast to a BC, a TC does not synchronise its internal time to the Master time and, therefore, does not need to implement a substantial part of the PTP protocol (e.g., state machines and master selection algorithm).
- **Full Timing Support (FTS)**: Support for the transport of timing over the entire network path between a PTP Master Clock and PTP Slave Clocks, i.e., the characteristic of a path over which all transport nodes are either TC or BC nodes.
- **Partial Timing Support (PTS)**: Support for the transport of timing over one or more segments of the network path between a PTP Master Clock and PTP Slave Clocks, i.e., the characteristic of a path over which some (but not all) transport nodes are either TC or BC nodes.

2.2 Design principles and functional elements analysis

In this section, we firstly introduce the main design principles which will be adopted in the design of the various functions developed in WP4. Secondly, we provide a high level design illustrating how the different WP4 functions are expected to interact together.

We adopt the following design principles:

- **Tenant state is maintained at the edge of the transport network**: This principle follows from the network design adopted in 5G-XHaul [3], and is motivated by the scalability and multi-tenancy requirements of the 5G-PICTURE transport network. In 5G-PICTURE "Tenant State" refers to state related to the RAN functions (RU, DU, or CU) connected to the transport network, e.g., the IP/MAC addresses of such RAN functions. The 5G-PICTURE transport network is unaware of this information and is only concerned about forwarding packets between transport tunnels. This assumption allows to flexibly reconfigure RAN functions without affecting the transport network.
- **Transport tunnels are pre-provisioned but potentially dynamic**: This principle involves having the control plane to pre-provision a set of default tunnels that provide connectivity through the infrastructure. Pre-provisioned tunnels may be of different priorities. However, the control plane may decide to re-configure tunnels dynamically, e.g., changing the actual path followed by the tunnel, without this having any effect on the connected RAN functions, due to tenant state maintained at the edge of the network.
- **Ethernet encapsulation is adopted as the common dataplane abstraction**. A major challenge in 5G-PICTURE is the integration of a wide set of heterogeneous technologies in the transport domain, namely wireless transport based on Sub-6 or millimetre Wave (mmWave), packet-based technologies such as Flex-Ethernet, and active optical technologies like TSON. A common dataplane encapsulation is required that can be processed by the datapaths embedded in all these technologies. For this purpose, 5G-PICTURE assumes an Ethernet encapsulation, meaning that packets generated by the connected RAN functions (DU, CU) are always encapsulated in an Ethernet packet. This assumption is in line with the major trends in the industry, where for example CPRI encapsulation over Ethernet has been recently standardised in IEEE 1904.3 [7], and Ethernet is also the underlying transport adopted by the eCPRI standard [8].
- **SDN-based control plane**: 5G-PICTURE adopts an SDN control plane whereby the control of different functional elements will be provisioned through logically centralised modular controllers, which can

interface with other levels of the infrastructure through well-defined Application Programming Interfaces (APIs) and data-models. REST and Yang will be favoured as API and data modelling technologies.

Figure 2 illustrates how the different functional elements that will be developed in WP4 relate to each other. In particular, we can see a heterogeneous transport infrastructure consisting of a wireless domain, an optical domain, and a packet (native Ethernet) domain. Two different tenants connect RAN functions, namely DU, CU, and packet Gateways to the shared transport infrastructure. Tenants may use different technologies and RAN functional splits.

We can see in Figure 2 how DUs and CUs from the same technology (same colour) are connected using transport tunnels that span various technology domains. In the same way, CUs and packet gateways belonging to the same technology are also connected using different transport tunnels. We can also observe how a Master Clock is connected to the network and provides a synchronisation service to one of the DU/CU pairs. The synchronisation requirements between each DU/CU pair may vary depending on the technology and functional split being implemented. It is worth noting how the separate multicast tunnel is used to transport clock related information.

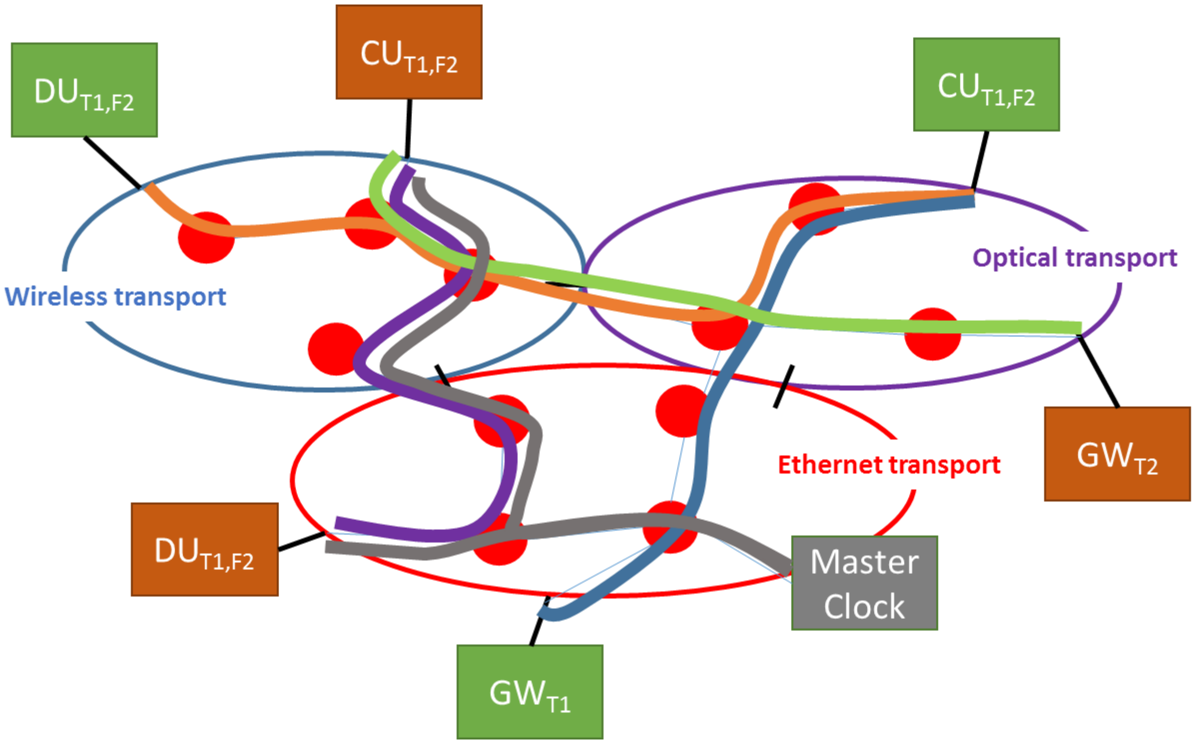


Figure 2: Interaction between functional elements considered in WP4. DU_Ti,Fj and CU_Ti,Fj represent respectively a distributed and centralised unit using technology i, and functional split j.

The high level design in Figure 2 will be followed to integrate WP4 functions in the dataplane. However, functional integration is also required in the control plane. Figure 3 depicts the high level control plane design adopted in 5G-PICTURE.

In particular, Figure 3 depicts a set of RAN functions, comprising DUs (pentagons), CUs (hexagons), and packet gateways (triangles), belonging to different tenants depicted using a different colour. RAN functions are connected through Transport Nodes (TNs) organised in different areas according to their technology domains. There are three main control planes that fall within the scope of WP4:

- The control plane of the multi-domain/multi-technology transport network. This control plane is presented as a hierarchical control plane composed of a set of controllers that work at different levels of abstraction, e.g., technology specific or technology agnostic. The design of this multi-domain control plane will be based on the hierarchical control plane defined by 5G-XHaul and is described in [3], appropriately extended to cover the additional novel technologies defined in 5G-PICTURE.

- The RAN control planes. It is worth noting that different RAN technologies, which may belong to different tenants, will come with their specific control plane functions; thus, separate control planes are depicted in Figure 3. Moreover, 5G-PICTURE will contemplate interfaces that enable interactions between the transport network control plane and the RAN specific control planes, in order to optimize performance.
- The synchronisation control plane. This control plane will be in charge of discovering synchronisation capabilities and defining the best path to forward synchronisation packets. In practice, the synchronisation control plane may be composed of individual control plane functions for each technology domain. Further details will be provided in Section 5.

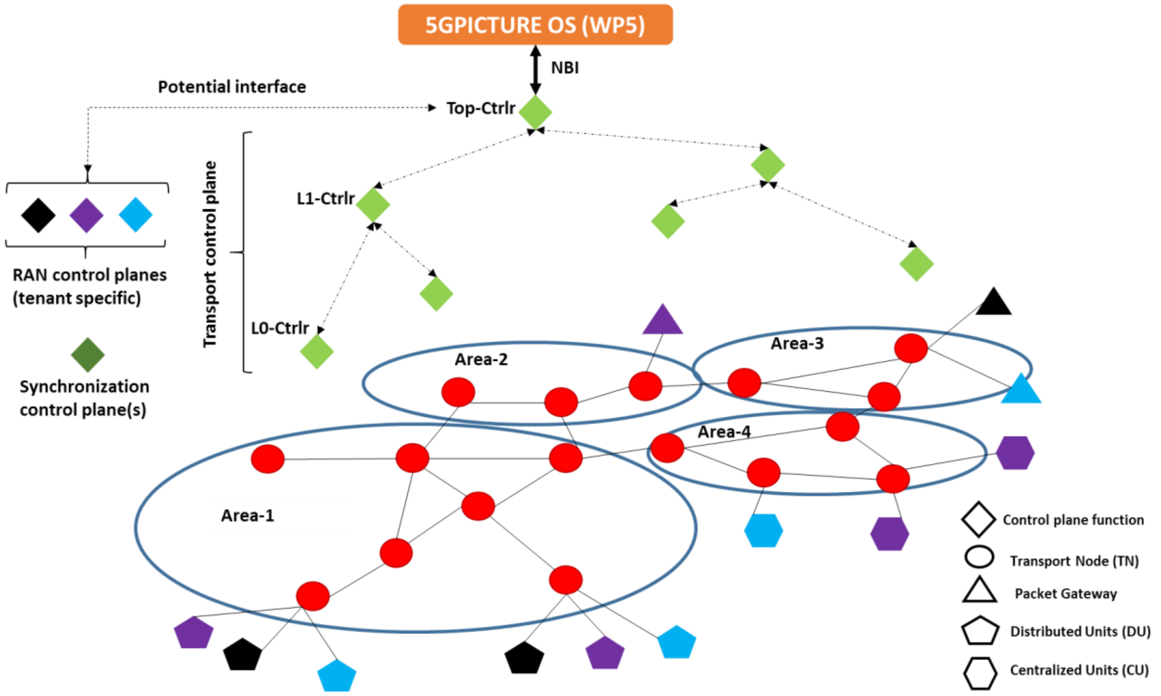


Figure 3: High level design of control plane for WP4 functions.

2.3 Methodology

This section defines the methodology adopted towards integrating the developments/approach on the Physical and Virtual Programmable functions (for both the RAN/Core network, and the transport network) and the approach for end-to-end synchronisation, with the overall 5G-PICTURE solution.

The sequential steps that will lead to the final integration include the outline of the infrastructure topology, the technology details on the Physical/Virtual Network Functions (PNFs/VNFs), the protocol specification and usage and finally integration with all 5G-PICTURE components, for example the orchestration and management defined in WP5.

The evaluation carried out in WP6 activities will be based on both the technical and business aspects of the solutions presented in the deliverables relevant to WP2, WP3, WP4 and WP5. The integrated solution will be used for the demonstrations for the *Smart Railway use case* and the *Stadium use case* which will showcase the efficiency of the technical approach adopted by the project.

2.3.1 Requirements and methodology towards integration

5G-PICTURE adopts a layered architecture defined in deliverable D2.2. A heterogeneous physical infrastructure layer includes a hybrid wireless domain composed of 5G NR/LTE/Wi-Fi radio access networks and a transport network used for the interconnection of the relevant network functions.

LTE and Wi-Fi technologies were selected as they are expected to play an important role in the next generation converged wireless access networks. 5G will be composed by evolved LTE for below 6 GHz, New Radio for below (e.g., 700 MHz and 3.5 GHz) or above 6 GHz (e.g., 26 GHz) and Wi-Fi, and these three RATs are expected to converge. Due to the increased complexity, the project focuses on the evolved LTE network adopting the Cloud-RAN concept [9] and Wi-Fi; nevertheless, the effort will be given to provide generic solutions for the heterogeneous wireless domain whenever possible.

A set of requirements towards 5G communications dictates and shapes the major functionalities and features that the 5G-PICTURE platform should support. In general, depending on the format, source and common characteristics, the requirements can be classified into several different types. Typical examples include requirements raised from stakeholders, technology makers, use case demonstrators, etc. In deliverable D2.1 [2] a set of requirements was defined for the overall 5G-PICTURE solution, with a detailed analysis on the requirements that drive the whole project activities.

2.3.2 Applied approach

Based on the rationale described in deliverable D2.1 [2], a set of requirements will be used to drive both the developments on each segment and the integration process. We adopt a top-down approach and from high level Business Requirements first, Service Requirements are derived that, in turn, lead to integrated Network Service Requirements that finally translate to Physical Infrastructure Requirements. To graphically represent the logical relationship between these requirements, a pyramid chart approach has been adopted as shown in Figure 4. The pyramid approach has been defined and described in [10], however we adapt the descriptions to be aligned with the Network Slice concepts described in [4] and [6]. In this deliverable the basic components for Network Slicing, which have been previously introduced, are:

- **Service Instance** [4]**:** An instance of an end-user service or a business service that is realised within or by a Network Slice.
- **Network Slice Instance (NSI):** a set of network functions and the resources for these network functions which are arranged and configured, forming a complete logical network to meet certain network characteristics required by the Service Instance(s)
- **Network Slice Sub-network Instance (NSSI):** a set of network functions and the resources for these network functions which are arranged and configured to form a logical network.

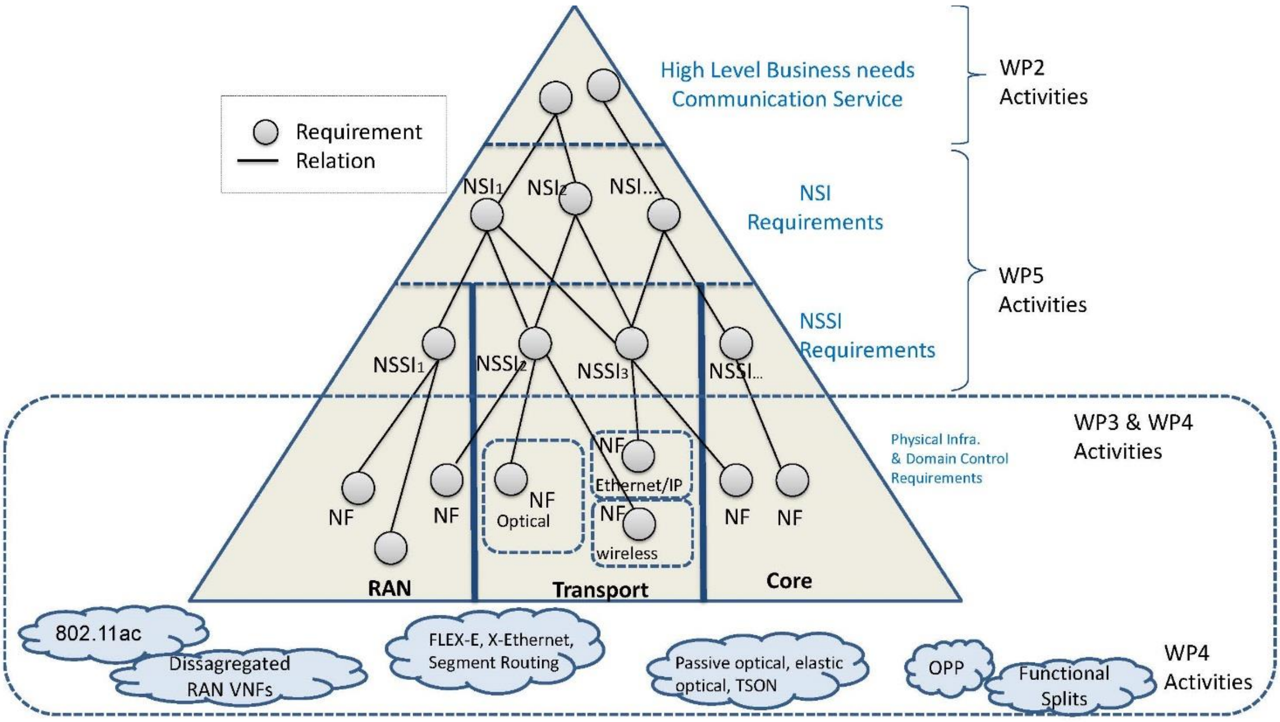


Figure 4: The requirements pyramid following the Zielczynski approach.

The high-level Business Requirements of the stakeholders reside at the very top of the pyramid. In the project an important innovation is associated with Network Slicing that is the main component around which the Business Requirements are described. The NSI, NSSI requirements and the Physical Infrastructure Requirements appear at the lower levels of the pyramid chart. As shown in Figure 4, the communication service (business requirements are investigated in WP2, WP5 is responsible for the end-to-end NSI orchestration mechanisms needed and the definition of their requirements, while in WP3 the necessary infrastructure components are designed and implemented. WP4 focuses on the NFs operation and the NSSI requirements satisfaction.

Based on the level of each requirement, different degrees of details are provided. More specifically, the lower the level, the more detailed the requirements are. It is clear that this pyramid graph also depicts the relationship between requirements at different levels and hence enables their traceability in a top down fashion. The integration of all components will lead to the final 5G-PICTURE solution. Because of the increased complexity, we will follow a step-by-step process, presented in Figure 5.

Note that Task 4.1 activities will focus on the RAN and the Core network part, Task 4.2 on the transport network part, while Task 4.3 will focus on the way to meet synchronisation requirements. For each technology, different sets of requirements are used. For example, in the transport network a need for a "hard slice" requires different technology drivers than a "soft slice", where a Virtual Private Network (VPN) solution can be used to connect network functions.

Each individual technology will be studied, and the relevant PNFs/VNFs will be designed towards integration with the necessary southbound and northbound APIs. Each data-plane and control-plane operation will be extensively tested in order to demonstrate the efficiency of the software/hardware and the ability to satisfy both the 5G-PICTURE system and user level requirements. This process is described in Figure 5

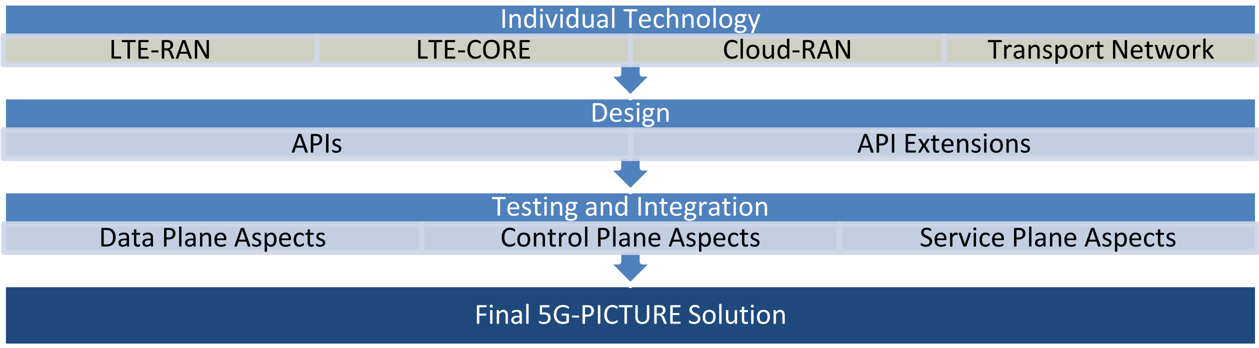


Figure 5: 5G-PICTURE solution development methodology.

2.3.3 Example: Transport slicing for converged wired-wireless fronthaul/backhaul networks

In the following, we elaborate on an example that aims to provide an end-to-end service via slicing the transport network. Such service can be used in any of the use cases described in deliverable D2.1 [2], e.g., Tactile Internet, based on its requirements listed in terms of latency, packet loss rate, data rate, etc.

- **High Level Business Requirement**: An end-to-end orchestration and management system is controlling the entire infrastructure and exploits multi-domain control mechanisms on per network slice basis. A stakeholder can drive the creation of network slice exploiting standardised templates.
  - A communication service is steered by end-to-end high level requirements.
- **NSI requirements:** A Network Slice Instance may be composed of Sub-network Instances, which as a special case may be shared by multiple network slice instances. The Network Slice Instance is defined by a Network Slice Blueprint. Instance-specific policies and configurations are required when creating a Network Slice Instance. Take the Tactile Internet for instance, the requirement of such NSI is provided in Table 13 of deliverable D2.1 [2].
- **NSSI requirements:** the transport network supports interconnection between RU and DU, DU and CU, and CU and CN in a cloud RAN concept supporting flexible functional splits. Specific Quality of Service (QoS) attributes and slice specific information can be considered for each link/node on per NSSI basis. We can see the stringent latency requirement of tactile Internet, i.e. less than 1 ms, may request the transport network for prioritisation and utilize the traffic rerouting when congestion happens. Note that other technology domain (e.g., RAN, synchronisation) will also provide corresponding NSSI descriptions to facilitate the end-to-end NSI development done in WP5.
- **Physical Infrastructure Requirement**: related to the requirements of the network topology, the Network Functions, the routers, switches, servers capabilities and so on. If an SDN solution is required, then the network infrastructure should support the decoupling of the data plane form the control plane.

- Depending on the approach considered and the type of the request for a connection a different network function maybe be used. For example, in the case of soft slice QoS can be enforced using specific Dynamic Host Configuration Protocol (DHCP) tags or Virtual Local Area Network (VLAN) priorities. SDN control can be used to apply the logic that will satisfy such requirements.

We note that specific demonstrators will utilize specific parts of the system, on a per technology basis, using the services exposed by the management and orchestration plane, and the control plane interactions. In our approach for every part of the network, software and hardware component testing will be applied at each domain independently prior to integration.

3 VNFs and PNFs for Dynamic 5G-RAN deployments

3.1 State of the art

Being the key enabler for the 5G ecosystem, the RAN is receiving wide attention and several design requirements and paradigms shall be fulfilled [11], [12]. Moreover, the 3rd Generation Partnership Project (3GPP) mentions several future RAN slicing realisation principles in [6], [13], such as RAN slicing awareness, resource isolation, etc. The network slicing vision aims to enable the deployment of multiple logical networks as independent business operations on a common physical infrastructure; hence, the RAN architecture should support slice isolation, slice instance life-cycle management, and slice selection and association mechanisms, as concluded in [14]. It is noted that slice isolation is a protection mechanism among slices that can reduce the interference between slices as well as guaranteeing performance.

In C-RAN, the legacy D-RAN concept is revisited and the RAN functions can be split between several physical entities [15]. Such C-RAN vision aims to support efficient network management and enables advanced coordinated and cooperative processing among cells in a centralised location. C-RAN replaces traditional monolithic BSs with distributed (passive) radio elements, called RRHs, with much smaller footprints than the traditional BS, and a centralised (remote) pool of BBUs where baseband and protocol processing for many BSs takes place. The C-RAN concept is more agile and versatile than D-RAN, when it comes to support future 5G characteristics, e.g., network softwarisation, network function virtualisation (NFV), and sharing of multiple substrates (e.g., multi-operator, multi-vendor). Further, the C-RAN concept also facilitates the vision of Ultra-Dense Networking (UDN) RAN deployment as it naturally supports centralised coordinated processing and interference management that are highly desirable for UDN. C-RAN also enables flexible RAN node densification among RAN edge equipment (i.e., RRH) and/or central entities (i.e., BBU), while D-RAN can only densify monolithic RAN edge infrastructures (i.e., BS) with a higher deployment expenditure.

In the original vision of C-RAN, each RRH is connected to a BBU pool with a point-to-point Fronthaul (FH) link that may be daisy-chained, and the FH transport protocol carries the time-domain air-interface samples standardised as CPRI [16]. Nevertheless, the excessive FH capacity requirements has led industry and academia to revisit the C-RAN concept by introducing different functional splits of RAN functionalities between RRH and BBU [17], in order to move some processing back to the edge infrastructure and to reduce FH capacity requirements. In this evolved C-RAN vision, the RRH becomes an active element that hosts a subset of additional baseband functions (e.g., FFT/IFFT, Orthogonal Frequency-Division multiplexing (OFDM) symbol (de-)modulation), and is renamed as RU or Remote Radio Unit (RRU). Furthermore, the BBU can be divided into DU and CU with a second higher-level functional split in between (e.g., a single PDCP layer entity at CU that aggregates several DUs, potentially with different RATs) with an X-haul link in between. Such three-tier (i.e., RU/DU/CU) C-RAN architecture is compatible with the proposed Remote Radio Unit (RRU), Radio Aggregation Unit (RAU) and Radio Cloud Centre (RCC) architecture defined by Next Generation Fronthaul Interface (NGFI) [18], and can better fit in future heterogeneous deployments with different RATs. For instance, the CU can possess a centralised PDCP functionality that allocates user plane PDUs among different RATs (e.g., Wi-Fi/LTE/5G NR) toward several DUs within its coverage. Thus, this architecture complements the application of larger bandwidth (licensed or unlicensed), multi-antenna and multi-connectivity transmission to boost spectral efficiency and to satisfy user QoS requirement.

In order to represent the segmented RAN processing in different RAN entities, several functional split options are proposed by 3GPP [14], Next Generation Mobile Networks (NGMN) [19] , NGFI [18], Small Cell Forum (SCF) [20], and eCPRI [8]. These functional split options correspond to how baseband processing functions as well as corresponding network functions are distributed and chained between disaggregated CU, DU and RU. The chosen functional split will highly impact the FH throughput and characteristics of the transported samples over the FH interface. In Figure 6, several functional splits options provided by 3GPP and eCPRI are shown. Function splits that are far away from the radio frequency part, i.e., the left side of the figure, have the most relaxed latency and data rate requirements, but offer the least centralisation gains, i.e., only centralised Radio Resource Control (RRC) in 3GPP option 1/eCPRI split A. From all the proposed splits, current standardisation efforts focus on the Option 2 split, for the disaggregation of the PDCP and above (CU), and RLC and below layers (DU) of the mobile stack, and by adding heterogeneous network capabilities as well. The communication between these layers is taking place through the F1 Application Protocol (F1AP), as indicated in the 3GPP standards for the NG-RAN interface [21] [22]. A comparison of user-plane traffic rate of different splits can be found in [20]. As for the *latency aspect*, the Small Cell Forum (SCF) provides latency

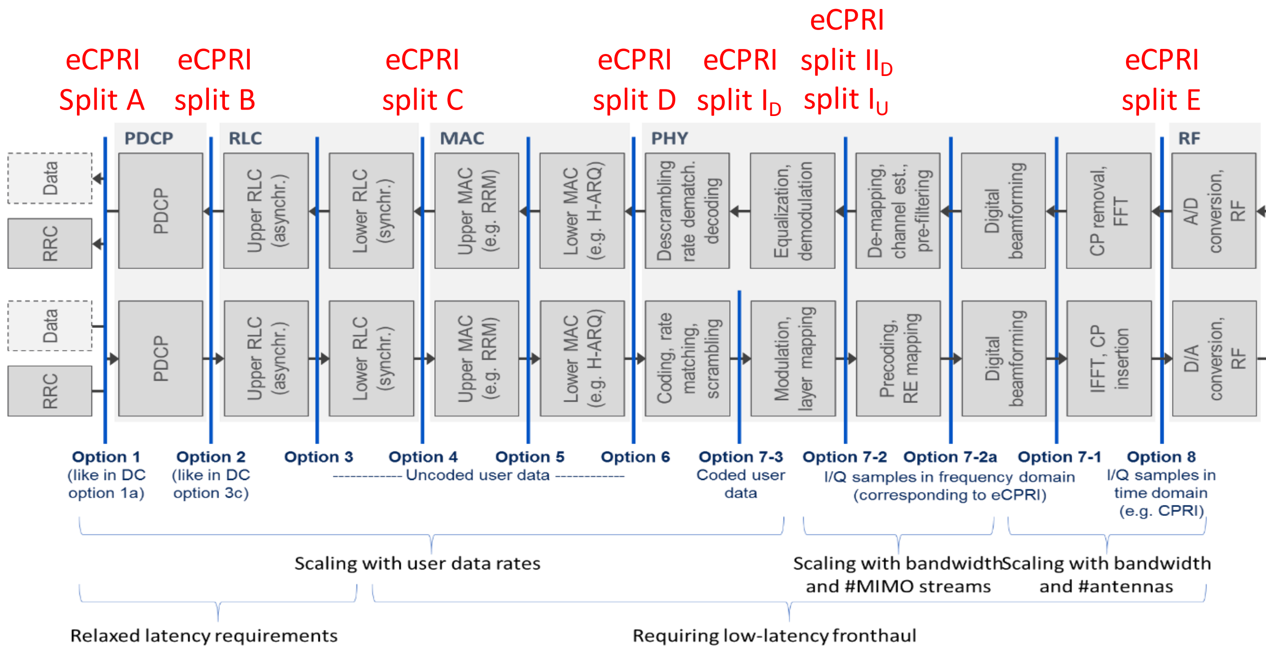


Figure 6: Main functional split options provided by 3GPP (bottom) and eCPRI (top) for 5G RAN.

prerequisite analyses of each split in [23]. It is also noted that the functional splits of Downlink (DL) and Uplink (UL) directions are not necessarily the same; hence, more flexibility is enabled by deploying network functions of different directions independently.

Further, customised functional splits for multiple instantiated services can satisfy the respective service requirements to enable a service-oriented view of 5G, adapting the performance of the protocol stack according to the required latency as shown in [24]. This information can be utilised to customize the required slice processing to fulfil specific latency requirements, following the analyses shown in [25] for services like enhanced Mobile Broadband (eMBB), ultra-Reliable and Low-Latency Communications (uRLLC) and massive Machine-Type Communications (mMTC). Hence, the functional split is envisioned to be both *horizontal* (e.g., between CU/DU/RU) and *vertical* (e.g., dedicated or shared network functions). More specifically, the vertical splits aim to provide customised network functions if requested by some services, with shared network functions being utilised by several services that do not request such customisation and can enhance statistical multiplexing gain. In particular, multiplexed network function instances shared by multiple slices need to maintain the mapping of traffic to individual slices, and a mechanism is required to influence traffic of a slice to be processed in the network function instance, e.g., SDN match-action principle [26]. Through such mechanisms, the separation of services and tenants is enabled in both dedicated and shared network functions, and the end-to-end network slicing is effectively spanning from the network infrastructure to the end users. In addition, a dynamic functional split is also envisioned in [27] to support the split (re-)configuration of baseband functionality (e.g., adapting to current traffic conditions or different RU-DU association) towards increasing the flexibility for different RAN deployments. Such dynamicity shall also respect the required FH capacity, latency and jitter. For instance, the FH network can be generally categorised into two different types: (a) Ideal network that provides low-latency and high-capacity links, and can thus support different functional splits all the way to full centralisation/coordination and (b) Non-ideal FH network that provides medium-latency and medium-capacity links to only allow for partially centralised deployments, keeping some baseband functionalities at RUs.

Unlike standard CPRI-based C-RAN, different types of traffic are transported over the FH link due to the applied functional splits between RAN entities, i.e. between CU/DU and DU/RU. For instance, frequency-domain samples are transported when adopting 3GPP split option 7-1, while non-coded bits are carried for option 6. This creates the need for different processing schemes to transport traffic of each functional split. For example, a radio sample (de-)compression scheme can efficiently reduce the required FH bandwidth, but different radio sample characteristics and delay requirements among different splits shall be taken into account in order not to deteriorate the compressed samples drastically or to violate latency constraints. Hence, the split-specific sample compression shall be included in the design of VNF/PNF for 5G-RAN. Moreover, different transport protocols shall be defined for communication and control between disaggregated RAN entities to maintain the overall RAN processing chain. For instance, eCPRI extends the work of CPRI via enabling packet-based transportation to carry samples corresponding to several splits inside the physical (PHY) layer and to be aligned with known technologies like Ethernet, so as to carry simultaneously eCPRI traffic with other types of traffic. In addition, the well-established Ethernet-OAM can be reused for operation, administration, and maintenance of the FH network. Last but not least, given the potential heterogeneity within FH network deployment, several transport technologies (e.g., wired, wireless) can be applied to fulfil the slice-specific requirements. These different transport technologies can support C-RAN in different conditions, for instance, a combination of Sub-6 GHz and mmWave transportation is suitable for agile C-RAN deployment utilising several available carrier frequencies, whereas the optical solution provides a sustainable C-RAN to serve multiple service requirements due to its high reliability.

Figure 7 illustrates an example with a three-tier RAN architecture that could support different deployment scenarios and functional splits based on the aforementioned 3GPP split options. Typically, a CU would cover a large area corresponding to a radius of 100 to 200 kilometres, whereas a DU would cover a radius of only 10 to 20 kilometres. The exact functional splits in the three-tier architecture are of course highly dependent on the transport network capabilities. When using an ideal FH network, only the lower part of the physical functions (L1-Low) should be placed at the RU to maximally exploit the benefits of coordinated signal processing at the DU. Distributed Antenna System (DAS) and massive MIMO are two typical deployment scenarios enabled with 3GPP split options 7 and 8 and (e)CPRI/NGFI Radio-over-Ethernet (RoE) transport protocols, or proprietary interfaces as implemented in OpenAirInterface (OAI) platform in [28], a software-based LTE/LTE-A system implementation spanning the full 3GPP protocol stack including User Equipment (UE), RAN and CN. The OAI platform can also support the Commercial Off-The-Shelf (COTS) UE and more details on its usage can be found in [29]. Both require a common transmission precoding and reception combining operation (cell-specific and user-specific) that must be placed either at the DU, to enable the coordinated beamforming across several geographically distributed RUs, or at a single RU driving a massive antenna array. For a non-ideal FH network, the entire PHY functions are moved to the RRU to relax the FH network and yet exploit the benefit of joint scheduling and interference coordination at the DU. Indoor-outdoor RAN sharing and virtual cell mobility are two representative deployment scenarios that can be enabled with the network Functional Application Platform Interface (nFAPI) interface [30], or a proprietary interface corresponding to 3GPP split option 5. In addition, the separation of Control Plane (CP) and User Plane (UP) on macro and small cell can be easily realised to seamlessly serve UP traffic via the centralised PDCP entity located either at DU or CU.

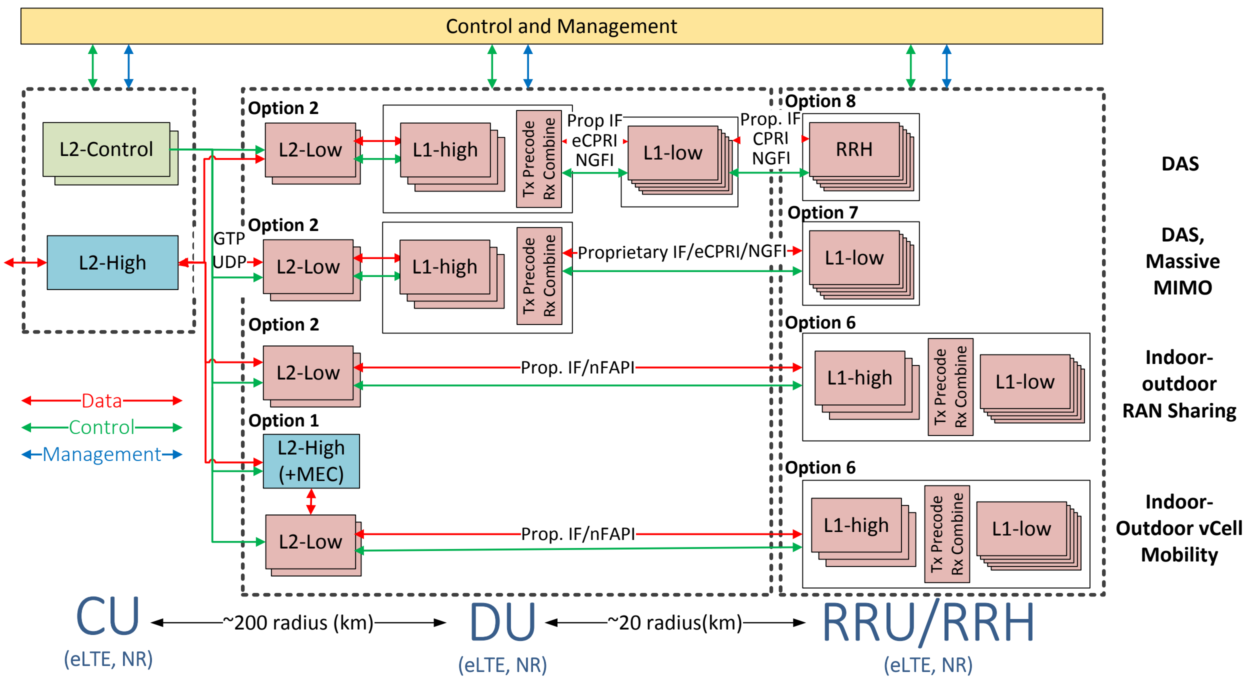


Figure 7: Three-tier RAN functional split in view of different deployment scenarios.

