5G-XHaul

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

D2.1 Requirements Specification and KPIs Document

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Executive Summary

The 5G-XHaul project aims at building up an ambitious converged optical and wireless network solution that relies on a flexible infrastructure able to support backhaul and fronthaul networks required to cope with the future challenges imposed by 5G Radio Access Networks (RANs). The main concepts underpinning the design of the 5G-XHaul solution are:

1. **Programmable optical and wireless network elements** that enable a tight control of the transport network.
2. An **SDN architecture**, where the control plane is decoupled from the individual transport network elements and logically centralised to achieve a holistic view of the network.
3. A **cognitive control plane**, able to measure and forecast spatio-temporal demand variations and accordingly configure the transport network elements.

With this first technical deliverable, the project has established the basis for the design process of the 5G-XHaul solution. For this purpose, the project has adopted the usual top down approach methodology, also employed by other projects and Standards Developing Organisations (SDOs), of identifying relevant use cases, and deriving requirements to start the network architecture design process. However, there are two fundamental aspects that are specific of 5G-XHaul in the application of the use case based methodology.

Firstly, given the characteristics of 5G-XHaul, which is focused on the transport infrastructure of 5G networks, it has been necessary to adapt the methodology to this circumstance. In this sense, two kinds of use cases have been identified, namely end-user use cases and operator use cases. In the former case the actor that plays the role of the user is the end user consuming 5G services (either a human being or machine), whereas in the latter case the role is adopted by the operator, service provider or enterprise that obtains connectivity services from the transport infrastructure and uses the services developed and provided by 5G-XHaul.

Secondly, the requirements for 5G-XHaul do not only arise directly from the end-user use cases and the operator use cases, but also from the physical layer requirements, such as latency, jitter, and overall capacity, that will be defined by the proposed Radio Access Technologies (RATs) for 5G systems, currently being designed by other 5G-PPP Phase 1 Projects. For this reason, several potential 5G RATs technologies (like the use of massive MIMO or mmWave) have been analysed, both from a single transport link perspective as well as from an aggregation transport network point of view. From these requirements, important guidelines for the overall design of the 5G-XHaul transport network have been identified.

The main outcomes of this deliverable are:

- The **development of a methodology** that, whilst consistent with those adopted by most 5G PPP projects, addresses the specifics of 5G-XHaul, distinguishing between different types of use cases, namely **end-user use cases and operator use cases**.
- The identification of a **set of end-user use cases** that cover the expected range of 5G experiences and applications. For all of them, the relevance for 5G-XHaul has been evaluated.
- The **identification of a set of operator use cases** that are relevant for the 5G-XHaul system, in order to identify relevant functional and performance requirements that may help in the definition of the network design.
- The **analysis of the impact of the expected new functionalities to be incorporated in the new 5G RATs** on the requirements of the transport infrastructure. This analysis takes into account different functional splits that may be required to support different use cases.
- The proposal of a **first system concept** for the design of a converged optical-wireless 5G transport infrastructure that is able to support the convergence of fronthaul and backhaul, as well as the performance requirements that are associated with the new proposed 5G radio access technologies.

- The identification of a **set of Key Performance Indicators (KPIs)** that will help to evaluate the progress of the project towards its intended objectives, as well as the contribution of the project towards the envisioned 5G-PPP global performance KPIs expected by 2020.
- The **identification and definition of a set of Transport Classes (TCs)** that may facilitate the support both of the convergence between fronthaul and backhaul as well as the new physical layer requirements from 5G RATs. These TCs are considered a first step in the definition of a network architecture that provides the expected functionalities and performance without incurring unnecessary complexity and cost.

Some of the ideas developed in this deliverable are the basis for a contribution to 3GPP [1] that will be supported by the partners that participate in the SDO 5G standardisation activities.

1 Introduction

The 5G-XHaul project focuses on the transport infrastructure required to support the new envisioned 5G services. The project studies the convergence of wireless and optical transport, with a unified control plane based on Software Defined Networking (SDN), as well as the convergence of backhaul (BH) and fronthaul (FH). This deliverable is intended to provide a first description of potential use cases, and the associated requirements and Key Performance Indicators (KPIs), as well as a first system concept proposal.

In this sense, the main outcomes of the deliverable are:

- The identification of a set of 5G use cases that are used to identify requirements, both in terms of functionality and performance, that the system must support.
- The adaptation of the use cases and requirements to the specific characteristics of the 5G-XHaul area of interest, which is the transport network that support these use cases.
- The derivation of the requirements for the transport infrastructure and the initial identification of the Key Performance Indicators (KPIs) that must be fulfilled.
- A preliminary system concept proposal that provides a high level view of the architecture and capabilities of the envisioned system.

1.1 Project introduction

Next generation mobile broadband systems will have significantly increased traffic volumes and data transmissions rates, but also will address many more use cases. Systems beyond 2020 will need to be flexible enough to accommodate all the diverse use cases without increasing the complexity of managing the network. Some use cases may require multiple dimensions for optimisation, while others may focus only on one KPI. Moreover, the network has to be able to provide much more dynamic resource allocation compared to current systems. This flexibility will demand new concepts and strategies of network management and control, such as the application of SDN principles to adapt the operation of the transport network to the needs of the Radio Access Network (RAN). Moreover, the proposed architecture has to be agnostic to current and future Radio Access Technologies (RATs), being able to adapt to and anticipate future integration of RATs.

The 5G-XHaul project aims at building up an ambitious converged optical and wireless network solution that relies on a flexible infrastructure able to support BH and FH networks required to cope with the future challenges imposed by 5G RANs. 5G-XHaul will provide an efficient, reconfigurable, modular and highly scalable platform to support RAN processing, depending on different architectural solutions, network elements and devices. The future 5G BH and FH requires higher flexibility to unlock the potential of increased, more efficient and more flexible spectrum usage. The high deployment cost of optical fibre will be alleviated in 5G-XHaul with the use of millimetre wave (mm-Wave) communications for both BH and FH purposes. 5G-XHaul will also perform a joint BH and RAN optimisation, with comprehensive topology control and load balancing based on mobility patterns detected in the RAN.

Access and BH convergence is another promising method to address future 5G requirements. Thus, in the converged scenario that 5G-XHaul proposes, the same wireless-BH technology can be used for both the BH and the access link, leading to a more efficient use of spectrum resources as they can be shared dynamically. 5G-XHaul ideas can be then extrapolated to the access, e.g. mobility management, Point-to-Multipoint (P2MP) techniques, etc.

The main concepts underpinning the design of 5G-XHaul are:

4. Programmable optical and wireless network elements that enable a tight control of the transport network.
5. An SDN architecture, where the control plane is decoupled from the individual transport network elements and *logically* centralised to achieve a holistic view of the network.
6. A cognitive control plane, able to measure and forecast spatio-temporal demand variations and accordingly configure the transport network elements.

5G-XHaul will design and demonstrate a flexible network architecture that will be able to support future RAN architectures, whether these will be shaped as distributed and dense small cells networks, as centralised Cloud-RAN deployments, or as a hybrid combination of both. For this purpose a converged wireless optical network is considered and depicted in Figure 1.1.

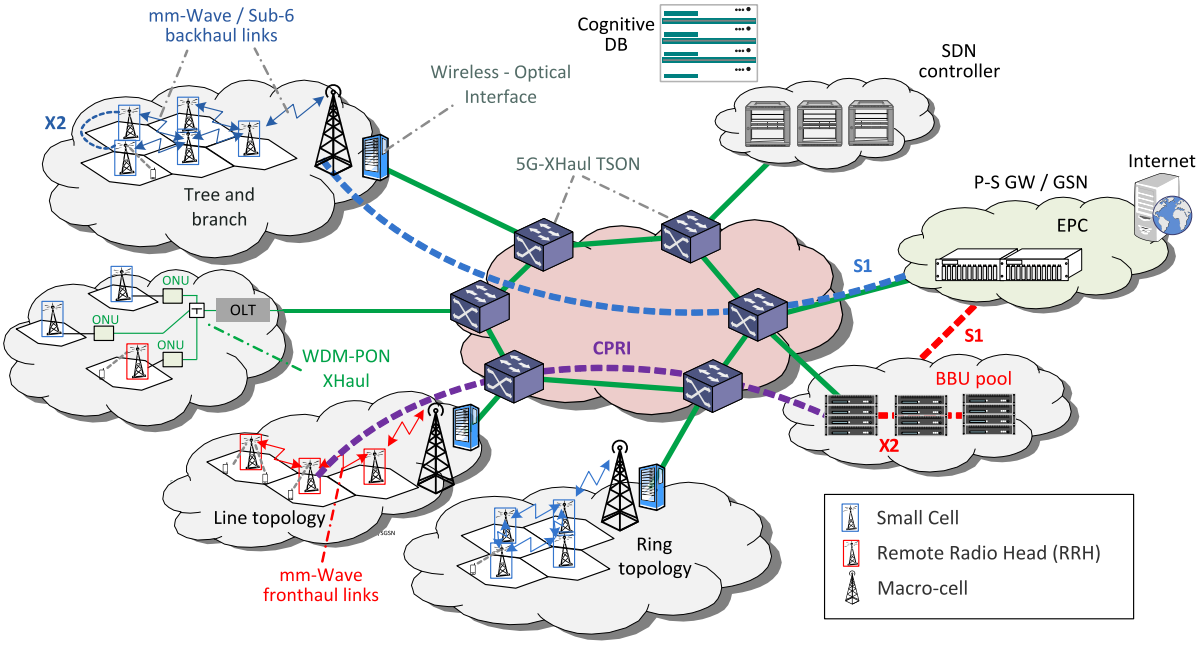


Figure 1.1: 5G-XHaul Network Deployment

1.2 Organisation of the document

This deliverable is structured in eight main chapters, plus references and list of acronyms. Beyond this introduction, Chapter 2 explains the methodology used for the design of the 5G-XHaul architecture. It follows a top down approach, similar to that of other 5G-related projects, based on the identification of relevant use cases that allow the definition of functional and performance requirements that the system designed must fulfil. The chapter also introduces the terminology used within the project.

Chapter 3 presents the set of 5G use cases that have been considered by the project as a starting point in the design process. They must satisfy the following:

- The use cases are representative of all potential 5G use cases that are being proposed in different fora.
- The use cases are representative of the different performance requirements that may be affected by the transport infrastructure designed in 5G-XHaul.

Chapter 4 provides a different viewpoint for the use cases, the one that involves the actors that implement and/or interact with the 5G-XHaul transport system. This new point of view is required in order to identify the specific requirements for the 5G-XHaul architecture. For this purpose, a set of operator use cases have been specified.

Chapter 5 looks at the state of the art of transport technologies used in mobile networks and how they can be used to support the different options for the distribution of processing functionalities in the 5G network, either on physical network entities or as virtualised network functionalities over a cloud infrastructure.

Chapter 6 indicates how the system designed by the project contributes to the achievement of the key performance indicators (KPIs) established by the 5G-PPP in the Horizon 2020 programme.

Chapter 7 provides an introduction to the 5G-XHaul system concept, that extends the vision provided in the project proposal in order to take into account the inputs coming from the rest of the deliverable. This first sketch of the system concept will be refined in Deliverable 2.2 (D2.2), entitled “System Architecture Definition”.

Chapter 8 provides a summary and the main conclusions from the deliverable.

2 Methodology

In this chapter we present the methodology adopted by the project in order to establish the use cases, requirements and constraints for the design the 5G-XHaul network architecture. For this purpose, first, the terminology used in the project is provided. Then, we introduce the need for a special set of use cases, namely "Operator Use Cases", not usually considered in the process of designing the different components of the 5G system. Finally, the different steps of the methodology are presented and justified.

It should be noticed that the methodology adopted does not significantly differ from the one used by other bodies working on 5G, such as standard development organisations or other 5G related R&D projects, it is rather an adaptation of the generic methodology to the specific characteristics of 5G-XHaul.

2.1 Definitions

Use case: A use case defines all the ways a system can be used to achieve a certain goal for a given user. Taken together the set of all use cases defines the overall usage of a system and illustrates the value the system provides. Applied to mobile systems, a use case typically describes how an end user (which may be a human or a machine) accesses a communication service through a mobile network implementation. However, in the context of 5G-XHaul, the user of the system, i.e. the transport network, specified by the project is not directly the end user consuming 5G services, but rather a mobile operator or Internet Service Provider (ISP), i.e. a *tenant*, which makes use of transport connectivity services delivered by the infrastructure developed in 5G-XHaul. Therefore, to properly capture requirements stemming from end users of the 5G system, which will also affect the transport network, and requirements stemming from the tenants directly using the transport connectivity services provided by 5G-XHaul, we distinguish hereafter two kinds of use cases:

- **End-user use cases**, which capture the interactions between end users and the overall 5G system. These use cases have received a lot of attention by various 5G related initiatives, such as NGMN [2], METIS [3] or ITU-R [4], and are now well established in the community. Notice that End-user use cases derive overarching requirements that need to be further analysed to identify their impact to the transport network.
- **Operator use cases**, which apply the definition of use case not to the 5G system as a whole but to the transport network sub-system, defined in 5G-XHaul.

Key Performance Indicator (KPI): A quantifiable metric that reflects the critical success factors of a proposed solution. KPIs reflect the goals captured by each use case, and link the proposed solutions to the intended use of the system.

Requirement: A description of what the system must achieve in order to support a given use case. The requirements provide the foundation for the system design. In the context of 5G-XHaul, the following types of requirements are considered:

- Functional requirements: Identify the kind of functionalities required in the network in order to support each use case.
- Performance requirements: Indicate values or ranges of values for network performance parameters required to achieve a good user experience under normal operational conditions.
- Other requirements: Requirements associated with the operation of the network that are not directly associated with user experience or with measurable network performance. For example, the requirement that a use case must be supported even if the network infrastructure is shared among different tenants falls into this category, as well as requirements related to energy efficiency.

Design principles: Principles derived from collective experience and expertise that guide the transition from requirements to the realisation of the network architecture.

System: Set of components that work together to provide connectivity, communications, and services to users of the system. Generically speaking, components of the system include applications, devices and networks.

User: Party outside the system, who interacts with the system in order to get communication services. It may be a person or a process in a machine.

2.2 General design methodology adopted in 5G-XHaul

The design methodology adopted in 5G-XHaul is driven by the utilisation of proposed use cases. Use cases'[1] are intended to help in the development of a system by first helping to understand how the system will be used and then driving the design of an appropriate system to meet the identified users needs. The knowledge acquired by the analysis of use cases is translated into a set of requirements that identify the functionality and the performance to be supported by the system. The design process then consists in finding the best technical solution supporting the identified requirements both from a technical and economic viewpoint.

The proposed methodology involves the following steps:

1. First, the main end user use cases for 5G systems are collected for description and analysis. For this purpose, the project has researched the state of the art on 5G use cases, which have been defined by numerous sources such as NGMN [2], 3GPP [5], ITU-R [4], and 5G-PPP [6].
2. From the analysis of the selected set of 5G use cases, we derive requirements that directly impact 5G transport networks. We distinguish between functional requirements, performance requirements and other requirements, as indicated in Section 2.1.
3. From the End-user use cases and their requirements, operator use cases are derived, which define the interactions between the 5G-XHaul system and its users, e.g. a tenant. The need for this additional step is explained in Section 2.3. The operator use cases are targeted to identify additional transport network requirements, both in terms of performance and functionality.
4. Finally, in addition to to End User and Operator use cases, the state of the art of transport technology, operational requirements, and the chosen design principles are considered together in the definition of the network architecture.

Figure 2.1 illustrates the adopted methodology followed to achieve a first definition of the 5G-XHaul transport network concept, highlighting in blue the aspects covered in this deliverable. In further deliverables this definition will be refined from the requirements and technology possibilities provided by 5G-XHaul consortium members.

[1] Use cases have a broader scope than just capturing requirements, as they can also be used for analysis, design, planning, estimation, tracking and testing of systems.

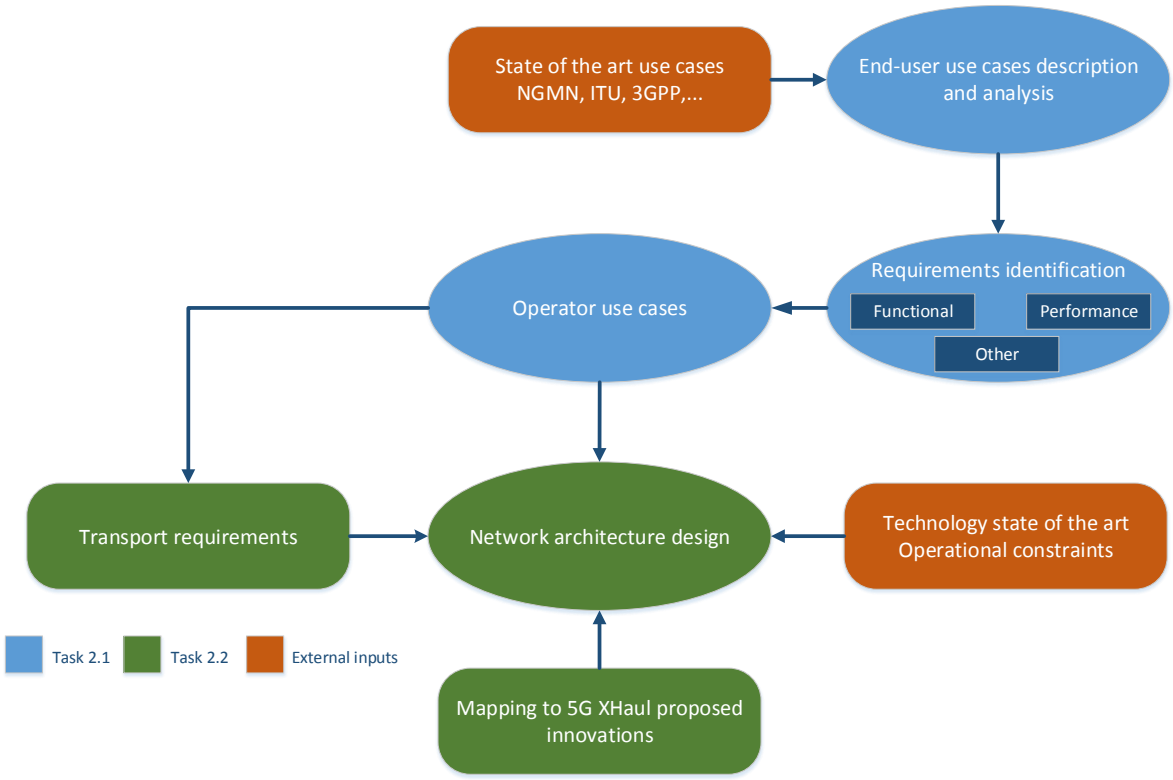


Figure 2.1: Flow diagram representing the 5G-XHaul design methodology

2.3 Specific methodological aspects considered in 5G-XHaul

As previously mentioned, the use case based methodology intends to guide the development of a system by defining how the system will be used. Consequently, the identification of the user becomes of paramount importance in order to apply the methodology in the design of the 5G-XHaul network architecture.