While the RAN is the most complex part of the mobile network infrastructure, it offers opportunities to benefit from the SDN principles. One reason is that to apply strategies and technologies for improving spectrum and spectral efficiencies, and for scaling system capacity, such as cell densification, or to use advanced physical layer techniques like Coordinated Multi-Point (CoMP), a high level of coordination among BSs is required. This can naturally be enabled by SDN, where control decisions are configurable through a centralised controller. In addition, softwarisation of the RAN control plane not only allows for an easier evolution through programmability, but enables a multi-service architecture supporting a wide range of use cases and novel services over the top. One of the main design challenges of a Software-Defined RAN (SD-RAN) is the stringent timing constraints associated with some key RAN control operations, such as flexible functional splits and Medium Access Control (MAC) scheduling. A high-level SD-RAN architecture can be realised through the FlexRAN platform [31] where the control plane follows a hierarchical design and is composed of three entities: centralised entity, edge entity and RAN agent. It is noted that the control plane and user plane is provided by the RAN agent API, which acts as the southbound API following SDN principles (e.g., OpenFlow) with the control plane protocol on one side and user plane on the other side. Moreover, the relationship between agent and RAN depends on the RAN deployment. For instance, a legacy BS only requires one agent, whereas three agents are required when using the three-tier C-RAN architecture. Depending on these different deployment scenarios, the agent-controller topology could vary from tree to mesh, and the edge entity could become part of the centralised entity.

3.2 Technical approach and KPIs

3.2.1 Technical approach

Based on the aforementioned state-of-the-art about 5G RAN deployment strategies, we introduce the main technical approaches that will be considered in this field in 5G-PICTURE. These approaches aim to compose RAN network functions in a flexible and programmable manner in order to allow a 5G-PICTURE operator to provide RANs on an “as-a-service” basis to its tenants, and to devise the sustainable and elastic network function distribution in heterogeneous deployments of mobile networks.

3.2.1.1 Optimal functional split derivation

Different functional splits have different characteristics in terms of the level of collaborative processing, and different FH requirements in terms of capacity and latency. In that sense, the optimal functional split is dependent on the target service (e.g., low-latency traffic), scenario (e.g., massive MIMO) to be provided towards the end-users and on the FH network conditions (e.g., ideal or non-ideal). For instance, the network utility optimisation problem can be formulated considering constraints such as FH capacity constraint, split latency requirement, and available FH transport network topology. Further, some hardware impairment and computation resource limitations can be included to better reflect the feasibility of the C-RAN deployment. Following this, the optimal functional split as well as corresponding user plane RAN parameters (e.g., transmission power, radio resources) can be derived by solving the formulated utility maximisation problem. Note that the optimal split also depends on the optimisation objectives, e.g., energy efficiency, network capacity, or QoS satisfaction, of the formulated problem based on the goal of deployed service.

This optimal split derivation approach can provide its results as inputs to update the existing service template over the RAN domain, i.e., apply derived functional split, based on the RAN monitoring information. This update shall follow the Service Level Agreement (SLA), and available public and private model libraries to rebuild the RAN service model. Further, it can also be used as prerequisite when orchestrating and deploying a new service in a region with a given limited number of resources in the FH network and hardware components. Correspondingly, such result also impacts the applicable sample compression scheme, the FH transport protocol, the feasible FH transport technologies, and thus the end-to-end service management.

3.2.1.2 Flexible functional split

Based on different functional splits at the RAN domain, there are several trade-offs that are observed. For instance, split option 8 can fully centralize the RAN processing but requires tremendous fronthaul bandwidth even without any user traffic. By gradually moving functions toward the network edge, the fronthaul requirements can be largely relaxed but at the cost of fewer coordination. To this end, this technical component aims to exploit both benefits at run-time via enabling on-the-fly flexible split changes between RAN nodes. Moreover, it can be utilised to tackle the dynamicity of the multiple services based on the latest service template describing the updated C-RAN functional split. A flexible functional split can also enable the network operator to provide customised RAN-as-a-service to multiple service providers (e.g., communication or digital service). In that sense, this technical approach aims to investigate the possibilities of dynamically changing the functional split (e.g., among split options in Figure 5), reconfiguration of network functions (e.g., customised or multiplexed), and updating the C-RAN node relations (e.g., mapping between CU and DUs) over common/specialised physical RAN infrastructures. To realize such flexibility, the state of CP and UP processing should be maintained in a database allowing to update the RAN processing and split on-the-fly while retaining the service continuity and isolation. Note that by maintaining the state between RAN entities (CU/DU/RU), the network functions are virtually turned into stateless processing allowing to update the service and recover the state.

It is noted that such dynamicity shall not impact other slice instances, to guarantee service isolation. For instance, when a slice changes its customised MAC and PHY processing into a multiplexed service (i.e., common for several slice instances), other slices shall still continually maintain their service requirements towards the served users. Moreover, as a single user can be mapped to multiple slices, conflicts may happen and shall be resolved. An example is when different user mobility measurements are requested by multiple slices that require to coordinate for reconfiguring the measurements with the largest common parameters and least denominator. Last but not least, the formulated FH transport topology shall support such reconfiguration between C-RAN entities.

To sum up, the architecture of a RAN entity shall be revisited to provide a flexible execution environment to run virtualised RAN instances with the required level of isolation and sharing of the underlying RAN modules and resources. Flexible functional splits will allow the slice owner to operate on a set of virtual resources (e.g., resource block or spectrum) or capacity (e.g., rate) and accessing their CP and UP state (e.g., user identity) that are revealed by underlying RAN entities. In that sense, a slice owner is allowed to control the slice compositions and the behaviour as per service requirements.

3.2.1.3 Slice-specific compression of radio samples

As detailed in the previous section, the compression of radio samples can bring the benefit of reducing the required FH capacity. However, it comes with the impact on sample distortion and (de-)compression processing delay. In this sense, this technical approach shall investigate this trade-off to provide a feasible real-time compression and decompression scheme applied to different functional splits. The envisioned compression scheme can be as simple as a static/dynamic look-up table, or even be programmable to flexibly provide different compression ratio on the data samples. Such programmable compression will require more computational resources (or even specialised hardware), longer latency for (de-)compression, and extra control overhead shall be transported between end nodes. Nevertheless, it can provide lower signal distortion and more flexible compression ratio. Furthermore, some slice-specific overhead removal can also be applied before compression. These overheads are originally designed for air-interface transportation to combat non-idealities and protect the desired signal. For instance, the removal of frequency-domain guard band (split option 7-1) or time-domain cyclic prefix (split option 8) can straightforwardly be used to reduce these overhead without introducing any losses.

Furthermore, such compression can be slice-specific or not depending on the slice service template and SLA description. The slice-specific sample compression can better reflect its target service QoS as the slice can fully control its compression ratio among different network conditions rather than following the unified compression ratio utilised by the infrastructure provider. Such slice-specific compression can also differentiate the experience of different tenants based on their conditions and priorities. Last but not least, it is noted that the sample compression scheme may generate extra control information exchange overhead between RAN entities (e.g., dynamic codebook and side information for decompression) between the FH interfaces that shall be taken into account when devising the transport protocol between RAN entities.

3.2.1.4 Transport protocol and technology

To transport radio samples in the network of FH, the transport protocol is a necessary enabling technical approach. Firstly, extra sub-headers related to the radio information (e.g., frame, subframe, channel information) are necessary to be included and packetised in order to facilitate the successful sample reception and the baseband processing. These extra sub-headers can also be used to synchronize the radio timing between RAN entities to simultaneously transport to the same user like in a distributed antenna system. For instance, the radio frame, subframe and symbol information can be encapsulated as the timestamp for the receiver side to do frame alignment and sequentially process the received radio samples. In addition, the designed protocol shall include the transportation of in-band or out-band control signalling, FH network timing and frequency synchronisation signals, etc. As the mapping between CU, DU and RU can follow the 1:n:m relationship, the devised protocol shall incorporate the possibility to dynamically associate each CU to a set of

DUs and each DU to a set of RUs, depending on the desired coordinated transmission and reception mode. Lastly, a flexible functional split shall be supported when applying such protocol.

Finally, different transport technologies shall also be investigated and validated such as wired (e.g., elastic optical transport, Ethernet) and wireless technologies (e.g., Sub-6 GHz, mmWave transportation). These different technologies may only be representative for specific services. For instance, different characteristics can be found between Sub-6 and mmWave transportation and a flow splitting can be considered to fit different service requirements using either wireless transportation technology. Moreover, the UDP and RAW Ethernet transportation is compared in [20], where the RAW mode utilizes the raw Ethernet that transports packets with minimal processing delay, whereas UDP offers the ability to accommodate multiple data flows under the same Ethernet interface at a slightly higher processing cost.

Along with such transport technology validation approach, a joint network slicing consideration of RAN and transport network is highly anticipated to better provision radio and transport resources, isolate the end-to-end slice customised processing, and fulfil the end-to-end service QoS requirement.

3.2.2 KPIs

There are four main perspectives on Key Performance Indicators (KPIs) when evaluating performance of the devised technical approaches: (i) **RAN domain perspective**, (ii) **Transport network perspective,** (iii) **Endpoint-related perspective**, and (iv) **User-plane perspective**. The RAN-domain KPIs are utilised for the derivation of optimal functional splits, mentioned in section 3.2.1.1 as the objective functions representing the specific goal of the target service applied at the RAN domain under the constraints of transport network (e.g., FH/MH link capacity), endpoint (e.g., hardware load), and the characteristic of different functional split (e.g., maximum allowable latency). Taking the eMBB service as an instance, its aim is to boost the cell spectral efficiency and provide mobile broadband communication toward end-user. Hence, we can adapt the data rate in bps listed in deliverable D2.1 [2] as the objective function to find the optimal functional splits and some other RAN parameters (e.g., resource allocation) under several constraints. Additionally, when the target use case is to apply massive MIMO for enabling energy-efficiency mobile communication, the goal is to facilitate the power-efficient communication and thus we can consider the power efficient metric listed in deliverable D2.1 [2], as the objective function in order to optimize the transmission power consumption but also provide sufficient service quality. To sum up, KPIs of such category are dependent on the communication service and scenario to be deployed at the RAN domain and are optimised to provide RAN as a service with awareness of constraints over other domains (e.g., transport network).

Moreover, when evaluating the slice-specific sample compression scheme, some straightforward metrics include the sample compression ratio, Error Vector Magnitude (EVM), and signal to distortion ratio incurred by the compression. However, such metrics cannot straightforwardly reflect the impact of sample compression on the user plane perspective as there are several error correction (e.g., channel coding) and retransmission (e.g., Hybrid Automated Repeat reQuest (HARQ) scheme) schemes over the protocol stack that can remedy the sample distortion and reduce the compression impact on the service quality. In this sense, we can measure several **user-plane metrics** as KPIs such as *FH link throughput*, *user-plane good-put*, *packet drop rate,* and *packet delay jitter* to examine the sample compression impact on the user experience. Moreover, we can also measure the **Transport network KPI** such as *Round Trip Time (RTT) of FH* to examine the trade-off between the extra sample (de-)compression processing time and the reduced FH read and write time as fewer bits are read from FH interface. Using these two types of KPIs, the impact of radio sample compression on the end-to-end service can be better reflected.

To evaluate the transport protocol and the transport technology, we can measure the KPIs of **Transport network perspective** (e.g., FH link throughput, RTT), **Endpoint-related** (e.g., RU/CU/DU hardware load in terms of CPU utilisation and memory utilisation), and **User-plane perspective** (e.g., user packet loss rate, user plane delay). For instance, the *FH link throughput* in bps and *RTT* in millisecond can validate transport technology and reflect transport protocol characteristics such as *sub-header overhead amount*, *packetisation compactness*, and *packet scheduling policies in FH network*. It is noted that the KPI of FH latency is crucial when applying C-RAN deployment, e.g., NGMN adopt 250 microsecond as the maximum one-way fronthaul latency [14] and SCF categorize the one-way FH latency from 250 microsecond to the millisecond level to evaluate the applicable functional split [15]. Additionally, endpoint-related KPIs, like *CPU utilisation* (the percentage of CPU processing time used by a process out of the total processing time) and *memory utilisation* (in bytes), can be used for two purposes: (i) Estimate the number of RUs that can be supported under the limited number of DUs/CUs given fixed RRU-BBU split, and (ii) Dynamic split based on the hardware load to fully utilize all available resources. These two purposes are enabled by the transport protocol of FH network to exploit the C-RAN dynamicity. Finally, the user-plane KPIs like *user-plane throughput* and *user-plane QoS* can be used to validate different transport technologies. For example, considering the comparison of Sub-6 GHz and mmWave technology, we can measure these user-plane KPI as the metrics for splitting the traffic on different technologies.

3.3 Technical components

In the following subsections, we will elaborate on the specific technical approaches proposed by 5G-PICTURE, which can be mapped to one or more of the aforementioned technical components. These technical components will also investigate a subset of KPIs of interest. Table 1 summarizes the relations between the Technical components described in this section and the technical approaches described in Section 3.2.1.

Table 1: Mapping between the proposed RAN domain technical components and the corresponding technical approaches.

Technical components	Technical approach
3.3.1 **Optimal functional split**	**3.2.1.1** Optimal functional split derivation
3.3.2 **Implementation of functional split using OpenAirInterface platform**	**3.2.1.2** Flexible functional split, **3.2.1.3** Slice-specific compression of radio samples
3.3.3 **Flexible Functional Splits**	**3.2.1.2** Flexible functional split
3.3.4 **LTE/5G RAN as VNFs implementation**	**3.2.1.2** Flexible functional split
3.3.5 **Wireless Transport Technologies with Functional Split Support**	**3.2.1.4** Transport protocol and technology

3.3.1 RAN Technical component 1: Optimal functional split derivation for specific scenarios

3.3.1.1 Involved technical approach and KPIs

Based on several functional splits described in Figure 6, the aim of this technical component is aligned with the approach mentioned in Section 3.2.1.1 via exploring the trade-offs and exploiting the most suitable functional splits based on the applied constraints of specific scenarios, e.g., FH link capacity, maximum allowed end-to-end delay. Note that the trade-off is originated due to the level of centralisation of different slices. For instance, split option 8 supports a fully centralised processing and the joint processing down to the physical layer for clustered RUs to boost the spectral efficiency, but with a cost of much higher FH link throughput compared to other splits [23]. By contrast, upper layer functional splits (e.g., MAC-PHY) can relax the stringent FH throughput requirement, but with the cost of distributed processing among RUs and fewer centralisation capabilities such as joint scheduling. We consider two different scenarios where the functional split is optimised. First, a Massive MIMO, based on a platform on a Massive MIMO array developed in WP3. Second, a scenario where CoMP clustering between Remote Units (RUs) is optimised.

RAN domain KPIs are related to the two considered scenarios (Massive MIMO and CoMP clustering). First, we consider both spectral and energy efficiency in the massive MIMO scenario. While the former measures how effectively the radio resources are used in transmitting data, the latter measures how efficiently energy is consumed in transmitting data. Thus, spectral efficiency is a metric more relevant for the eMBB use case, while energy efficiency is a more relevant metric for the mMTC use case. In addition, fairness among UEs is another RAN domain specific KPI of interest. This can be ensured by assigning weights to the users based on their priority, which are then updated based on the data received by the users in the past. This approach to ensuring fairness among UEs has its roots in the network utility maximisation framework [32]. In the second scenario, we consider the densely-deployed RAN deployment in order to maximize the spectral efficiency among all users, i.e., bps/Hz. We optimize the clustering of RUs to benefit from the CoMP scheme. In the following paragraphs, we present an initial design for these two scenarios.

3.3.1.2 Initial design and technology innovation

3.3.1.2.1 Massive MIMO scenario

Massive MIMO improves spectral efficiency by achieving power gain, as it is able to generate very narrow beams using a large array of antennas and spatial multiplexing gains by serving multiple users in the same time-frequency resource. Since the FH data rate increases linearly with the number of antennas for split 8, it is clearly not scalable to the massive MIMO scenario. Thus, higher splits are considered, particularly, the intra-

PHY split 7 with its sub-options split 7-2, 7-2a, and 7-3. Further, given the practical constraints such as finite capacity, non-negligible latency and FH jitter, the access network must be designed considering these aspects. This calls for a joint design of access and transport network.

We consider a two time-scale approach to manage the radio resource in the access network. At a faster time-scale, the precoding/digital beamforming is carried out at the RU and is based on the rapidly varying channel conditions. In contrast, functionalities such as power allocation to UEs, coordinated scheduling, and cooperative uplink training in case of Time-Division Duplexing (TDD) mode of operation are done at a slower time-scale. Therefore, these decisions are based on long-term channel conditions, for example, large-scale fading coefficients, and can be done at the DU. Given this two time-scale approach, the instantaneous channel state information is not required at the DU. This reduces the load on the FH. Furthermore, the convergence rate of the algorithms would not influence the performance much as these optimisations are done at a slower time-scale.

A generic block diagram of the two time-scale approach to access network design is shown in Figure 8. We briefly discuss the KPIs, which determine the objective functions of optimisation, different access network parameters for optimisation, and lastly, how FH constraints are incorporated into the optimisation framework.

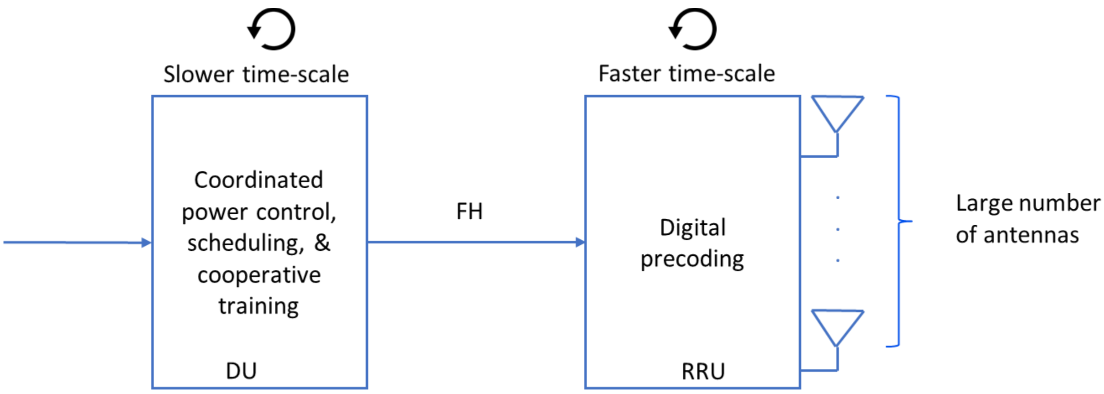


Figure 8: A conceptual diagram illustrating radio resource management in massive MIMO.

<u>*Access Network Optimisation Parameters:*</u> Since precoding is done locally at the RRU, coordinated beamforming is no longer possible. However, the interference in the access network can still be managed through the coordinated power control and scheduling. In the former, the transmit powers allocated to the UEs in the network are decided jointly, while in the latter, the scheduling decisions are coordinated across multiple cells. An example for coordinated scheduling is as follows. When an RRU is serving a cell-edge UE, the neighbouring RRUs decide to not schedule UEs close to the cell-edge UE in order to ensure that the interference experienced by it is low. This, in turn, ensures sufficient data rate to a cell-edge UE even though the signal power received by it is low. Through coordinated power control and scheduling, much of CoMP gains can be realised. Again, since these optimisations are carried out based on long-term channel conditions, they are not very sensitive to imperfections in the channel knowledge due to either estimation errors or propagation delays in FH.

Another key access network parameter is the pilot allocation among UEs in the network. This determines the extent of pilot contamination, which is one of the main factors limiting the performance of massive MIMO. Given that massive MIMO is expected to mostly operate in TDD mode, the channel gains are estimated via uplink training during which UEs send pilot sequences to the RRUs. Since pilot sequences are shared among the UEs, the allocation of pilot sequences needs to be coordinated in order to ensure that the UEs sharing a pilot sequence are sufficiently far apart. This allocation needs to be updated only when a UE moves to a new location or leaves the network area or when a new UE enters the network area. Thus, cooperative training through coordinated pilot allocation can be done at a slower time-scale and at the DU.

<u>*Fronthaul Network Constraints*</u>: The aforementioned access network parameters will be optimised considering the limitations of the FH network. The first constraint is the finite capacity of FH. In this case, the access network should be designed so as the aggregate data rate requirement on the FH is less than its capacity. In case the FH network is congested, i.e., when the data rate of the FH services is close to its capacity, the DU might decide to not serve some UEs or offload them to neighbouring RRUs. These decisions are optimally

made by the coordinated scheduling algorithm as a function of the network scenario and the KPIs of interest. Secondly, the FH network introduces latency. If the packet arrives at the destination (RRU in case of downlink and DU in case of uplink) past the delay deadline, the transmission is wasted. This again calls for coordinated decisions to manage congestions in FH.

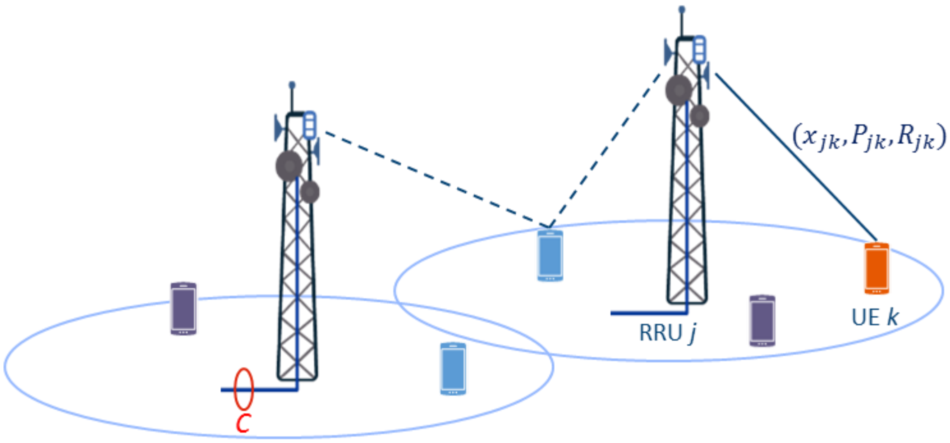


Figure 9: An illustration of system model.

Optimisation Problem Formulation: As shown in Figure 9, the link between RRU j and UE k is characterised by the tuple (x_{jk}, P_{jk}, R_{jk}). They respectively denote the binary scheduling decision, transmit power, and rate achieved on the link. In a network with K users and L RRUs, the weighted sum rate maximisation can be expressed as shown below.

$$max \sum_{k=1}^{K} \alpha_k \sum_{k=1}^{K} x_{jk}\, R_{jk}$$

$$s.t. \ \sum_{k=1}^{K} p_{jk} \leq P_t,$$

$$\sum_{k=1}^{K} R_{jk} \leq C$$

$$\sum_{j=1}^{L} x_{jk} \leq 1, x_{jk} = \{0,1\}$$

The constraints are the transmit power, the FH capacity, and the scheduling constraints respectively – the UE can only be served by at the most one RRU. Here, α_k denotes the priority assigned to the UE k.

The optimisation problem is a mixed-integer, non-convex optimisation problem. Iterative algorithms are being devised to solve the problem. Since FH capacity is a parameter of the model, the above formulation can be applied to manage power and scheduling with any FH technology. We expect the optimised network performance to be significantly higher than that of a baseline scheme with no coordination between the RRUs.

Split Precoding for FDD massive MIMO: Another work on improving the access network with Frequency-Division Duplexing (FDD) massive MIMO involves split precoding. Here, precoding is divided between RRU and DU. This approach is quite similar to precoding in split option 7-2a in Figure 6. Thus, from the perspective of DU, the effective channel is the combination of the precoder employed by the RRU and the actual channel. This effective channel matrix has lower dimensionality. This avoids the problem of FH data rate increasing linearly with the number of antennas, if precoding is done at RRU, while achieving the benefits of coordinated beamforming. This approach is appealing for FDD system as it also reduces channel feedback overhead over FH to DU.

A variant of split precoding that is of our interest involves post-IFFT beamforming at RRU. Therefore, precoding is applied to the time-domain IQ samples. This approach reduces the computational requirements at the RRU as precoding is not frequency-selective. Further, this precoder is decided based on the second order statistics of the channel, which capture the spatial/angular information of the UEs in the network. By employing a finely quantised codebook of precoding matrices at RRU, we expect to achieve significant performance improvement over a legacy LTE 2x2 MIMO system. We plan to implement the split precoding algorithm on massive MIMO hardware provided by Airrays and developed in WP3.

3.3.1.2.2 Clustered RUs of densely-deployed RAN

In our second scenario, we aim to cluster RUs into disjoint RU clusters for joint processing based on the applied functional splits within the formed clusters. An example is depicted in Figure 10 with three RU clusters serving different sets of users within each clusters, e.g., 2/4/4 served users for cluster 1/2/3, respectively. It is noted that users served by other clusters can potentially generate inter-cluster interference and correspondingly reduce spectral efficiency. Moreover, as observed in the example, RUs within the same clusters shall apply the same functional split and centralize their processing at the same CU/DU. Furthermore, the multi-segment FH links between RUs and DUs are responsible for routing the FH traffic between distributed RUs and the centralised DU while respecting the per-link throughput and latency constraints.

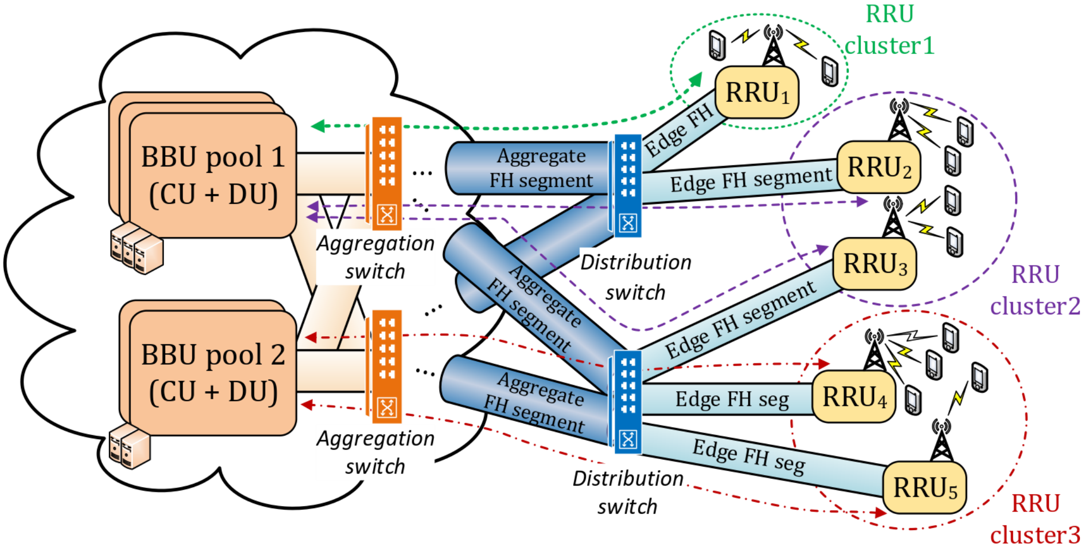


Figure 10: A RU clustering example.

To better represent the problem, in Figure 11, a graph notation is presented. In this case, there are eight users $\{u_1, u_2\dots u_8\}$ to be served by a group of RUs $\{r_1\dots r_4\}$ and DUs $\{b_1, b_2\}$. A group of six forwarding nodes $\{v_1, v_2\dots v_6\}$ are the ones that forward the traffic in the FH network and can be programmed following the SDN principle. As there are two formed RU clusters, their functions are split between RUs and the anchored DUs (i.e., b_1 for cluster 1 and b_2 for cluster 2) based on the applied functional splits (i.e., split option 7-1 for cluster 1 and option 6 for cluster 2). In addition, the routing paths of each RU are selected individually toward the anchor DUs correspondingly, e.g., nodes $\{r_1, v_1, v_3, v_5, b_1\}$ represent the routing path from the r_1 toward b_1 and nodes $\{r_2, v_2, v_3, v_5, b_1\}$ are the path from r_2 to b_1. We can see that a single FH link can be multiplexed by more than one RUs but the corresponding FH capacity and latency shall be fulfilled. For instance, the capacity of FH link (v_3, v_5) shall be larger than the summed FH throughput from r_1 and r_2 toward b_1.Last but not least, users are also partitioned to be served either by the first or second cluster, e.g., $\{u_1, u_2, u_3\}$ are served by the first cluster and will generate interference to the reception of $\{u_4,u_5,u_6,u_7,u_8\}$ at the second cluster (denoted as grey dashed line in Figure 11). To sum up, our aim here corresponds to optimize the aggregated network spectral efficiency summed over all users based on variables of five different aspects: (i) User scheduling, (ii) RU clustering, (iii) Function splitting, (iv) DU anchoring and (v) FH network routing. Specifically, the related constraints are enumerated as follows:

- Each user shall be served by only one RU cluster;
- The number of served users of each cluster shall be less than the maximum supported users;
- RUs within a cluster shall utilize the same functional split and anchored to the same DU;
- All FH link capacity shall not be less than the summed FH throughput from all RUs;

- The end-to-end C-RAN delay shall satisfy all RUs, i.e., RU processing time, FH latency, and DU processing time.

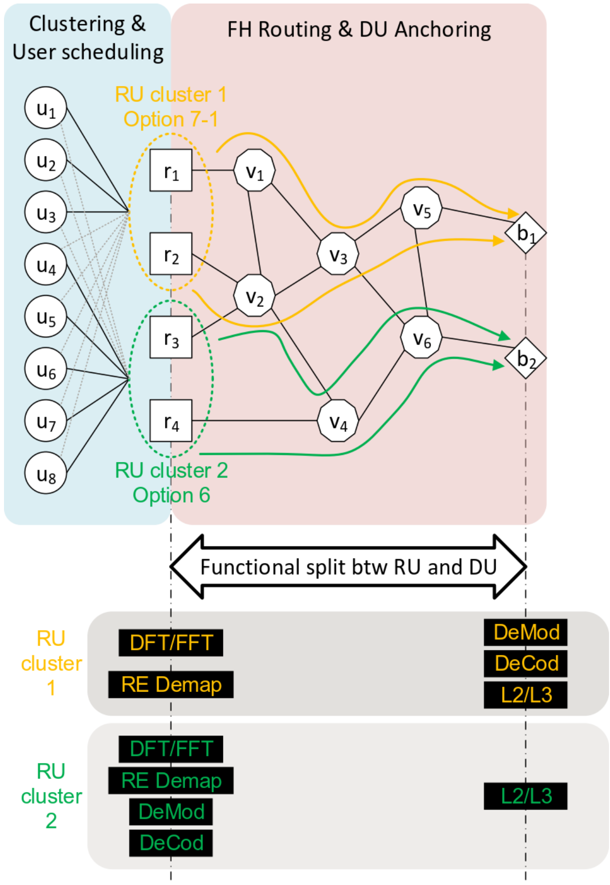


Figure 11: Graph representation of the considered functional split optimisation problem.

3.3.1.3 Expected outcomes

Based on the approach presented for the two scenarios, we expect that the optimal functional splits shall be decided based on the objective function as well as the constraints. Such optimal functional split can be used as input for the orchestration logic of WP5 to dynamically place and chain the end-to-end RAN service with another domain (e.g., transport network) based on the limited number of resources (e.g., compute, storage, and networking). Moreover, one could also use the monitoring information from the underlying RAN domain to indicate the real-time controller to change the functional split based on the dynamics of user and spatio-temporal traffic.

3.3.2 RAN Technical component 2: Implementation of functional split using the OAI platform

3.3.2.1 Involved technical approach and KPIs

Several functional splits are aimed to be implemented using the OAI platform [28], in which a software-based LTE/LTE-A system implementation can be run on General Purpose Processors (GPPs), and can be deployed on the virtual or physical infrastructure provided by WP3. Moreover, this implementation can provide the prerequisites for the derivation of optimal functional split decisions (Section 3.2.1.1) and is related to the split-specific sample compression state in Section 3.2.1.3 and transport protocol design mentioned in Section 3.2.1.4. Such implementation concerns the endpoint-related KPIs and end-user KPIs mentioned in Section 3.2.2. In the end-point KPIs, the implementation of functional splits shall be accommodated with proper number of resources (i.e., computing, memory, storage) to reduce the expenditure for future densely-deployed RANs. In terms of the end-user perspective, different functional split shall at least provide the approximately same experience over the user plane data transportation, such as user good-put, round-trip time, and packet delay jitter, as the ones provided in the legacy monolithic RAN. Last but not least, even the implementations of functional splits are irrelevant to the transport technologies over the FH; however, the applied transport technology will support the requirements of the applied functional split in terms of throughput and round trip time.

3.3.2.2 Initial design and technology innovation

The supported functional splits in RAN are given in Figure 7. Figure 12 shows the generic RAN module architecture and the available/planned modules packaged as software entities. It is composed of:

- A northbound interface (backhaul/midhaul/fronthaul and in-band configuration).
- A southbound interface (midhaul/fronthaul and in-band configuration)
    - Several management interfaces are used to dynamically manage (instantiate, configure, delete, migrate, etc.) the entity via a network interconnection such as the interface toward the Operation/Business Support System (OSS/BSS) and FlexRAN platform [31] shown in Figure 12. Such FlexRAN platform can utilize specified northbound API to enable RAN monitoring and control.
- A configuration file which can be used to statically configure the entity at run-time when it is read in.

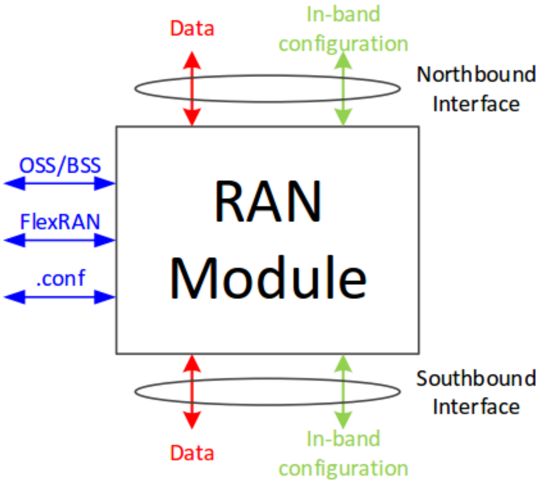


Figure 12: Generic interface ports for OAI entities.

Currently, OAI implements the following modules:

- **RRH module**: It possesses the interfaces towards/from the radio frontend based on NGFI IF5 definition and can be mapped to the 3GPP option 8 in Figure 6.
- **L1-low**: It includes the FFT/IFFT based on the NGFI IF4.5 and can be mapped to the 3GPP option 7-1 in Figure 6.
- **L1-high**: It includes the entire physical layer processing (e.g., precoding/combining, channel encoder/decoder) for all physical channels, and supports the nFAPI interface toward the DU/CU. This is mapped to the 3GPP option 6 in Figure 6.
- **L2-low**: It includes the MAC, RLC and the corresponding F1AP interface toward the CU. It can be mapped to the 3GPP option 2 in Figure 6.
- **L2-high**: It includes the PDCP and receives information from RRC layer as well as S1AP interface toward the core network. It can utilize the 3GPP option 1 in Figure 6 and a new E1 interface is defined by 3GPP toward the RRC entity.
- **L3**: It includes RRC, receives non-access-stratum information from the core network via the S1-C interface and provides configuration information to underlying L2.

It is noted that the compression scheme can be applied as parts of the implementation of a functional split, which is able to further reduce the data rate by a compression factor with acceptable performance degradation. In the following two paragraphs, we provide details for two slice specific RAN architectures.

3.3.2.2.1 RAN architecture design for 3GPP split option 8 and 7-1

Among 3GPP splits 8 and 7-1, the RU is generally an entity that hosts multiple RF front-end devices, processes the incoming samples based on the split (i.e., FFT/IFFT for option 7-1), and transmits/receives digitised samples through the connected FH interface. These functions are also (mostly) mirrored in the centralised DU as well. The flexible RU/DU architecture that we propose is shown in Figure 13, and consists of the following main components:

- **RF front-end configuration and monitoring unit**: It is responsible to apply the configuration (e.g., antenna gains, operating frequencies, etc.), indicated by the DU, to the RF front-end equipment and to provide the status report to the DU. Thus, it serves as an agent on behalf of the DU for the (re-)configuration and monitoring of the RF front-end devices.
- **Split IF function unit**: It performs the split-specific signal processing on the incoming data samples in both uplink and downlink directions based on the different functional splits.
- **(De-)Compression unit**: It provides a (de-)compression service for the data samples, to lower the FH capacity requirements, and is configured by the DU.
- **(De-)Mapping unit**: It maps the corresponding DU to each connected antenna port of the RU and constitutes a control information transported in each packet. Via the mapping approach, the extra antenna identity is included in the header and the packet will be transported through the according interface to/from the corresponding remote DUs.
- **Transport configuration unit**: This unit serves two purposes. First, it applies the packetisation scheme, chosen by the DU, i.e., the payload size (as a function of the radio bandwidth) and the network Maximum Transmission Unit (MTU) for the FH link. Secondly, it adjusts the timestamp between the RU and DU, with respect to round trip time statistics measured between the two. The timestamp of each packet is generated to have a reference clock of the RF front-end. When a packet reaches the DU, it bears the time value of the RF front-end device when the payload was generated. On the other hand, when a packet reaches RU, it is stamped with an adjusted version of this timestamp.
- **Synchronisation unit**: It enables the synchronisation mechanisms to provide a reliable frequency distribution from the DU across multiple RUs. The IEEE 1588 protocol can be used to provide a precise synchronisation through a grandmaster acting as a time server.