In the case of 5G-XHaul, the user of the system specified by the project is not directly the end user consuming 5G services (either a human being or machine), but an operator, service provider or enterprise that obtains connectivity services from the transport infrastructure and services designed in 5G-XHaul. In addition, and without loss of generality, it is assumed that conceptually the transport infrastructure defined by 5G-XHaul is operated by a specific actor that may differ from the actor directly offering 5G services to end users.

Figure 2.2 introduces 5G-XHaul specific terms to identify the involved actors as well as their interactions with the system being designed.

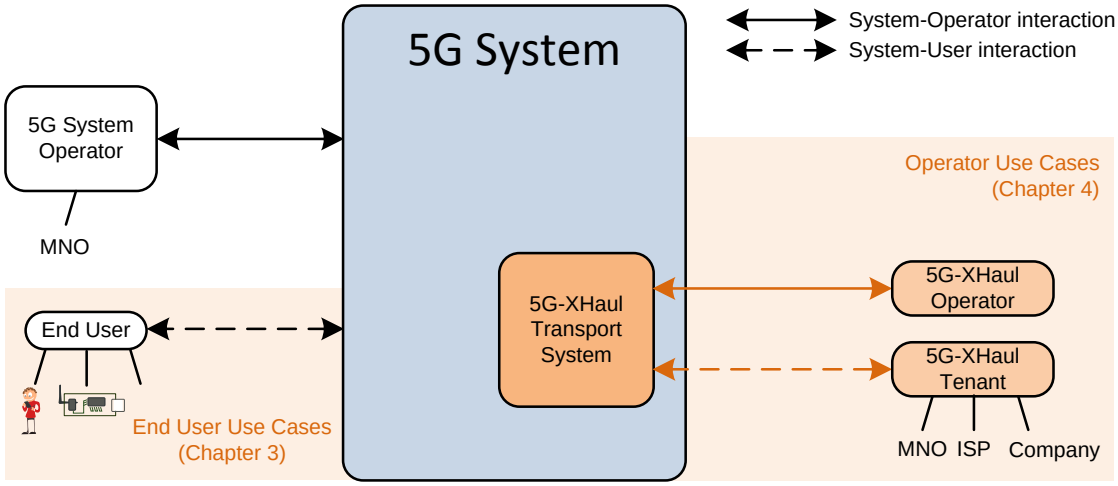


Figure 2.2: Actors interacting with 5G-XHaul transport system

Figure 2.2 identifies two relevant systems:

- The **overall 5G System**, broadly comprising the RAN, Transport, Mobile Core and Service segments
- The **5G-XHaul Transport system**, which corresponds to the Transport segment of the overall 5G system, and is the main object of study in 5G-XHaul. Notice that the 5G-XHaul Transport system cannot be considered in isolation because the requirements derived from the intended uses of the overall 5G System have a cascading effect on the 5G-XHaul Transport system.

Figure 2.2 also depicts the different actors and the way they interact with the previous systems. In particular, two main types of interactions are identified:

- A **System-User interaction**, signalled by a dashed line in Figure 2.2, which describes the use of the system by the actor that receives a service from the system.
- A **System-Operator interaction**, signalled by a solid line in Figure 2.2, describing the use of the system by the actor that provides services over the system.

According to the aforementioned systems and interactions, four main actors are identified in 5G-XHaul:

- **End User**: The End User is the actor that receives a service from the overall 5G System. The End User does not have a direct interaction with the 5G-XHaul Transport system. However, the requirements derived from the use that the End User makes of the overall 5G System will indirectly impact the 5G-XHaul Transport system. In a practical setting End Users are, e.g. smartphone users, tablets, wearables, or sensors connected to a 5G network.
- **5G System Operator**: The 5G System Operator, is the operator providing 5G services to end users. Within 5G-XHaul, it is considered that the 5G System Operator does not directly interact with the 5G-XHaul Transport system. In a practical setting a 5G System Operator could be a Mobile Network Operator (MNO) offering 3G, 4G and 5G services.
- **5G-XHaul Tenant**: The 5G-XHaul tenant is the user of the 5G-XHaul Transport system, which receives connectivity services over the transport network. In a practical setting a 5G-XHaul tenant could be a MNO leasing BH connectivity, a company connecting enterprise branches, or an ISP interconnecting several data centres. Notice that a 5G System Operator may also act as a 5G-XHaul Tenant.
- **5G-XHaul Operator**[2]: The 5G-XHaul Operator is the actor who provides services over the 5G-XHaul Transport system. The users being serviced by the 5G-XHaul Operator are the 5G-XHaul

[2] 5G-XHaul Tenant and 5G-XHaul Operator would be equivalent to the 5G Transport Network Tenant and 5G Transport Network Operator in a generic 5G system.

Tenants. In a practical setting the 5G-XHaul operator is the entity owning 5G-XHaul infrastructure that offers connectivity services.

As mentioned previously, several of these actors could be instantiated by a single business agent. For example, a MNO owning transport infrastructure could act as 5G System Operator, and 5G-XHaul Operator.

It can be argued that operator use cases can be derived directly without going through the phase of identifying End User use cases and associated requirements. However, it is clear that value from a system is only generated if it is actually used. It is therefore important that operator use cases can be mapped to actual requirements derived from end user use cases, since implementing functionalities that are not going to be used would be detrimental to the system value.

In terms of KPIs, the parameters selected and their values should be consistent with the expected user experience and the applications supported. In the case of 5G-XHaul it is important to identify what is the contribution of the transport network to the end-to-end (e2e) values. As an example, in Figure 2.3, the different contributions for e2e latency in the network are represented for two different services.

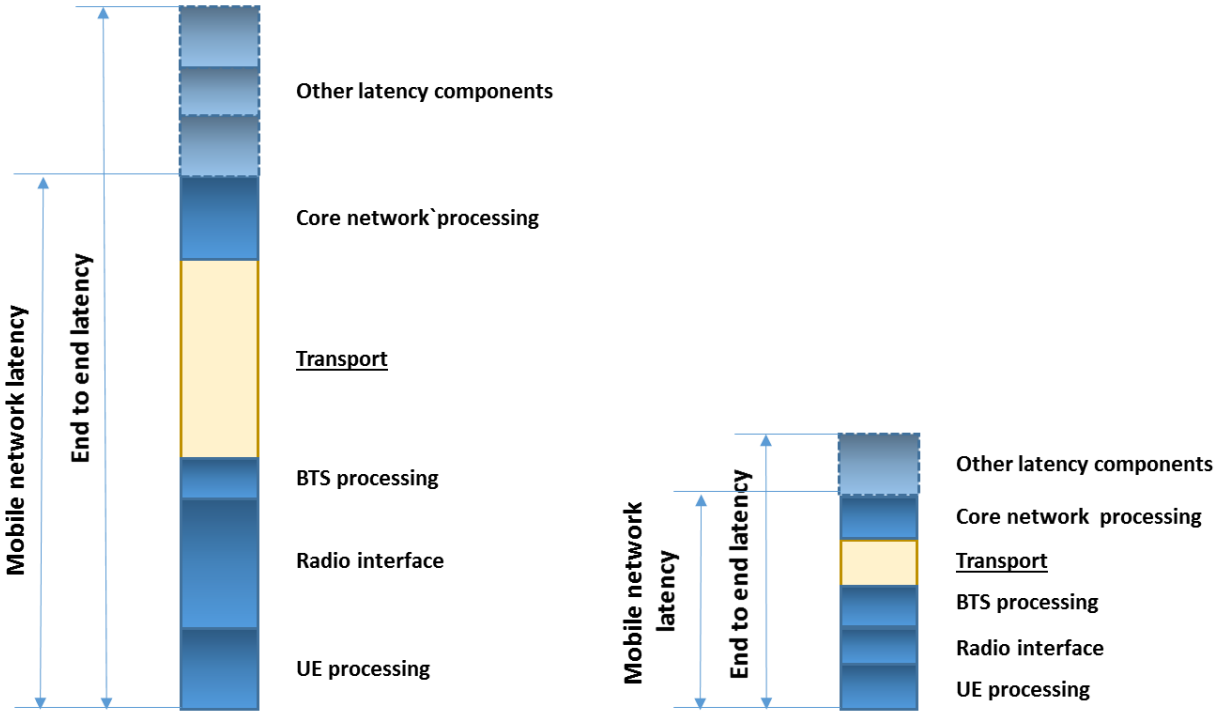


Figure 2.3: Illustrative latency contribution by transport network for two example services

The bar on the left of the figure may represent the e2e latency budget associated with massive IoT services, while the bar on the right may be the one associated with applications that require very low latency, like traffic safety and control of industry processes. The transport network contribution in each case should be consistent with the overall latency requirements and the contributions coming from different processes involved in the provision of the service. Certain flexibility (e.g. implementing different functional splits), and trade-offs are feasible to match the capabilities of the different elements of the network infrastructure in order to meet the e2e target KPIs.