In Figure 14, the negotiations and protocol for RU control and configuration are provided. These four steps utilize the in-band or out-of-band control. Note the out-of-band control is mainly used for parameter setup at the RU side, during the configuration setup period. While in-band control coexists with the user plane data transportation and can be used to monitor the link quality and status.

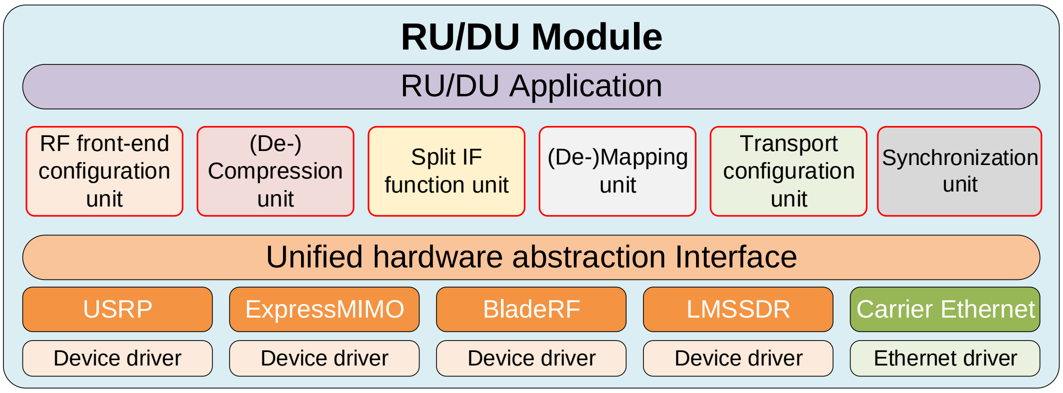


Figure 13: RU/DU architecture for split option 7-1 and 8.

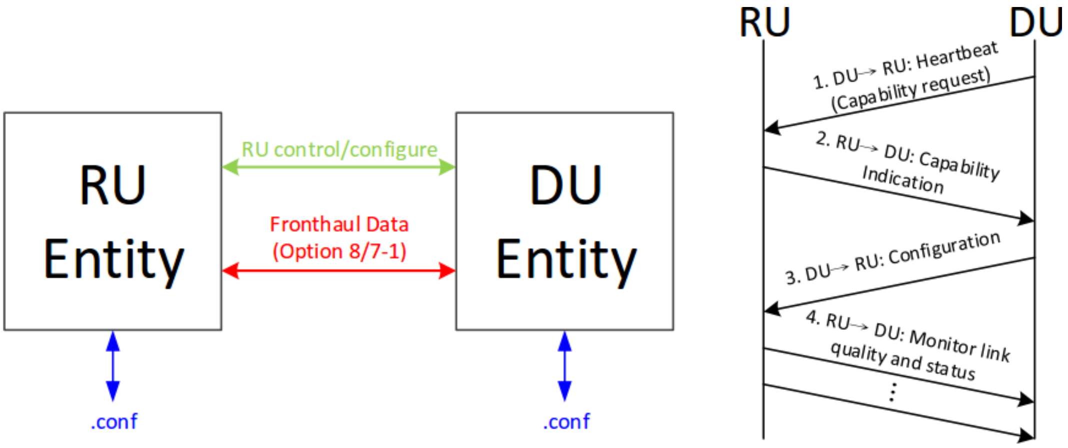


Figure 14: Negotiation (left) and protocol of control and configuration (right) between RU and DU.

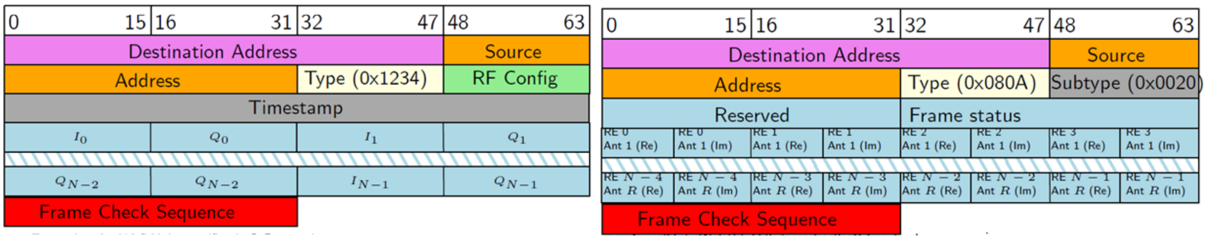


Figure 15: Downlink packet format of split option 8 (left) and 7-1 (right).

Last but not least, we introduce the data place packet format for functional splits 8 and 7-1 in Figure 15. In the split option 8, several extra contents are included in the header: (1) 2 type bytes that specifies the RoE protocol, (2) RF configuration that specifies the antenna index and can be later used for gain/timing adjustment, (3) 8 bytes timestamp in the number of samples of the of the first sample in the data part. As for the option 7-1, (1) the first two bytes specify the RoE protocol, (2) the following two bytes indicate the packet subtype (i.e., downlink, uplink shared channel, or uplink random access channel), and the last 4 bytes are used to indicate the antenna and frame status. More specifically, these 4 bytes include the following information: Number of antennas, Antenna index, and OFDM time index (frame index, subframe index and symbol index).

3.3.2.2.2 RAN architecture design for 3GPP split option 6

The DU architecture for 3GPP split option 6 is depicted in Figure 16, in which the functions are split between MAC and PHY layer. We can see that the MAC/PHY interface can based on the Cisco's open-nFAPI P5/P7 VNF-PNF interface[1] or via direct function call when PHY and MAC reside in the same physical machine (i.e., passthru in Figure 16). In both cases, the MAC/PHY interface uses the Small Cell Forum (SCF) interface description in the case of a networked implementation (e.g., nFAPI). Between MAC and PHY, OAI uses three basic messages to exchange configuration, signalling payload and transport channel payload. The three messages are explicitly are:

- PHY-Config-Req (MAC→PHY): It provides the cell configuration and user-specific configuration to the PHY instances and is a one-to-one mapping with the NFAPI P5 control message CONFIG.request mentioned in [30]. It is worth noting that the other optional NFAPI configuration message user CONFIG.request is not implemented since this message is required if the PHY implements user state information, which is no longer the case.
- UL INDICATION (PHY→MAC): This is an uplink indication that sends all UL information received in one Transmission Time Interval (TTI), including Physical Random Access CHannel (PRACH), if available. It amounts to an aggregation of all uplink nFAPI messages and also implicitly provides the subframe indication for the DL scheduler. Specifically, it maps to the following FAPI P7 messages mentioned in

[1] https://github.com/cisco/open-nFAPI

[30]: SUBFRAME.indication, HARQ.indication, CRC.indication, RX ULSCH.indication, RX SR.indication, RX CQI.indication, RACH.indication, SRS.indication.

- SCHEDULE RESPONSE (MAC→PHY): This message contains the scheduling response information and several FAPI P7 messages: DL CONFIG.request (program PHY for DL), UL CONFIG.request (program PHY for UL), TX.request (send MAC PDU), and HI_DCI0.request (send UL DCI and Physical channel HybridARQ Indicator Channel).

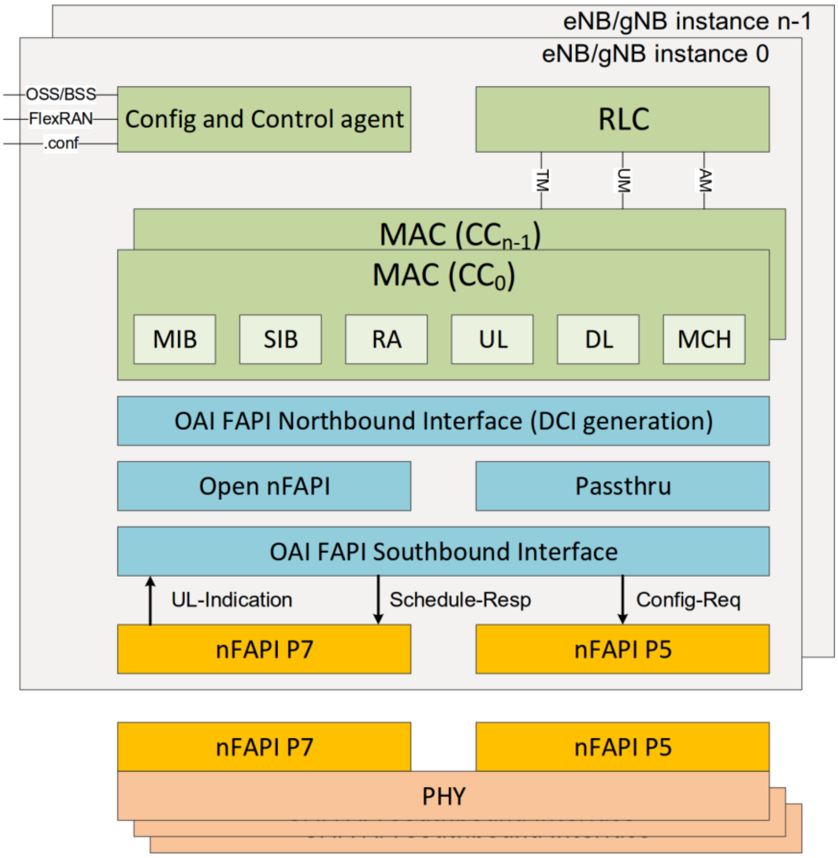


Figure 16: DU architecture for split option 6.

In Figure 17 we provide a draft state machine applied at the RU. The RU starts from the IDLE state and waits for the DU_TICK message from the DU. Upon this reception, the RU will be in CONFIG state and sends it capability via the RU_CAPAB message to the DU. Afterwards, DU composes the RU configuration and sends the RU_CONFIG message. After applying the configuration from the DU, the RU can feedback the acknowledgment RU_CONFIG_OK message and then enter the READY state. Upon receiving the RU_CONFIG_OK message, the DU can send the RU_START message to start the RU. In the case when RU is a master, it can enter the RUN state immediately and serve the RAN service; however, the RU will go to the SYNC state and try to synchronize in time with the master RU. When synchronisation is done, the RU will send the SYNC_OK message to the DU and be in the RUN state. Within the RUN state, the DU can (a) stop the RU via sending the RU_STOP message, or (b) reconfigure the RU by sending a RU_CONFIG message with a new configuration. Further, when any error occurs at the RU side, an error timer starts. Such timer will stop normally when the RU successfully receives the RU_STOP message from the DU and the RU enters again the READY state for restarting. Nevertheless, when the timer expires, the connection between the RU and the DU is considered to be lost and the RU shall be back to the IDLE state.

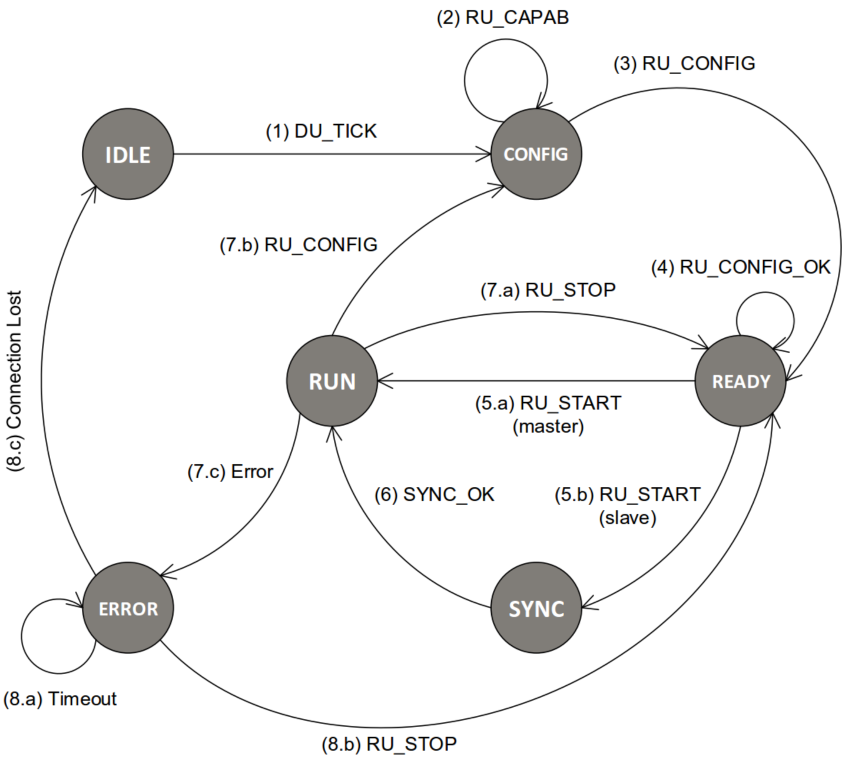


Figure 17: State machine of RU and DU.

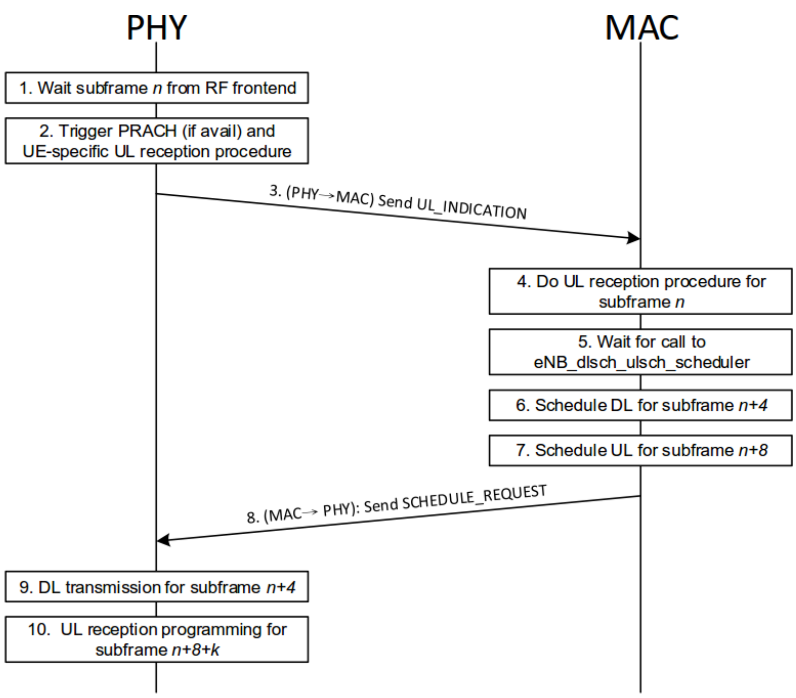


Figure 18: Protocol of MAC/PHY functional split.

In Figure 18, we provide the protocol of the MAC/PHY interface relying on the aforementioned in UL_indication and Schedule_Resp message on nFAPI P7. It is noted that the downlink and uplink scheduler are scheduled 4 and 8 subframes beforehand following the HARQ timing requirement.

3.3.2.3 Expected outcomes

Based on the aforementioned functional split implementation over the OAI platform, we expect that the outcomes can be deployed on the general hardware infrastructure provided by the WP3 with programmability. In addition, such implementation can be utilised as inputs for the orchestrator of WP5 to place the dedicated or shared network functions and chain these network functions to form a complete end-to-end RAN service for multiple services.

3.3.3 RAN Technical component 3: Flexible functional splits

3.3.3.1 Involved technical approach and KPIs

According to the aforementioned functional split options one common question coming out naturally is whether these splits should be fixed or flexible within a specific geographical region. Note that as the trade-off between different functional splits in terms of (1) RAN function centralisation degree and (2) resource requirements like FH throughput, the most suitable functional split is highly related to the spatio-temporal traffic dynamics and resource availability (e.g., networking, compute). In this sense, the flexible functional split approach aims to dynamically adjust the applied functional split between RAN entities and reorganize the RAN function chain. In this sense, it can better reflect the C-RAN potentials among different scenarios and respond to network dynamicity. For instance, a higher centralisation degree can enable the CoMP scheme when needed; however, it could be switched to the non-CoMP scheme with a lower degree of centralisation not only to save energy for non-coordinated processing but also to relax the requirements on FH transportation. Further, such approach can be straightforwardly incorporated with the 5G multi-service paradigm via changing between the shared and dedicated network functions (VNF/PNF) to serve the specific service needs. It corresponds to the technical approach mentioned in Section 3.2.1.2.

Moreover, such technical component is focusing on the RAN service continuity, since it might take some time to reconfigure the service chain during a split change. Furthermore, the synchronisation challenge arises when we target to change the functional split between RAN entities when a 1:m:n relation is applied among CUs, DUs and RUs. To this end, we focus on the RAN-domain KPIs. Specifically, we consider the functional split reconfiguration time (ms) and failure recovery time (ms) of our interested KPIs. The former one represents the agility of this technical component, while the latter shows its reliability to provide RAN service toward end users.

3.3.3.2 Initial design and technology innovation

Among all introduced functional split options in Figure 6, here we target to investigate the flexible split changes between option 8, option 7-1 and option 6 (i.e., nFAPI) which are implemented in the OAI platform as these three functional splits represent three different levels of centralisation as well as different FH throughput. Hence, the OAI platform shall be able to soft-restart the involved lower layers RAN functionalities (i.e., based on the source and target functional split) and re-chain the RAN service functions. However, an important challenge will be a temporary loss of service continuity toward end users within a period of time, which will be further investigated in details in deliverable D4.2.

To enable the flexible change between disaggregated RAN entities, a logically centralised real-time controller is introduced to hold the information about the chained RAN functions and to decide the split change based on the monitoring or feedback messages from the underlying RAN. For instance, the user-plane KPIs (e.g., traffic data rate) and Transport network KPIs (e.g., FH round-trip-time)[2]. This centralised design can not only remedy the inconsistent split change decisions made by distributed entities due to the aforementioned 1:n:m relations, but also reduce the considerable control information exchange overhead between them.

We hereby apply the FlexRAN platform [31], which is able to control the underlying RAN via utilising a centralised FlexRAN controller and incorporating the FlexRAN agent on top of the monolithic OAI BS currently. In this sense, the FlexRAN platform is expected to be extended to support underlying disaggregated RAN entities via introducing the *split-aware agents*. Note that each split-aware agent is on the top of each disaggregated RAN entity and is restrained respectively to the applied functionality of underlying RAN entity. In the following, we summary some changes to be applied for the split-aware agent:

- The agent reports a capability bitmap to the controller as well as the corresponding BS identities for controller to identify (1) the relations between agents and the BSs, and (2) the applicable functional

[2] The end-point KPIs such as CPU and memory usage can also be used to enable split change and are monitored by the (virtual) infrastructure manger.

splits;

- The agent can support the split-specific operations, such as to extract the functional split-specific information, stop the source functional split, and start the target functional split;
- Split-aware RAN reconfiguration operation between a single controller and multiple agents;

Further, the controller shall also be extended to incorporate information from different agents to appear as a single BS, while retaining the information of applied functional split. A plot of the new architecture is shown in Figure 19, with RU/DU split implementing option 6 and DU/CU split using option 2.

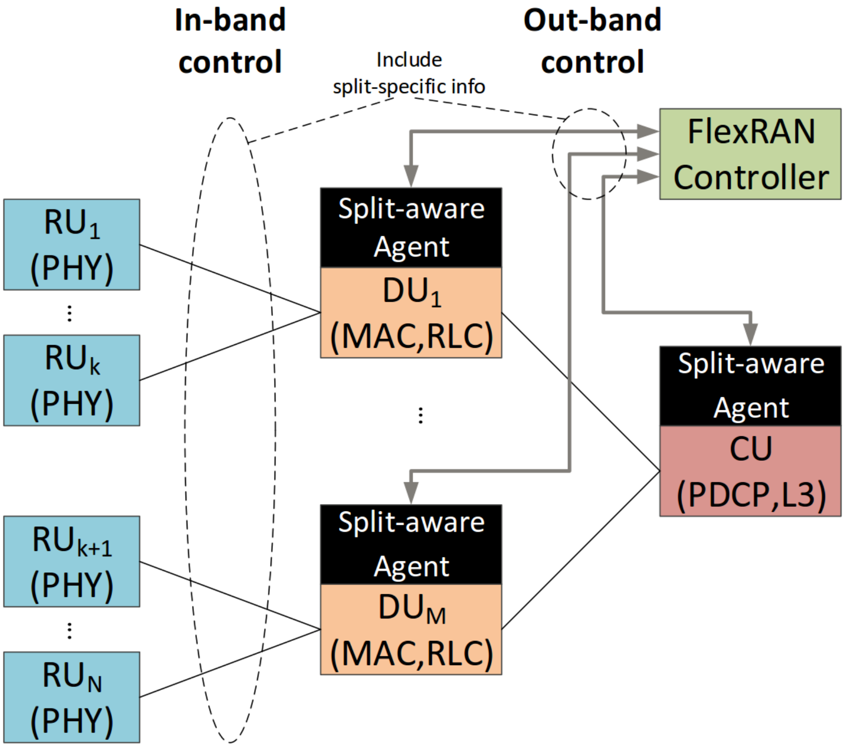


Figure 19: FlexRAN controller and agents in a disaggregated RAN.

We can notice in Figure 19 that the in-band control is applied between the RU and DU. The reason behind is that the RU is considered as a black box and hence the DU can inquire the RU capability following the state diagram presented in Figure 17. We can also see the state diagram in Figure 17 supporting such capability inquiry message exchange. Further, the functional split between RU/DU is controlled and configured centrally by the FlexRAN controller. The CU may also take part in facilitating the functional split changes such as stop traffic transportation to the corresponding DU when changing the functional splits between RU/DU. Regarding the connected RUs from the DU perspective, they can be seen as extensions of the DU from the perspective of controller and hence the in-band control can reduce the extra control overhead. Moreover, when the split between DU/CU is going to be changed, we can apply the controller-agent model to transport the out-band control information between involved DUs and CU. Note that the connected RUs will go from RUN state to READY state and wait for the RU_START message from DU. To sum up, our proposed hierarchical control framework can take both advantages in the distributed (i.e., between RU and DU) and centralised (i.e., between DU and CU) decision making.

However, even with the aforementioned enablers for the flexible functional split, an inherent challenge is on the RAN service continuity. In the simplest case, the agent will stop the involved network layers and restart them after having set up another functional split. We can refer the state diagram of Figure 17 to see that RU will go from RUN state to the CONFIG state. RAN service to connected users shall be stopped before going back to the RUN state. To circumvent this condition, several approaches can be applied. Firstly, we can do the inter-cell handover and serve users by another BS under the control of the FlexRAN controller before terminating the RAN service. Such scheme is a high-level solution that can be operated in a larger time-scale. However, users may still suffer from the QoS drop or even radio link failure. On the other hand, we can configure another (virtual) RU instance at the same time based on the target functional split, and do the intracell handover in a shorter time-scale (e.g., subframe or frame level). This approach is more favourable from the user's perspective but will incur higher resource requirements at the RU side. Furthermore, additional sets of control logic are necessary at the agent side and the FH support shall be confirmed when applying some non-straightforward protocol changes, e.g., from RAW Ethernet transportation to nFAPI P5/P7 messages. Given such outlined trade-off between aforementioned two approaches, we will further examine them on the FlexRAN and OAI platforms in deliverable D4.2.

3.3.3.3 Expected outcomes

Within such approach, we expect to change the functional split on-the-fly, which can be controlled by the orchestration and management function of 5G operating system in WP5 following a real-time manner. Further, the control logics of dynamically changing the functional splits can be incorporated with the logics of function placement in order to auto-scale the resource to better deploy ultra-dense RANs. Some underlying RAN information are needed to be monitored and provided as feedback, such as the CU and DU information, user state information, buffer status, resource utilisation ratio, and the QoS requirements such as throughput and latency, etc.

3.3.4 RAN Technical component 4: LTE/5G RAN as VNFs implementation

3.3.4.1 Involved technical approach and KPIs

A crucial component of 5G networks will be the disaggregation of the functions that traditionally are running on a base station, and the subsequent deployment of parts of the base station stack as cloud services. Based on the aforementioned functional splits, we will engage in the development of such functionality using the OAI open source platform [28]. Currently, several splits of the platform are supported by OAI; namely split option 6, 7-2 and 8 have been developed by the OAI Software Alliance, whereas other options are available in the community (e.g., split option 6 and 2 in [33]). Nevertheless, these options are commonly non-organised efforts that do not comply with the recently published standards for the NG-RAN interface [22]. These splits regard the option 2 of the 3GPP splits for 5G-RAN, with the introduction of the F1AP protocol for the intercommunication between the CU and DU components.

The technical architecture of the standardised interface for option 2 split is shown in Figure 20. A CU includes the processes of the PDCP layer and upwards, able to control multiple DUs incorporating the RLC layer and downwards. The communication between the CU and the DU is taking place over the newly introduced F1 interface, utilising the F1AP protocol, supporting DUs providing heterogeneous wireless network connections (e.g., 5G, LTE, Wi-Fi). A single CU should be able to serve multiple DUs (1:n relationship), whereas each DU is served from a single CU (1:1 relationship). The data plane traffic (payload traffic forwarded to the network UEs) is transported over the F1-U interface, encapsulating the traffic with GPRS Tunnelling Protocol (GTP) headers over UDP/IP, whereas the control plane (e.g., RRC signalling) is using the F1-C interface, running over SCTP/IP. Since this disaggregation of the base station functionality takes place at a higher layer, it allows for lower layer splits to be also incorporated, thus creating a multi-tier disaggregated architecture.

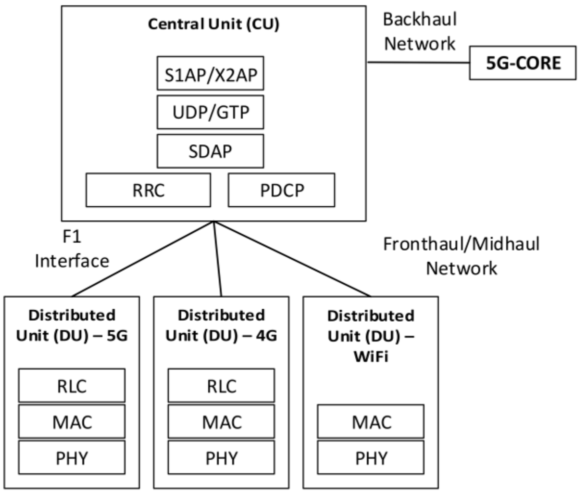


Figure 20: 5G RAN architecture for CU/DU operation.

Our approach in 5G-PICTURE involves the realisation of the F1 interface for the communication between CUs and DUs. This interface will be developed inside the OAI software platform, which currently provides support for the instantiation of 4G network elements (evolved Node B (eNB), Home Subscriber Server (HSS), Mobility Management Entity (MME), Serving/Packet Data Network Gateway (S/P-GW)). The software stack of OAI is expected to evolve to a 5G compatible stack, by incorporating the Next Generation RAN (NG-RAN) interface. The designed solution will be built to constantly support all the upcoming developments in the OAI code base, thus being enhanced constantly with new features for the RAN and Core Network (CN). As the standards for the intercommunication between the CUs and DUs are not finalised yet, we will initially follow the approach of developing our own solution for addressing and intercommunication of the different components, and later tailor it appropriately to fit the NG-RAN standards.

Regarding the performance indicators of this technology solution, and as the development of the split 2 functionality deals with the transport network, we plan to measure the performance of the developed functionality based on the transport network KPIs as defined in Section 3.2.2. Performance regarding the RTT and Midhaul (MH) throughput will be monitored, as these parameters are crucial for defining the maximum distance that the CU and DU units can be located. Other parameters involve the CU utilisation in terms of CPU and Memory usage, depending on the number of DUs that are being served, are also considered as the end-point KPI denoted in Section 3.2.2. Finally, the overall throughput and delay performance that the end-users are receiving, which shall be close to the performance delivered by the existing non-disaggregated solutions (i.e., User-plane KPI in Section 3.2.2).

3.3.4.2 Initial design and technology innovation

The interface for the effective communication between the CU and DU, should be able to support at least the following processes, as defined in [21]:

- **F1 interface management**: these processes include the initial setup of the MH link between the CUs and DUs in the system, handle any interface related errors that are reported from either side or activate/deactivate cells based on exchanged information.
- **System Information Management**: these functions regard the handling of broadcast transmissions of system information.
- **F1 UE Context Management**: these processes regard the establishment and modification of the overall UE context. The establishment of such context is initiated by the CU side (i.e., RRC) and is accepted or rejected by the DU based on the admission control criteria.
- **RRC Message transfer**: In legacy setups, the RRC messages are exchanged in order to setup the context between the RRC sublayer and PDCP, RLC and MAC. In such split architectures, all the protocols shall be decoupled from each other. Therefore, the CU should support the transferring of the RRC messages to the DU side (RLC and MAC). These messages are transferred over the F1-C interface.
- **User Data transfer**: Over the MH interface, the user data should be transmitted between the CU and DU interfaces. This type of data is transmitted over the F1-U interface.
- **Flow Control**: These functions regard the flow control of the downlink user data flow from the CU to the DU.

Based on the type of data that is exchanged over the MH interface, this shall be transmitted over either the F1-C or the F1-U interface. The indicated protocol stack for these interfaces is shown in Figure 21 and Figure 22.

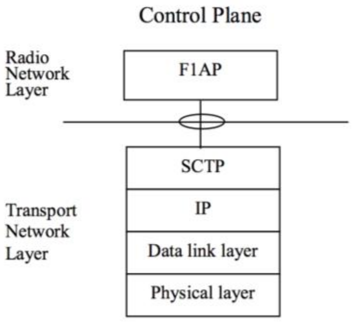


Figure 21: F1-Control Plane protocol structure defined in [21].

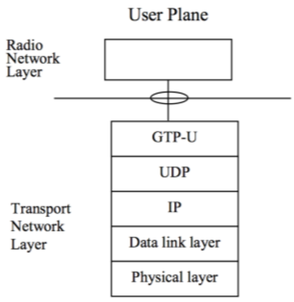


Figure 22: F1-User Plane protocol structure defined in [21].

The developed solution shall be able to support heterogeneous types of DUs. This means that for incorporating new DU functionality to the system (e.g., a Wi-Fi device), it should be augmented with the respective functions for handling the communication with the respective CU side, for both control and user plane as well as monitoring functions. As not all of the standards are yet finalised, regarding the F1 interface setup, we will adopt the following methodology in the developments of the VNFs for CU and DU operation:

- Initially we will provide an IP interface for the communication between the CU/DU interface, for both control plane and user plane traffic. This interface is hereby mentioned as F1 over IP (F1oIP).
- Later in the project, we will develop the 3GPP compatible interface.

The first solution relies on the creation of an IP interface for the logical connection between the CU and DUs, whereas the traffic can be transferred using any of the common transport protocols on top (UDP/TCP/SCTP). For the successful communication of the components, we need to define a new protocol for addressing the CUs and DUs, their type, as well as include information that is currently being used by the lower layers of the stack, residing at the DU, for controlling the scheduling of the transmissions in the RAN. For this purpose, a solution that is currently being developed is shown in Figure 23. As the implementation is based on the OAI platform, the processes for the CU (RRC, PDCP) and DU (RLC, MAC, PHY) operation already exist. We hereafter focus on the new elements of the network, being the F1oIP exchange protocol, and the Wi-Fi DUs.

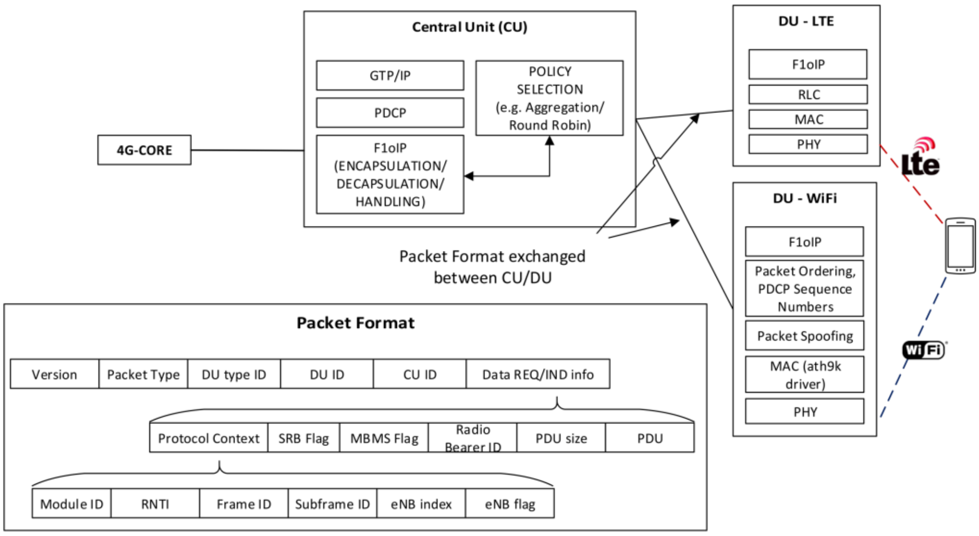


Figure 23: F1oIP protocol structure and message exchange with heterogeneous DUs.

3.3.4.3 Communication Setup and Message Exchange

The CU and DU units should be able to discover each other upon the system start, using predefined capabilities and a configuration file with the locations of the different modules. Upon the initial connection over the MH between the CU and the DUs, capabilities messages shall be exchanged with each other, stating the technology used by each DU. From this point, the exchange of the user-destined data taking place either on the DL or the UL channels, is being carried out through the F1oIP functions. Since both ends need to be informed of all the values needed for carrying out any computations at each receiving end (e.g., hash tables with the network users), extra fields shall be allocated at each packet piggy-backing all the needed information.

Each packet should include fields for packet type, DU type, and addresses each side through the DU ID and the CU ID. Different types may be supported for the same DU, as a single unit may incorporate functionality for both technologies, whereas the selection of the interface is made by the CU. The overall overhead posed by this header, along with the current status in the size of the respective variables that shall be used and exchanged for OAI is measured to be 80 bytes long.

3.3.4.3.1 Wi-Fi DUs

As the Wi-Fi stack significantly differs from the mobile networking stack in terms of the supported procedures, different processes need to take place upon the reception of the F1oIP packets for transmitting the payload to the network UE, or sending the data back to the CU. These processes include the reception of the F1oIP packets transmitted from the CU, unpacking and stripping off the respective headers, and subsequently delivering the payload to the wireless driver running on the DU device. For the UL data flow, payload traffic shall be encapsulated in the respective headers for the PDCP instance running on the CU. This includes dedicated processes for assigning new sequence numbers for the packets sent to the CU, as well as packet compression. In order to incorporate the information that does not exist in Wi-Fi (e.g., protocol context, data bearer ID) and allow the transparent handling of the packet reception at the CU side, mapping between the Wi-Fi end-points with the related protocol context should take place in the DU. This process requires that the initial packet transmission happens from the CU to the DU, in order to keep this information. In the case where the end-client side uses a similar joint PDCP procedure, this process can be omitted.

3.3.4.4 Expected outcomes

The work in this technology component will contribute to the open source OAI community with a new option split for the platform. It will allow us to get tangible evidence on the maximum locations that components of the NG-RAN architectures can be located, without impacting the end-user Quality of Experience (QoE). Finally, the provided functionality will be packed in VNFs for realising the CU and DU functionality that will be able to be instantiated from the orchestrator solution developed in WP5.

3.3.5 RAN Technical component 5: Wireless transport technologies with functional split support

3.3.5.1 Involved technical approach and KPIs

This technology component contributes to the technical approach mentioned in Section 3.2.1.4 on transport protocols and related technologies. The goal of this technology component is to validate how SDN-enabled wireless transport technologies address the requirements of different functional splits.

To evaluate the applicability of wireless transport to different types of functional split, we intend to build on the following wireless transport technologies:

- Typhoon 60 GHz modules developed by BWT. These radios use a compliant IEEE 802.11ad MAC and are capable of achieving 4 Gb/s on point to point configurations. These devices are equipped with a software switch that can be controlled by an SDN controller using OpenFlow.
- IEEE 802.11ac based wireless devices being developed in 5G-PICTURE as part of WP3. These devices include multiple radios configured to operate at the 5 GHz band, which achieve data rates close to 400 Mb/s with channels of 80 MHz bandwidth. All these interfaces are connected to a software switch that can be controlled by an SDN controller.
- A hybrid SDN control plane developed during the 5G-XHaul project [34], which consists of an agent running on each wireless transport node that detects when there is a link break and quickly reconfigures the data-plane to forward packets through a pre-established back-up path, and a logically centralised controller that hosts algorithms to pre-compute main and backup tunnels.

The OAI platform [28] will be used to analyse multiple functional splits. The following splits will be preferably considered:

- 3GPP Split 8 (NGFI split) for low carrier bandwidths.
- OAI proprietary split (compressed Split 8).
- NFAPI interface (L2/L1 split).

The goal of this technology component is to understand how state of the art wireless transport technologies affect the performance of different NG-RAN architectures. Hence, we will consider both access level and transport level KPIs, for example:

- Considered transport level KPIs will include delays (ms), jitter (ms) and goodput (bps) between CU and DU, under different traffic conditions in the transport network. These KPIs will be measured using different wireless transport technologies based on IEEE 802.11ad and IEEE 802.11ac.
- Considered access level KPIs will include end user throughput, SNR, or link losses measured at the end user terminal. Extensive analysis will be carried out to understand how the access and transport level KPIs correlate.

3.3.5.2 Initial design and technology innovation

Figure 24 illustrates an example testbed set-up that we intend to develop to evaluate the impact of wireless transport technologies on different functional splits. As depicted in the figure, the mobile network will consist of application servers, the Core Network (i.e., Evolved Packet Core (EPC)), the CU and DU, along with possibly an alternate radio technology based on Wi-Fi. Terminals (Station (STA) and UE) will be connected to each radio technology to measure application performance. The transport network will be composed of a combination of Sub-6 and 60 GHz wireless nodes, containing an SDN agent managed by an external SDN controller. The exact number of devices included in our testbed still needs to be determined.

The testbed will allow to test different representative topologies encountered in city environment. The blueprint small cell deployment proposed by the 5G-XHaul project in [35] will be used as basis to derive the actual topologies. Our experiments will consider multiple transmission strategies in the wireless transport, like: i) bundling 60 GHz and Sub-6 interfaces to enhance data-rate, ii) using Sub-6 as a backup technology when 60 GHz is in outage, or iii) balancing traffic from different CU-DU pairs across different paths to maximize aggregate capacity.

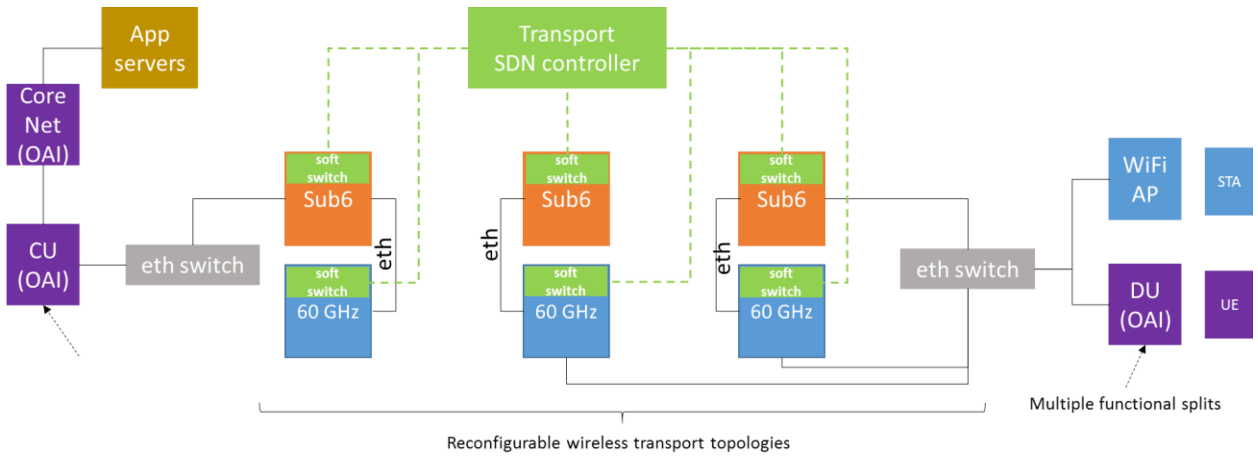


Figure 24: Example testbed set-up.

3.3.5.3 Expected outcomes

The work in this technology component will provide a deeper understanding of the feasibility of different NG-RAN architectures (functional splits) over a wireless transport network. Wireless transport is a key enabler for massive deployment of outdoor small cells, which are key to deliver the capacity promised by 5G.

The work in this technology component will leverage the wireless platforms developed by i2CAT and BWT in WP3.

3.3.6 Technical component KPI targets

Based on aforementioned RAN technical component, we summarize all involved KPIs in Table 2. Note These KPIs follow the four different KPI categories mentioned in Section 3.2.2 and will be further studied in the deliverable D4.2.

Table 2: Summary of KPIs for the RAN domain technical components.

KPI Category (cf. Section 3.2.2)	**RAN-domain**		**Transport network**			**Endpoint-related**		**UP perspective**	
KPIs	Spectral efficiency [bps/Hz]	Energy efficiency [J/bit]	Transport capacity [bps]	Transport Delay [ms]	Transport jitter [ms]	RAN function size [MB]	Function instantiation Delay [ms]	Power consumption [J]	UE QoS [b/s]
Split 7-2 optimize for Massive MIMO	Optimisation target	Optimisation target	Model parameter < 1 Gb/s for 10MHz bandwidth	< 1 ms	-	-	-	Follows from model, typically 8 Watts	-
RU clusters in dense RANs	Optimisation target	-	< 1Gb/s	E2E delay <1 ms- T_{DU}-T_{RU}	-	-	-	-	-
SW functional splits in OAI	-	-	Fronthaul < 1Gb/s for radio bandwidth ≤ 10MHz	FH RTT < 1ms	E2E FH < 1ms	Depends on BW, CPU core ≤ 4, Memory ≤ 2GB	-	-	Comparable to D-RAN for use-case KPI
Protocol for RU-DU negotiation	-	-	Fronthaul < 1Gb/s for radio bandwidth ≤ 10MHz	FH RTT < 1ms	E2E FH <1ms	-	<n*1 ms, depends on target function	-	-
Split aware FlexRAN	-	-	-	-	-	-	< n*10 ms, depends on function/ handover	-	Optimisation target for minimum impact
Split 2 support for heterogeneous RANs	Optimisation target	-	<500 Mb/s for 10 MHz bandwidth	-	-	-	-	-	-
Functional splits for wireless transport	-	-	500 Mb/s (Sub-6) 3 Gb/s (60GHz)	<1 ms per hop	<1 ms end to end	-	-	-	-

3.4 Positioning in the overall 5G-PICTURE solution

In this section, the initial design of VNFs and PNFs for the RAN domain is investigated and we summarize the target functional splits in the RAN domain to be implemented, as well as the corresponding contributing partners (as well as their VNF/PNF implementation platform that will be more elaborated in Deliverable D4.2) in Table 3.

Table 3: Targeting RAN functional split to be implemented.

Functional split	Partner (platform)
3GPP Option 8 (eCPRI split E)	**EUR** (OpenAirInterface)
3GPP Option 7-1	**EUR** (OpenAirInterface)
3GPP Option 7-2 (eCPRI split II_D/I_U)	**TUD** w/ **AIR**
3GPP Option 6 (eCPRI split D, nFAPI)	**EUR** (OpenAirInterface)
3GPP Option 2 (eCPRI split B)	**UTH** (OpenAirInterface)

Moreover, we have identified synergies between the RAN VNFs and PNFs and other WPs in 5G-PICTURE. In terms of WP3, the development of RAN VNF/PNF relies on the OAI platform using either GPP or other (specialised) hybrid processors for different RAN network function development purposes (e.g., higher data rate, low processing latency) and specific use cases (e.g., massive MIMO). It is also highly related to the WP3, in terms of leveraging the developed wired/wireless transportation platform for the inter-connection between disaggregated RAN entities, as the characteristics (e.g., maximum latency, average capacity) of applicable transportation schemes will impact the feasible functional split as mentioned in Section 3.1. To sum up, the designed RAN PNFs/VNFs of task T4.1 shall rely on the programmability characteristic provided by WP3 platforms to enable different functional splits for different scenarios. Moreover, the advanced optical/radio infrastructure technologies and interfaces offered by WP3 facilitate a flexible configuration of dynamic FH/BH techniques and the applicable RAN heterogeneities.

Further, the identified RAN functions are also highly related to other two domains developed in WP4, i.e., transport network slicing and synchronisation services. In terms of slicing the transport network, RAN-aware slicing is necessary to isolate the perceived performance, as well as efficiently utilize available transport resources. For instance, the applied RAN functional splits shall be satisfied by the development of transport technologies that provide sufficient end user QoS guarantees. In addition, the applicable functional splits are also related to the challenges faced by the synchronisation service. For instance, the stringent synchronisation required by the low-PHY split (e.g., Option 8) between involved RAN entities is crucial to enable a distributed antenna system scenario. Thus, the requirements imposed by the applied RAN functional splits shall be validated by different wired/wireless synchronisation functions mechanism surveyed in T4.3.

In terms of WP5, the designed RAN VNFs/PNFs shall support the multi-service multi-tenant vision that can be orchestrated and real-time controlled by the 5G-PICTURE OS. More specifically, the 5G-PICTURE OS developed in WP5 can utilize the inputs from the (1) optimal functional split results (Section 3.3.1), (2) implemented split-specific NG-RAN VNF/PNF (Section 3.3.2 and 3.3.4) as well as the applied sample compression scheme, and (3) feasible functional split changes (Section 3.3.3) to dynamically place and chain the end-to-end RAN service with another domain (e.g., transport network, core network) utilising the dedicated and/or shared network functions based on the real-time monitoring RAN information. Such multi-service chaining and placement shall also respect the limited number of resources (e.g., compute, storage, and networking) provided by the physical/virtual infrastructures of WP3 and the applied transport network scheme (e.g., wireless) examined in Section 3.3.5.

4 Transport Slicing for converged wired-wireless FH/BH networks and integration with 5G-PICTURE orchestrator

With respect to the terminology used in [4] and [36] by 3GPP, [37], [38] and [39] as transport network we consider the Fronthaul (FH), Midhaul (MH) and Backhaul (BH) communication networks that are used to interconnect Physical and Virtual Network Functions (PNFs, VNFs). In the case where the C-RAN or the disaggregated RAN paradigm is adopted, these NFs reside in the CU, DU, RU, and in the Core Network (CN).

In the last fifteen years there is a clear movement towards packet-based services and provisioning for packet-aware capabilities in both the mobile and the transport networks. For the mobile network, the "all-IP, all-Ethernet" design paradigm led for a complete redesign of the core network from a connection-oriented 3G core to a IP-based 4G Evolved Packet Core (EPC), while for the transport network great effort was put towards the exploitation of the benefits of using Ethernet technologies as the data link layer technology of choice, independently of the PHY.

Although a packet based flat-network design greatly simplifies the control and management procedures and promotes network efficiency, future network designs also will consider network operation in the light of the recently proposed concept of network slicing. In principle, a 5G network slice supports the communication service of a particular connection type with specific requirements and configurations for handling the control and data plane [40]. An "all-IP, all Ethernet" flat network design offers the ideal ground-floor over which the concept of network slices can be realised.

In the following subsections we analyse the state-of-the-art for the transport network technologies and the network slicing techniques available for the transport network. We then present the technical approach and the key technologies we will consider together with the relevant KPIs in order to realize the concept of network slicing.

4.1 State of the art on transport networks and network slicing

We analyse the state-of-the-art for transport network technologies for the following three categories: optical networks, Ethernet/IP and wireless networks. The reason for selecting this classification is that unlike layer 2 and layer 3 networks, optical network resources and transport format are different due to their analogue nature. Physical layer constraints, such as wavelength continuity and physical layer impairments differentiate optical and other network resources [41]. Similarly, when using wireless technologies these are subject to issues like interference or channel variations that we do not meet in optical networks.

4.1.1 Transport technologies landscape

4.1.1.1 Optical transport

5G networks are expected to integrate FH and BH into a common transport network interconnecting RUs and end-users with the mobile cores and distributed Data Centres (DCs) (Figure 25.a). This is to meet the strict targets for true broadband throughput, low latency, increased density and energy efficiency of 5G infrastructures. Therefore, existing networks relying on legacy and mobile specific architectures and protocols need to be transformed into open, scalable and elastic platforms. Furthermore, in 5G networks, C-RAN services can be facilitated through optical-fibre technologies to offer converged fronthaul and backhaul services over shorter or longer distances. This section, summarises the state-of-the-art on optical transport network technologies supporting FH/BH services.

To address the high bandwidth connectivity requirements of the 5G-PICTURE solution the use of optical transport to support 5G networking will be adopted (Figure 25.a). The optical transport proposed will be based on two different Wavelength Division Multiplexing (WDM) technologies, including an active and a passive solution. In terms of passive solution used in the access network, we propose the Passive Optical Network (PON). PON is an architecture for supporting fibre-based broadband access to a set of customers. An Optical Line Terminal (OLT), which is part of a CO, is connected through a tree-branched passive distribution network to the Optical Network Units (ONUs), which are located at the customer side. Such networks have several advantages, as they are very simple, easily scalable, and are easy to maintain [42]. In the Time Division Multiplexed PONs (TDM-PONs), standardised by IEEE [43] and ITU-T [44] [45], the different user signals are multiplexed in time in the upstream. The latest standard, the Next-Generation PON 2 (NG-PON2), envisions to increase the overall capacity supported by adopting both TDM and Wavelength Division Multiplexing (WDM) [46] that can enable converged FH and BH services. PONs can facilitate the interconnection of remote CUs and DUs to support FH services, as CUs can be located at the edge between the access and the metro network, while the DUs can be located at various points of the access network. The Remote Nodes (RNs) in the PON structure are typically implemented either employing simple power splitting or wavelength selective devices. Various architectures can be deployed to support this functionality ranging from PONs that can be fully dedicated to support only radio signal delivery using e.g. specifically designed hybrid TDM/WDM-PONs [47], or more flexible WDM-PON approaches such as the one reported in [48]. However, the envisioned 5G transport is expected to jointly support FH and BH services avoiding the deployment of separate networks for the two different types of service. This solution is challenging, as it has to fulfil a huge volume of greatly varying set of services including traditional fixed optical access network services and at the same time a set of new 5G related services.

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 higher degree of elasticity in the optical domain. In view of these new requirements we propose a dynamic frame based optical network, able to allocate the optical bandwidth elastically. The elastic optical network allows to efficiently support the varying degrees of bandwidth and latency requirements introduced by the different RAN deployments in addition to all other fixed services that it is expected to support. The 5G-PICTURE frame based elastic optical network solution is referred to as Time Shared Optical Network (TSON) offering increased degree of dynamicity and granularity and thus improved efficiency and scalability features [49]. To further increase capacity TSON employs WDM. It includes two different types of nodes, namely edge nodes and core nodes, incorporating different functionalities and levels of complexity. The edge nodes provide the interfaces between wireless, PON and data centre domains to the optical domain and vice versa. The ingress edge nodes are responsible for traffic aggregation and mapping, while the egress edge nodes support the reverse functionality. These interfaces allow handling of Ethernet frames, natively supporting a broad range of framing structures and communication protocols including CPRI (or eCPRI), Open Base Station Architecture Initiative (OBSAI), 10G Ethernet as well as protocol extensions required in support of the functional split concept under discussion in the framework of 5G. In the framework of the 5G-PPP 5G-XHaul project, a hybrid WDM PON TSON optical transport solution was adopted [50].

More specifically in 5G-PICTURE, at the ingress TSON edge node, the interfaces receive traffic frames generated by fixed and mobile users. The incoming traffic is aggregated into optical frames, which are then assigned to suitable time-slots and wavelength for further transmission. At the egress point, the reverse function takes place, recovering the original data that need to be forwarded to their destination. Moreover, the optical edge node is also equipped with elastic bandwidth allocation capabilities supported through the deployment of Bandwidth Variable Transponders (BVTs) also referred to us sliceable (S-)BVTs. These deliver data flows with variable spectral occupancy and rate, according to the network and path conditions [51] [52]. The parameters to be configured at each (S-)BVT include wavelength, spectral occupancy and modulation format/power per flow. Among all options for implementing the (S-)BVTs, those based on direct detection are preferred. For the metro network (Figure 25.c), we consider a frame-based optical network solution [51] where the ingress edge nodes aggregate the incoming traffic into optical frames, which are then assigned to suitable time-slots and wavelengths for further transmission. At the egress point the reverse function takes place. The objective of the optical transport network is to provide connectivity for a number of RUs and end-users with a set of compute/storage resources. The use of GPPs enables the concept of virtual BBUs (vBBUs), facilitating efficient sharing of compute resources. This joint functionality is enabled by the edge nodes that comprise a subsystem able to handle both continued (CPRI data streams) and packetised flows (Ethernet flows). The design of such a subsystem is out of the scope of the present study; however, an indicative architecture supporting both types of service is provided in [51]. A practical implementation of this subsystem could be facilitated through a hybrid CPRI-Ethernet switch. The CPRI switch handles transport classes with strict synchronisation and bandwidth constraints, i.e., split (1) and (2) in Figure 25 (cf. split option 8 and 7-1 in Figure 6 respectively), while the Ethernet data switch handles BH traffic and relaxed FH transport classes, i.e., split (3) to (5) in Figure 25 (cf. option 7-2, 7-3 and 6 in Figure 6). An analysis of these splits is provided in [49]. FH data streams are supported by a synchronisation block that manages the synchronisation signals between the end points.

The advent of elastic optical networking, enabled by the adoption of a flexible channel grid and programmable transceivers, opens the door to a truly dynamic active management of optical networks [53] [51]. This is especially interesting in the context of supporting greatly varying transport services of FH services for the RAN jointly with BH services.

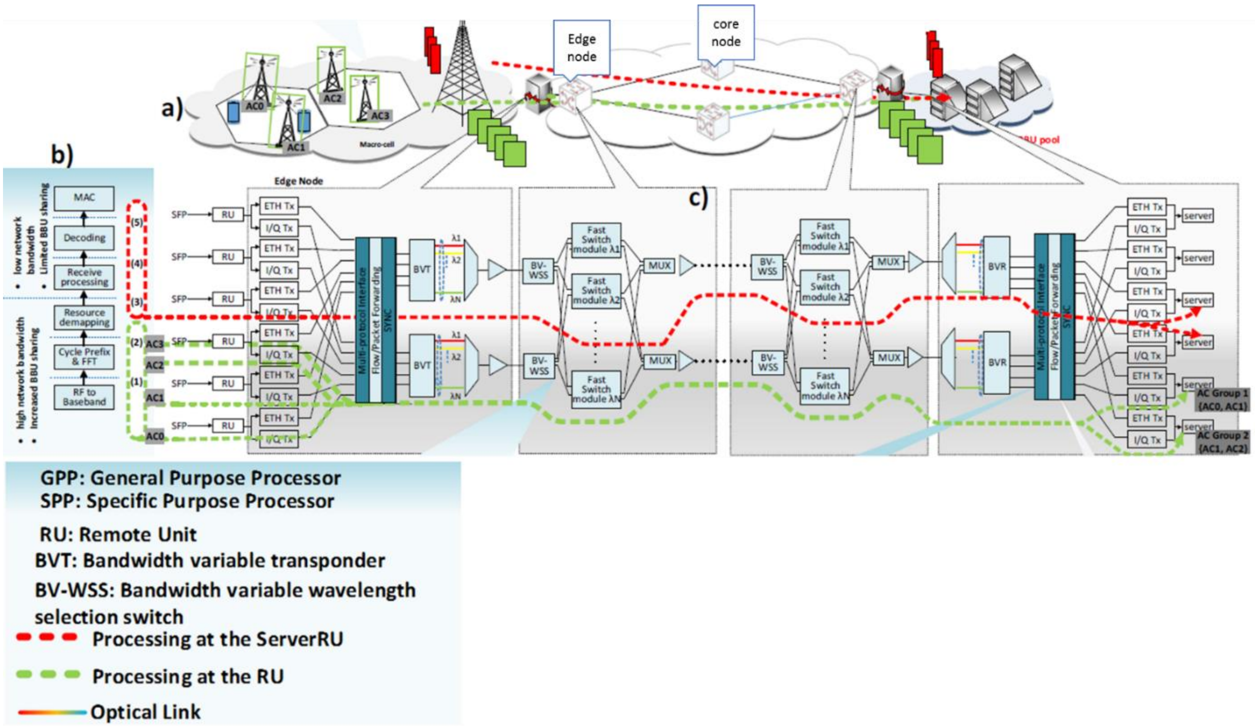


Figure 25: a) General architecture, b) Functional split of RU processing, c) Optical transport network.

4.1.1.2 Ethernet/IP transport

In this section, we begin by describing the "all IP, all Ethernet" technology landscape focusing on the transport network and the state of the art on network slicing.

On the radio side efforts are around eCPRI and Radio over Ethernet (RoE). On the transport network the adoption of Ethernet technology is known as Carrier Ethernet. In principle carrier Ethernet enables service providers to provide premium Ethernet services for the Metropolitan Area Network (MAN) and the Wide Area Network (WAN). From the industry perspective, Metro Ethernet Forum (MEF), is a non-profit international industry consortium, dedicated to adoption of Carrier Ethernet networks and services[3].

According to ITU-T a migration from a legacy network to a new packet transport network is one of the most serious issues for telecom carriers [54]. ITU-T Recommendation G.709 describes the Optical Transport Network (OTN) as a replacement of legacy Synchronous Optical Networking/Synchronous Digital Hierarchy (SONET/SDH) networks that is able to efficiently accommodate IP/Ethernet-oriented services. OTN has already standardised line rates such as OTU3 43.01 for transporting 40 gigabit Ethernet signals and Optical channel Data Unit (ODU)4 for 100 gigabit Ethernet signals. In contrast to SONET/SDH (that supported fixed frame rates), OTN supports a fixed frame sizes that facilitates mapping of IP/Ethernet services for the carrier network. Other solution like the TeraStream network by Deutsche Telecom [55] considers for an IPv6 solution that directly operates on top of WDM, avoiding the functional overlap when operating IP over Asynchronous Transfer Mode (ATM) over SDH over WDM.

Regarding the "all-Ethernet" landscape, in the mobile network domain the relevant activities are mainly around eCPRI and RoE (IEEE P1904.3) while for the transport network the main activities are summarised in Table 4.

[3] See also the Ethernet Alliance (http://ethernetalliance.org/) activities and MEF https://www.mef.net/)

Table 4: Technology landscape.

Transport Network all Ethernet		
Technology	**Description**	**Relevant Standards**
Ethernet over Multi-Protocol Label Switching (EoMPLS)	EoMPLS is a tunnelling mechanism for Ethernet traffic through an MPLS-enabled layer 3 core. Ethernet over MPLS is the main WAN technology used by Internet Service Providers (ISPs).	IETF RFC 4448, 4905, 4906
Ethernet over SONET/SDH (EoS)	SONET/SDH transfers multiple digital bit streams synchronously over optical fibre. With EoS Ethernet frames which are to be sent on the optical link are sent through an encapsulation block called Generic Framing Procedure (GFP) to create a synchronous stream of data from the asynchronous Ethernet packets. GFP maps a Variable Bitrate (VBR) signal like Ethernet packets into a Constant Bitrate (CBR) signal.	IETF RFC 4448, 4905
Packet over SONET (PoS)	POS is defined in IETF RFC 2615 as Point-to-Point Protocol (PPP) over SONET/SDH. POS can be used to map any packet technology like also ATM traffic. Under POS, PPP encapsulated IP packets are framed using High-Level Data Link Control (HDLC) protocol and mapped into the SONET Synchronous Payload Envelope (SPE) or SDH Virtual Concatenation (VC) [56]. The main function of HDLC is to provide framing, that is, delineation of the PPP encapsulated IP packets across the synchronous transport link.	IETF RFC 2615
Ethernet over DWDM	Typically carriers are deploying Coarse WDM (CWDM) for smaller deployments and DWDM for customers with tremendous bandwidth needs. DWDM enables one to create multiple “virtual fibres” over one physical fibre. The DWDM layer is protocol and bit rate independent, which means that it can carry ATM, SONET, and/or IP packets simultaneously. A new generation of devices provides options that come with both SONET and DWDM. Ethernet over DWDM combines packet-processing intelligence and optical-wavelength assignment into a single, unified system. ITU-T's concept for transport in optical networks (including WDM) is OTN and is specified in G.872.	ITU-T G.872
Ethernet over OTN	OTN is the successor of SONET/SDH. E-Line services can be delivered over OTN using Ethernet over OTN as specified by the ITU-T G.709 recommendation. In essence, Ethernet over OTN requires the mapping of ingress frames at a User Network Interface (UNI) (ingress port) to a specific container called an ODU. For example, the most appropriate OTN container for Carrier Ethernet services at the UNI is ODU0, which supports the transport of a 1000BASE-X signal mapped to the container using GFP. This is a scalable solution for delivering high bandwidth Ethernet Private Line (EPL) services. Ethernet over OTN provides the same resiliency as SONET/SDH but with more flexible bandwidth allocation. It is fully transparent to the Ethernet frame, meaning any L2CP frame can be tunnelled over the OTN-based network. No MAC learning, forwarding or filtering is performed. Support for EVPL is limited and requires specific mapping and depends on the topology.	ITU-T G.709

Flexible OTN (FlexO)	It is described in ITU-T G.709.1/Y.1331.1 recommendation. Flex-O provides OTN interfaces with comparable functionality as to what was introduced in Flexible Ethernet (Flex-E) [57] for Ethernet interfaces. It provides an interoperable system interface for OTUCn transport signals; while it enables higher capacity ODUflex and OTUCn, by means of bonding m standard-rate interfaces.	ITU-T G.709.1/Y.1331.
Flex-E	FlexE enables Ethernet-based services to be mapped over a next-generation optical transport network with the most efficient utilisation of capacity possible [43]. It was originally conceived to meet the challenges of Internet Content Providers (ICPs) for higher capacities and dynamicity, and as a new mechanism for the Data Center Interconnect (DCI) [43]. It was proposed by OIF in IA # OIF-FLEXE-01.0 on March 2016.	IA # OIF-FLEXE-01.0

The industry consensus is that OTN-WDM will actually serve as the PHY underlay towards 5G, besides just being the successor of SONET/SDH.

4.1.1.3 Wireless transport

Micro-wave based wireless backhauling is currently very widely deployed and expected to grow in the next years, i.e., 65% of the base station sites by 2022 [58], driven especially by the adoption of 4G networks in emerging countries. In 5G-PICTURE though we target an emerging scenario for wireless transport technologies, namely the adoption of wireless transport in dense urban scenarios. Two are the main use cases that motivate the adoption of wireless transport technologies in dense urban scenarios. Firstly, the possibility for operators to provide the Fixed Wireless Access (FWA) at low cost, hence replacing expensive Fibre-to-the-home deployments. Secondly, the support of dense deployment of outdoor small cells, which are expected to be rolled-out in 5G in order to densify the network thus increasing area capacity.

There are three main approaches currently competing in the FWA space: wireless technologies operating at the V-Band (60 GHz), pre-standard 5G NR radios operating at 28 GHz, and lightly licensed E-band (70-80 GHz) based radios. Regarding wireless technologies operating at the unlicensed V-Band (60 GHz) we can distinguish between proprietary technologies like those developed by Siklu [59], and technologies based on the IEEE 802.11ad MAC, which aim at achieving very low costs through economies of scale. IEEE 802.11ad, originally coined as WiGig, was designed as a radio interface operating at 60 GHz for cable replacement scenarios, e.g., HDMI replacement, in indoor environments. However, recent innovations have demonstrated the feasibility of developing wireless backhaul solutions with multi-gigabit performance based on this MAC. Examples of wireless backhaul products based on the IEEE 802.11ad MAC are the Terragraph project from Facebook [60], the Edge-Haul solution from Interdigital [61], or the Typhoon devices developed by Blu Wireless Technology (BWT) in the 5G-XHaul project, which can achieve data-rates above 3 Gb/s [62]. In addition, IEEE 802.11 is developing the IEEE 802.11ay standard [63], which also operates in the V-Band and extends 802.11ad to achieve data rates above 20 Gb/s by means of MIMO and channel bonding. A simulative evaluation of this technology was carried out in the 5G-XHaul project [64]. Regarding FWA in the 28 GHz band, Verizon developed a pre-standard 5G NR specification, which proposes a technology based on OFDM-CP and up to eight 100 MHz component carriers able to achieve multiple gigabits/second per link [65]. There have been several field trials demonstrating the capabilities of 5G NR as a technology for FWA [66]. Finally, operating at the E-band (70-80 GHz) we can already find today devices providing 1 Gb/s for links of up to 3 Km. E-Band technology is growing, since the lightly licensed approach of this band is currently supported in a large number of countries. E-band radios are expected to support 10 Gb/s in the upcoming years, and be scalable up to 100 Gb/s, by means of MIMO and larger channel bandwidths. In addition, future radios operating in the W-band (92-114.25 GHz) and the D-band (130-174.8 GHz), which have 50 GHz of available bandwidth, are still under research [58].

The other trend driving the adoption of wireless transport technologies in dense urban scenarios is the need to support massive deployment of outdoor small cells at low costs, which is not possible using fibre based transmission technologies. In 5G, a dense layer of outdoor small cells installed on street furniture is expected to provide additional capacity, while complementing the coverage provided by macro-cells installed at rooftop level. For this purpose 5G NR has adopted a novel functional split, known as F1 interface [67], which transports IP packets between the CU and the DU. In this split the CU implements the SDAP, PDCP and RRC layers, whereas the DUs implement the RLC, MAC and PHY layers. This functional split refers to split option 2 in

Figure 6. Hence, in dense small cell deployments, the CU could be implemented in a central location, e.g., running on an x86 server co-located with a macro-cell site, whereas the small cells mounted on street furniture would implement the DU[4]. The requirements on the F1 interface are similar than those associated with a traditional backhaul, with slightly more stringent requirements on latency (< 5ms) [58]. Hence, wireless transmission technologies would be an excellent candidate to implement the transmission network between the CU and the DU in dense small cell scenarios. The same technologies listed for the FWA use case are also good candidates to support small cell backhauling, and the F1 interface. In addition, in some cases, it is convenient to complement the previous high data rate technologies with Non-Line of Sight (NLoS) radios, because in cluttered city environments it may be difficult to always guarantee the LoS conditions[5]. Commonly used NLoS solutions are based on IEEE 802.11 radios to achieve low costs, using directive antennas and the 5GHz band. The 5G-XHaul project developed a solution that bundled two IEEE 802.11ac wave 1 radio modules, using channel bonding of 80 MHz in each interface, and supporting an aggregated bandwidth at the application layer of 500 Mb/s [68].

Related to support easy deployment of outdoor small cells, another approach that is generating a growing interest is the use of Integrated Access and Backhaul (IAB), which consists of sharing spectrum between access and backhaul links in order to facilitate deployment. 3GPP has launched a study item on IAB targeting the second phase of 5G NR standardisation, IAB should be applicable to both below and above 6 GHz. IAB networks are expected to support multi-hop deployments, over a small number of hops (< 5) [69]. To fulfil the vision of IAB, work is required in the areas of topology management, route optimisation, dynamic resource allocation between access and backhaul links, and enhancements in spectral efficiency and reliability or backhaul links. IAB is expected to be an enabler for the deployment of mmWave small cells, which are subject to short scale blocking that cannot be overcome with traditional RRC based handovers and require faster layer 2 switching mechanisms. IAB is expected to rely on previous work done about relay extensions for LTE. In addition, there is ongoing work aiming to support integrated access and backhaul functionalities on IEEE 802.11 based radios, using software based Time Division Multiple Access (TDMA) scheme on top of traditional Carrier Sense Multiple Access (CSMA) [68].

4.1.2 State of the art on transport network slicing

The concept of network slices has been refined by NGMN [40], 3GPP [70] [5] and ITU [71], while it is adopted and adapted by the main Telecom manufacturers and Telecom operators. In principle, a 5G network slice supports the communication service of a particular connection type with specific requirements and configurations for handling the control and data plane. A more generic definition is described in [72] where a network slice can be defined as a composition of adequately configured network functions, network applications and underlying cloud infrastructures that are bundled together to meet the requirement of a specific use case.

In this section we present the state of the art for network slicing for the transport network. Similarly to the previous subsection, we analyse the state of the art using a layer-based approach for slicing the optical networks, Ethernet/IP and wireless networks.

4.1.2.1 Optical transport network

Network slicing will be introduced as one of the key enablers to support the required level of flexibility in 5G networks. Network slices are essentially multiple logical networks deployed over the same physical infrastructure. In the highly heterogeneous 5G transport, a critical challenge that needs to be addressed is that of cross-domain slicing. To address this challenge the combination of the SDN and the European Telecommunications Standards Institute (ETSI) NFV standard is proposed. However, this proposition does not solve all incompatibility associations relative to the different heterogeneous technologies. To address this challenge, a relevant interface needs to be defined. The TSON interface is proposed to address this challenge. In 5G-PICTURE, TSON allows functionalities for the network slicing to create, manipulate, and destroy intra-domain TSON connectivity. Thus, the main procedures for the network slicing in TSON are related to the creation, modification and deletion of network paths, with the specification of attributes like end-points, tributary traffic, bandwidth, timing constraints in case of advance reservations, and resilience options. In the procedure, a method of notifications to notify events related to the established network connection is necessary for a

[4] A single CU can coordinate multiple DUs through the F1 interface.

[5] Notice that LoS are easier to achieve in FWA deployments where the CPE can be located at rooftop level, and fibre drops can be used to reach different apartments.

failure or a modification triggered by internal procedures. The TSON node uses also the VLAN tag to facilitate the management of the network slicing. The different functionalities to handle the transport network slicing in the TSON network are implemented within the SDN controllers integrated with an orchestrator, which cooperates together for the on-demand provisioning of connectivity between TSON nodes. The modules implemented in SDN controllers can provide a set of services, which act as consumers of the TSON driver, making use of the methods exposed by its interface to configure and collect information of the TSON domain. The interface of TSON functions can be described through an API. It is exposed as an internal interface within the SDN controllers, but it may also be exported as an external interface enabling a common protocol, such as HTTP. The interface implements an Application-Controller Plane Interface (A-CPI) instance and services can be consumed from external entities.

In 5G-PICTURE, the TSON features such as time slice size, overhead size, and frame size are directly controllable and configurable for the network slicing. The TSON nodes are located in the same network to remain the same configurations as the TSON needs to operate in a synchronised manner with identical attributes. The attributes are related to the overhead considered for time slice, the frame size in the duration of time slices for data, and the number of time slices. Apart from the attributes, the operational information such as time slice allocation, header match, and switching information, are sent to the nodes to provision the TSON paths for different traffic flows.

The TSON nodes are abstract models for network virtualisation. For the network slicing, TSON features in 5G-PICTURE can be determined, which are parameters such time slice length, overhead, and frame duration. In the operation, TSON paths are established and updated where time slices are allocated to different flows at the ingress node, which are transparently switched in the TSON cores. An application between SDN controllers and network hardware infrastructure parses and maps the information passing between upper and lower layers in 5G network. For instance, in a scenario where a TSON node is split into three nodes, the application takes care of mapping between the layers to stay agnostic to this operation. Then, the network hardware infrastructure in the physical layer, such as FPGAs, is communicated to coordinate the TSON paths on the data plane.

4.1.2.2 Ethernet/IP transport

Up to now the way to slice the transport network in the MAC and the IP layers was relying on MPLS label tagging and VPN tunnelling, where each flow was identified with a specific label and/or transferred within a specific VPN tunnel. For each slice/flow, bandwidth was guaranteed in software, through packet classification and traffic rate limitation on each hop.

VPN solutions are used for the separation of routing table and address space information. Actually a VPN is used to construct an overlay network, with lack of control in the underlay network resource and path selection, while final performance is subject to competition between VPNs. Although it is suitable for non-critical and best-effort services, it cannot meet strict service performance requirements on per network slice basis. In practice VPN can only provide “soft slicing” and cannot meet critical service requirements.

In the light of network slicing VPN enhancements have recently appeared in order to provide dedicated network resources for each network slice, based on the slicing capability of the network infrastructure (e.g., nodes, links) and integration between overlay and underlay networks. Key requirements are guaranteed performance and isolation between different network slices and sharing when possible for services within the same slice.

Enhanced VPN solutions will rely on techniques like Segment Routing (SR) [73]. SR achieves source routing by steering packet through a list of Segment Routing Identities (SIDs). SIDs used to represent topological, service or other instructions. SR leverages the source routing paradigm. An ingress node steers a packet through an ordered list of instructions, called segments. Each one of these instructions represents a function to be called at a specific location in the network. A function is locally defined on the node where it is executed and may range from simply moving forward in the segment list to any complex user-defined behaviour. Network programming consists of combining segment routing functions, both simple and complex, to achieve a networking objective that goes beyond mere packet routing.

On the Ethernet level hard slicing solutions by means of slice performance isolation have recently appeared like Flex-E. Flex-E technology is running on top of OTN-WDM and is able to provide Ethernet services, where multiplexing of users is done in time. Essentially every Flex-E Ethernet client can exploit a hard-pipe over bonds of PHYs with guaranteed performance. Time multiplexing between client groups is performed in a layer between the MAC and the Physical Coding Sublayer (PCS). PCS is part of the PHY and performs auto-negotiation and coding such as 8b/10b.