3 End User Use Cases

The 5G-XHaul architecture aims at providing future networks with the required flexibility to cope with most stringent requirements for network performance and consistent user experience as well as with a wide range of existing mobile broadband use cases and their evolution along with the countless emerging 5G applications. In this chapter the End User use cases selected by 5G-XHaul are presented and described.

3.1 End User Use Cases selected

Taking into account the representative example use cases for 5G currently available in the literature (e.g. those developed by NGMN [2], 3GPP [5]), as well as in the context of 5G projects such as 5G NORMA [7] and METIS-II [3]), 5G-XHaul adopts the following list of use cases, as most relevant. Even though these use cases are not the only ones to challenge the key innovations of the 5G-XHaul solution they lead us towards the system architecture design through the elaboration of the widest possible range of system and user requirements:

1. Cloud Service offerings, including heavy data storage, retrieval, sharing, e.g. mobile/smart office data/services for business users, personal content (Ultra High Definition (UHD) videos, photos) for individuals
2. High Speed Train and Vehicular data services (e.g. internet/infotainment)
3. Intelligent Transport Services, focusing on safety applications to drivers
4. Large Number of Sensors and Actuators with relatively low data traffic requirements, e.g. smart cities applications such as environmental monitoring, smart transportation & traffic monitoring systems, smart building/ home/agriculture/metering, smart wearables
5. Medium Number of Sensors with high data traffic requirements, e.g. surveillance for buildings, nature protected areas, remote facilities including mobile Augmented Reality applications
6. On-line Gaming
7. Tactile Internet, e.g. precisely controlling a drone in a windy environment
8. Communications Support in case of Natural Disaster Occasions (e.g. earthquakes, tsunamis, floods)
9. Public Safety Communications including critical video applications support
10. m-Health Applications, including remote surgery, health care remote monitoring, remote diagnosis/virtual visit
11. Industrial Control and Factory Automation
12. UHD Video/Photo Sharing in Heavily Crowded Spots (e.g. stadium, concerts)
13. TV Programs Broadcasting over 5G offering UHD experience
14. Distributed Virtual Orchestra, meeting the musicians' requirements when performing a musical piece, each residing at different remote locations.

It is important to assess that these use cases are representative enough of the panoply of use cases identified for 5G. Different Standards Developing Organisations (SDOs) like ITU-R [4] or 3GPP are considering the grouping of specific use cases into more general sets that share common characteristics from a technical point of view. The most usual ones are (taken from [4]):

- Enhanced Mobile Broadband.
- Massive Machine Type Communications.
- Ultra-reliable and Low Latency Communications.

Each of these categories is linked to a certain dominant technical feature (e.g., number of devices connected or maximum latency) which is considered as the most distinctive for each set. It is thus important that the use cases selected in 5G-XHaul cover the whole range of technical features. In Figure 3.1 a

graphical representation (taken from the 5G NORMA project [7]) of the use cases is provided, taking into account the number of devices that need to be served on a per eNB basis (device density / eNB), the throughput required by the application itself and the latency/reliability needs[3].

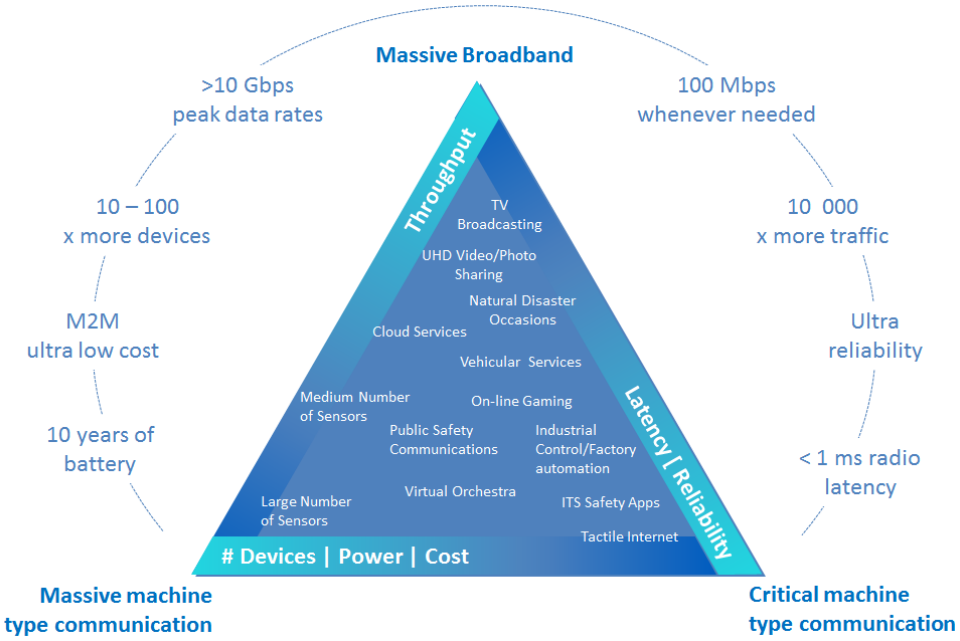


Figure 3.1: 5G-XHaul Use Cases categorisation according to the ITU-R/5G NORMA framework

It is clear in Figure 3.1 that use case (UC) 8, 12 and 13 belong to the bandwidth hungry applications, while UC 3, 7 and 11 exhibit ultra low latency requirements, and UC 4 requires the support of a massive number of devices.

3.2 Detailed description of use cases

In this section the use cases selected are described, while the main requirements (functional, performance related, etc.), potential constraints/restrictions and challenges are highlighted. In addition, the innovation that the 5G-XHaul solution will bring to the support of these use cases is underlined.

Use Case 1	Cloud Services
Type	End User Use Case
Goal/Objective	To support Cloud Services, which entail high throughput-demanding mobile services and/or heavy data management, in a ubiquitous and efficient way.
Description	Nowadays, Cloud Services constitute a rapidly evolving Information Technology (IT) domain, ranging from private cloud services (such as remote storage, hosting, back-up, retrieval of personal high volume data/material e.g. videos/photos) to business cloud services (such as specialised distributed applications, centralised storage, backup, retrieval of high volume business data/material, mobile/smart office services e.g. office collaboration based on data sharing, etc.). The users may be static or on the move, possibly at a high speed, and in any case they need ubiquitous and efficient access to their data wherever they are.

[3] In the figure, the Massive Broadband category maps to ITU's Enhanced Mobile Broadband, while the same happens with Ultra-reliable and Low Latency Communications and Critial Machine Type Communications.

Use Case 1	Cloud Services
	The specific service requirements (e.g. in terms of data volume exchanged over the network, upload/download bitrates and tolerable delays) are determined by a variety of factors such as: specific personal or business activities, the location and number of participating users, service quality requirements, etc.
Requirements	Functional: • The network shall be able to reconfigure itself depending on traffic demands and user's mobility characteristics/requirements. • The network shall be able to reconfigure its resources by utilising appropriately nodes of different access technologies and network layers (macro-/microcells). • The network shall be able to prioritise the communication services of certain traffic (e.g., premium services/users). • For services that involve asynchronous exchange of bulk data (periodical back-up of business terminals, personal cloud services synchronisation/backup, etc.), the network shall be able to take advantage of the low traffic time-windows for data transfer. Performance: • The network shall serve the peak traffic demands anytime. • The network shall be able to reconfigure itself within strict time limits in order to guarantee high mobility for speeds even exceeding the 250Km/h (e.g. a user requesting cloud services while traveling by train/car).
Constraints/ Restrictions/ Challenges	• Network reconfiguration for the support of peak traffic demands without over-dimensioning. • Effective network reconfiguration implies the utilisation of real-time and/or historical traffic data.
Relevance within 5G-XHaul	The support of mobile Cloud Services ubiquitously at anytime and anyplace, would require network resource over-dimensioning which is highly inefficient, considering that traffic exhibits periodic/occasional patterns. 5G-XHaul will support the implementation of this use case by providing a unified BH and FH infrastructure that will allow flexibility in reconfiguration and reallocation of resources and functionalities to support high data volumes while fulfilling the QoS/QoE needs and avoiding network over-dimensioning.

Use Case 2	High Speed Train & Vehicular data services
Type	End User Use Case
Goal/Objective	To provide high throughput, low latency mobile broadband services to users using public transportation (buses, trams, trains, high-speed trains) and/or taxis and cars.
Description	With the increasing dominance of WLAN in meeting smartphone data needs for indoor users, an important area for mobile broadband (i.e. using cellular networks) is the provision of services to users travelling in cars, taxis or public transportation media. Especially in the latter, users are free to use the main internet applications, including video, the dominant traffic type today (and projected into the future). In many cases, the vehicle represents a moving hot-spot, which cannot be handled by traditional cellular design.

Use Case 2	High Speed Train & Vehicular data services
Requirements	Functional: • RAN shall provide connectivity to end-users, either directly from an external base station or using an indoor cell or WLAN. Service interruption as the user or moving hot spot is handed off between different base stations shall be undetectable (seamless service provision). All internet services should be supported along with VoIP services (e.g., voice, video conferencing). The transport network shall provide support mechanisms to implement seamless handover in high speed scenarios • Service should be maintained or degraded gracefully when there is congestion (for example, in a traffic jam for car users, or when pulling into a busy station for train/bus case). • Service should be maintained in tunnels/ underground areas. Performance: • Average/peak user data rates/performance should be equal to that expected by pedestrian users.
Constraints/ Restrictions/ Challenges	Challenges have been described above in general terms. Additional considerations are: • Many vehicles move in straight lines (railways, highways) requiring linear cells. Transport technologies have to be designed considering these environments. • To provide connectivity to a moving hot-spot requires either wide-area coverage antennas or directional antennas with fast beam tracking. • Frequent handovers by users in a moving hot-spot can induce signalling storms.
Relevance within 5G-XHaul	Current situation (Long Term Evolution – LTE): • Top-end cars include LTE connectivity (with in-car WLAN). • Buses use LTE BH (with in-bus WLAN). • Trains do likewise. Operators have deployed cells to cover high speed lines. • Moving LTE relays have been studied by 3GPP (but not standardised). • LTE is required to support speeds up to 350km/h or 500km/h, depending upon the frequency band. Relevance to 5G-XHaul: In dense 5G deployment, it will be important to be able to predict traffic variations and power-up small capacity cells on demand. RAN design needs to allow flexibility to move resources to meet variable needs (especially with high volume transit, like trains). Pooling of resources (C-RAN) is one approach. The transport network is also a key part of this RAN flexibility, and SDN is a promising approach to tackle this. Wireless BH with steerable antennae is one interesting way to handle moving hot-spots.

Use Case 3	Intelligent Transport Services (including Safety Applications)
Type	End User Use Case
Goal/Objective	To provide advanced Intelligent Transport Services (ITS) innovative services / applications necessitating the exchange of information in real-time under

Use Case 3	Intelligent Transport Services (including Safety Applications)
	strict delay constraints among the vehicles.
Description	On top of infotainment services that could be offered (such as web browsing, video streaming, social cloud services, file downloads), a wide range of ITS safety related services can be envisaged: • Real time positioning of vehicles moving in the vicinity (distinguishing direction of movement, within a certain distance depending on the speed). • Detailed information (e.g. speed, distance, acceleration/deceleration) regarding the vehicle in front (in the same lane). • Visual and/or audio alerts in case of an imminent collision. • Safety hints/warnings to drivers (traffic/accidents/navigation). • Live streaming content ("See-What-I-See") from the vehicle in front (same lane, within a certain distance depending on the speed). • Hazardous event and obstacle recognition, e.g. see stopped vehicle ahead in dead spot, vehicle ahead moving with an extremely slow speed. • Personalised "time to destination" based on driver profile/behavior (average speed, average number of line changes, etc.) and current traffic statistics. Additional applications could include the automated upload of HD video/audio streaming to the nearest PSAP (Public Safety Answering Point) in case of an accident. The provisioning of vehicle related information (timestamp, location, speed, bearing, altitude, acceleration/deceleration etc.) may be communicated either directly (D2D) to other vehicles or via 5G infrastructure.
Requirements	<u>Functional:</u> • Cooperative automotive services require availability, reliability and low latency, especially in safety-related services. • Cooperation between different network operators. • Ability to handle high data traffic and prioritise based upon service required. <u>Performance:</u> • In general, latency required should be less than 50 ms • For safety automotive services latency should be less than 5 ms • Throughput on a per vehicle basis depends on the application itself (high throughput for infotainment services, low throughput for safety related services)
Constraints/ Restrictions/ Challenges	The main challenges in this scenario are: • Vehicles' positioning accuracy below 0.5 m (especially in cases that GPS is not available) • Investigation of different mobility scenarios and user density (i.e. urban area/highway/etc.) • High QoE (reliability, availability, high throughput, extremely low latency)
Relevance within 5G-XHaul	5G-XHaul will support the implementation of this use case by: • Deploying flexible unified BH and FH networks • Considering different user density and user mobility scenarios • Efficient functional splits that can help handling and prioritising traffic

Use Case 3	Intelligent Transport Services (including Safety Applications)
	better, and therefore decreasing latency and increasing users' QoE overall.

Use Case 4	Large number of sensors and actuators with low data traffic
Type	End User Use Case
Goal/Objective	To accommodate a huge number of sensors (thousands of them per base station) providing monitoring, tracking and alarm handling mainly in urban areas.
Description	One of the key use cases which are envisioned to be part of 5G is the massive deployment of sensors. These sensors can be defined as low power, low cost and low energy devices (e.g. smart meters, smart cities, environmental monitoring, and agriculture) and can be used for various applications. This use case takes into consideration two scenarios: (a) periodic measurements / monitoring and (b) asynchronous event-triggered traffic (alarms, power outage). In particular, as defined by NGMN [2], 3GPP [5] and METIS [8], there can be various types of sensors with diverse requirements. Some possible applications of this use case mainly for object tracking are highlighted: • **Sensors to monitor product failure and expiry**: In this category we may have some tools (e.g. drills) which are subject to failure or other products that might expire (groceries etc.). Hence the communication with this type of sensor is essential to prevent malfunction or expiry. • **Sensors to monitor fragile and sensitive products**: Fragile (e.g. bottles of wine) or sensitive (e.g. pots) need to be monitored to ensure certain quality and send an alarm if this is not the case. • **Sensors that collect statistical information from products**: The collection of statistical data from a company which deploys sensors might increase performance, usability and energy efficiency of the product. • **Sensors to prevent theft of expensive products**: For example hand-bags or jewellery, where communication nodes could raise an alarm in case of unauthorised movement. • **Smart wearables**: numerous ultra-light, low power sensors to be integrated in clothing. These sensors can be used to measure environmental and health attributes, e.g. pressure, temperature, heart rate, breathing rate and volume, skin moisture, etc. Other examples of use cases for the monitoring of, e.g. environment, materials, may include: • **Smart agriculture**: Some promising applications of sensors in modern agriculture [9] can be for: equipment monitoring (e.g. tractors, pumps can be monitored to check condition, location etc.), precise agriculture (remotely observing, measuring and monitoring crops and equipment using real time data.), environmental monitoring (observing the negative impact on environment.), livestock and fishery management (helping farmers gain precise information about the health and well-being of their livestock) • **Material monitoring**: sensors can be deployed in various types of cases (e.g. wind turbine, trains, buildings) to monitor vibrations and other early indications for potential material failure.

Use Case 4	Large number of sensors and actuators with low data traffic
	• **Smart Cities**: sensors can be deployed in Smart-Cities [10] to improve the living quality of their rising populations in urban areas, while keeping the cost, resource, and process efficiency of cities high. Some key examples of use cases can be applied in Smart Transportation and Traffic Monitoring (e.g. for avoiding congestion) and Smart buildings / homes (sensors/actuators for automation and security applications)
Requirements	Functional: • The network should be able to prioritise the communication services for certain groups, based on different type of traffic (periodic vs. alarm). At the same time, in case of emergency it should be possible to block devices to prevent the network becoming unusable. • New group-based control plane functionalities (e.g. for location management) might be required to cope with the large amount of sensors. • The network should be able to discover the topology of the networks that may have been established between the devices. • The network should provide mechanisms for avoiding congestion situations. Performance: • The network should be able to support a very high number of connected devices, while controlling their activity in order to preserve energy and preclude congestions. Number of devices will be 10-100 times more compared to the current status. According to [8], the goal of 5G is to provide connectivity to 300,000 devices per cell. • Minimum possible signalling overhead to ensure low latency in C-Plane (e.g. idle-to-connected). Other: • Long battery life (on the order of 5+ years) of the wireless device • Low cost for the wireless device • 99.99 % coverage
Constraints/ Restrictions/ Challenges	• The coexistence of massive sensor deployments with other 5G applications (mainly human type communications) will pose some questions regarding the priority handling, resource allocation, group management and possible synergies that might be required between applications.
Relevance within 5G-XHaul	• The current 4G deployments might be inadequate to cope with the huge number of sensors. • Flexible BH / transport network and SDN-based control plane will be necessary to meet the periodical and unpredicted demand from millions of sensors in a cost and energy efficient manner. • Event-based traffic may require reconfiguring the transport network.