Regarding the Flex-E standardisation activities OIF is providing the implementation agreements for the Flex-E data plane and IETF for the Flex-E control plane. On January 2015, the project was setup in OIF; while IA1.0 was published on March 2016. In [74] IETF presents the primitives for a GMPLS solution on the control plane, while potential impact is expected based on the work in Common Control and Measurement Plane (CCAMP). This is relevant with the understanding of the Flex-E technology and the relevant use cases, requirements, architecture, extensions to RSVP-TE to establish signalled FlexE channels, PCE operations, support for Deterministic Ethernet (DetNet) and routing algorithms support (Open Shortest Path First (OSPF), Intermediate System to Intermediate System (IS-IS)).

4.1.2.3 Wireless transport

The support for advanced traffic management features like slicing on wireless transport technologies deployed at the edge of the network is rather limited. Traditionally, wireless bridges have acted as edge Ethernet devices, supporting features such as MAC learning, QinQ to differentiate between customer and service VLANs, and the ability to configure pre-provisioned QoS profiles according to the VLAN priority bits, Differentiated Services Code Point (DSCP) bits or MPLS Experimental bits (EXP). These QoS profiles act at layer 3, hence applying priorities or traffic profiles on the packets transmitted over the RF interface, but are not able to provide a guaranteed data rate, as may be required for hard slicing.

The ETSI white paper on crosshauling [75] introduces requirements for slicing transport networks. In the wireless transport a 5G compliant slicing solution should fulfil the following requirements:

- A programmable data-path allowing for a flexible definition of QoS classes, for example using interfaces like OpenFlow or NETCONF. Such programmable data-plane would allow an operator to define QoS classes in a flexible manner. For example, instead of having all QoS classes defined with VLAN IDs, you could define QoS classes using the GTP Tunnel Endpoint Identifier (TEID) field typically used in mobile network, or any other field of interest. The key technology to provide this data-path flexibility is the use of software based switches, such as Open vSwitch [76], on ARM based platforms typically used by wireless bridges. Software base data-paths have been proven to sustain more than 1 million packets per second (Mp/s) data rates [77], which are sufficient at the edge of the network.
- Ability to provision end to end paths over the wireless transport using an external control plane, i.e., an SDN controller. The SDN controller should expose high level REST interfaces that allow to integrate this control functionality with additional support systems, e.g., an infrastructure controller in an NFV ETSI-MANO deployment, or a hierarchical multi-domain control plane. This SDN control would also host the intelligent traffic management algorithms, which could then be easily customised by the operator. An example intent-based interface for wireless transport, and traffic management algorithms, has been developed in the 5G-XHaul project that instantiates unidirectional end to end paths between wireless bridges [78].
- Expose standard SDN management interfaces, like those defined by the wireless transport group at the ONF [79]. This interface defines a common data-model using YANG and NETCONF, which can be integrated in a multi-vendor SDN controller.

Providing deterministic data-rate guarantees in wireless networks is difficult due to the varying nature of the wireless medium. However, wireless transport links should enjoy higher stability to favour at least soft data-rate guarantees. A practical alternative for wireless links is to provide hard guarantees on the actual time-frequency resources allocated to each slice. To accomplish this enhanced isolation mechanisms are needed that use cross-layer schemes to bind the QoS class scheduler at layer 3 with the resource allocation mechanisms operating at layer 2. This feature is critical, especially in point to multipoint technologies, where different paths may be subject to different RF conditions, resulting in a different amount of RF resources being consumed to sustain the same data rate across different paths. A preliminary airtime based scheduler that allocates pre-defined shares of the airtime resource to virtual interfaces, associated to different slices in 802.11 based wireless transport, has been defined in [80].

4.1.2.4 Programmable dataplane for network slicing

Today's networks, with their "one-size-fits-all" architectural approach, are unable to directly address the diverging performance requirements of the envisioned 5G network slicing. Recently Network softwarisation has been proposed as a potential enabler for accomplishing this. Technologies like SDN and Network Functions Virtualisation (NFV) have been identified as the key elements to provide the programmability, flexibility, and modularity that is required to create multiple logical (virtual) networks, each tailored for a given use case, on top of a common network [81]. A description of a network slicing architecture based on the Open Networking Foundation (ONF) vision has been presented in [82]. The SDN architecture discussed in [82] has an intermediate control plane that dynamically configures and abstracts the underlying forwarding plane resources to deliver tailored services to different clients/applications. This efficiently provides a mechanism to satisfy a wide range of service demands in an agile and cost-effective manner, as required by the 5G network slicing approach.

In [83], an intermediate SDN controller is inserted between the multiple controllers of the network slices and the physical network infrastructure. This intermediate controller slices the OpenFlow network by intercepting all the OpenFlow-protocol messages sent by the switches to the controllers and forwarding them to the correct controller accordingly to pre-defined policies. The mapping between network slices and packets' are realised with tagging mechanism that can use the VLAN id, the MPLS labels or QinQ tag stacking.

However, the above mentioned methods require that the underlying switching hardware is able to support the set of SDN functionalities used to provide the slicing (e.g., the selected tagging mechanism should be supported by all the switches in the network, or specific tag mapping nodes should be deployed), thus limiting the vendor independence of the physical network and preventing the actual widespread adoption of those methods.

Moreover, the dynamical nature of the network slicing approach creates a significant pressure on the SDN controller both in terms of throughput between the control plane and the dataplane and in terms of latency. The problem of latency in SDN rules update has been widely discussed in literature [84], [85], [86] and could represent a limiting factor of the SDN approach to network slicing.

Finally, an efficient slicing mechanism requires to deploy directly in the dataplane several network functions for fulfilling the slice requirements in terms of bandwidth, latency, scalability, reliability etc.

All the above mentioned limitations are mainly related to the static nature of OpenFlow-like SDN dataplanes. In fact, the control plane can configure the set of predefined packet headers to extract from a packet, the forwarding rules and can select the actions to apply to each packet. But cannot configure (program) the packet parser to manage new protocol stacks (e.g., a new encapsulation/tunnelling protocol), the sequence of ruleset against which perform the matching operation and cannot define new actions to apply to the packet.

This scenario is now changing due to the rise of new languages for dataplane programming, like P4 [87] and due to several proposals of hardware programmable dataplanes [88], [89]. In particular, [89] is the starting point of the architectural work done in WP3 about the Open Packet Processor (OPP). Readers interested in a detailed discussion about the OPP architecture and the comparison with other programmable dataplanes such as [88] can refer to Deliverable D3.1 of the 5G-PICTURE project [90]. Here we only underline that the OPP architecture is based on a per-flow stateful dataplane that is able to allocate for each flow a set of registers (called flow content) that represent the state associated to each flow. This stateful property not only simplifies the problem related to the communication with the SDN controller but also allows deploying directly in the dataplane complex network functions that are described in the form of Finite State Machine (FSM) [91].

4.2 Technical approach and KPIs

The overall technical approach takes into account the three main attributes for the new transport network as defined by the Third Network, MEF [92]. According to MEF:

- **Agile**: the service providers' operational environment need to be more agile to achieve accelerated time-to-market for new service introduction.
- **Assured**: the network as a service will provide consistent performance and security assurances.
- **Orchestrated**: dynamically and automatically service management of the entire lifecycle of connectivity services.

In all the technical approaches, we consider that slice specific SLAs need to be enforced. Furthermore, transport network orchestration will be in accordance with the technical approach of WP5 activities and will be on per slice basis.

5G-PICTURE explores a multifaceted technical approach regarding enabling network slicing in the transport network. One path considers bringing the required flexibility into the optical layer exploiting technologies like TSON. In higher layers we will investigate and advance solutions like Flex-E, built on top of OTN-WDM in order to decouple the MAC layer from the PHY and provide hard bandwidth guarantees on a per slice basis.

4.2.1 Optical transport network

5G-PICTURE has the goal to transport and to converge the data traffic from the various heterogeneous access networks. Our technical approach is based on the combination of ETSI NFV standard and SDN (Figure 26).

As described by Figure 26, the different VNFs deploying the various technologies can access appropriate PNFs via the optical TSON transport network to provide the end to end connectivity. To deploy the virtual networks on demand, the orchestrator selects the right VNFs and runs the corresponding instances. Also, after checking the different catalogues, it sends some instructions to the TSON SDN controller which indicates the end-to-end TSON resources necessary to form the suitable PNFs and provide end-to-end connectivity, the VLAN tag to set in order to identify the different network slices in the TSON network, and the different requirements of the physical link. The TSON SDN controller receives the instructions, calculates the path and configures the different TSON nodes to provide the end-to-end service. The notification of the allocated resources is sent from the TSON SDN controller to the orchestrator responsible to update the suitable catalogues.

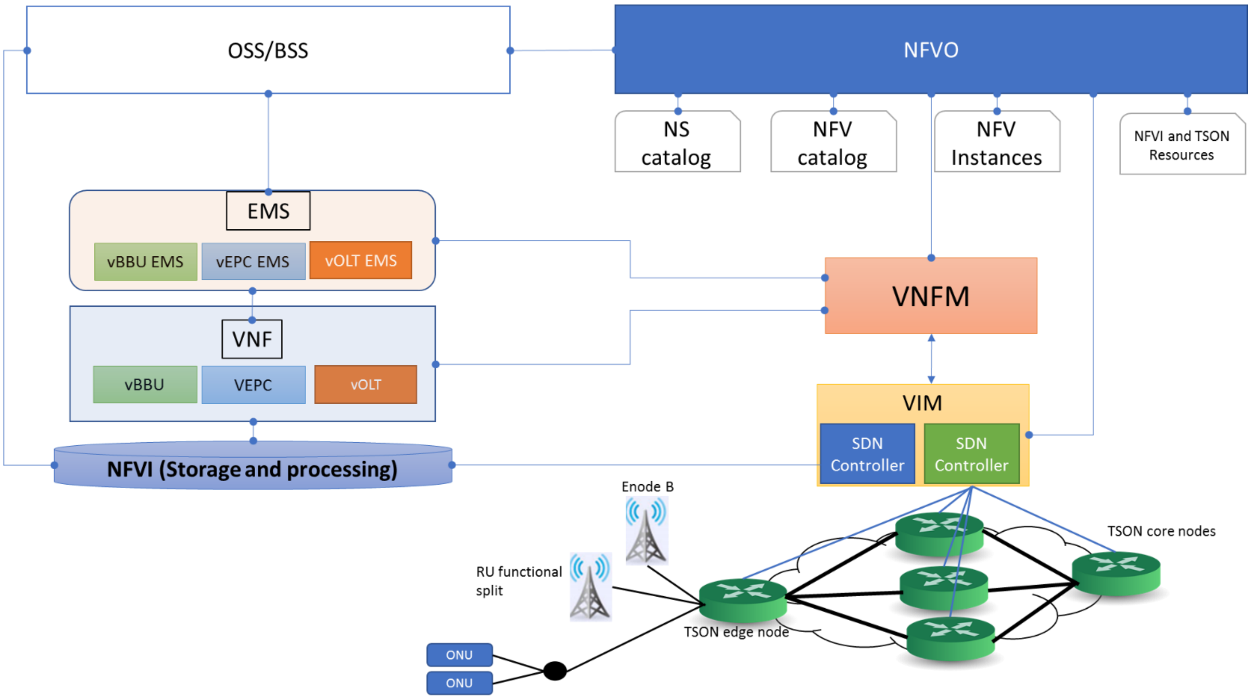


Figure 26: Technical approach based on ETSI NFV and SDN.

For this technical approach the considered KPIs are:

- Control plane:
  - The communication time between the orchestrator and the TSON controller.
  - The impact of the communication time between the TSON SDN controller and the TSON node on the latency following each technology.
  - The impact of the isolation of the network slice identified by a VLAN tag in the performance of the deployed network service. This impact can be measured in bit error rate, latency, and packet variation delay.
- Data plane:
  - The time slot allocation resources in terms of bandwidth.
  - Time slot duration.
  - Time slot number.

4.2.2 Ethernet/IP transport

The technical approach we are considering (see Figure 27) combines the notion of Interface Slicing (hard slicing) together with Logical Network Slicing (soft slicing):

- **Interface Slicing**: In 5G-PICTURE, we will investigate the Flex-E and the X-Ethernet technologies as a means to realize interface slicing and fast switching respectively. Flex-E will be investigated as a key technology that is able to split a physical interface into isolated sub-channels, decouple MAC rate from PHY rate and achieve “hard” bandwidth isolation. X-Ethernet technology introduces Ethernet PCS switching, eliminates table lookup and buffer queuing and will be investigated as a fast switching mechanism that is exploiting PCS layer relay.
- **Logical Network Slice**: Customised logical networks (VPN based) can be created based on the demand of service/tenant. Computation of network topology and the required resources for network slice needs to be allocated by the orchestration/management and control systems. These are also responsible to allocate sliced network resources from the network infrastructure, and associate dedicated resources with the logical network slice.

On one hand, Flex-E/X-Ethernet technologies provide the primitives for interface isolation and fast switching for extreme performance. On the top of the end-to-end pipe that Flex-E is able to construct, we will investigate the way to build virtual networks (like VLAN or enhanced VPN solutions base) on a per slice basis. Note that the enhanced VPN solutions require network information collection, which will be implemented through the Segment Routing (SR) technique recently proposed in IETF [73]. Using segment identifiers to represent reserved links and node resources for the slice, we are able to construct sliced networks that are using explicit routes and realize end-to-end policies without creating any per-flow state in the network.

4.2.3 Wireless transport: Multi-tenant small cells with integrated access and backhaul

5G-PICTURE aims to develop novel technologies that support the massive deployment of outdoor small cells required to fulfil the 5G promises on capacity. In this regard, 5G-PICTURE puts forward the concept of multi-tenant small cells with Integrated Access and Backhaul (IAB) support.

Figure 28 provides a description of our target technology, whereby a neutral host or infrastructure operator, e.g., the 5G-PICTURE operator, deploys small cells mounted on street furniture or lamp-posts. In order to reduce deployment costs, these small cells support both access functionalities, to connect to client devices, and wireless transport functionalities, to create a small multi-hop network until nearby fibre drops (Fibre Point of Presence (PoP). Small cells connected to a Fibre PoP are hereafter referred to as gateways. Using a software-based management and control plane, the 5G-PICTURE operator is able to dynamically instantiate slices for its customers, e.g., MNOs. In this scenario, a slice is defined by the following parameters: i) the physical small cells where the tenant wants to instantiate “access presence”, meaning that a virtual radio instance is created on the small cell representing that tenant (e.g., SSID in 802.11 or PLMN ID in 3GPP), ii) the set of gateway devices that instantiate a tunnel interface to transport the tenant traffic to its home network, and iii) parameters related to the QoS treatment that this tenant’s traffic receives when being forwarded through the wireless transport.

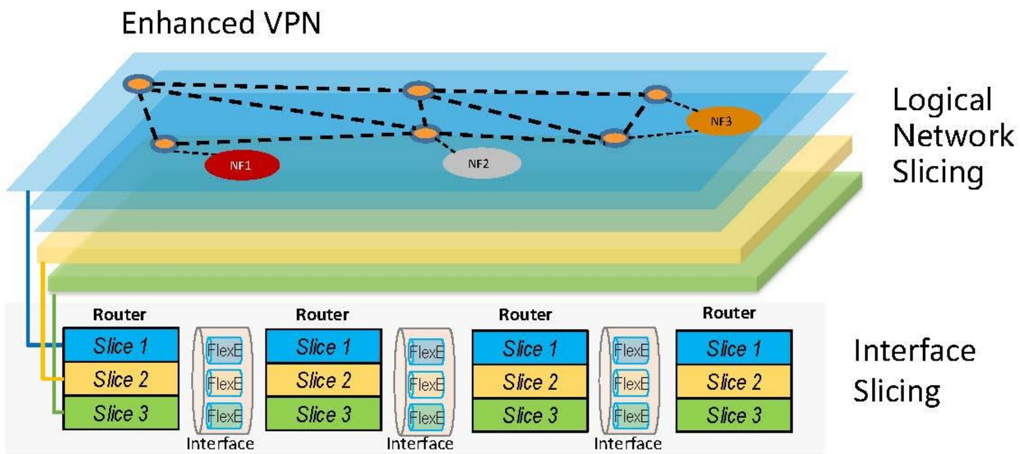


Figure 27: Interface and logical network slicing: virtual networks are operating on top of Flex-E X-Ethernet used for the fast pipes.

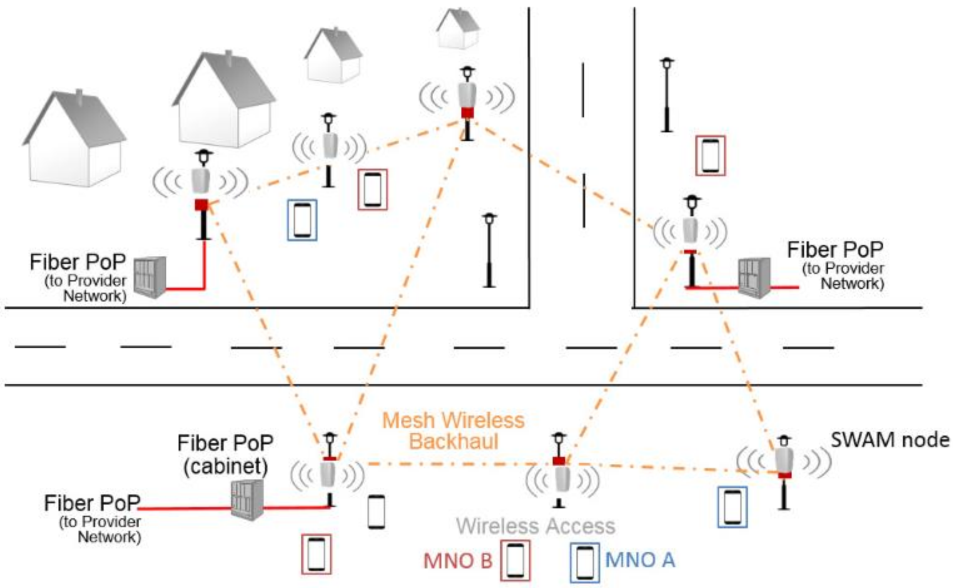


Figure 28: SWAM to 5G-PICTURE or small cell.

Summarising, the proposed technology will allow a 5G-PICTURE operator that manages a small cell deployment in an urban scenario, to dynamically instantiate virtual networks on behalf of its tenants (i.e., MNOs). The MNO's customers will be able to discover the virtual access network, connect to it without the intervention of the 5G-PICTURE operator, execute handovers between the tenant's virtual small cells, and have their traffic transported until the tenant's home network, where appropriate billing and services can be applied. It is worth highlighting that the 5G-PICTURE operator is completely transparent to the end-user who only has a business relation with the Mobile Network Operator (MNO).

The KPIs that will be used to evaluate the technologies that address this technical approach are the following:

- Control plane KPIs: e.g., backhaul reconfiguration time (ms) when the tenant's customer handovers between two small cells, link failure restoration time (ms) when an error occurs in the wireless transport, signalling overhead between small cells and software controller (bps).
- Overall network capacity: use of traffic engineering algorithms (e.g., load balancing), and other control plane mechanisms, to evaluate the aggregate capacity of the network (bps).
- Slice isolation: measuring the impact that concurrent traffic from different slices (tenants) have on each other. This KPI can be measured in terms of the percentage of degradation with respect to the agreed per-tenant SLA.

4.3 Technical components

In this section, we elaborate on the considered technical components that can be mapped to aforementioned technical approaches. Table 5 presents the mapping of technical components the project will focus on, in accordance to the technical approaches described in the previous section.

Table 5: Mapping between the technical components and the corresponding technical approaches.

Technical Components	Technical Approach
4.3.1 Time Shared Optical Network (TSON)	**4.2.1** Optical transport network
4.3.2 Flex-E **4.3.3** X-Ethernet **4.3.4** Segment routing for enhanced VPN **4.3.6** Open Packet Processing (OPP)	**4.2.2** Ethernet/IP transport
4.3.5 Solution based on IEEE 802.11 technologies, both for access and BH (802.11ac modems)	**4.2.3** Wireless transport

4.3.1 Transport Technical component 1: Time Shared Optical Network (TSON)

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. The FPGA platforms are based on Xilinx FPGA evaluation boards (156.25 MHz clock frequency), supporting multiple 10 Gb/s (for control and transport) DWDM Small Form-factor Pluggable+ (SFP+) transceivers. For the optical layer, TSON relies on fast optical switches 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 Data Centre (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 have 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 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. TSON allows handling of Ethernet frames, it natively supports a broad range of framing structures and communication protocols and has already been extended in the framework of 5G-XHaul to include CPRI and will be further extended in 5G-PICTURE to support the recently standardised eCPRI solution.

The TSON core nodes switch transparently optical frames to the appropriate output port. These nodes adopt the wavelength selective architecture and as such require one switch per wavelength, to direct the incoming optical frames 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 control of the fast optical switch. The FPGA Look Up Tables (LUTs) are filled from the control plane, through customised Ethernet communication carrying information regarding the configuration of the fast optical switch in order to establish and maintain optical paths across the TSON domain. The basic functions for the operation of the TSON domains have been implemented in internal modules, within the SDN controller, that cooperate together to achieve on-demand provisioning of connectivity between TSON core and edge nodes. Overall, the TSON network offers a hierarchy of three levels of resource granularity: connections, frames, and time-slices, as illustrated in Figure 29.

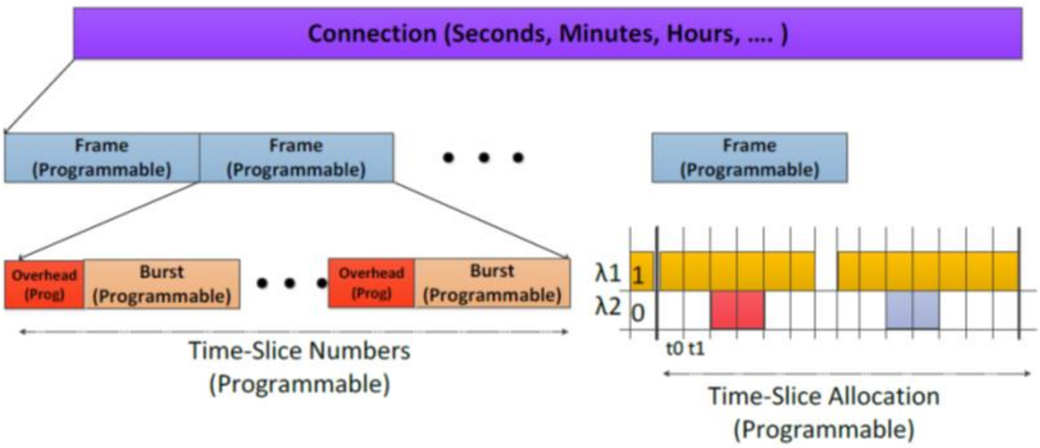


Figure 29: TSON frame structure.

4.3.2 Transport Technical component 2: Flex-E

Flex-E technology is introduced as a thin layer (called Flex-Shim) between Ethernet MAC and PCS and is able to support multiple MAC clients over multiple PHY layers. The idea is that through Flex-E, the MAC layer speed of a client can be decoupled by the actual PHY layer speed. Flex-E functionality is based on a time-division multiplexing mechanism that is able to drive the asynchronous Ethernet flows over a synchronous schedule over multiple PHY layers.

Flex-E Terminology:

- **Flex-E Client**: A Flex-E client is an Ethernet flow based on a MAC data rate that may or may not correspond to any Ethernet PHY rate. The MAC rates supported in OIF v1.0 implementation agreement are 10, 40, and multiples of 25 Gb/s.
- **FlexE Group**: refers to a group of Ethernet PHYs that are bonded together. OIF IA v1.0 supports FlexE groups composed of one or more bonded 100GBASE-R PHYs. Higher rates like 400GbE are under development in the IEEE P802.3bs project and will be supported in future Flex-E releases.
- **FlexE Shim**: is the layer where the mapping or de-mapping of Flex-E clients over a Flex-E group is made. This procedure is based on a calendar-based slot scheduling. Essentially a set of slots is assigned to each client, according to the MAC layer speed and the group participation.

Currently there are three use cases defined. These depend on the way MAC layer speed is related to the PHY speed (higher or lower) or the way clients are multiplexed in time. As depicted in Figure 30, these are bonding, sub-rating and channelisation.

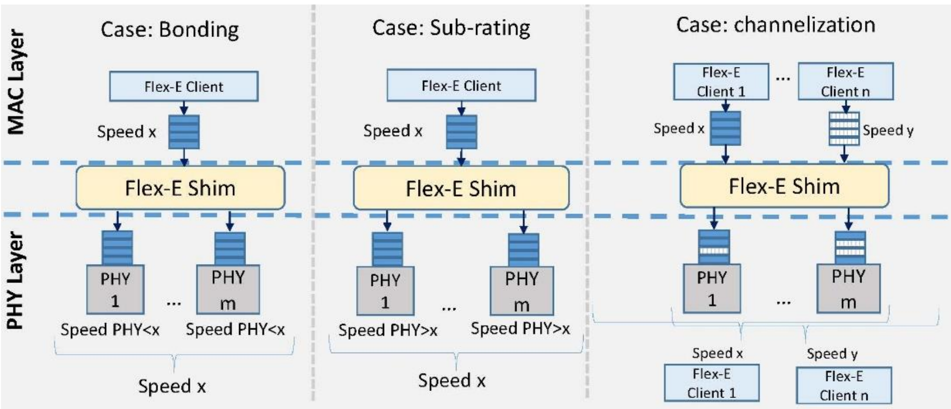


Figure 30: Flex-E use cases.

- **PHY bonding:** MAC layer speed is higher than the actual PHY. Multiple PHYs are grouped to serve the flow.
- **PHY sub-rating:** MAC layer speed is less than the actual PHY. Multiple PHYs are grouped to serve the flow.
- **Channelisation:** Multiple Flex-E clients share a Flex-E group through time division multiplexing in the Flex-Shim.

These options allow increased flexibility towards 5G, since depending on the use needs Flex-E is able to fine-tune the path for a specific slice and handle dynamicity in a level that is very close to the physical layer.

Flex-E introduces a Flex-E Shim layer that is responsible for the mapping of Flex-E clients (Ethernet flows) to groups of PHYs. From a layering perspective Flex-E Shim is introduced between the Ethernet MAC and the PCS sublayers (as depicted in Figure 31).

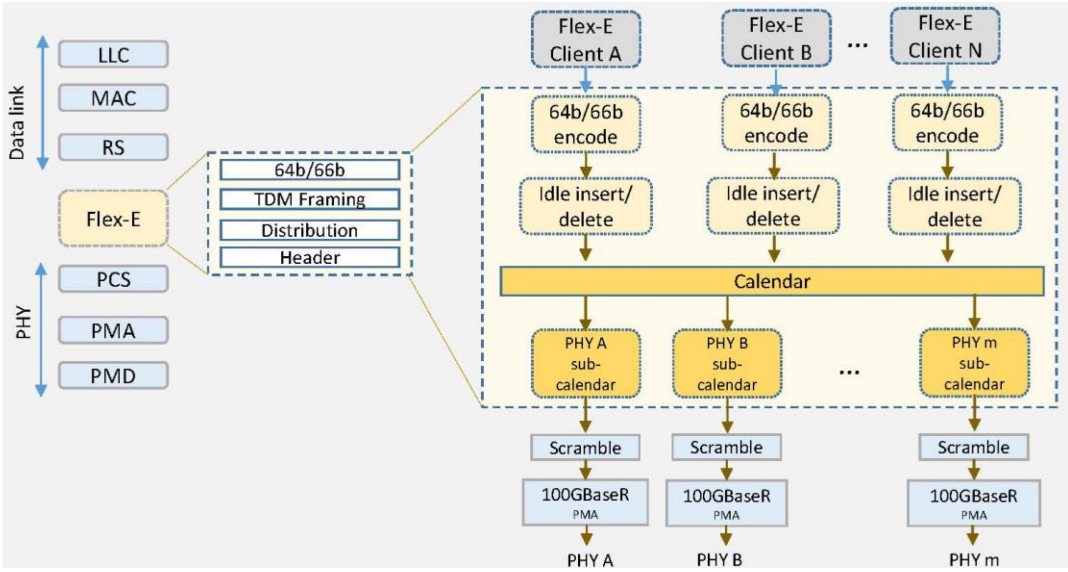


Figure 31: Flex-E layer between Ethernet MAC and PCS. Additional FlexE Shim distribute/aggregate sub-layer in PCS/PMD (Physical Media Dependent).

Our work in the context of the WP4 activities is related to the establishment of Flex-E multi-hop paths with the end-to-end synchronisation. Note that existing solutions consider for a pre-configured Command Line Interface (CLI)-based Flex-E group configuration and client assignment. A Flex-E testbed will be also provided for the project purposes. Another dimension of our research is related on the way FLEX-E will be used to support logical network slices with enhanced VPN support.

4.3.3 Transport Technical component 3: X-Ethernet

According to the layered architecture illustrated in Figure 32, L3 includes switching technology like IP, L2 switching technology like Ethernet and L1 switching technology like OTN/SDH. As illustrated in Figure 32, the higher layers provide statistical multiplexing but suffer from large forwarding latency. As mentioned in section 2, 5G-PICTURE incorporates also Ethernet-based technologies. X-Ethernet has a native Ethernet core, and is Ethernet friendly.

X-Ethernet's interface is an extension of Flexible-Ethernet's basic concepts, such as Flex-E clients, groups, calendars, etc., have no difference. Several new functions have been added into X-Ethernet to enable finer granularity and multiservice. To avoid synchronisation message loss, a marker could be used to instruct of original data stream and locate in an appropriate location.

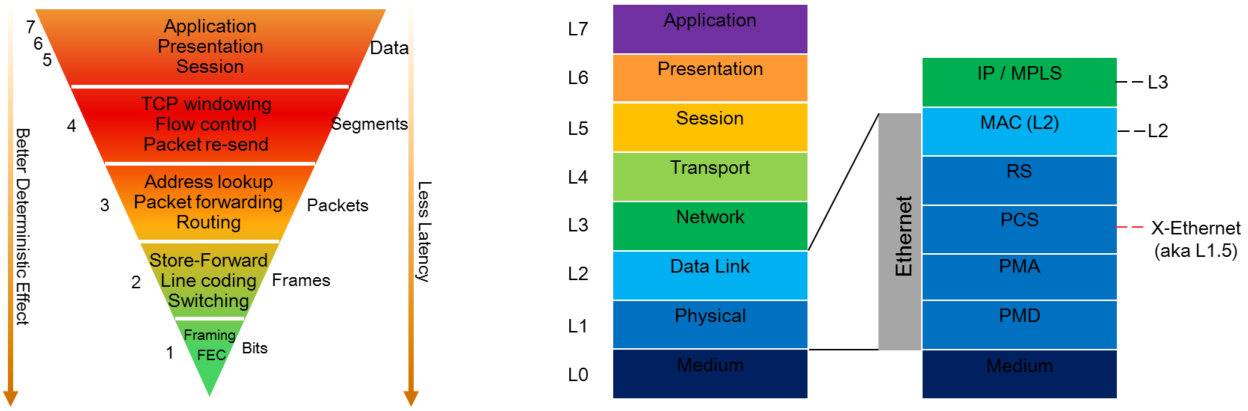


Figure 32: Forwarding latency of different layer.

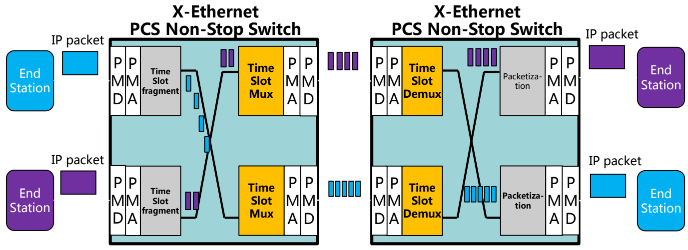


Figure 33: X-Ethernet PCS NSS switching mechanism.

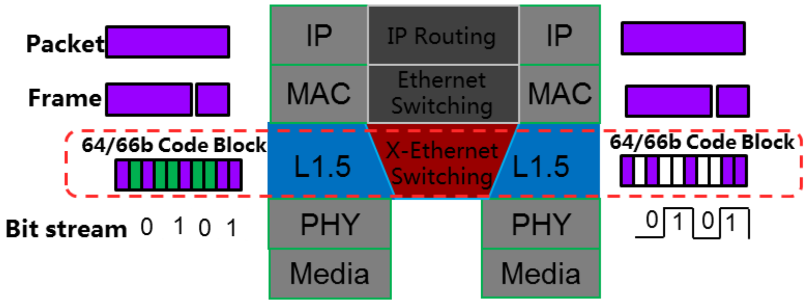


Figure 34: Multiple forwarding layer in one device.

X-Ethernet introduces Ethernet PCS switching based on the interface offered by Flex-E. The switch device redirects data units (e.g., 64B/66B block streams) from its inbound port to its outbound port without waiting for the arrival of the whole Ethernet frame for FCS checksum and forwarding decision with table lookup. Therefore, all time consuming procedures, such as encapsulation/decapsulation, queuing and table lookup, can be removed. PCS switching is also referred to as PCS Non-Stop Switch (NSS). The remaining procedure processing time is predictable, which results in deterministic device latency. Idle insertion or deletion according to IEEE 802.3 may be performed to rate-adapt Flex-E Client to the Flex Group. A schematic view of PCS NSS is depicted in Figure 33. In addition, X-Ethernet PCS NSS mechanism is independent of evolving ingress physical interface (e.g., CPRI, IB, FC, etc.) and codec technologies (8B/10B, 64B/66B, etc.). The X-Ethernet NSS switching device will forward Flex-E Clients or decoded general frame/packet data units from its ingress port to its egress port.

Thanks to X-Ethernet, the NSS switching mechanism could provide multiple forwarding layer in a same device. Figure 34 shows that IP Routing, Ethernet switching and X-Ethernet switching can be integrated in a same device.

In the context of WP4 activities, X-Ethernet technology will be investigated (through simulations, emulations, or implementations as a means to perform fast PCS switching. The technical approach on how it can be also integrated to the overall 5G-PICTURE will be also described.

4.3.4 Transport Technical component 4: Segment routing for enhanced VPN

Segment Routing (SR) is an architecture based on the source routing paradigm that seeks the right balance between distributed intelligence and centralised programmability. SR can be used with an MPLS or an IPv6 data plane to steer packets through an ordered list of instructions, called segments [73]. SR achieves source routing by steering packet through a list of segments (SIDs), where SIDs are used to represent topological, service or other instructions.

A segment may be associated with a topological instruction. A topological local segment may instruct a node to forward the packet via a specific outgoing interface. A topological global segment may instruct an SR domain to forward the packet via a specific path to a destination.

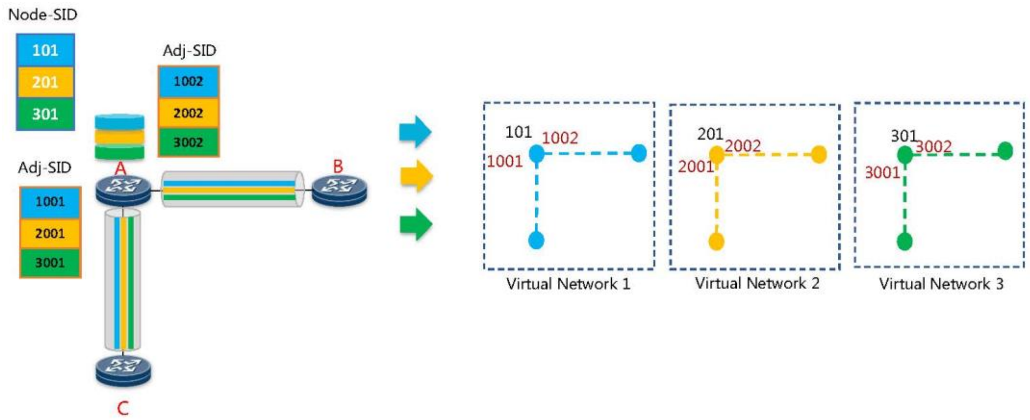


Figure 35: Segment routing primitive operation.

SR enables advanced features like Service Function Chaining (SFC). A Service Function (SF) may be a physical appliance running on dedicated hardware, a virtualised service inside an isolated environment such as a virtual machine (VM). SR enables SFC by assigning a segment identifier, or SID, to each SF and sequencing these service SIDs in a segment list. A service SID may be of local significance or directly reachable from anywhere in the routing domain. The latter is realised with SR-MPLS by assigning a SID from the global label block [93], or with SRv6 by advertising the SID locator in the routing protocol [94].

Our work in 5G-PICTURE will focus on the way segment routing is able to enable network slicing concepts for the transport network and support enhanced VPN solutions. For example, currently there is no mechanism to implement actual resource reservation with SR. For network slicing, SR needs to be extended to support slice based resource reservation. This is also related to the slice-based path computations that can be constructed using different set of SIDs. Slice path computations require information regarding the slice topology and the network resources needed and slice based resource allocation by means of link/nodes. Other open issues that we plan to investigate are related to the mapping of VPNs to a sliced SR network, where in the case of N:1 mapping, multiple VPNs can share the same slice, while still being isolated from services in other slices.