Use Case 5	Medium number of sensors with high data traffic
Type	End User Use Case
Goal/Objective	To accommodate a medium number of sensors (hundreds of them per base station) generating high loads of data traffic providing monitoring, tracking and alarm handling.
Description	Several applications will require sensors producing high volume of data traffic, while the density of these sensors will not be as high as the applications with ubiquitous sensors. Such applications are: • Video surveillance for buildings/outdoors: Low resolution for counting objects, high resolution for security purposes including features such as face-recognition. Remote operation of Pan-Tilt-Zoom (PTZ) cameras will involve interactivity, hence low latency will be required. • Firmware updates of the sensor nodes can be critical when a firmware bug compromising their correct operation or posing a severe security breach is found out. Such traffic is not expected to be frequent, however, might create high volume of data. • m-health applications can generate high volume of data based on the "sensors" that are in use (e.g. 4K camera video streaming in case of remote surgery). • Augmented reality requires the communication of big volumes of data through the use of several sensors. • Smart grid applications, which consider cellular connectivity of data concentrators of smart meters also generate high volume of data.
Requirements	Functional: • Macro cells providing service to outdoor video surveillance applications, especially in remote areas (e.g. nature reserves, isolated facilities), shall support several hundreds of devices simultaneously generating high uplink traffic loads. • The network should be able to provide downlink broadcast mechanisms to distribute heavy firmware updates efficiently to hundreds of simultaneous receivers per base station. • Based on the type of the application data, different QoS requirements should be satisfied. For example, in the smart grid case, if an alarm occurs, this information should be sent with the lowest latency possible. However, periodic data does not have a specific latency requirement. Performance: • Most video surveillance applications do not require high quality image and use H.264 or H.265 (Base Profile level 2 or less) coded video at 6-10 fps. This translates to average uplink traffic of 0.5 Mbps and peaks of 2 Mbps per camera. • More sensitive surveillance applications require a higher video quality, which can be achieved by H.264 or H.265 (Base Profile level 3 or less) at 20-30 fps. In this case, each camera generates an average of 6Mbps and peaks of 10 Mbps. • Interactivity of remote PTZ camera operation requires latencies of less than 200 milliseconds. • Current high-end 4K cameras that can be used for augmented reality requires 300 Mbps (using H.264) at 30 fps • Smart grid application requirements vary based on the response time decided by the utility company and the number and type of activities that require communication. Transfer rates up to 70 Mbps could be

Use Case 5	Medium number of sensors with high data traffic
	necessary while latency for alarm messages should be in the order of 5 sec[4] . Other: • Some sensors are expected to be sustained by batteries or a combination of batteries and power harvesting and, therefore, the network should be able to keep energy consumption of devices at minimum and allow long sleeping/doze periods (e.g. cameras activated only upon movement detection). • Event based activation of sensor devices can trigger sudden peaks of traffic.
Constraints/ Restrictions/ Challenges	• Sensor traffic may be very heterogeneous in terms of requirements, therefore the transport network should support different levels of priorities to appropriately serve this traffic. • Sensor traffic may not be continuous, which opens up the opportunity of reducing energy consumption by means of shutting down links in the transport network. • Sensor devices may be deployed in places where wired or wireless Line-of-Sight (LoS) transport may not be suitable. Wireless Non-Line-of-Sight (NLoS) is a key technology for this use case. • In some cases the sensor device may be a mobile sensor. • For critical applications, e.g. face recognition, m-health, a very reliable transport infrastructure is required.
Relevance within 5G-XHaul	Currently this use case is addressed either with wired or dedicated wireless P2P links. 5G-XHaul will support the implementation of this use case by: • Providing a programmable mapping of the sensor generated data into transport classes of service. • Allowing to reconfigure the transport network, mostly its wireless segment, according to the traffic generation patterns of the deployed sensors. For example provisioning additional transport resources when data transmission is triggered due to an external event. • Improving reliability by: ▪ Provisioning multiple paths in a meshed transport BH network, instead of the single-path tree based BH networks deployed today. ▪ Detecting congestion at any point of the transport network, and re-routing the sensor generated data accordingly.

Use Case 6	Online gaming
Type	End User Use Case
Goal/Objective	To support an adequate experience of gaming when processing is carried out in the cloud and/or when there is interaction with other remote players, 5G network should guarantee a level of capacity and latency which are not feasible with current mobile systems.
Description	5G networks may help to improve the experience of gaming in two areas:

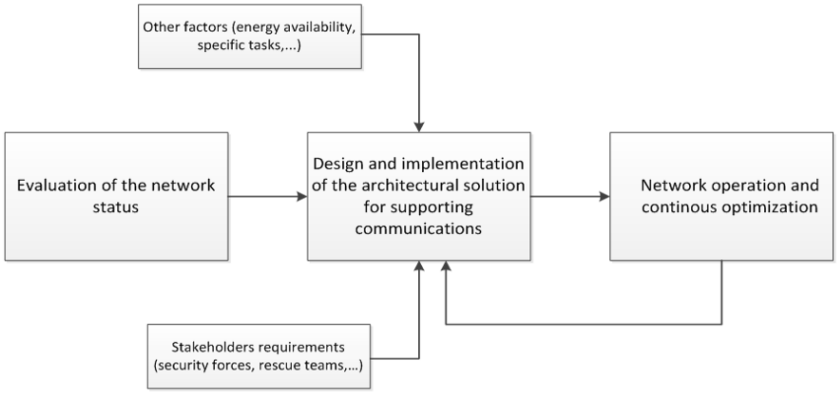
[4] http://www.energynetworks.org/modx/assets/files/electricity/futures/smart_meters/ENA-CR008-001-1%204%20_Data%20Traffic%20Analysis_.pdf

Use Case 6	Online gaming
	cloud-assisted games and massively multiplayer online games. Gamers use different platforms for playing games. When using mobile devices for gaming, limitations in the processing capabilities and in the power consumption limit the kind of games can be played. One solution is to transfer part of the most complex processing associated to the game to the cloud. This may help to incorporate new functionalities to the games, like the support of Virtual Reality, without increasing the cost of devices. Another area 5G networks can play a role is in the support of interactive gaming with a large number of remote players. Games where players compete with each other require that end to end latency is limited, depending on the kind of interaction associated to the game. With the support of lower latencies, new games may be feasible to be played with adequate quality of experience in a mobile environment. On top of this, it may be feasible to use the mobility of the user as an element of the game. In this sense, if may be an option that new games make use of exposed information.
Requirements	<u>Functional:</u> • The transport network should be aware of the latency and capacity requirements associated to the selected game. • It would be also convenient that the network becomes aware also of the phase of the game that is being played, as different phases will have different requirements. E.g., when a game host is being setup or players seek other players out, latency requirements can be relaxed. • Some network related information should be exposed to the game control, so it may be feasible to adapt the characteristics of the game to the actual performance of the network.
	<u>Performance:</u> • In general, latency required should be less than 5 ms, even lower for some special games. • A certain capacity should be guaranteed depending on the game (and the phase of the game played). • Integrity of the information sent is also a major requirement for certain games (or for specific blocks of information of the game).
Constraints/ Restrictions/ Challenges	The main challenges in this scenario are: • The transport network should be able to adapt to the requirements from games in terms of latency, capacity and integrity of the information. • Some of the processing capabilities associated to the support of games may be necessary to be located close to the mobile edge. They may also need to be reconfigured.
Relevance within 5G-XHaul	5G-XHaul will support the implementation of this use case by: • Deploying flexible unified BH and FH networks which can adapt to the requirements of each game. • Providing the support of different functional splits, as well as the support for edge clouds, that may facilitate a better quality of experience. The greater flexibility of the 5G-XHaul transport network can also be used to enhance the online gaming experience.

Use Case 7	Tactile internet
Type	End User Use Case
Goal/Objective	To provide very low end-to-end (e2e) latencies for both professional/industrial as well as private users. Ideally, e2e latency, including application processing both in the mobile terminals and the application servers, and the transmission times in the RAN and transport networks should be of the order of 1 ms.
Description	With the advent of the IoT, not only people but also physical objects will be (inter)connected via the internet. While in the first phase, the connectivity will be mostly limited to monitoring and configuration, requiring low data rates with very relaxed latency constraints, the final step of the IoT will enable a real-time manipulation and control of physical objects or systems. Tactile internet applications could include controlling a drone or a robot, or using virtual reality apps. While these applications can to some degree be realised with today's networks, the latency typically faced today makes the interaction sluggish and imprecise. E.g., to enable a remotely piloted robot to catch a falling object, or to control a drone precisely in a windy environment, a much lower latency is required to provide "tactile" feedback. To some degree such low latencies will be also required for the use cases 3. ITS (safety apps), 6. On-line Gaming, 10. m-Health (remote surgery) and 11. Industrial control.
Requirements	<u>Functional:</u> • The network should be able to measure e2e latencies and be aware of the current latencies between network elements • The network should be aware of the minimum possible latencies that can be guaranteed between different network elements and which data rates can be provided under these latencies • The network should be aware of where application servers for tactile internet applications are located within the network, e.g. the location of cloudlets • The network should be able to be configure itself to provide low latencies between dedicated end-points, e.g. prioritising tactile packets on a route between a base station and a cloudlet • The network should be able to recognise requests for a connection to a tactile application as well as recognise packets that correspond to such an application • The network should be able to route traffic directly from user (controller) to user (controlled object) without traversing the core network <u>Performance:</u> • The transport network should be able to guarantee maximum latencies of well below 1 ms between dedicated end-points. • The transport network should provide multi-path as a way to guarantee a high level of reliability on these routes • Ideally, the network should provide multi-Gbps data rates on these routes for e.g. virtual reality video streaming
Constraints/ Restrictions/ Challenges	• The ideal objective of 1 ms e2e latency will be very hard to achieve in the short- to mid-term • The provision of tactile services will be largely impacted by the application processing hardware in the mobile terminals and application serves, over which the transport network has no control • The provision of tactile service requires the interaction with Over-The-Top (OTT) players, e.g. a request for tactile application will most likely be

Use Case 7	Tactile internet
	sent from a user to an application provider, who has to notify the network operator of the request. Conversely, the operator can notify application providers and users where and when tactile services are available
Relevance within 5G-XHaul	Current networks provide very low and guaranteed latencies on the FH segment but unpredictable and long latencies on the BH. A converged BH and FH network as proposed by 5G-XHaul will provide lower latencies on certain segments to support Common Public Radio Interface (CPRI)-like traffic. At the same time, processing power will be moved closer to users for baseband (BB) processing. These steps are necessary to support an efficient C-RAN operation but, at the same time, can complement the tactile internet use case. If low latencies can be achieved to support FH, user traffic can also achieve these low latencies using the same converged network. At the same time, cloud centres used for BB processing can also process application data, thereby shortening the distance to the users and further enhancing the economies of scale of the cloud centres. The SDN capabilities envisioned for 5G-XHaul could be used to configure network elements to prioritise tactile traffic to ensure low latencies, or to measure current latencies, thereby generating awareness of where and when tactile services could be supported.

Use Case 8	Natural Disaster Occasions
Type	Network Operator/End User Use Case
Goal/Objective	To ensure that 5G networks can be used for supporting communications in case of a natural disaster, even if the integrity of the network cannot be preserved.
Description	Due to a natural disaster (e.g., earthquake, tsunami, flood, hurricane) part of the network infrastructure is destroyed. Users need to communicate their situation, contact family members, find rescue shelters, etc. and rescue teams may use the mobile network to coordinate their activities. As the natural disaster may have affected the power grid, the energy consumption of both terminals and network infrastructure must be reduced. The network may be used for locating victims and broadcast alerts. Users' devices battery life should be extended as much as possible. Based on operator's policy, the system shall be able to define minimal services necessary in case of disaster or emergency that are conditional on e.g. subscriber class (i.e. access class), communication class (i.e. emergency call or not), device type (i.e. Smart phone or IoT device), and application. Examples of those minimal services are communications from specific high priority users, emergency calls, and a disaster-message-board type of application that helps people reconnect with friends and loved ones in the aftermath of disasters.
Requirements	<u>Functional:</u> • The network should be able to reconfigure itself with the network elements available. The network should be able to evaluate its own status in order to determine the best configuration to provide the functions defined by the operator policy. It should also be able to incorporate new elements and nodes as they become available.

Use Case 8	Natural Disaster Occasions
	 • The network should be able to prioritise the communication services for certain groups, like rescue teams. At the same time, it should be possible to block users to prevent that they make the network unusable. • The network should be able to seize resources (e.g., frequency channels) from other operators or systems to support the operation. • The network should support broadcast mechanisms to disseminate alerts with enough flexibility in terms of selecting areas or user groups where location-specific alert information can be directed. • The network should be able to discover the topology of the networks that may have been established between the devices. • The network should be able to support the access to certain contents and data by name, independently of their location, adopting the approach of information-centric networking (ICN). • The network should support User Equipment (UE) devices location capabilities, adapted to the infrastructure available.
	<u>Performance:</u> • The network should guarantee a high level of reliability at all levels of its infrastructure, so enough network resources may survive a disaster in order to allow for the recovery of the minimum set functionalities required. • The network should be able to reconfigure itself to provide basic services in a limited period of time (in the order of minutes) • The network should be able to support a very high number of connected devices, while controlling their activity in order to preserve energy and preclude congestions • The network should provide mechanisms for avoiding congestion situations without precluding a high level of utilisation.
	<u>Other:</u> • The network should be able to reduce the energy consumption (including that of devices), especially when connection to the power grid is not available or is not reliable.
Constraints/ Restrictions/ Challenges	The support of this use case faces significant challenges: • In economic terms, the support of some functionalities required for it would be difficult to justify, as there may be no synergies with other applications – especially those that result in the need of a higher level of reliability for the network. • The different levels of infrastructure destruction that may be associated

Use Case 8	Natural Disaster Occasions
	to a disaster make it very complex to plan for emergency network configuration options.
Relevance within 5G-XHaul	5G-XHaul solution may provide significant advantages with respect to legacy solutions: • The possibility of using a unified BH and FH network allows for much more flexibility in terms of reconfiguration and reallocation of functionalities after a disaster (e.g., in an LTE network CPRI interfaces cannot be reconfigured to support conventional traffic). • The kind of algorithms that are used in 5G-XHaul to adapt to the change in traffic conditions can be reused for defining the configuration of the network after a disaster.

Use Case 9	Public Safety Communications - Mission Critical Video/Applications
Type	Institutional User Case
Goal/Objective	To exploit the flexibility provided by a vast number of communicating nodes, high density cells, as well as dynamic and opportunistic network management to provide the required communication functions in public safety scenarios. Such scenarios are characterised by the need for uninterrupted communications in unpredictable environments to quickly gather and process information from a wide variety of sources, and then to convey data to decision makers and safety personnel involved.
Description	The effectiveness of safety operations relies, to a large part, on the capabilities for acquiring, processing and communicating of data. These communication capabilities are increasingly significant because of new generations of devices such as low power sensor nodes as well as novel handset devices that assist the safety personnel in their relief actions. A major application in this case is mission critical video. A major challenge of public safety communication is to provide these services with ultra-high reliability, even in the case that the functionality of parts of the network infrastructure may be compromised by the disaster event itself.
Requirements	Functional**:** • Information broadcast: Provide appropriate means for conveying news and information in large geographic areas. Broadcasted information can include instructions for appropriate behavior in order to limit a certain risk, to gain control and to limit the risk of panic. • Group communication: Safety personnel such as police, fire fighters, and ambulances heavily rely on reliable, resilient, and secure voice, video and data communication to coordinate activities. • Sensor/Actuator communication: Sensors help to prevent emergencies by detecting faults and errors for example in materials of a building or airplane. They help to detect emerging risks and catastrophe as in the case of natural disasters such as earthquakes, tsunamis, and fires. Sensors support the actions of rescue teams or actuators such as robots and drones that may operate in environments that are unsafe for humans. Clearly, the aspired massive deployment of M2M communication devices and the increasing amount of communication devices with all kinds of sensors bring along great opportunities for a substantial improvement in public safety. The requirements to support these services are similar to UCs 4,5. Performance:

Use Case 9	Public Safety Communications - Mission Critical Video/Applications
	• Ultra-high availability & reliability: The communications for public safety has to be provided with ultra-high reliability and ultra-high availability (coverage). The service quality has to be scalable. Messages with the highest relevance need to be communicated basically everywhere, some other, more demanding services may be compromised if necessary. Reliable communication can be provided by careful planning, deployment and efficient operation of the infrastructure. However, parts of the infrastructure itself may be destroyed in case of a catastrophe or stops operating due to long lasting power outage. It is therefore required that such networks can be re-configured or re-deployed quickly. In a major crisis, the reliable network operation is also stressed by the increasing demand for communication in the society as a whole. Thus, it is required to distinguish different services and users in order to prioritise the exchange of data that is vital for public safety. This is increasingly difficult, because such communication will not only relate to safety personnel but also all kinds of other sensors and devices. • Diversity: The public safety sector depends on communication services with very different requirements, not only in terms of point-to-point communication, but also in terms of the network as a whole. • Data rate: NGNM requires data rates of 10 Mbps for UL as well as for downlink to support video and other data demanding applications. The traffic density is potentially high. • Latency: The requirement is less than 10 ms • Mobility: up to 500 km/h
Constraints/ Restrictions/ Challenges	The challenge is to design a fail-safe, low-power communication infrastructure that is prone to potential loss of infrastructure in order to provide communication in a devastated environment. In order to provide the most reliable service possible, the network has to include the whole spectrum of diverse communication infrastructure as depicted in including satellites, multi-hop communication through various terminals, which can also be carried on cars, airplanes, helicopters, etc.
Relevance within 5G-XHaul	Current cellular communications systems perform poorly or fail completely in unpredictable and harsh radio environments, which occur in serious disaster scenarios such as earthquakes or tsunamis. Currently, the most widely used communications systems in the case of an emergencies are public protection and disaster relief networks such as Terrestrial Trunked Radio (TETRA). However, in the future (within the next five years) public safety networks and operators are expected to migrate towards broadband capable cellular communications systems and standards such as LTE and 5G because TETRA is not capable to support the requirements described above. 5G-XHaul supports the implementation of this use case by providing the means for a highly adaptive and flexible network infrastructure that is capable: • To re-route BH capacity based on the specific demands of a disaster scenario • Provide appropriate means to prioritise safety critical communications • Provide means to include new network nodes that are added to cater to the needs of the disaster scenario • Provisioning multiple paths in a meshed transport BH network, instead of the single-path tree based BH networks deployed today

Use Case 9	Public Safety Communications - Mission Critical Video/Applications
	(from UCs 4, 5) • Detecting congestion at any point of the transport network, and re-routing the sensor generated data accordingly (from UCs 4, 5).