4.3.5 Transport Technical component 5: Involved technical approach and KPIs

This technology component relates to Technology Approach mentioned in Section 4.2.3 on multi-tenant small cells with integrated access and BH.

The designed solution will be based on IEEE 802.11 technologies, both for access and backhaul. The reference platform will be developed in WP3. This platform integrates various IEEE 802.11ac modems in an outdoor enclosure. The embedded radios will be used for backhaul and access purposes according to the chosen configuration. The requirements for the designed solution are the following:

- **R1**: Integrated Access and Backhaul: The Wi-Fi small cells will provide wireless access to the customers of each MNO, but will simultaneously support wireless connections to each other (mesh) to avoid the need of a wired backhaul.
- **R2**: The 5G-PICTURE operator managing the network will be able to manage by software the lifecycle of new tenants over the infrastructure.
    - Virtual APs will be instantiated on the physical Small-Cells to represent each tenant.
- **R3**: The 5G-PICTURE operator will be able to offer a wireless slice to each tenant. For each slice the 5G-PICTURE operator will be able to specify:
    - The physical small cells where a given tenant wants to have presence
    - The physical small cells that have a wired connection, over which the traffic from this tenant customers' is allowed to be carried
    - The home network of the tenant where the traffic from its customers has to be delivered
- **R4**: The instantiated wireless slices will provide mobility support, i.e., customers of an MNO will be able to move and handover between wireless APs as long as they have coverage. The wireless backhaul network will be reconfigured accordingly to direct each customer packets towards the proper physical small cell.

- **R5**: The 5G-PICTURE operator should be able to flexibly control the mapping between access traffic and wireless backhaul resources. It should also be able to implement Traffic Engineering (TE) mechanisms on the wireless backhaul.

The proposed technology component will be mostly evaluated in terms of control-plane related KPIs, including:

- **K1.** Handover interruption time when a tenant customer moves from one virtual AP to another one or when the control plane reconfigures the network (e.g., gateway relocation), measured in ms.
- **K2.** Number of rules kept in the software data-path, i.e., per-tenant state, measured in scalar units.
- **K3.** Network performance in terms of overall goodput carried by the network measured in bps. The performance of this KPI depends on the supported Traffic Engineering functions
- **K4.** Tenant isolation properties, measured in terms of the impact that traffic from one tenant has on the performance of another tenant, measured in goodput (b/s) and delay (ms).
- **K5.** Service provisioning time, measured on the time required by the 5G-PICTURE infrastructure provider to instantiate a slice for a new tenant.

4.3.5.1 Initial design and technology innovation

Figure 36 depicts an initial design for the proposed solution. In the figure a set of wireless nodes, referred to as *s_i*, instantiate per-tenant virtual Access Points (vAPs), depicted with a coloured triangle, per-tenant tunnel interfaces, depicted with a coloured circle, and common backhaul interfaces, depicted with a dark square. Per-tenant client devices connect to their corresponding vAP and have their traffic forwarded until the tenant's Home Network, which also provides IP address allocation. The 5G-PICTURE wireless controller manages the access and transport functions in the multi-tenant wireless nodes.

The main design principle of the proposed system is a separation between the control planes of the wireless access and the wireless backhaul network. The wireless backhaul is comprised of a set of transport tunnels that carry packets between each pair of wireless nodes *s_i* and *s_j*. The actual path followed by these tunnels is defined by a backhaul module running on an SDN controller, depicted as "Backhaul module" in Figure 36. In our case, we build on a solution developed within the 5G-XHaul project to control wireless small cell backhauling [78]. This solution has the following characteristics:

- The SDN controller is based on OpenDaylight [95], and the southbound interface is based on OpenFlow.
- Transport tunnels are unidirectional, and they are uniquely identified with a VLAN tag. This VLAN tag is unique to the control plane area controlled by a controller instance.
- OpenFlow is extended with custom port statistics to communicate wireless specific parameters to the SDN controller, e.g., channel load observed by each radio interface.
- Traffic engineering algorithms optimize the path followed by each transport tunnel. Algorithms have been proposed that take interference into account between wireless nodes into account. The interested reader is referred to [96].
- A REST based north-bound API is available in the controller to instantiate end-to-end transport tunnels on demand (http://docs.5gxhaul.apiary.io/)

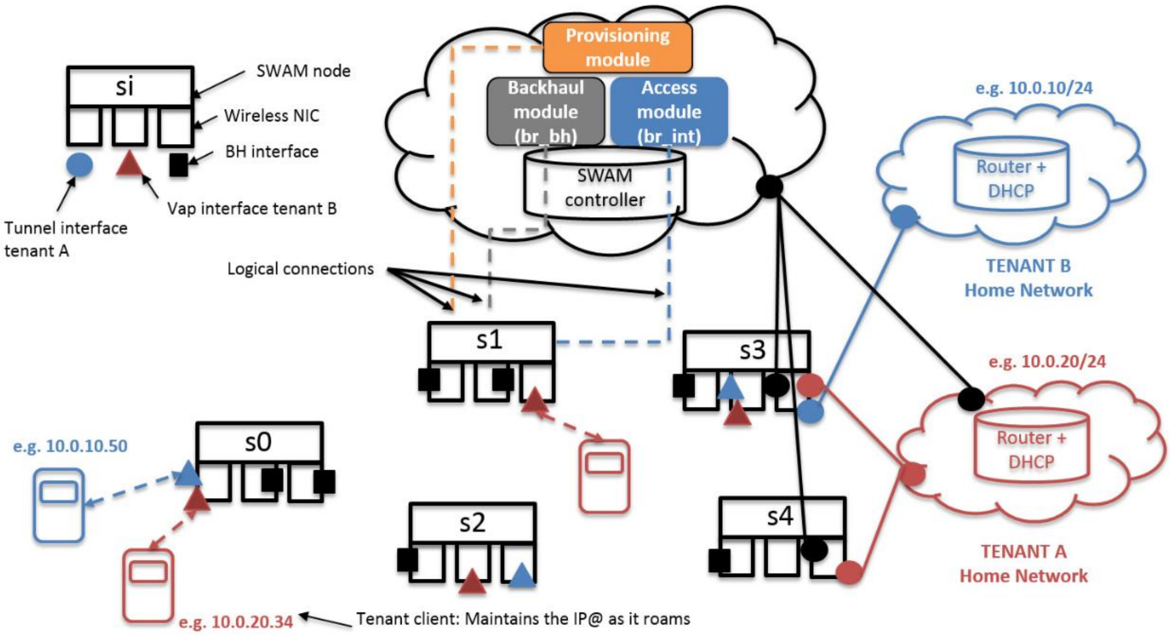


Figure 36: 5G-PICTURE wireless controller.

On top of the 5G-XHaul wireless BH solution described above, this technology component consists of a novel software data-plane and associated control plane, which runs on the same wireless nodes, i.e., *s_i* in Figure 36, and implements the following functionality:

- Connects and multiplexes the per-tenant virtual AP to the transport tunnels
- Supports mobility, whereby when a tenant customer moves from one virtual AP to another, packets are appropriately redirected within the wireless backhaul
- Supports multi-gateway deployments, whereby traffic from a single tenant can be connected to the wired network through multiple gateways, in order to balance traffic over the wireless backhaul.

We briefly introduce here a preliminary design of the software data-path for this technology component. A detailed design including the control plane, and an evaluation will be included in the upcoming 5G-PICTURE deliverable D4.2.

The software data-path is illustrated in the left part of Figure 37 and consists of three back-to-back software bridges. The bottom bridge, known as the backhaul bridge or *br_bh*, is controlled by the backhaul module in the controller, and its function is to forward transport tunnels, i.e., its populated with rules of the form "*vlan=TUNNEL_ID, action=output:N*". At the top of the data-path we have a per-tenant software bridge that connects all the local virtual interfaces that belong to a given tenant, i.e., all the virtual APs and home network tunnels for a given tenant instantiated on the wireless node. In addition, the per-tenant access bridges have a virtual interface representing all the other physical wireless nodes where this tenant has instantiated a virtual interface. For example, the access bridge depicted as "bridge B" in the left part of Figure 37 has tree south-facing virtual interfaces representing direct connections to the physical wireless nodes s1, s2 and s3. Thus, the access bridge implements standard data plane MAC learning, maintaining the state of where (what physical node) other customers of this tenant are connected to. Finally, an integration bridge, referred to as *br_int*, maps the south-facing virtual interfaces stemming out of each per-tenant access bridge to the corresponding transport tunnel, and vice-versa. Notice that this architecture easily allows to enforce per-tenant QoS related policies, by mapping traffic from different access bridges to different transport tunnels.

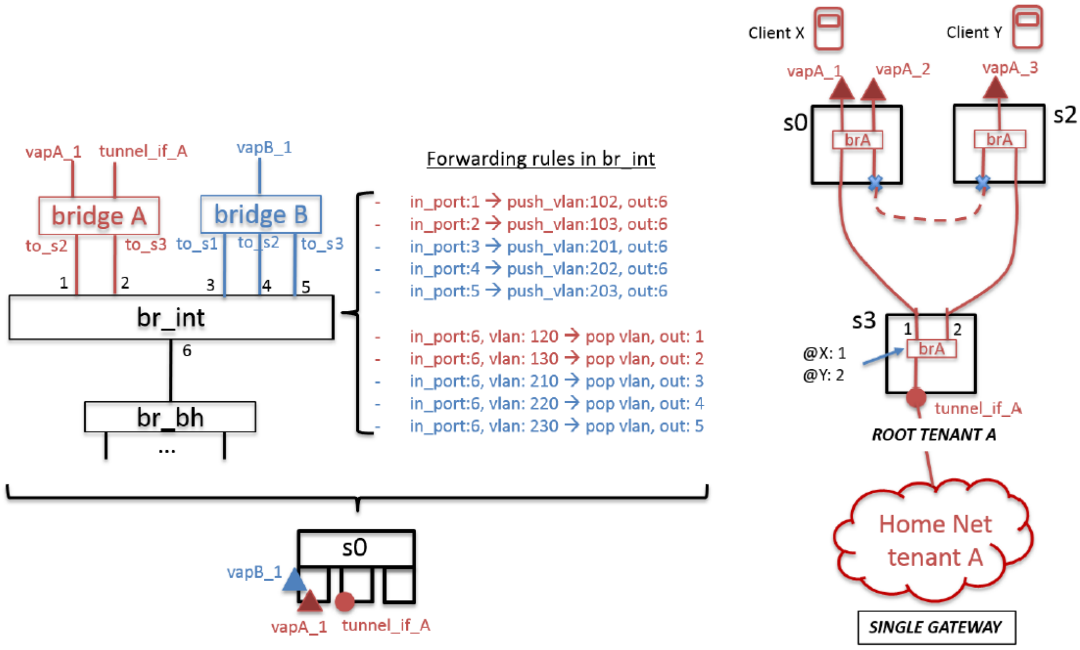


Figure 37: Proposed software data-path (left) and resulting per-tenant network (right).

The right part of Figure 37 depicts the resulting logical view of the network from the perspective of the red tenant. The overlay network results in a set of connected access bridges, which implement data-plane based MAC learning. Hence, a control plane is required to avoid loops in this architecture. Our preliminary design consists in having the control plane proactively avoid loops, by forcing the leaf nodes to have a single active interface that connects to a root node, where the root node is a physical device with wired connectivity that has a tunnel with the home network for that particular tenant. This architecture though, forces all traffic from one tenant to exit the wireless network through the same root device, which may result in congestion in the wireless backhaul. In deliverable D4.2, we will propose control plane extensions to support multiple gateway nodes, hence allowing to better balance the traffic within the wireless network.

4.3.5.2 Expected outcomes

The work required to develop this technology component will consist of software development to implement the software data-path and associated control plane described in the previous section. The presented data-path will be developed using the Open vSwitch software switch [76], and the control plane components will be developed on OpenDaylight [95].

The work on this technology component leverages work on WP3 and WP5, in the following way:

- The wireless nodes described in this section will be prototyped using the Gateworks platform developed as part of WP3 to support joint access and backhaul. The NETCONF interface and YANG models developed in WP3 will also be used to implement the management plane that allows to instantiate virtual APs on demand.
- This technology component will also interact with WP5 in the following way. The control plane defined in this technology component, allows to instantiate a slice for a tenant, defined as a set of virtual vAPs for a particular tenant, and the corresponding mappings between these vAPs and the aforementioned transport tunnels to carry tenant traffic to their correspondent home network. In WP5 this definition of slice will be "packaged", by defining a descriptor, e.g., based on Topology and Orchestration Specification for Cloud Applications (TOSCA) [97], which will allow the Orchestrator defined in WP5 to instantiate per-tenant slices on demand.

Finally, these developments will be demonstrated firstly on an in-house wireless testbed, and the NITOS testbed in Task 6.2 will be used to evaluate more complex network topologies.

4.3.6 Transport Technical component 6: Open packet processing

Two technology components are developed that will permit to enhance the programmability of the datapath of the transport nodes. The two components are i) OPP, the Open Packet Processor and ii) PMP, the packet manipulator Processor. OPP is a programmable pipeline with stateful functionalities that is able to offload from the control plane many network functionalities. PMP is a Very Long Instruction Word (VLIW) CPU tailored to perform operations on network packets. Figure 38 depicts the main processing elements of the OPP/Packet Manipulator Processor (PMP) technology components.

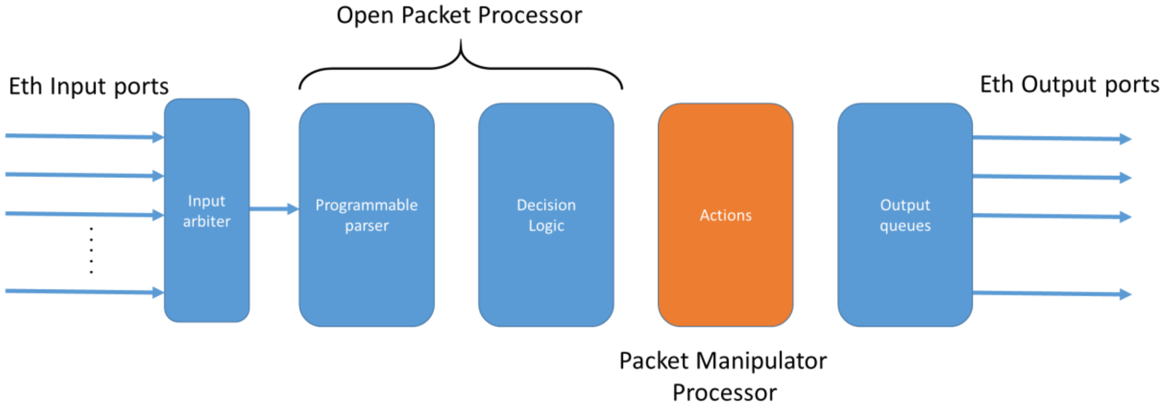
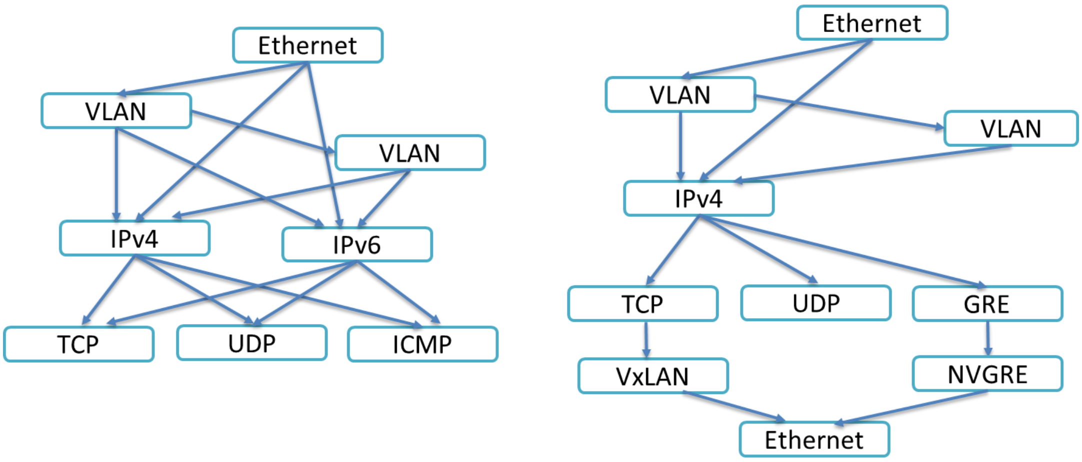


Figure 38: OPP/PMP Initial architecture design.

The main blocks composing the OPP/PMP technology components are:

- The **input arbiter** that takes packets from multiple input ports: as stated in Section 2.2 in the transport network the Ethernet technology is widely adopted and is going to be ubiquitous. Therefore, we designed OPP/PMP for a scenario in which all packets are Ethernet encapsulated. The input arbiter collects packets for different ports and brings them inside the programmable pipeline. We plan to make the input arbiter programmable to provide different processing features (latency, jitter, etc.) for each input port.
- The **programmable parser**. This functional block process the incoming packets depending on the packet header graph to extract the relevant fields that will be used to take decisions on the packet (forwarding, encapsulate/decapsulate, QoS, etc.). An example of two different parsing graphs is depicted in Figure 39. It must be noticed that this is a key element of the OPP/PMP technologies for 5G-PICTURE since it allows managing the different protocols encapsulated inside the common carrier Ethernet layer. We will exploit the P4 language functionalities (see deliverable D3.1 [90]) to program the programmable parser.
- The **decision logic**. This is the core of the OPP technology component. The decision logic is composed by a pipeline of OPP stages (see deliverable D3.1 [90]) that perform a per-flow stateful analysis of the processed packet and take the decisions to apply to the packet. We remark that the stateful analysis is performed directly in the dataplane, providing a low latency and low communication overhead with SDN controllers. This feature will enable the development of network functionalities such as load balancing and QoS directly in the network node.
- **Programmable Actions.** This functional block is specular to the packet parsing, since it is in charge to rebuild the packet starting from the packet header fields extracted by the parser. This corresponds to perform different encapsulation/decapsulation operations depending on the decisions (e.g., to which output port forward the packet) taken by the decision logic. Due to the heterogeneity of the network, and in spirit of enhancing the programmability of the network, we focused on programmable action functionalities able to concurrently manage different encapsulation/decapsulation schemes. Since the programmability of this functionality can be really demanding in terms of processing requirements we are developing PMP as an ad-hoc Very long instruction word (VLIW) processor tailored to provide flexible packet manipulation tasks at high speed.



(a) enterprise. (b) Data center.

Figure 39: Example of two different parsing graphs. In the specific example case a) is an enterprise network, while case b) is a data centre network.

The technology component is controlled by the local microcontroller. This microcontroller works also as an OpenFlow-like agent that interacts with an external SDN controller for the configuration of OPP/PMP. In particular, the agent implements the following functionality:

- Receive from the external SDN controller the configuration of the network node and consequently update the configuration of the programmable pipeline.
- Query the state registers of the programmable pipeline to retrieve the status of the network node.
- Send to the external SDN controller messages when specific events occur (for example to signal network anomalies or link failures).

While in WP3 the hardware blocks composing the OPP and PMP technology components will be developed, in WP4 CNIT will focus the work on exposing the programmability of OPP/PMP using the agent to communicate with the OpenFlow-like controller. Since OPP/PMP are currently under development, this work will closely intertwine with the work done in WP3. The OPP/PMP technologies will be implemented on FPGA board and the corresponding control software will be developed. The outcomes of the design effort will be demonstrated both with an ad-hoc testbed that will be used also for debugging and verification purposes, and with one of the testbeds that will be defined in Task 6.2 to evaluate the effectiveness of OPP/PMP with more complex network topologies.

4.3.7 Technical component KPI targets

Table 6 summarises the KPI targets that are aimed to be achieved by the technical components discussed in this section.

Table 6: Summary of KPI targets for the transportation network technical components.

	TSON	Flex-E	X-Ethernet	OPP	Segment routing	Small Cells with IAB
MAC rate/PHY rate decoupling availability	N/A	YES	N/A	YES (Basic)	N/A	N/A
Slicing optical transport	YES	N/A	N/A	N/A	N/A	N/A
Slicing packet transport	N/A	YES N*2 Gb/s granularity	YES	Partially	YES	YES
Slicing wireless transport	N/A	N/A	N/A	N/A	N/A	YES
Programmable transport functions	YES	YES (Basic)	YES (Basic)	YES	YES	YES
Slice provisioning time	< 1 min	N/A	N/A	< 1 min	< 1 min	< 10 s
Delay	<160 μs latency, <25 μs jitter	<10 ms (load dependent)	Ethernet Switching in ns level	N/A	<10ms (load dependent)	5 ms
Handover time	N/A	N/A	N/A	N/A	N/A	< 30 ms
Recovery time	N/A	N/A	N/A	N/A	N/A	< 200 ms

4.4 Positioning in the overall 5G-PICTURE solution

In this section we analysed the state of the art for the transport network technologies and the network slicing techniques available for the transport network. We then presented the technical approach and the key technologies we will develop in order to realize the concept of network slicing. The analysis is made over the following axis: optical technologies, Ethernet/IP technologies, wireless technologies and programmable data plane technologies.

The activities described in this deliverable are directly related to WP3, WP5 and WP6 activities. This deliverable and the relevant subtasks of Task 4.2:

- Exploit the work delivered in WP3 regarding functional extensions of an OPP for line-rate stateful packet/flow processing, elastic optical networks and the custom mac80211 stack and a virtualisation substrate.
- Provide input to WP5 by means of available technologies and network components and functions to support slicing for the transport network; the interfaces needed regarding the orchestration and management solution will be designed in order to build the integrated 5G-PICTURE OS solution.
- Provides input to support the use cases execution provisioned in WP6. All the transport technologies required and the way they will be used will rely on the work delivered in this subtask.

5 PNFs and VNFs to support synchronisation services in converged FH/BH networks

5.1 State of the art

The evolution towards 5G RAN brings new challenges in terms of time synchronisation requirements imposed to radio transmissions. This is not only because 5G adopts new radio and framing configurations, but also due to novel RAN services, such as localisation [98]. In the scope of this chapter, the importance of this trend lies in the fact that new accuracy levels are expected to be achieved by BH and FH networks while transporting synchronisation signals.

To achieve such accuracy in the transport of timing, the expectation is to continue relying on a mix of centralised or distributed Global Navigation Satellite Service (GNSS) receivers networked towards the synchronisation clients (e.g., base stations) through packet-based timing transport such as IEEE 1588 PTP [99]. This has been the conventional approach due to inviable costs of deploying GNSS receivers in every base station, especially when considering indoor equipment. However, going forward one major aspect where the timing network is expected to evolve significantly is in terms of its degrees of programmability. This will become essential to accommodate and coordinate the ever-growing number of network domains and transport technologies over which timing can be transported.

The remainder of this section first explores the evolution towards state of the art (5G) synchronisation requirements and provides an introduction to the main technologies adopted within the components of current timing transport networks, particularly with focus on the associated sources of error.

5.1.1 5G synchronisation requirements

There are a few noteworthy trends regarding timing requirements in 5G with respect to LTE or LTE Advanced (LTE-A). One example is in TDD, where stations serving adjacent or overlapping cells must time-align their DL and UL transmissions to avoid interference. In this particular case, the trend in 5G relates to the fact that shorter frames are going to be supported for low-latency communications. Then, since the frame time alignment error tolerance is proportional to the frame size, the error budget is expected to be reduced in 5G [100]. While LTE required a Time Alignment Error (TAE)[6] within $\pm$1.5 µs (or $\pm$5 µs for cell radius larger than 3 km) [101], the analysis presented in [100] indicates 5G might reduce this budget up to $\pm$ 390 ns.

In contrast, as indicated in [100], the timing requirements to support carrier aggregation and CoMP transmissions are likely to be maintained in 5G. Nevertheless, since instead of alignment at frame level these modes become more effective when alignment is achieved on a sample level (jointly-processed samples transmitted concurrently), it is still possible that the requirements are updated for some 5G modes to comply with higher sampling frequencies. However, since this is not yet specified, only the 4G requirements are reviewed in the sequel.

In 4G, MIMO or transmission diversity transmissions require the TAE to be under or equal to 65 ns, as specified in [102]. This is 4G's most stringent TAE requirement. However, it should be noted that such transmission modes are generally carried through co-located antennas (normally on the same board) and, therefore, timed by the same clock signal or one coming from a common source. In this case, the time alignment does not need to rely on any synchronisation provision by the transport network. Both the sample streams and their timing are originated in a common source, so they are inherently well synchronised.

The second most stringent requirement in LTE/LTE-A is for intra-band contiguous carrier aggregation [102]. However, as argued in [100], this is also generally performed by antennas that are located in the same cell site, which can physically share the same clock source. Typically, it is only the inter-band carrier aggregation transmission mode that involves different cells (i.e., is inter-site) and, therefore, depends on timing provisions by the transport network. This scenario is specified in [102] to require a maximum TAE of 260 ns, which translates into a requirement for the timing network to achieve an accuracy within $\pm$130 ns with respect to reference time, the latter usually thought as Coordinated Universal Time (UTC).

[6] 3GPP's definition of TAE implies that it is the largest timing difference between any two signals being transmitted in distinct antenna ports of a base station or in interfaces of different base stations.

A similar TAE requirement is typically assumed for CoMP in 4G, particularly in the scenario where multiple (non-co-located) base stations perform joint transmission in DL. For this mode, [103] specifies an overall timing variation within a range of 2.5 µs for the signals that arrive at a user from different serving cells, including the propagation delay variations. A small portion of this budget is allocated for the TAE contribution to the offset and, then, the resulting TAE requirement falls within the order of inter-band carrier aggregation requirement (of 260 ns).

In terms of new 5G services, a new demand for time synchronisation arises due to the introduction of localisation services via the mobile network itself, as an alternative to GNSS. Since time synchronisation is critical for localisation by trilateration and triangulation techniques, such applications are expected to require the highest levels of synchronisation accuracy. In [100], it is stated that a relative time error of less than 10 ns is required for the base stations involved in the position computation.

Nevertheless, it should be reinforced that the requirement for localisation is solely in terms of relative time synchronisation. This means the time error is computed from each base station's time to each other, rather than from each station to UTC, in contrast to the previous applications. The relative condition substantially alleviates the problem. Particularly with regard to the transport network, only the subset of transport nodes that are not common to the three base stations performing triangulation or trilateration are the ones that add to their time errors. For example, if the three stations are served through the exact same X-Haul path and are slaves to the same synchronisation master (e.g., an edge switch), then only their internal time fluctuations contribute to the relative error.

In summary, it can be argued that the transport network is likely to be required to support a TAE of 260 ns in 5G, or, equivalently, an error within ±130 ns, except for the relative 10 ns for localisation service. The challenge, however, is that this total error budget must be distributed among the different sources of timing error, namely the time server, the transport nodes and the slaves. Ultimately, each component has to deal with a tighter budget.

There are only indications of error budget in ITU-T recommendations. For example, ITU-T G.8261 [104] defines a performance test topology for timing distribution that is composed by 10 switches. When considering level accuracy 4 from ITU-T G.8271 [105], namely the case of LTE TDD for small cells (error to be within ±1.5 µs), the budget discussed in ITU-T G.8271.1 [106] allocates ±420 ns solely for the constant Time Error (cTE) to be introduced by the transport nodes. Assuming that such nodes are of Class B [107], i.e., introduce ±20ns of cTE each, it is concluded that a total of 20 nodes can be supported in this case.

Meanwhile, in terms of the individual performance to be achieved by each timing transport node (or “switch”), a 2017 release (edition 2.0) of the ITU-T Recommendation G.8273.2 determines the target performance for the 1588-aware transport node known as Telecom Boundary Clock (T-BC), as defined in the ITU-T G.8275.1 profile, detailed in the next subsection. The performance metrics in G.8273.2 [107] are categorised in terms of noise generation, noise tolerance, noise transfer and transient response, where “noise” should be interpreted as time error. The objective is to specify the performance to be met in each of those aspects such that a device can be categorised as compliant to two different accuracy levels, Class A and Class B. Once a transport node fits in one of these levels, the timing transport network can be planned with adequate number of hops, following a time error budget such as the aforementioned one. It can be argued that these two accuracy classes are defined based on the underlying objective of recovering time with an error constrained to ±1.5 µs relative to UTC at base stations, as this is the main use case for the G.8275.1 profile. In this context, Class A devices are appropriate within shorter synchronisation chains, while Class B devices are for longer chains.

For 5G, in contrast, in order to achieve the time error bounded to ±130 ns at the base station with respect to UTC, transport nodes are expected to be allocated with tighter allowances. The work in [100] assumes 90 ns as the total transport budget, while 40 ns is assigned for the master time server, slaves and link asymmetries. In this case, a network composed by class B transport nodes would only support 4 hops. Alternatively, the accuracy of transport nodes would need to be improved to within ±4.5 ns in order to support 20 hops.

Lastly, another dimension of synchronisation requirements of the RAN concerns the different demands of functional splits. For example, when splitting at the upper layers, such as split option 2 (see Figure 6), i.e., between the PDCP layer and the RLC layer, all of the aforementioned requirements are left to be handled at the DUs or RUs, with no specific constraint on the CU. This is because the CU in this case sends IP packets towards the DU, so it does not foresee the timing of the upcoming synchronous radio transmission (to be generated after baseband processing). In contrast, when adopting splits at lower layers, the synchronisation workload is also potentially applicable to both ends of the transport.

One scenario in which both FH endpoints participate in the process of time-alignment of I/Q samples is functional split 8 (between the low PHY and the RF interface), specifically when the transported stream of IQ samples is coordinated with respect to IQ streams transmitted by other distinct RUs (e.g., the case of CoMP). For example, in the case of the lower part of layer 1 being implemented at DUs (see Figure 7), after the DU transmits IQ packets towards RUs, the RUs are required to re-align the IQ samples after the variable delays that their corresponding packets experience in the FH. In this process, even though effectively only the time alignment achieved at the RUs matter, the DUs could participate either by triggering the IQ-bearing packets in specific instants or by scheduling transmission time at the RUs.

5.1.2 Timing transport components and technologies

Current RAN deployments rely primarily either on GNSS-based time synchronisation at base stations or GNSS time acquired at a previous (upstream) node with time synchronisation transported towards the base station via IEEE 1588v2 PTP [99], potentially combined with frequency transport through the physical layer, such as with SyncE [104]. In most cases, the IEEE 1588v2 configuration is set to adhere to a telecom 1588 profile[7] defined by ITU-T, more specifically either the ITU-T G.8265.1 profile [108] for frequency synchronisation or the G.8275.1 profile [109] for time (and therefore also frequency) synchronisation. The latter allows the use of both PTP BCs and TCs [99], although necessarily with the entire transport network (all of its nodes) supporting timing distribution. By definition, this consists in the so-called Full Timing Support (FTS) mode. A third profile (ITU-T G.8275.2 [110]) gives the possibility for Partial Timing Support (PTS), which is suitable for when a mobile operator partially relies on third-party transport networks that do not support timing transport.

The referred GNSS receivers compose the Primary Reference Time Clocks (PRTCs) in the timing network, namely the units that provide the time reference for a segment of the network. The PRTC acquires a reference time that is traceable to a time standard, such as UTC. Its output, then, is fed to a PTP master clock, more specifically a Telecom GrandMaster (T-GM) in the case of ITU-T profile architecture. Importantly, part of the error in the transport of synchronisation is incurred in the PRTC and T-GM themselves. For many timing applications this error is negligible, but this is not the case when considering the tight 5G error budgets.

As highlighted in [100], a GNSS receiver can rely on different methods, with different accuracies. The common one-way GNSS receiver normally has an error within $\pm$50 ns. An alternative is to use the so-called common-view technique, where two GNSS receivers compare the time that they independently recover from a common GNSS satellite and, by doing so, reach an accuracy around 10 ns. Another alternative is the Two-Way Satellite Time Transfer (TWSTT), where two ground stations exchange their time by concurrently transmitting to each other via a Geosynchronous (GEO) satellite transponder in a symmetric-path configuration. This comes at the expense of high costs for microwave transmission towards the GEO satellite, so it is practically only adopted for synchronisation between UTC laboratories, rather than regular Global Positioning System (GPS) receivers (e.g., ones in base stations). Moreover, there is also the possibility of leveraging on the knowledge of the phase of the GPS carrier, known as GPS carrier phase [111]. In general, however, the conventional one-way broadcast GPS ($\pm$50 ns accuracy) is more typical. In fact, ITU-T G.8272 [112] specifies that the combination of the PRTC and the T-GM should be accurate within 100 ns relative to UTC, which is within one-way GPS accuracy range.

With regards to the timing transport nodes, the highest accuracy is generally achieved with FTS. The reason is that in FTS the nodes overcome the variable queuing delay that the PTP message experiences in each transport node, which otherwise would disturb offset estimations carried at PTP slave clocks (highly sensitive to delay variations). A TC deals with packet delay variation (PDV) by measuring and reporting the time that a PTP message resides within itself (as a transport node), from ingress port to egress port, i.e., measures the so-called *residence time* [99]. A BC, in turn, implements the full slave logic in the port that receives PTP messages and rebuilds master logic in the port that transmits the PTP message downstream. While doing so, the BC synchronizes its internal clock as a regular slave would and, because the incoming PTP message is processed in the slave port of the BC and not forwarded (a new message is instead formed in the master port), the BC avoids queuing of PTP event messages.

Ultimately, the overall time error due to timing transport nodes alone is dictated by the individual TC or BC accuracies. These are influenced by constant and dynamic time error components (c.f. Appendix IV in [106]). For instance, one potential source of error in TC nodes is the time offset that its internal clock accumulates

[7] A 1588 profile is a set of configuration attributes and features (prohibited and allowed) that are specified for a particular application in order to meet its performance levels and ensure inter-operability.

from ingress time to egress time of a PTP event message. If a budget of ± 1 nanoseconds is assigned for this error alone, for example, assuming a maximum residence time of 10 milliseconds, the offset in the frequency that drives the time count of the TC would need to be less than ± 100 ppb (also interpreted as 100 ns of error accumulated per second).

In fact, since accuracy of a frequency source determines the amount of time offset that a node accumulates over time and stability of a frequency source determines whether the frequency error changes over time, it is generally beneficial for synchronisation nodes (either endpoint and intermediate transport nodes) to rely on high stability and high accuracy oscillators. In other words, the quality of the oscillators employed along BCs and TCs has a big impact. As a balance between oscillator cost and performance, common practice is to rely on either temperature-controlled or oven-controlled crystal oscillators (Temperature Compensated Crystal Oscillators (TCXO) or Oven Controlled Crystal Oscillator (OCXO)), with around 1 ppm or finer accuracy.

In terms of transport protocol, IEEE 1588 messages are traditionally packed in raw Ethernet frames or UDP (IPv4 or IPv6) datagrams. Nevertheless, the *networkProtocol* attribute in [99] indicates support to other protocols, including profile-defined ones. Also, in terms of transport medium, copper or fibre-based Ethernet links (such as the ubiquitous 1000BASE-T) are more commonly used. However, again, nothing prevents other technologies (such as wireless) from being adopted, as long as PTP messages can be encapsulated and their transmission or arrival timestamped with sufficient accuracy. A typical solution would be, e.g., to frame PTP messages within Ethernet format and transport this Ethernet frame encapsulated (or glued) within any other link technology. For example, an Ethernet PTP message could be mapped to an IEEE 802.11 data frame.

A further component of current telecom timing networks is the transport of frequency via the PHY to complement the IEEE 1588-transported time reference. The rationale is that the PHY reference is always present at a slave node, which prevents clock drifts in the gaps between consecutive 1588 messages. In the specific case of SyncE or SDH nodes, a frequency reference is transported by relying on the fact that the adopted transmission is synchronous (continuously running) and with enforced dense bit transitions in the waveform (using e.g., 8b/10b) such that the receiver can recover the transmitter's clock. Nevertheless, in principle PHY frequency transport can be achieved in any communication system whose receiver can estimate and correct its frequency error with respect to transmitter, such that a synchronised chain of nodes can be established.

Lastly, it should be noted that all of the given components, i.e., time references, transport nodes and timing links need to be carefully managed by current synchronisation service providers. The referred synchronisation protocols do support management interfaces and messages. For example, the IEEE 1588 specification [99] defines management nodes that can coordinate Ordinary Clocks (OCs), BCs or TCs by sending management messages to request (get) attributes, set attributes, trigger commands (events) and respond with the results or acknowledgement of previous requests. However, the actual usage of this interface in telecom deployments is not specified within the ITU-T profiles [108] [109] [110], just like SyncE's management interface is not specified in [113]. A key aspect of the subsequent sections is on the programmability and scalability of synchronisation services under a multitude of physical layers and protocols. In particular, improved management of the different synchronisation domains is focused.

5.2 Technical approaches and KPIs

The previous section highlights, above all, that current timing networks are required to deal with a myriad of requirements, transport technologies and configurations. At the same time, the timing transport infrastructure is expected to be used by multiple service providers and applications. Hence, it becomes appealing to leverage on an extra layer of abstraction where the synchronisation hardware resources are decoupled from their services. These software or physical resources, in turn, become virtualised (VNFs and PNFs), instantiated on demand, and not specifically tied to any particular provider or application. This concept is presented in [39] in the specific context of synchronisation transport for telecom networks.

The remaining part of this section elaborates on the referred framework for synchronisation as a service. Additionally, it explores the guidelines for establishing timing paths through some of the transport technologies considered for synchronisation support in the context of 5G-PICTURE. More specifically, approaches applicable for IEEE 1588 transport over IEEE 802.11ad mmWave mesh nodes, IEEE 802.11ac and Flex-E [57]. Finally, it outlines evaluation goals both in terms of pure timing metrics as well as radio performance, such as in different functional splits.

5.2.1 Technical Approaches

5.2.1.1 Synchronisation as a service framework

In the context of 5G-PICTURE networks, where heterogeneity and flexibility are key aspects, it is attractive to rely on a synchronisation harmonizer in the control plane, namely an entity that has views on the different synchronisation domains, such as the one proposed in [114]. To introduce this idea, Figure 40 illustrates a case in which a DU requests time synchronisation with respect to UTC time and the latter can be provided by a master clock that is hypothetically embedded in a CU in the network. Timing support is available in all transport nodes along the network, but with different error contributions. The harmonizer ensures that the path (highlighted) introducing the minimum total node processing error is used.

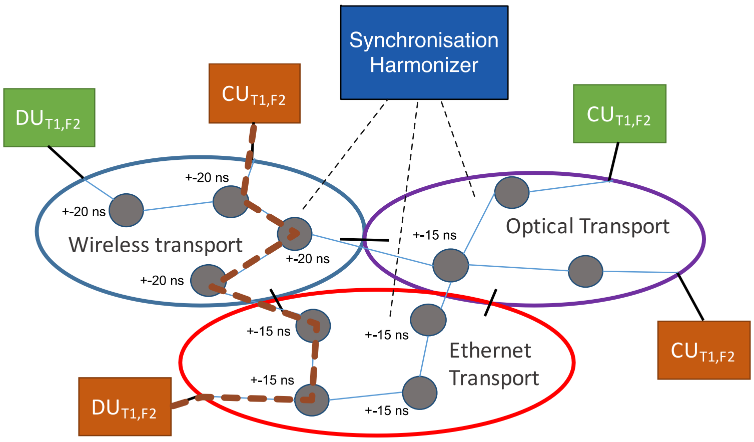


Figure 40: Harmonizer with knowledge of synchronisation features along the 5G-PICTURE network.

As argued in [114], first of all this architecture requires the definition of the relevant parameters and attributes to be exchanged between the harmonizer and the synchronisation PNFs and VNFs. An important aspect in this context is to ensure that these parameters apply for the miscellaneous combinations of physical layer and network protocols that can be used in the network. Secondly, the architecture requires the specification of the communication interfaces between the harmonizer and the nodes, for example regarding how to use or leverage on the existing IEEE 1588 management interface [99]. Besides, other remaining issues concern performance monitoring and the coordination of applications that can concurrently use the shared infrastructure with different accuracy demands.

When time synchronisation is requested from the control plane for a specific application equipment in the network, it is sensible to assume that the requestor would be able to specify parameters such as the ones summarised in Table 7. For example, the application equipment (e.g., a base station) could request time synchronisation via 1588 accompanied by a complimentary PHY-based frequency reference, specifically with time and frequency accuracies in compliance to strict 5G requirements (e.g., $\pm$130 ns in time and 50 ppb in frequency). It could also demand for instance the FTS ITU-T profile (G.8275.1) and specify the preferred master clocks, potentially owned by the application provider itself.

Table 7: Example synchronisation request parameters.

Parameter/Attribute	Values
Synchronisation mode	Time/frequency or frequency-only
PHY frequency reference	Required or not required
Time accuracy	Value in ns
Frequency accuracy	Value in ppb
Time accuracy reference	UTC or another node's time
1588 Profile	None, G.8265.1, G.8275.1 or G.8275.2
Custom BMCA rules	E.g., preferred grandmaster port identity

Table 8: Properties that can be reported by a synchronisation transport node to the harmonisation layer.

Parameter/Attribute	Values
TC support	Present or absent.
BC support	Present or absent.
max|cTE|	Maximum constant time error introduced by the node.
RTC resolution (granularity)	Value in ns.
Local oscillator characteristics	Frequency tolerance in ppb, aging per time period etc.
Holdover specification	Value in ns per e.g., 24 hours (or any time interval).
Timestamping uncertainty	Value in ns.
Link length	Known length between target PTP port and its link peer.
Link delay asymmetry	Known asymmetry between "downlink" and "uplink" delays.

Once a request is issued to the harmonizer, the next step is to optimally launch the service. To do so, the harmonizer needs to have knowledge regarding the various resources across the network. With respect to node-level performance, some relevant parameters are summarised in Table 8. For example, using the local oscillator characteristics, the RTC resolution and the timestamping uncertainty, the harmonizer can derive a rough approximation of the error that can be incurred in the residence time computation at a given TC node. Based on that, the harmonizer can select the best TCs for timing transport.

In IEEE 1588's existing features, useful information can be retrieved by the so-called *clockClass*, *clockAccuracy* and *timeSource* parameters [99], which can be read via management GET requests. However, the information in Table 8 noticeably goes beyond this level of information, including specifications of the deployment itself (such as link length), the node hardware (such as the RTC resolution) and the PHY. In this case, an additional management layer (software) running in the node could be adopted to communicate with the harmonizer using SDN-friendly APIs and data models. Also, algorithms can be developed to weight the importance of these metrics when attempting to make decisions.

It is worth noting that the Best Master Clock Algorithm (BMCA) specified in IEEE 1588 already ensures that the master clock having superior accuracy becomes the grandmaster of a given domain. However, the specification does not provide any means for selecting transport nodes when multiple path alternatives exist and neither to ensure accuracy levels. Traditionally this is achieved by careful network planning and timing path isolation. The parameters exemplified in Table 3 are helpful this purpose.

Lastly, in order to maintain the quality of timing transport, it is suitable to rely on monitoring metrics acquired at the harmonizer. For example, while communicating directly to endpoint 1588 clocks (slave clocks) or to BCs, the control plane can check the statistics of the delay, time offset and frequency offset estimations produced locally. A major constraint in such clocks is that the true reference time or delay is not available to the node (otherwise synchronisation would be unnecessary), so the nodes cannot measure their estimation errors directly. Nonetheless, since typically synchronisation occurs in closed-loop (estimated error is corrected such that next estimated error is lower), it is still useful for the harmonizer to receive the mean and standard deviation of clock offset estimations. With these, the monitoring layer can check whether estimations have converged or not and realize how much fluctuation is expected while in steady-state. If, for example, the fluctuation itself is larger than the requested maximum tolerable error, then the given path can be immediately excluded or modified in terms of configuration.

5.2.1.2 Synchronisation over 5G-PICTURE transport technologies

The given control plane infrastructure has the purpose of automating the provision of synchronisation services in the context of a highly-heterogeneous and dynamic network such as the 5G-PICTURE transport network. Building on this infrastructure, a further objective is to develop support for timing transport within specific technology domains that have not been traditionally used for this purpose. More specifically, the transport of PTP messages over 60 GHz (IEEE 802.11ad) mesh nodes, Sub-6 GHz wireless (IEEE 802.11ac) nodes and Flex-E. The next part of this section discusses the unique constraints of these technologies and covers how the proposed harmonisation layer can deal with them.

Generally speaking, every transport technology introduces unique constraints towards the transport of timing protocol messages. The first obstacle refers to the technology's timestamping capabilities, particularly its ability to provide timestamps as close to the physical medium as possible, in hardware. The second major obstacle refers to the transport and recognition of IEEE 1588 messages. The idea is that PTP-aware transport nodes are required to recognize PTP messages encapsulated within other protocols and this may be challenging in particular hardware implementations. Lastly, there are technology-specific sources of timing uncertainty, which in turn call for specific solutions.

To illustrate technology-specific constraints on timestamping, consider the case of IEEE 802.11. Most commercial IEEE 802.11 network interface cards are restricted with support solely to software timestamping. The standard, however, does support and rely on hardware timestamping methods, particularly the ones in the so-called Timing Synchronisation Function (TSF) timer synchronisation and the timestamping involved in the Timing Advertisement (TA), Timing Measurement (TM) and Fine Timing Measurement (FTM) procedures [115]. However, in most cases, none of these alternatives are made available to upper layers, so in the end are not usable for IEEE 1588 transport. At the same time, none of these approaches are strictly necessary or perfectly suitable for implementation of IEEE 1588-aware wireless transport nodes.

Ultimately, the problem of timestamping in IEEE 802.11 can be addressed by a hardware timestamping approach more similar to the conventional Ethernet approach, discussed later in this work.

The other two aforementioned technology-specific obstacles for PTP transport are also demanding in IEEE 802.11. For the transport and recognition of PTP messages, for example, it is reasonable to assume most implementations would require some form of flagging within the 802.11 frame header so that the receiver can know whether or not to timestamp the incoming frame as close to the physical medium as possible, before decoding or parsing the frame content. Meanwhile, in terms of sources of uncertainty, different issues arise with the wireless nature of the transmission. For instance, wireless receivers perceive propagation delays with wider fluctuations when compared to wireline systems, due to time-varying multipath propagation. Also, wireless transmission needs to deal with higher packet loss rates due to problems such as interference and channel fading. These issues are also covered in the next section.

In the context of Flex-E, there are yet different technology-specific obstacles. The most important functionality in order to have a functional Flex-E setup is that, for each PHY, the multiplexer and de-multiplexer units share the same sub-calendar, otherwise it would be impossible to decode the slot information to a specific Flex-E client. However, in a multi-hop setup this sub-calendar information sharing can be quite challenging and specially demanding in terms of synchronisation.

As a first step in every Flex-E client flow, a 64b/66b encoding is performed to facilitate synchronisation procedures and allow Clock and Data Recovery (CDR) at the receiver. In particular, a procedure of idle insert/delete is performed, which is necessary for all Flex-E clients in order to be rate-adapted to the clock of the Flex-E group. The rate of the adapted signal is slightly less than the rate of the Flex-E client in order to allow alignment markers on the PHYs of the Flex-E group and insertion of the Flex-E overhead in the steam. Then all the 66b blocks from each Flex-E client are distributed sequentially into the Flex-E group calendar where the multiplexing is performed. Note, however, that establishment of Flex-E multi-hop paths with end-to-end synchronisation is not currently supported. Existing solutions consider for a pre-configured CLI-based Flex-E group configuration and client assignment. This multi-hop scenario will be part of our investigation.

5.2.2 KPIs

There are two main perspectives for evaluation of timing performance in the context of telecom deployments. The first relates to the impact at the radio level, especially when considering the aforementioned radio access transmission methods (such as CoMP or carrier aggregation) that rely on time alignment. In this case, applicable metrics are either the TAE between reference IQ samples or radio frames, or related figures. Due to the typical difficulty with directly probing TAE at radio hardware level, performance metrics such as EVM or Signal to Noise Ratio (SNR) can be adopted, as they can be degraded due to unacceptably large TAE in certain coordinated transmission modes. Meanwhile, the second assessment perspective is within the isolated domain of timing hardware. In this case, a more typical evaluation considers parameters such as Time Deviation (TDEV), Time Interval Error (TIE), Maximum Time Interval Error (MTIE) [116], or simply the statistics of the time offset between the slave nodes and the master reference.

Both perspectives are relevant for the evaluation of the synchronisation framework proposed for 5G-PICTURE.

An important aspect of the proposed infrastructure is whether it suits well for the delivery of synchronisation requirements associated to various functional splits over a multi-tenant network. In this context, the reasonable KPIs are the aforementioned communications-quality metrics (e.g., EVM). The goal is to assess whether the functional splits achieve their sample or frame-alignment requirements and the different degrees of SNR or EVM impact due to timing errors.

By contrast, while assessing the accuracy achieved in synchronisation transport nodes alone, the aforementioned “timing-centric” figures (such as TDEV) can be employed. In particular, when assessing synchronisation slave performance, these figures should be contrasted directly with respect to 5G TAE requirements. Meanwhile, when assessing BCs or TCs in the transport network, a suitable approach is to evaluate the node’s contribution to the overall time error budget that the slave can tolerate. To do so, a possible approach is to output one pulse-per-second (1PPS) signals in both master and slave nodes, measure the time difference between their rising edges using an oscilloscope and post-process the measurements to obtain the target metric (e.g., TDEV or MTIE). Then, conduct these measurements iteratively by incrementally adding BCs or TCs in the master-to-slave path, such that the individual transport contributions can be understood.

The timing performance evaluation draws on the guidelines established in ITU-T G.8273.2 [107]. It is useful to evaluate whether a transport node can meet Class A or Class B accuracy, even though for 5G, depending on the use case, a Class A or B node may restrict the network to a few hops. As mentioned earlier, conformance to these classes can be tested by assessing the noise (time error) generation, transfer, tolerance and transient response. For time error generation, constant (i.e., cTE), dynamic Time Error (dTE) and maximum absolute Time Error (max|TE|) components need to be evaluated. The first, cTE, can be obtained by averaging the time error over a given observation interval. The dTE component is obtained by computing the TDEV, MTIE and peak-to-peak errors in the filtered time error sequence. Lastly, max|TE| consists in the maximum on the unfiltered time error sequence. Similarly, the time error tolerance at the PTP input can be assessed based on dTE (more specifically MTIE), as defined in [106]. The time error transfer, in turn, can be evaluated by means of a transfer function that is obtained by feeding sinusoidal time errors in the PTP input and observing the amplitude of the time error PTP output, c.f. Appendix VI in [107]. This transfer function should meet a specified mask. Finally, transient performance can be measured based on time error and MTIE masks.

Table 9 summarises the main KPIs and the target levels discussed thus far, based on 5G requirements as well as current ITU-T timing transport performance levels. Note that, some of the evaluation metrics from G.8273.2 [107] can involve complex and time-consuming measurement, such as the case of time error transfer functions and MTIE masks. Meanwhile, evaluation of the time error generation metrics (cTE, dTE and max|TE|) is relatively more accessible, so these can be adopted for insights on transport node accuracy.

Table 9: Summary of synchronisation KPIs and target figures.

KPI	Category	Target
Time Alignment Error (TAE)	Radio Access Assessment Metrics	▪ ±1.5 µs (LTE-TDD cell radius < 3km) ▪ ±5 µs (LTE-TDD cell radius larger than 3 km) ▪ ±390 ns (expected 5G TDD accuracy requirement) ▪ ±130 ns (inter-band carrier aggregation) ▪ ±130 ns (CoMP joint-transmission) ▪ ±10 ns relatively (localisation/triangulation)
cTE (time error generation)	Timing Transport Node Assessment Metrics	▪ ±50 ns average time error (Class A) ▪ ±20 ns average time error (Class B)
dTE (time error generation)		▪ 40 ns MTIE measured on the low-pass filtered version of the time error sequence over 1000 s observation interval on constant temperature (both for Class A and Class B) ▪ 40 ns MTIE measured on the low-pass filtered version of the time error sequence over 1000 s observation interval on variable temperature (both for Class A and Class B) ▪ 4 ns TDEV measured on the low-pass filtered version of the time error sequence over 1000 s observation interval on constant temperature (both for Class A and Class B) ▪ 70 ns peak-to-peak error measured on the high-pass filtered version of the time error sequence over 1000s observation interval (both for Class A and Class B)
Max|TE| (time error generation)		▪ 100 ns (Class A) ▪ 70 ns (Class B)

Time error tolerance		▪ MTIE mask from Figure 7-2 in [106]:
		  o 200 ns MTIE at 1.3 s observation interval
		  o 277 ns MTIE at 2.4 s observation interval
		  o 580 ns MTIE at 275 s or longer observation interval

Time error transfer		▪ Bandwidth between 0.05 Hz and 0.1 Hz ▪ Phase gain smaller than 0.1 dB in the passband
Holdover		▪ MTIE mask from Figure 7-1 in [107]

5.3 Technology Components

This section addresses the specific technical approaches that are covered in the previous subsection by means of specific solutions that form the technical components of this deliverable. There are specifically five technical components. Their relationship to technical approaches is summarised in Table 10 and their solutions are detailed in the sequel.

Table 10: Mapping between synchronisation technical approaches and corresponding technical components.

Technical components	Technical approach
5.3.1 IEEE 1588 over IEEE 802.11ad	**5.2.1.2** Synchronisation over 5G-PICTURE technologies
5.3.2 IEEE 1588 over off-the-shelf IEEE 802.11ac	**5.2.1.2** Synchronisation over 5G-PICTURE technologies
5.3.3 Heterogeneous synchronisation transport testbed	**5.2.1.1** Synchronisation as a Service Architecture **5.2.1.2** Synchronisation over 5G-PICTURE technologies
5.3.4 Synchronisation harmonizer	**5.2.1.1** Synchronisation as a Service Architecture
5.3.5 Over-the-air synchronisation for FH networks	**5.2.1.2** Synchronisation over 5G-PICTURE technologies

5.3.1 Synchronisation Technical component 1: IEEE 1588 over IEEE 802.11ad

5.3.1.1 Hardware timestamping in IEEE 802.11ad

As thoroughly discussed in [117], a reasonable hardware timestamping "reference plane" [99] (position) for IEEE 802.11 nodes in general is one related to acquisition of frame boundaries in the PHY, more specifically preamble identification. In the receiver's baseband processing chain, frame timing recovery is performed to identify the start of incoming PHY PDUs. This is done by using cross-correlation between the incoming stream of symbols and the known sequence in the so-called Short Training Field (STF) of the preamble. When a peak is observed in this computation, the receiver infers this is the start of frame and correspondingly requests a timestamp from the Timestamping Unit (TSU). Subsequently, this timestamp is reported to upper layers as the time of arrival of the incoming frame. In the transmit chain, in turn, the time of departure would typically be taken at an analogous position in the transmit baseband processing hardware. However, in this case the timestamp strobe is triggered simply when the PHY effectively starts a transmission requested from the MAC.

The motivation for timestamping at the PHY layer can be explained by using Figure 41. Whenever an IEEE 1588 message is pushed from an application towards the network device for transmission, the message crosses layers. A typical (but not mandatory) scenario is one in which the IEEE 1588 stack runs as an application in an OS. The transmit message, then, has to cross the OS layer (the OS network stack and the network device driver), where it experiences substantial delay variation and the network device's MAC, until it ultimately reaches the PHY. It is typically only the hardware path from PHY baseband chain onwards (until the antenna) that presents a more consistent latency, i.e., not varying among transmissions, due to the absence of intermediate variable buffering stages. Since timestamping fluctuations shall be avoided for performance, the PHY layer becomes preferable for timestamping.

The concept is better understood by noting that ultimately the goal is to use the timestamps for comparing the time in two spatially separated devices while relying on timestamps (t1 and t2 in Figure 41) that are not taken at the same time. To do so, the time of departure (t1) from the PTP message sender needs to be corrected by a value corresponding to the delay from departure to arrival (estimated separately) at the message receiver. That is, t1 needs to be adjusted to the time that the sender has when the arrival timestamp is taken at the message receiver, so that a fair comparison between the two clocks (in the sender and receiver) becomes possible. This can only be successfully achieved if the latency between the departure and arrival timestamp is consistent among independent transmissions, otherwise the delay estimated separately would hardly match with the actual delay experienced by a given PTP message.

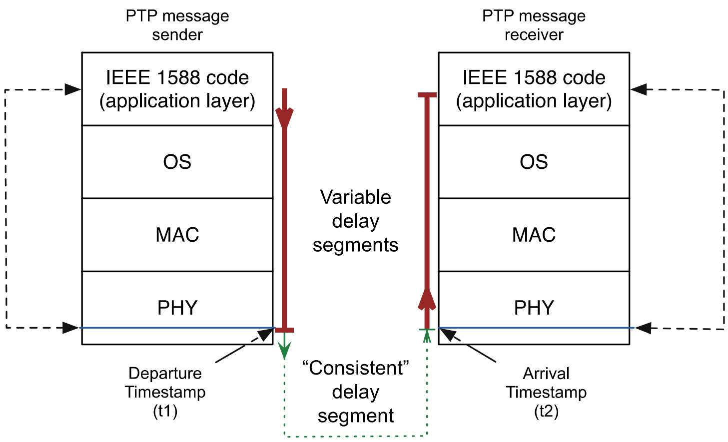


Figure 41: Hardware timestamping layering model.

In the context of IEEE 802.11 wireless stations, there is one additional motivation for pursuing this choice of timestamping reference plane at the PHY and specifically related to the STF field in the PHY Protocol Data Unit (PPDU). It is the fact that it allows timestamps not to be influenced by the Modulation and Coding Scheme (MCS) being used in the PPDU itself. The rationale is that the PPDU preamble (STF and channel estimation fields) is always composed by the same number of symbols regardless of MCS choice, as long as single-carrier and OFDM PHY modes are used (these fields differ in the so-called "control PHY" mode). Hence, for a fixed sample rate, the STF latency in the PHY is constant, so that the delay of this information from one wireless station to the other is consistent over independent packet transmissions. By contrast, if the recognition of the end of frame in the PHY was used as timestamping reference place instead, for example, even if the 802.11

frames carrying PTP messages were always sised equally, the latency from one station to the other would highly depend on the symbol rate mandated by the MCS for the PPDU data.

In terms of timestamping support, the IEEE 802.11 standard itself introduces support for departure and arrival timestamping at the PHY layer. The architecture is such that the MAC can access those timestamps via the PHY Service Access Point (SAP). During transmission, the sequence is as follows: the MAC requests the PHY to start transmitting a Physical Service Data Unit (PSDU), particularly by issuing a "*PHY-TXSTART.request*". Within this request, the MAC encloses a structure named "TXVECTOR", where the parameter named "TIME_OF_DEPARTURE_REQUESTED" should be asserted, as indicated in IEEE 802.11-2016 Section 8.3.5.6. After the PHY effectively starts the transmission of the corresponding PPDU, it replies with a *PHY-TXSTART.confirm* primitive, within which it sends a structure named "TXSTATUS" containing the actual "TIME_OF_DEPARTURE" field. This exchange is illustrated in Figure 42. Similarly, during frame reception, the PHY indicates to the MAC when an incoming PPDU starts via the so-called *PHY-RXSTART.indication* primitive. The time of arrival should then be obtained by the MAC in this instant by requesting a timestamp from the TSU.

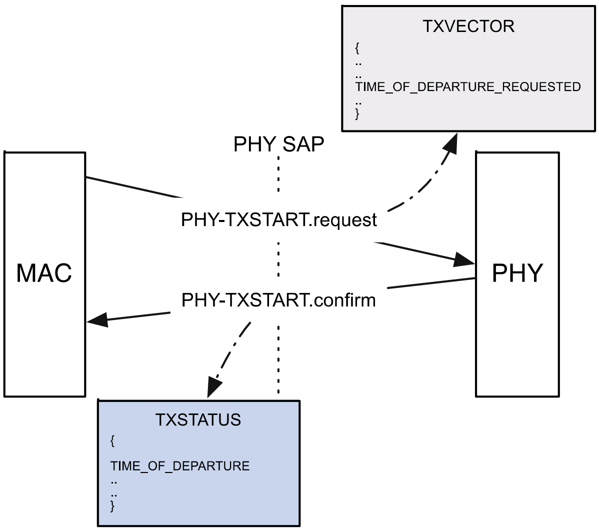


Figure 42: IEEE 802.11 departure timestamping request-response interface.

It should be pointed out, however, that even though this timestamping MAC-PHY interface is standardised, it can still be considered as a rather unexplored feature, especially when considering the application of a higher layer synchronisation protocol (i.e., IEEE 1588). The original motivation for introducing the given interface in the standard relates to the aforementioned TM and FTM protocols, in which the IEEE 802.11 MAC needs to collect timestamps. However, for supporting IEEE 1588 in a model such as that of Figure 41, the interface is not sufficient, i.e., another mechanism needs to be implemented in order to convey timestamps to the layers that lie above IEEE 802.11ad MAC. This will be further explored in 5G-PICTURE.

One relevant additional aspect is that the IEEE 802.11 standard also provides a mechanism for the PHY to inform (to the MAC) offsets that can be used in order to correct timestamps taken within inner sublayers of the PHY to the time that the preamble (STF field) of the corresponding PPDU appears at the transmit or receive antenna. This is valuable when applying wireless station localisation procedures, such as in the FTM procedure of IEEE 802.11-2016, Section 6.3.58, since the resulting timestamps (after adjustment) can be used to more accurately estimate on-air time, excluding in-hardware time. For the departure timestamp, the adjustment is done by adding the offset value informed to the MAC within the TXSTATUS structure, sent along the *PHY-TXSTART.confirm* primitive. Meanwhile, for the arrival timestamp, the adjustment is done by subtracting the offset value informed within the "RX_START_OF_FRAME_OFFSET" field of the RXVECTOR structure. As per the standard, both offsets are given in units of 10 ns.

It is important to note that support for time of departure and the corresponding arrival and departure offsets is specific to each PHY clause in the standard. In the Directional Multi-Gigabit (DMG) PHY used by IEEE 802.11ad, these are supported as optional features. However, the transport of the timestamps to upper layers (i.e., to the OS in the model of Figure 41) is implementation specific.

5.3.1.2 IEEE 1588 message transport and identification

A common issue in the transport of IEEE 1588 is the feasibility of identification of PTP messages at a given transport node without packet content inspection. The rationale is that IEEE 1588-aware transport nodes at a minimum are required to timestamp PTP-bearing packets at ingress and departure, so they are required to identify those packets. Ideally, a transport node would be able to identify PTP content by relying solely on packet header information. For example, in the conventional transport of PTP over Ethernet, a special EtherType field value readily indicates that an Ethernet frame carries a PTP message. Meanwhile, in the transport of PTP over UDP, a specific UDP destination port provides the indication. However, naturally only a few transport technologies are standardised in this aspect (IEEE 1588-2008 specifies only 6 network protocols, for instance), so an implementation-specific solution can be adopted. An illustrative ongoing discussion in this aspect is found in IEEE 1588 transport over MPLS network [118].

The solution proposed for identification of PTP messages in IEEE 802.11ad transport is based on the Higher Layer timer Synchronisation (HL-SYNC) procedure presented in IEEE 802.11-2016, Section 6.3.28. The strategy is to send PTP messages within ordinary data frames, but to use a specific group address within Address 1 field (receiver address) of the frame as a way of indicating PTP content. This allows the receiving station to immediately recognize incoming frames carrying PTP events based solely on the MAC header, so that it can proceed with corresponding actions such as taking and reporting time of arrival to upper layer. Consequently, this prevents the need for inspection of payload content, which in addition to crossing the MAC layer boundary, adds complexity and can lead to performance penalties, depending on implementation. Note that this transport strategy is only required for PTP event messages and not for PTP general messages [99], since only event messages are timestamped on departure and arrival.

While the solution of using a unique group address in Receiver Address (RA) suits perfectly well for multicast-addressed PTP messages, such as the ones mandatorily adopted in the ITU-T G.8275.1 telecom profile for IEEE 1588, a consequence of the approach is that handling of unicast-addressed PTP messages can become more complex. When transporting unicast PTP messages, one solution is to separate the individual (unicast) PTP destinations in independent groups. Nevertheless, since IEEE 802.11ad transmissions are highly directed by beamforming, it can be feasible to rely on a single pre-defined group RA and still accomplish transmission to a single destination station, i.e., effectively achieve a unicast transmission while strictly using a multicast-addressed 802.11 frame. The destination station to which the beam is directed, in this case, is resolved in the MAC based on the original destination address of the upper layer packet.

The other potential downside of using a group RA for unicast PTP transport concerns the need for address translation. Considering that a unicast packet needs to be passed from the 802.11 MAC up to the network layer as a unicast-addressed layer-2 frame, the station receiving a frame with RA equal to a PTP group address needs to translate the incoming RA back to a unicast address. More specifically, it needs to replace the incoming PTP group RA by its own local address or another known destination address. In this context, then, two possibilities emerge, either to overwrite the received RA based on a pre-configured address or to rely on ancillary information in the frame itself. As detailed next, the latter approach suits well for IEEE 802.11ad mesh transport nodes and, therefore, is the approach proposed for investigation.

The solution relies on the fact that 802.11 MAC frames having both the “To DS” (to distribution system) and “From DS” (from distribution system) flags in the MAC header asserted carry four addresses, the source address, transmitter address, Destination Address (DA) and RA. The proposition then is to transport PTP messages with these two flags (“To DS” and “From DS”) asserted, so that the original DA of the upper layer packet carrying the PTP message can always be preserved within the DA (address 3) in the frame, regardless of RA being overwritten to the PTP group RA. This is especially suitable in the context of IEEE 802.11ad mesh transport nodes, since this form of transmission (“To DS” = “From DS” = 1) is the very expected one in this case. The mesh node receiving such a PTP-bearing frame, then, can forward the PTP message based on the DA that is preserved in the MAC header. In the particular case of unicast DA, it can forward the message to the specific single next-hop destination.

5.3.1.3 Reliability in IEEE 802.11ad for timing transport

A peculiar issue in the transport of PTP over IEEE 802.11 or more generally wireless communications is the higher packet loss when compared to wireline transport. To overcome this, IEEE 802.11 itself relies on acknowledgment and retransmissions. However, the acknowledgement mechanism becomes complicated and is typically disabled when transmitting group-addressed frames, such as in the transport strategy proposed for PTP event messages. Hence, reliability needs to be considered in the proposition.

In the case of group-addressed transmissions, one solution is to rely on multicast optimisation schemes such as Directed Multicast Service (DMS), where multicast messages are sent individually to each station in the group as normally acknowledged unicast transmissions. Again, due highly directed transmissions with the DMG PHY, this can be feasible. However, if the added complexity is preferably avoided, the robustness of the IEEE 1588 protocol can be leveraged instead. In general, the protocol continues to behave normally in the event of a gap in the sequence number between PTP messages. The only concerning implication is the increased time between clock corrections in the event of packet losses, but assuming the underlying oscillators do not drift substantially in the interval of a few synchronisation periods (typically a few milliseconds), no appreciable performance degradation is expected. The trade-offs involved between the two approaches are going to be further explored, particularly by evaluating timing KPIs such as the statistics of time offset measurements when adopting each approach.

5.3.1.4 Performance Issues

A typical challenge within IEEE 1588 implementations is to apply clock corrections as quick as possible after clock error estimations are produced. Considering the model of Figure 41, a typical situation would be to estimate clock frequency and time misalignments at the IEEE 1588 application, but then send a clock adjustment command down to the timer in the TSU of the network device (in the PHY or MAC level), passing through the OS and (or) MAC layers. In this case, substantial delay can be incurred in the command, so that by the time the clock adjustment is effectively executed, the estimated misalignments can already be outdated. Besides, the estimations themselves are already outdated right when computed, as they are based on timestamps from the past, taken at the bottom layer, when the incoming PTP message started crossing the layers from the PHY up to the IEEE 1588 application.

This motivates the pursuit of reduced latency in the path that PTP messages traverse to cross layers. In this context, it is helpful to rely on QoS prioritisation. That is, for improved timing performance, PTP messages should be prioritised while passing packets from the 802.11 MAC up to device driver and network stack. The same holds for clock correction commands, if attainable. Nevertheless, it should be noted that this latency issue only affects transport nodes implementing BC functionality. This is because a TC transport node, in contrast, does not need to perform any clock misalignment computation at the application layer and, correspondingly, does not need to discipline the local clock. The only related constraint in TC is that of forwarding incoming PTP messages as fast as possible to avoid errors in residence time measurement due to oscillator drift, which again can benefit from QoS prioritisation. The performance gains due to QoS are going to be explored using timing KPIs.

A second performance issue comes from the potential delay variation perceived due to fluctuations in the frame timing recovery (and in fact also symbol timing recovery [119]) of an IEEE 802.11 receiver, as discussed in [117] [120]). The extreme case concerning frame timing is when similar peaks are observed in the preamble detector cross-correlator, as in the case of propagation paths with similar strengths (i.e., in a non-line-of-sight multipath scenario). In this case, since recovery is typically threshold-based, most frame timing recovery algorithms are likely to be confused as to which of the two signal replicas is the one where effectively the start-of-frame is. For the purposes of demodulation, this is normally not problematic, as both such replicas could likely be decoded with proper equalisation. However, for the purposes of arrival timestamping, this introduces inconsistency over consecutive packet transmissions. A potential solution in this case is to observe the channel impulse response estimation or preamble cross-correlation outputs taken in the PHY and attempt to identify when the timing instant fluctuates, such that it can be compensated in the corresponding arrival timestamp. Meanwhile, with regard to symbol timing fluctuations, the reader is referred to the framework proposed by [117].

Lastly, a third unique performance issue in IEEE 802.11 relates to the protocol support for frame aggregation. More specifically, if a PTP message is sent for transmission by an IEEE 802.11 network device and this device behaves normally as if the content was any other data, the PTP message could be lumped with other data in an aggregated MAC service data unit (A-MSDU) or aggregated MAC protocol data unit (A-MPDU). The issue, in this case, comes from the fact that a typical IEEE 802.11 implementation would timestamp the arrival of a PPDU, rather than the arrival of a specific segment of data within the PPDU payload. In the end, if the PTP message is aggregated and its position is not fixed or informed within the aggregated frame, the arrival timestamp fluctuates. The proposed solution in this case is to disable aggregation on frames carrying PTP event messages. The MAC needs to know when passing PTP data for transmission by the PHY and correspondingly disable both aggregation levels in the outgoing frame.

5.3.1.5 5G-PICTURE integration

In order to promote the integration of PTP-aware IEEE 802.11ad mesh transport nodes into the synchronisation as a service framework proposed for 5G-PICTURE, the configuration, information and monitoring APIs need to be supported. Following the layering model in Figure 41, an expected scenario would be of an IEEE 1588 application code running under an OS and relying on an IEEE 802.11ad network device with support to hardware timestamping. In this context, an independent application can be executed in the OS in order to gather local information, control the IEEE 1588 configuration and respond to a remote orchestrator in the 5G-PICTURE control plane.

In order to accomplish this, the management application would need to coordinate the information and configuration APIs of both the IEEE 1588 application code (at application layer) and the IEEE 802.11ad device itself, potentially by communication to its driver layer. For example, hardware specific properties from Table 3 such as RTC granularity can be responded to the management application by the device driver, while TC/BC support information, for example, can be fetched from the IEEE 1588 application, potentially by using standard PTP management messages routed internally through the OS.

It should be noted that the IEEE 802.11 standard itself provisions support for requesting timestamping characteristics, particularly by means of the “PLME-CHARACTERISTICS” primitive requested by the Station Management Entity (SME) to the PHY through the PHY-layer management entity SAP (PLME SAP). The response to such a request can return metrics related to the maximum time of departure and time of arrival timestamp error (i.e., “aMaxTODError”, “aMaxTOAError”, “aMaxTODFineError” and “aMaxTOAFineError”). This primitive, if implemented, can be leveraged at network device level in order to be able to pass information to a management layer, as well as any similar implementation-specific solution.

5.3.2 Synchronisation Technical component 2: Synchronisation in IEEE 802.11-based sub-6 GHz nodes

As discussed in Section 5.2, IEEE 802.11-based technologies pose several challenges for synchronisation, not only as a transport means for synchronisation signalling, but also as the target of the synchronisation itself in order to run time-sensitive mechanisms in 5G-PICTURE’s sub-6GHz transport nodes. Unlike the previous Section 5.3.1 that relies on the hardware/low-level customisations/strategies intended to improve transport of synchronisation signalling (i.e., IEEE 1588) over IEEE 802.11ad on the Typhoon module, this section is more focused on synchronisation of transport nodes (via IEEE 1588 or other means) using COTS 802.11ac/n wireless chipsets.

5.3.2.1 Involved technical approach and KPIs

Due to the limitations widely discussed in Section 5.2.1.2, Section 5.3.1 and further extended in the following section, IEEE 802.11-based sub-6GHz transport nodes do not emerge as a suitable solution for backhauling cellular access nodes implementing advanced techniques such as CoMP or carrier aggregation. Therefore, it makes no sense to measure KPIs related to communications-quality metrics (i.e., impact at radio-access level) while, on the other hand, “timing-centric” parameters become an interesting objective.

However, with the idea of exploring different applications benefiting from synchronisation such as implementation of hybrid Carrier-Sense Multiple Access/Time Division Multiple Access (CSMA/TDMA), as explained in the next sub-section, the impact of a good synchronisation precision could also be measured in terms of achieved throughput or collision probability over a wireless link.

5.3.2.2 Initial design and technical innovation

The first challenge to overcome is the synchronisation of 5G-PICTURE’s IEEE 802.11-based sub-6GHz transport nodes. Synchronising sub-6GHz transport nodes will enable advanced partitioning of transport resources to support multi-tenancy; for example, by means of distributing the air-time devoted to different tenants in a TDMA-like fashion, for which synchronisation of neighbouring sub-6GHz nodes sharing the same channel is required. Note that IEEE 802.11 access is non-deterministic since it is based on a CSMA scheme, which hampers the implementation of a precise time-schedule. This work is of special interest due to the fact that the platform used to build 5G-PICTURE’s sub-6GHz transport nodes (based on Gateworks boards with ARM architecture, cf. deliverable D3.1 [90]) is known to be prone to considerable clock skews.

Therefore, the first idea is to measure the precision of the synchronisation achieved by the sub-6GHz nodes developed in WP3 with different synchronisation sources, including GPS (or other GNSSs) receivers and the exploration of synchronisation through a secondary radio both in an out-of-band or in-band fashion. In the first case, a secondary radio based on a different radio access technology, such as IEEE 802.15.4a, for example, can be used to exchange synchronisation-related signalling. On the other hand, the presence of a low-power/low-rate secondary radio accompanying the main IEEE 802.11 radio, as envisioned by the current work of the IEEE 802.11ba task group, would enable different in-band signalling mechanisms (e.g., with the purpose of synchronisation) to co-exist with transport of data. IEEE 802.11ba equipment is not expected to be commercially available in the short term but the use of other low power receivers designed with similar purpose (e.g., receiver described in [121]) could be explored for that matter.

With regards to IEEE 802.11-based sub-6GHz transport nodes used to distribute synchronisation signalling through, e.g., IEEE 1588, it is interesting to explore the limits of the accuracy achieved by a multi-hop wireless mesh network, where CSMA-based wireless transmitters are used as transparent clocks or boundary clocks where each node in the path acts both as a slave in uplink direction and as master in the downlink (i.e., towards the farthest access node). These two lines of action will be limited by the availability of IEEE 802.11 equipment with support to hardware timestamping. Software timestamping (that is, a timestamp is recorded at the driver level when the packet is pushed to the hardware queue) is expected to provide a very low accuracy, in general, because of the contention-based access scheme; packets could remain in transmission queues for an undetermined amount of time before they are transmitted due to a busy wireless channel. However, in a clean channel (i.e., no other interfering or contending stations), access to the medium becomes near-deterministic and, therefore, software timestamping could provide enough accuracy if additional measures are considered, namely:

- Apply AC_VO (voice access category) quality of service to synchronisation packets to reduce queueing times.
- Relax (or skip) IEEE 802.11's CSMA/CA etiquette only for synchronisation packets: in this way, synchronisation packets will not observe waiting times mandated by 802.11 protocol operation at the cost of increasing collision probability of those packets.

5.3.3 Synchronisation Technical component 3: Heterogeneous synchronisation transport testbed

The wireless testbed of the NITOS facility will be exploited for the evaluation of the IEEE 1588 (PTP) synchronisation technique. Some of the aforementioned scenarios will be applied and evaluated over multiple 802.11 wireless technologies, using either the sub-6 GHz or 60GHz spectrum. The wireless NITOS testbed consists of almost 50 powerful Linux-operated machines. Each of these nodes is equipped with two 802.11a/b/g/n/ac wireless Network Interface Cards (NICs). Thus, NITOS is capable to support the creation of mesh/adhoc networks, using the one interface of each node, and the parallel operation of secondary wireless networks for the synchronisation-related signalling, with use of the second interfaces. Moreover, the NITOS nodes are equipped with 802.15.4 (ZigBee) sensors that could be used alternatively for the synchronisation-related control network. Finally, the NITOS testbed has six BWT nodes, for wireless transmissions using mmWave that could also be utilised for experimental evaluation of the proposed synchronisation schemes over the 60GHz spectrum. The utilisation of all these technologies can also be assisted by the Ethernet and OpenFlow network connecting all these nodes.

In particular, the experimentation on the NITOS platform will evaluate the performance of the synchronisation required between VNFs hosted at the NITOS nodes. These VNFs could be either virtual sub-6GHz or 60GHz nodes sharing the same channel and using TDMA, or BBUs that control RRUs performing Massive MIMO, or instances of a Cloud-RAN that uses functional split and requires synchronisation. The PTP execution at the application layer for the synchronisation of a network segment including these VNFs is independent of the underlying transport technologies used by this segment. This happens because the packets are encapsulated as Ethernet packets after leaving or before being pushed to each technology-specific driver. However, as we have already explained in previous sections, there are many challenges and problems for synchronisation at the application layer. Thus, the use of low level synchronisation techniques is required for some scenarios, which means that the special capabilities of each wireless transport technology should be exploited. The limitations and the special requirements of each solution will be explored through our experimentation in the NITOS platform.

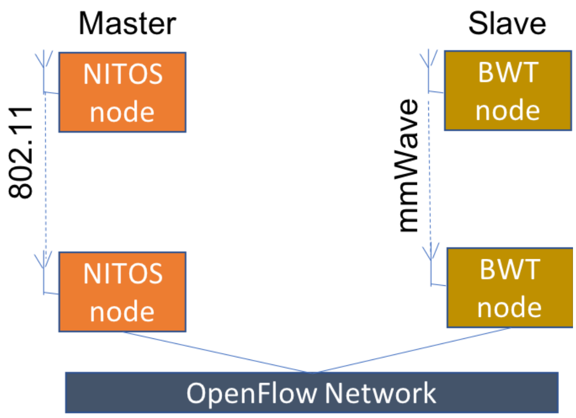


Figure 43: Synchronisation architecture for experiments in NITOS.

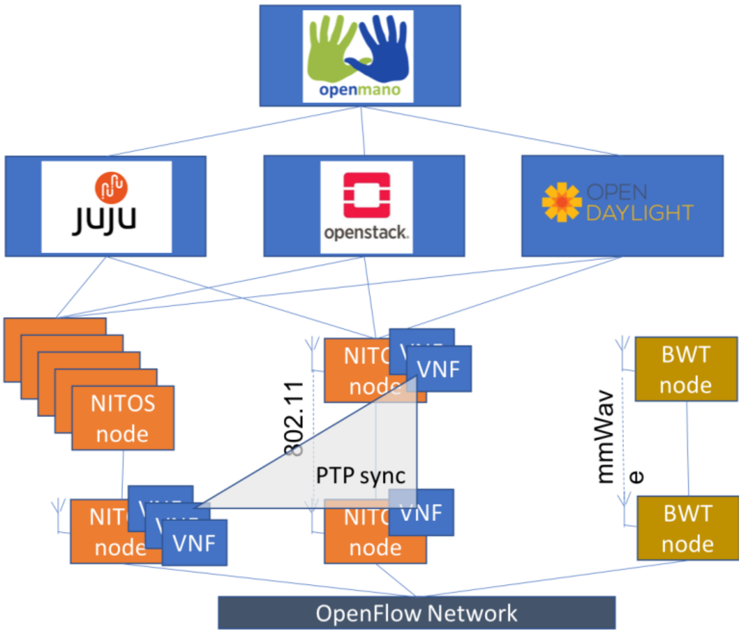


Figure 44: The NITOS platform.

The problem becomes even more challenging, especially when concerning the synchronisation over heterogeneous paths exploiting multiple networking technologies. The synchronised nodes (the master and the slave) are not necessarily directly connected, but could either be end-points of a path bridging different technology domains. For example, the following Figure 43 illustrates an example when Ethernet, Wi-Fi and mmWave are used for connecting the synchronised end-points.

The experimentation will be assisted by open source software tools existing in NITOS, such as OpenStack/Devstack [122], OpenDaylight [95], OpenMANO [123], JuJu [124], OpenAirInterface [28], Compat-wireless driver, etc. We will leverage on the work done in other WPs and tasks for deploying Network Services (NSs) in NITOS, relying on particular VNFs that are connected in a specified virtual network topology. The VNFs connected in specific sequences are developed through the service function chaining capability. The following Figure 44 demonstrates the NITOS experimentation facility, and how these tools can be exploited for the deployment of NSs, in order to evaluate the efficient synchronisation of their utilised VNFs.

5.3.4 Synchronisation Technical component 4: Synchronisation harmonizer

In the proposed converged FH/BH transport network architecture, sharing a synchronised clock among the VNFs or PNFs that are part of a tenant slice, is a critical function which requires the development of synchronisation primitives. To encompass the varied synchronisation requirements associated to different areas of the network, developing a synchronisation harmonizer becomes of key importance. The synchronisation framework associated to this entity must be able to expose to the requestor the required synchronisation levels/policies and mapping necessary for the communication.

5.3.4.1 Involved technical approach and KPIs

In 5G-PICTURE, the abovementioned synchronisation harmoniser will leverage the availability of synchronisation capabilities at the device intended for interfacing of technologies developed in WP3. The synchronisation resources become virtualised (VNFs and PNFs) and can be instantiated on demand in WP4. Previous works on synchronisation harmonizers [114] are taken as reference to develop the 5G-PICTURE synchronisation harmonizer.

Assessing the performance of the harmonizer entails the two categories of synchronisation KPIs described in Section 5.2, i.e., purely timing and radio performance metrics. Regarding the former, it seems feasible to implement it in a real testbed, where different synchronisation is provided across different technology areas within the transport network. Radio performance metrics, in turn, would require the involvement of the radio part of the network together with the transport network itself. This would require the implementation of more complex schemes aiming at an interaction between both network domains, e.g., CoMP, etc. which would fall out of the scope of the Task.

5.3.4.2 Initial design and technology innovation

Figure 45 depicts the general architecture for the synchronisation harmoniser. The harmonizer must be aware of the different synchronisation domains and their respective characteristics. The harmonizer will be responsible for coordinating the different technology domains (transport areas) present in the transport network and will be able to select and to distribute the synchronisation references throughout the network. Different strategies and algorithms will be developed, which will enable us to analyse the synchronisation quality parameters. These algorithms will be responsible for choosing the desired synchronisation configuration among the different possibilities offered. This architecture is intended to support synchronisation services (e.g., instantiation of services across multiple domains), which are configured by the synchronisation functions (VNFs/PNFs) deployed.

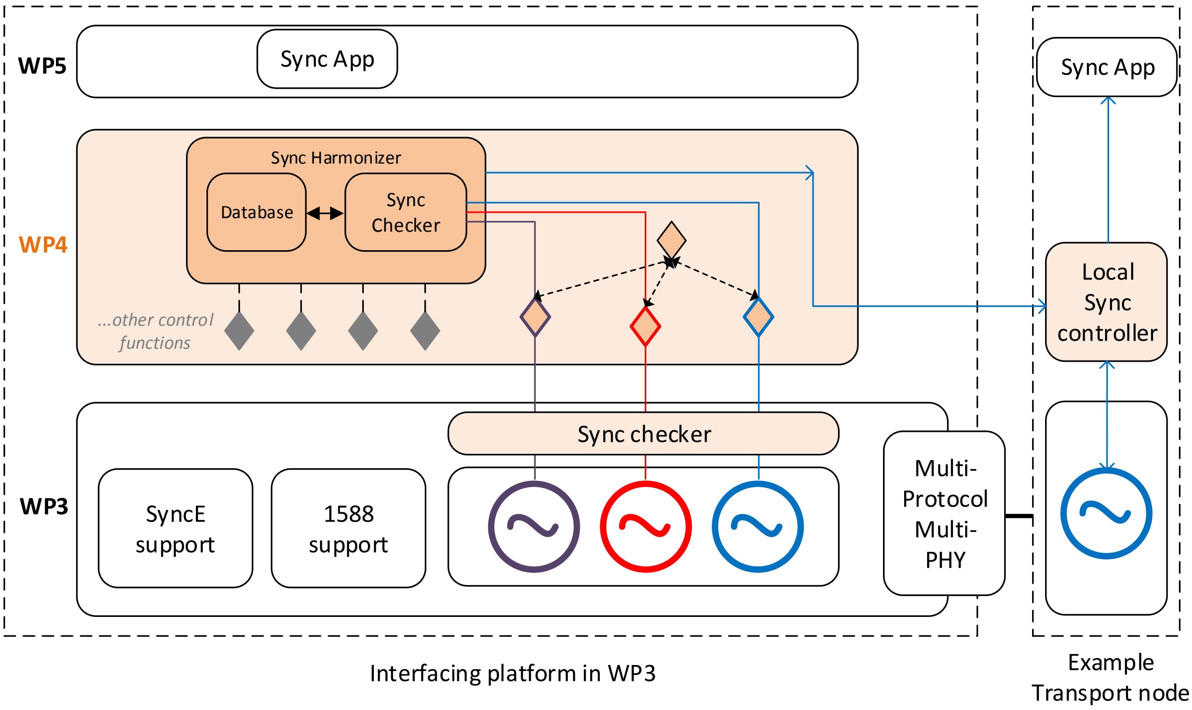


Figure 45: Sketch of the synchronisation harmonizer implemented on the interfacing platform to synchronize/coordinate multiple heterogeneous domains. Example of a transport node.

Such harmoniser consists of the following components:

- A database with real-time measurements and metrics is accessible by all entities (requestor and provider). These can be compared against an SLA and can serve to react in the event of a degraded performance.
- Synch checker, who based on the synchronisation algorithms available and the synchronisation alternatives outputs the solution to be adopted and evaluates (monitors) the "synchronisation quality".

The different transport nodes present in the network are expected to communicate with the synchronisation harmonizer, e.g., via a software application. This additional block in the transport node (plotted in Figure 45) would be in charge of collecting local measurements and to control the synchronisation capabilities (either 1588 or SyncE), being as well responsible of the interaction with the harmonizer. A possible scenario of an IEEE 1588 implementation that supports PTP management will be the following:

1. The sync harmonizer sends requests to the local sync controller in the transport node.
2. The local sync controller sends a PTP management message to the PTP application or PTP standalone module (if not run as an application in the OS).
3. The PTP application (or standalone module) receives the PTP management message and gets configured.

Regarding technology innovations, one of the novel aspects which will be a matter of study within Task 4.3, relies on how a synchronisation function can be made available to the different functions instantiated in a given transport slice. Additionally, we intend to expand previous research on this type of architecture [113] considering the unique heterogeneous context of 5G-PICTURE.

5.3.4.3 Expected outcomes

The architecture defined for the harmonizer aims at successfully identifying and adopting the optimal timing paths in real-time. To assess the feasibility and performance of the proposed solution, a series of experiments will be carried out. As an example, one experiment could consist of changing the network topology in real-time so the harmonizer reacts to this change and rearranges the synchronisation configuration.

5.3.5 Synchronisation Technical component 5: Synchronisation techniques for FH networks

In the RANs with the centralised baseband processing as depicted in Figure 46, accurate time and frequency synchronisation is required in order to achieve the high-spectral efficiency transmission and to minimize the computational complexity at the end-user devices. The accuracy targets should be chosen so that the resulting additive error due to the frequency and phase mismatch between distributed transceivers (RRUs shown in Figure 46) is insignificant in comparison to the other sources of error in the system, namely thermal noise and quantisation error due to the digitisation of analogue signals. Synchronisation is also loosely related to the FH protocol, and mechanisms are often coupled with the underlying physical transport of radio signals. This is reflected by the distribution switch which, in addition to its role in distributing digitised radio signals to and from the RRUs and the baseband processing centre, it also relays time/frequency information from an atomic reference somewhere in the network to each RRU. The atomic reference is typically a receiver synchronised to a satellite-based system such as GPS (or another GNSS), although other freely available atomic references or dedicated atomic clocks in the baseband processing centre or its network can also be used.

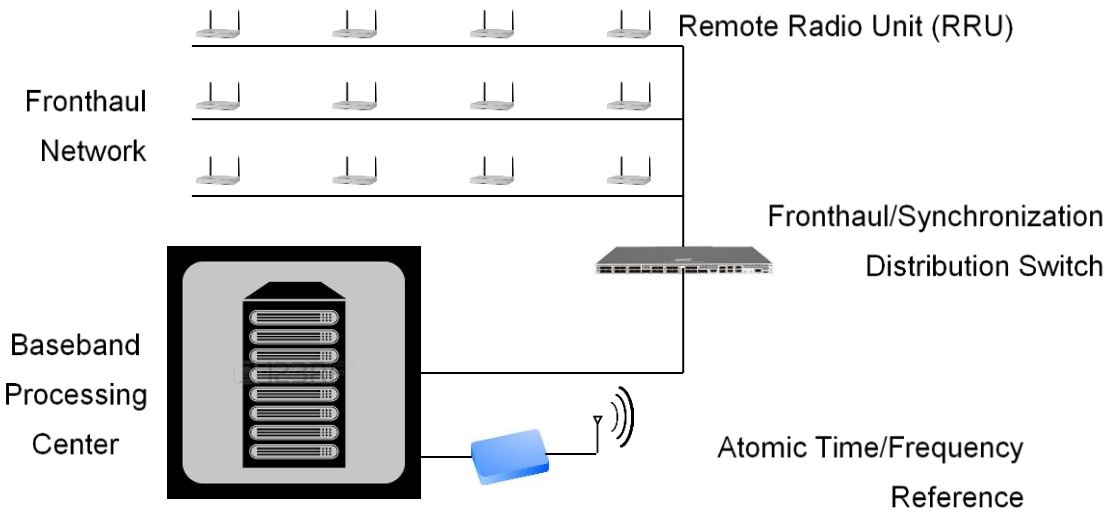


Figure 46: Example of FH and synchronisation network.

More specifically, two types of synchronisation are required in the fronthaul network. Frequency synchronisation guarantees firstly that the local oscillators in the RRU which are used to upconvert and downconvert baseband signals to the system carrier frequency are all tuned to the same reference carrier frequency. This is a necessary requirement for the RRUs to perform joint transmission and reception as a distributed antenna array. Secondly, the local oscillator used to digitize baseband signals in the RRUs also has to be tuned to the same reference for the same reason. Timing synchronisation is needed so that all RRUs are loosely time synchronous (to within 10 s of nanoseconds for 4G or 5G signal waveforms) and more importantly that they do not drift relatively to each other.

5.3.5.1 PTPv2 and SyncE Methods

In order to achieve this time/frequency distribution in the fronthaul network the most common methods on Ethernet networks are the IEEE 1588v2 [99] or the SyncE protocol [104] which both achieve accurate time synchronisation through the insertion of time-stamps in the Ethernet frames. Further, the White Rabbit extension to PTP (WRPTP) introduced in [125] can be utilised to accommodate hardware-supported mechanisms to increase PTP synchronisation accuracy. The CPRI industry standard uses a similar non-Ethernet based approach. In all cases, the time-stamps are triggered by some hardware clock source linked to an atomic reference. In the case of a PTPv2 network, this function is performed in the so-called *grandmaster* entity which inserts the time-stamps somewhere in the network. End-devices (i.e., RRUs) have clients which derive electrical timing signals from the incoming Ethernet frames. These are typically in the form of Pulse-Per-Second (PPS) signals which are used to trigger time/frequency circuits in the end devices. Note that this requires special circuitry in the end-devices. In addition to this timing synchronisation method, frequency synchronisation is achieved by deriving a reference frequency from the incoming Ethernet signals. Typical reference frequencies are 10 MHz or 30.72 MHz in the case of 3GPP networks. This requires very accurate (low phase-noise) frequency generation in both the baseband processing centre and the distribution switches in order to achieve the performance required by 3GPP standards. Moreover, the Ethernet devices are not built using commodity chipsets and moreover are costlier due to the additional synchronisation circuitry required in the end-devices which need to be coupled with the analogue RF and baseband electronics.

5.3.5.2 Explicit reference-frequency distribution

Low-cost methods in experimental research networks can avoid the use of PTPv2 or SyncE entirely and decouple synchronisation from the fronthaul distribution protocol. This can be achieved by using commodity Ethernet solutions for fronthaul distribution and an additional wired or wireless synchronisation network. Wireless synchronisation can be achieved by providing a reference over-the-air to each RRU either on a secondary channel (e.g., GPS) or using the uplink frequency. The latter reuses the radio of the communication system for synchronisation. In TDD networks, over-the-air synchronisation can be achieved by allowing each RRU to listen to each other. Clearly, a combination of these methods can also be used. For example, accurate frequency synchronisation can be achieved by distributing a reference along with Ethernet and then using less-critical over-the-air transmission between the RRUs to synchronize temporally to within 10s of nanoseconds. This is depicted in Figure 47 where a PTPv2 client is placed with the distribution switch and generates a common 10 MHz reference for the RRUs in its vicinity which is distributed in a wired coaxial network. In this case, conventional Ethernet equipment can be used for fronthaul distribution. Temporal synchronisation is achieved by over-the-air signalling between the RRUs and is reasonably simple to achieve. If the RRUs are implementing a part of the PHY layer (e.g., OFDM modulation/demodulation) this is a simple additional step during the start-up of RRU.

5.3.5.3 Fully centralised resynchronisation

Perhaps the most flexible method would be to resynchronize all signals in the central baseband unit coupled with over-the-air signalling. This would relax the need for explicit reference signal distribution altogether and greatly reduce the cost of the system, especially in an ultra-dense deployment scenario. This method puts all the processing in the central location and simplifies the electronics and timing requirements of the fronthaul network. Accurate clocks are still required in the RRUs, but they need not be quasi-perfectly synchronised using analogue electronics. The main difficulties with this method is that either time-domain signals need to be distributed to the RRUs and thus fronthaul data rates will necessarily be higher, or time/frequency adjustments are computed in the central unit and need to be fed along with the digitised fronthaul signals sent in the frequency-domain. In the latter case, time/frequency corrections are applied in an adaptive fashion in the RRUs under the control of the central unit. This would be the preferred method and an interesting subject for scientific investigation.

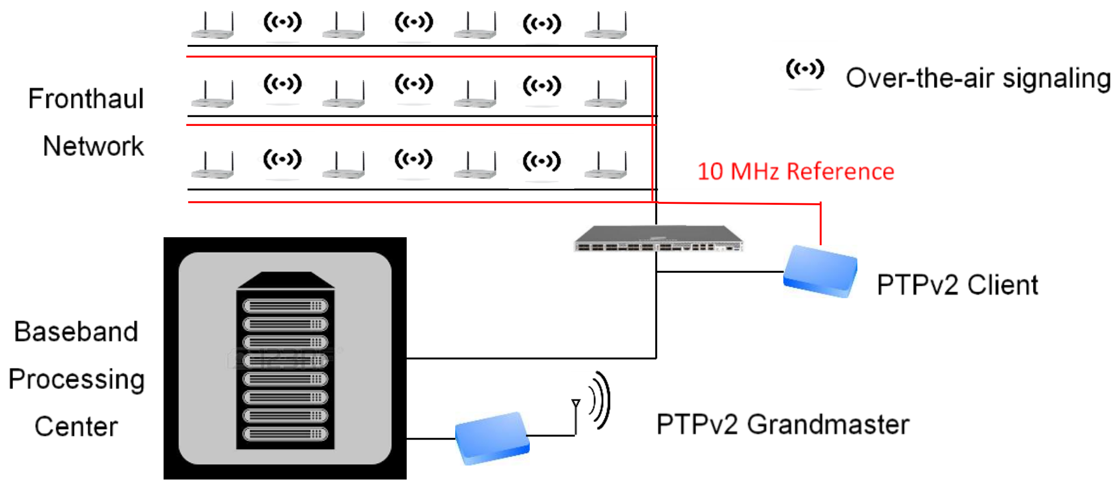


Figure 47: Example of FH and synchronisation network with addition reference-frequency distribution.

5.3.6 Technical component KPI targets

Table 11 summarises the KPI targets that are aimed to be achieved by the technical components discussed in this section. They follow the relevant KPIs listed in Table 11 and the 5G error requirements discussed previously.

Table 11: Summary of KPI targets for the synchronisation technical components.

	Time alignment error (TAE) at PTP Slave	Generated constant time error (cTE)	MTIE on low-pass filtered error over 1000 s	TDEV on low-pass filtered error over 1000 s	Peak-to-peak on high-pass filtered error	Maximum time error (Max|TE|)	Number of nodes supported from PRTC to slave for 5G accuracy
1588 over 802.11ad	N/A	±20 ns	40 ns	4 ns	70 ns	70 ns	4 (for ±130 ns accuracy)
1588 over COTS 802.11ac	N/A	N/A	N/A	N/A	N/A	100 µs	T.B.D.[8]
Heterogeneous Synchronisation Transport	±130 ns to ±390 ns (5G TDD)	N/A	N/A	N/A	N/A	N/A	4 to 20 (for ±130 to ±1500 ns accuracy)
Synchronisation Harmonizer	±130 ns to ±390 ns	N/A	N/A	N/A	N/A	N/A	N/A
Over-the-air Sync for FH Networks	±130 ns to ±390 ns	N/A	N/A	N/A	N/A	N/A	N/A

5.4 Positioning in the overall 5G-PICTURE solution

In WP5, the overall 5G-PICTURE architecture in terms of control and orchestration hierarchy is being defined. In the proposed 5G-PICTURE OS architectural framework, one of the components consists in the so-called multi-domain orchestrator, whose role is to communicate with the domain orchestrators that are assumed to be located in the scope of each individual domain. That is, the architecture relies on a combination of distributed orchestrators that cooperate with a centralised “orchestrator of orchestrators” at the top of the hierarchy. At each domain, then, the domain orchestrator interacts with domain controllers such that, together, the physical infrastructure can be decoupled from the services that are provided through it.

The architecture defined in this chapter for synchronisation as a service indeed fits in this scenario. It is expected that each individual domain is going to have its own peculiarities in terms of synchronisation support, be it due to different hardware capabilities or due to different transport technologies. Then, as highlighted for the harmonisation architecture, a local controller becomes responsible for reporting these unique capabilities towards the synchronisation harmoniser that operates based on the global view of the network. In the end, orchestration is achieved at both infrastructure and service scopes, as the domain controllers are able to be tightly coupled to the infrastructure and the multi-domain controller, in turn, is able to collect a global network view that allows the synchronisation service to be optimally launched.

Given this context, the synchronisation harmonisation layer proposed in this section is expected to be investigated alongside the development of the 5G OS framework in WP5. With regard to the orchestration of infrastructure resources, one can expect the need for a control such as that of SDN southbound APIs, namely one in which a synchronisation controller is able to configure the data plane’s behaviour in terms of forwarding and interaction with synchronisation traffic. Meanwhile, at the service level, an orchestrator needs to be able to manage, allocate and monitor the synchronisation resources along the network. These different roles are expected to be more clearly defined as the work of WP5 progresses.

[8] The number of nodes supported from PRTC to slave is 1 to 4; however, this technical component is not expected to fulfill 5G requirements described in Section 5.3.2. More inspections will be conducted in D4.2.

From another perspective, the abovementioned harmoniser requires the availability of programmable synchronisation capabilities at the PNFs and VNFs that are aimed to be used for synchronisation service instantiation. Hence, the efforts on these programmable network functions is tightly related to the activities in WP3. The physical or virtual synchronisation functions defined in this section and the corresponding investigations to be pursued in the scope of WP4 Task 4.3 are going to be developed alongside the definitions of programmable interfaces, hardware abstractions and programming models to be carried in WP3. Ultimately, these interfaces are going to be critical for testbed implementation and corresponding evaluation efforts that are going to be reported by the end of the project within D4.3.

Lastly, in general terms, Task 4.3 positions itself towards contributing to the overall 5G-PICTURE framework by addressing novel challenges in synchronisation transport. Among the proposed technical components, a key and distinctive topic refers to the ability of implementing synchronisation support in the transport technologies that are considered for 5G-PICTURE networks. This deliverable initiates the work towards investigating and defining the innovative provision of IEEE 1588 transport over IEEE 802.11ad mesh nodes in mmWave wireless links, synchronisation transport over Sub-6 GHz wireless links with COTS hardware and the alternative approach (non-IEEE 1588 and non-SyncE) for synchronisation provision to radio units over the fronthaul with over-the-air signalling between RRUs. Results collected along these investigations will enrich the collection of synchronisation tools that can be leveraged and combined for the provision of time transport services over a heterogeneous network scenario.

6 Summary and Conclusions

In this deliverable, the study of the state-of-the-art and some initial network function designs are presented to enable the disaggregated and service-orientated NG-RAN vision promoted in 5G-PICTURE. More specifically, the surveys and designs conducted in this work are separated into three respective domains including the (1) RAN domain that is related to the optimal functional split derivation, applied functional splits, and their relations to the applicable transport capabilities (Section 3), (2) Transport network domain that aims to enforce the network slicing mechanism for the considered heterogeneous optical, Ethernet/IP and wireless transport network technologies (Section 4), and (3) Synchronisation primitives that meet demands across the converged FH/BH network for network entities across multiple domains via exploiting the synchronisation harmonisation (Section 5).

These initial function designs can be viewed as the foundations to bridge the gap between the underlying physical/virtual infrastructures and the integrated orchestration and management solution provided in the 5G-PICTURE OS developed in WP5. In this sense, the works delivered in WP3 are exploited regarding the involved infrastructure components, the programmable technologies, and the exposed APIs to guarantee infrastructure's flexibility and adaptability toward the diverse needs of considered 5G services. Moreover, the designed functions can be utilised as inputs by the orchestration and management logic of WP5 to support various services and multiple tenants over a single physical network. Hence, WP5 can enforce the intelligence to adaptively (re-)allocate the network components and multi-version functions to serve the diverse service requirement to build the integrated 5G-PICTURE OS solution. Last but not least, this deliverable also provides essential technology required by the WP6 experiments to validate the considered use cases.

Our initial function design described in this deliverable will be extended and evaluated in the deliverable D4.2, and will be further integrated to the 5G-PICTURE OS system view defined in the WP5 in deliverable D4.3.

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8 Acronyms

Acronym	Description
3GPP	Third Generation Partnership Project
5G	Fifth Generation
A-CPI	Application-Controller Plane Interface
A-MPDU	Aggregated MAC Protocol Data Unit
A-MSDU	Aggregated MAC Service Data Unit
AP	Access Point
API	Application Programming Interface
ATM	Asynchronous Transfer Mode
BBU	Base Band Unit
BC	Boundary Clock
BH	Backhaul
BMCA	Best Master Clock Algorithm
BS	Base Station
BSS	Business Support System
BVT	Bandwidth Variable Transponders
CBR	Constant Bitrate
CCAMP	Common Control and Measurement Plane
CDMA	Carrier Sense Multiple Access
CDR	Clock and Data Recovery
CLI	Command Line Interface
CN	Core Network
CO	Central Office
CoMP	Coordinated Multi-Point
COTS	Commercial Off-The-Shelf
CP	Control Plane
CPRI	Common Public Radio Interface
C-RAN	Cloud-RAN
CSMA	Carrier-Sense Multiple Access
cTE	constant Time Error
CU	Centralised Unit
CWDM	Coarse WDM
DA	Destination Address
DA-RAN	Disaggregated Radio Access Network
DAS	Distributed Antenna System

DC	Data Center
DCI	Data Center Interconnect
DetNet	Deterministic Ethernet
DHCP	Dynamic Host Configuration Protocol
DL	Downlink
DMG	Directional Multi-Gigabit
DMS	Directed Multicast Service
D-RAN	Distributed-RAN
DS	Distributed System
DSCP	Differentiated Services Code Point
dTE	dynamic Time Error
DU	Distributed Unit
DWDM	Dense WDM
eCPRI	enhanced CPRI
EDFA	Erbium Doped Fibre Amplifier
eMBB	enhanced Mobile Broadband
eNB	evolved Node B
EoMPLS	Ethernet over Multi-Protocol Label Switching
EoS	Ethernet over SONET/SDH
EPC	Evolved Packet Core
EPL	Ethernet Private Line
ETSI	European Telecommunications Standards Institute
EVM	Error Vector Magnitude
EXP	Experimental bits
F1AP	F1 Application Protocol
F1oIP	F1 over IP
FDD	Frequency-Division Duplexing
FFT	Fast Fourier Transform
FH	Fronthaul
Flex-E	Flexible Ethernet
FlexO	Flexible OTN
FPGA	Field-Programmable Gate Array
FTM	Fine Timing Measurement
FTS	Full Timing Support
FTS	Full Timing Support
FWA	Fixed Wireless Access
GEO	Geosynchronous

GFP	Generic Framing Procedure
GNSS	Global Navigation Satellite Service
GPP	General Purpose Processor
GPS	Global Positioning System
GTP	GPRS Tunneling Protocol
HARQ	Hybrid Automated Repeated reQuest
HDLC	High-Level Data Link Control
HL-SYNC	Higher Layer timer Synchronisation
HSS	Home Subscriber Server
HW	Hardware
I/Q	In-phase/Quadrature
IAB	Integrated Access and Backhaul
ICP	Internet Content Providers
IFFT	Inverse Fast Fourier Transform
IS-IS	Intermediate System to Intermediate System
ISP	Internet Service Provider
KPI	Key Performance Indicator
LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Medium Access Control
MAN	Metropolitan Area Network
max|TE|	maximum absolute Time Error
MCS	Modulation and Coding Scheme
MEF	Metro Ethernet Forum
MH	Midhaul
MME	Mobility Management Entity
mMTC	massive Machine-Type Communications
mmWave	millimetre Wave
MNO	Mobile Network Operator
MTIE	Maximum Time Interval Error
MTU	Maximum Transmission Unit
NB-IOT	NarrowBand-Internet of Things
nFAPI	network Functional Application Platform Interface
NFV	Network Functions Virtualisation
NGFI	Next Generation Fronthaul Interface
NGMN	Next Generation Mobile Networks
NG-PON2	Next-Generation PON 2

NG-RAN	Next Generation RAN
NIC	Network Interface Card
NLoS	Non-Line of Sight
NR	New Radio
NS	Network Service
NSI	Network Slice Instance
NSSI	Network Slice Sub-network Instance
OAI	OpenAirInterface
OBSAI	Open Base Station Architecture Initiative
OC	Ordinary Clock
OCXO	Oven Controlled Crystal Oscillator
ODU	Optical channel Data Unit
OFDM	Orthogonal Frequency-Division Multiplexing
OLT	Optical Line Terminal
ONF	Open Networking Foundation
ONU	Optical Network Unit
OPP	Open Packet Processor
OS	Operating System
OSPF	Open Shortest Path First
OSS	Operation Support System
OTN	Optical Transport Network
PCS	Physical Coding Sublayer
PDCP	Packet Data Convergence Protocol
PDU	Protocol Data Unit
PDV	Packet Delay Variation
P-GW	Packet Data Network Gateway
PHY	Physical
PLME SAP	PHY-layer Management Entity SAP
PMD	Physical Media Dependent
PMP	Packet Manipulator Processor
PNF	Physical Network Function
PON	Passive Optical Network
PoP	Point of Presence
PoS	Packet over SONET
PPDU	PHY Protocol Data Units
PPP	Point-to-Point Protocol
PPS	Pulse-Per-Second

PRACH	Physical Random Access CHannel
PRTC	Primary Reference Time Clock
PSDU	Physical Service Data Unit
PTP	Precision Time Protocol
PTS	Partial Timing Support
QoE	Quality of Experience
QoS	Quality of Service
RA	Receiver Address
RAN	Radio Access Network
RAT	Radio Access Technology
RAU	Radio Aggregation Unit
RCC	Radio Cloud Center
RF	Radio Frequency
RLC	Radio Link Control
RN	Remote Node
RoE	Radio-over-Ethernet
RRC	Radio Resource Control
RRH	Remote Radio Head
RRU	Remote Radio Unit
RTT	Round Trip Time
RU	Radio Unit
SAP	Service Access Point
S-BVT	Sliceable-Bandwidth Variable Transponder
SCF	Small Cell Forum
SDH	Synchronous Digital Hierarchy
SDN	Software-Defined Networking
SD-RAN	Software-Defined RAN
SF	Service Function
SFC	Service Function Chaining
SFP+	Enhanced Small Form-factor Pluggable
S-GW	Serving Network Gateway
SID	Segment Routing Identities
SLA	Service Level Agreement
SML	Station Management Layer
SNR	Signal to Noise Ratio
SONET	Synchronous Optical Networking
SPE	Synchronous Payload Envelope

SR	Segment Routing
STA	Station
STF	Short Training Field
SW	Software
SyncE	Synchronous Ethernet
TA	Timing Advertisement
TAE	Time Alignment Error
T-BC	Telecom Boundary Clock
TC	Transparent Clock
TCXO	Temperature Compensated Crystal Oscillator
TDD	Time-Division Duplexing
TDEV	Time Deviation
TDMA	Time Division Multiple Access
TDM-PON	Time Division Multiplexed PON
TE	Traffic Engineering
TEID	Tunnel Endpoint Identifier
T-GM	Telecom GrandMaster
TIE	Time Interval Error
TM	Timing Measurement
TN	Transport Node
TOSCA	Topology and Orchestration Specification for Cloud Applications
TSF	Timing Synchronisation Function
TSON	Time Shared Optical Network
TSU	Timestamping Unit
TTI	Transmission Time Interval
TWSTT	Two-Way Satellite Time Transfer
UDN	Ultra-Dense Networking
UE	User Equipment
UL	Uplink
UNI	User Network Interface
UP	User Plane
uRLLC	ultra-Reliable and Low-Latency Communications
UTC	Coordinated Universal Time
vAP	virtual Access Point
vBBU	virtual BBU
VBR	Variable Bitrate
VC	Virtual Concatenation

VLIW	Very Long Instruction Word
VMiet	Virtual Machine
VNF	Virtual Network Function
VPN	Virtual Private Network
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WRPTP	White Rabbit extension to PTP