Use Case 10	m-Health Applications
Type	End User Use Case
Goal/Objective	Support of a wide range of m-health related applications with different QoS requirements in terms of throughput, latency, mobility, etc.
Description	A plethora of m-health applications can be considered in the context of the 5G systems, such as: • Telemedicine and health care remote monitoring, (e.g. cardiac pulses, blood pressure, glucose level, etc. via biosignals captured by wearable sensors) and uploading to a cloud service. • Early diagnosis/prevention of diseases (e.g., Parkinson) by uploading/processing of relevant health-related information. • Remote diagnosis / virtual visit (e.g., UHD videocall between a patient and a doctor). • Real-time medical care on the move using UHD cameras “attached” to first responders or on an ambulance roof-top. • Remote surgery (e.g., UHD videocall between a doctor and another doctor / hospital). • Surgery follow-up (cardiovascular). • Real-time patients’ location tracking and clinical/psychological status monitoring information to caregivers and doctors. The impact of the above-mentioned applications on the access interface as well as on the transport network depends on the application itself. For example, remote surgery, remote diagnosis, medical care on the move and surgery follow-up have strict throughput and latency requirements, while remote health care monitoring, early disease diagnosis and patients’ location tracking exhibit the characteristics of an IoT service (frequent uploading of low data volume).
Requirements	<u>Functional</u>: • The QoS requirements shall be satisfied on a per application basis • Traffic prioritisation between certain groups, e.g. remote surgery, first responders’ UHD video to doctor/hospital • Consideration of user mobility scenarios (UHD video from ambulance, location tracking of patients) • Strong authentication, integrity protection and encryption in order to provide data confidentiality and users’ privacy. <u>Performance</u>: • Efficient handling of huge upload traffic (e.g. multiple UHD videos / cell). • Latencies of less than 200 milliseconds in case of remote PTZ cameras. • Support of 4K cameras requiring 300 Mbit/s (using H.264) at 30 fps <u>Other</u>: • The network shall be able to keep energy consumption of end-devices at minimum and allow long sleeping/doze periods (e.g. cam-

Use Case 10	m-Health Applications
	eras activated only upon movement detection). • Event based activation of sensor devices can trigger sudden peaks of traffic, which should be handled dynamically by the network.
Constraints/ Restrictions/ Challenges	• m-health related traffic may be very heterogeneous in terms of QoS requirements and therefore the transport network should support different levels of priorities. • m-health traffic may not be continuous, which opens up the opportunity of reducing energy consumption by means of shutting down links in the transport network. • For critical e-health applications, e.g. remote surgery, a very reliable transport infrastructure is required. • Transmission of UHD video contents may become the most important challenge for the transport network in terms of capacity.

Relevance within 5G-XHaul	Currently, not all the above mentioned m-health applications can be supported efficiently by 4G networks at the required quality imposed by the applications (UHD video quality, traffic prioritisation between specific user groups, etc.).
	5G-XHaul will support the implementation of this use case by:
	• Allowing transport network reconfiguration according to the traffic demand and QoS characteristics (e.g. low latency, traffic prioritisation).
	• Improving reliability by:
	  ○ Provisioning multiple paths in a meshed transport BH network, instead of the single-path tree based BH networks deployed today.
	  ○ Detecting congestion at any point of the transport network, and re-routing the relevant traffic accordingly.

Use Case 11	Industrial Control/Factory Automation
Type	End User Use Case
Goal/Objective	To leverage open wireless solutions for industry automation. Industrial automation requires "robust" wireless technologies to be used for their critical wireless links in industrial applications.
Description	The new open wirelessly connected world envisioned for 5G is also applicable in industrial environments. Wired connections in such environments impact the mechanical design of machines as well as being subject to wear and tear; thus need to be replaced regularly. Moreover, they lack mobility and flexibility. The problem with current proprietary/tailored wireless solutions is that they are expensive as well as suffering from the lack of available frequency bands.

Use Case 11	Industrial Control/Factory Automation
Requirements	Functional: • The network should be able to reconfigure itself with the network devices available; in particular to discover the topology of the networks established between them. • The network should be resilient, reconfigure fast upon a failure, and have fast failover to redundant links in case of a primary link interruption. • Strong authentication between devices and network in order to prevent unauthorised communication. Integrity protection and encryption. • Having the same frequency bands available in different countries or regions is an essential requirement. Performance: • Ultra-reliable communication that is capable of handling different kinds of traffic associated with periodic data, sporadic data and configuration messages. • The network should support very low latency, in the order of less than 1ms (250 µs-1 ms). • The network should enable stable latency (i.e. determinism) within defined tolerance limits on a low total latency level (e.g. 5 - 15 ms) • The system shall support high uplink data rate (tens of Mbps per device in a dense environment). • The network should support very high reliability, with error rates down to 10^{-9}. • The network should be able to re-establish connectivity seamlessly (which depends upon latency requirements). • The network should be able to support large user densities.
Constraints/ Restrictions/ Challenges	The support of this use case faces significant challenges: • Critical wireless link of an industrial application can be interrupted (interfered), or not respond instantaneously; therefore, safety measures beyond communication have to take effect immediately. • Industrial users very much depend on the chosen technical solutions for their seamless operational procedures, i.e. a high dependability is envisaged. • Mandatory use of adequate spectrum sharing mechanisms to be implemented by the equipment. While the non-critical links could use existing spectrum and existing ETSI standards, including the 2,4 GHz up to 2,4835 GHz band, new frequencies (outside the 2,4 GHz band) need to be identified for the critical links of industrial applications.
Relevance within 5G-XHaul	5G-XHaul solution may provide significant advantages with respect to legacy solutions: • The flexibility and re-configurability of the 5G-XHaul transport network will allow for latencies in the order of 1 ms.

Use Case 12	UHD Video/Photo Sharing in Heavily Crowded Spots
Type	End User Use Case
Goal/Objective	To efficiently serve exchanging of high quality video/photo content in places where a large number of people have been gathered (e.g. stadiums). The service either belongs to the "pull" category (traffic coming from outside the stadium), or belongs to the "push" category (traffic generated within the stadium and transmitted elsewhere) [3].
Description	This use case is characterised by a high connection density and potentially temporary use (e.g., in a stadium, concert, or other events). Several hundred thousand users per km^2 shall be served, possibly integrating physical and virtual information such as score, information on athletes or musicians, etc., during the event. People can watch Ultra High Definition (UHD) playback video, share live video or post UHD photos to social networks. These applications will require a combination of ultra-high connection density, high date rate and low latency [2].
Requirements	Functional: • Flexible remote reconfiguration of the BH/FH through high-level directives to cope with observed high-demand (topology changes, function relocation, etc.). Performance [2]: • User data rates: UL: 25 Mbps DL: 50 Mbps. • e2e latency: 10 ms. • Mobility: Pedestrian. • Connection Density: 150,000 / km^2 (30,000 / stadium). • Traffic Density: DL: 3.75 Tbps / km^2 (0.75 Tbps/stadium) UL: 7.5 Tbps / km^2 (1.5 Tbps/stadium).
Constraints/ Restrictions/ Challenges	• To accommodate huge amount of traffic generated for a quite short time period, i.e. the duration of the event, while the traffic in the area is normal or very low for the rest of the time.
Relevance with 5G-XHaul	• The current deployments might be inadequate to cope with the huge amount of traffic generated during such events. • SDN-based flexible controlled transport based on demand predictions (or even unexpected) will provision the network resources with appropriate QoS to cope with the performance requirements imposed by such a use case.

Use Case 13	TV Programs Broadcasting
Type	End User Use Case
Goal/Objective	To ensure that 5G networks can be used for supporting the broadcast of audiovisual contents to a selected geographical area.
Description	Users that have subscribed to the services can access TV channels through devices connected to the 5G network. The service should allow a similar user experience to that provided by other TV distribution networks. The 5G network should also support interactivity related to the contents being broadcasted.
Requirements	Functional: • Support of broadcast/multicast of audio and video signals, as well as

Use Case 13	TV Programs Broadcasting
	metadata, to a selected area. • Possibility of switching channels and accessing to programming information. • Support of switching between multicast/broadcast and unicast transmission modes based on the number of users of the service. • Support of the video quality provided as a function of the coverage and capacity that users are experiencing. • The transport network should be able to interact with the video quality control function to provision a guaranteed QoE. <u>Performance:</u> • Quality provided should be comparable to that provided by other distribution channels, like cable, terrestrial TV, satellite • Transmission of high fidelity acoustic signals. Estimated data rate is 576 kbps for a 48 ksps, 12 bit AD-converted signal. This allows an audio frequency range up to above 20 kHz. • Transmission of high quality video images, up to 4K resolution with reasonable buffering time. • Switching time between channels comparable to that of other transmission media. • Seamless mobility <u>Other:</u> • Support of security and conditional access mechanisms comparable with other broadcasting technology options.
Constraints/ Restrictions/ Challenges	• Transmission of high quality video contents may become the most important challenge for the transport network in terms of capacity. • The local caching of contents to be broadcasted may help to reduce the latency of the services.
Relevance within 5G-XHaul	• It implies that 5G-XHaul network should support multicast and broadcast. In order to reduce the impact on the transport network, more intelligence will be required (e.g., delivering contents only to those areas where there are active users). • Additional functionalities may be provided, like content caching and analytics, which may help to enhance the user experience.

Use Case 14	Distributed Virtual Orchestra
Type	End User Use Case
Goal/Objective	To ensure that 5G networks can be used for supporting the interplay of a number of musicians in a live environment.
Description	Two or more musicians perform a musical piece on their instruments while synchronising their efforts to the acoustical input from the other players.

Use Case 14	Distributed Virtual Orchestra
Requirements	Functional: • Multicast of audio and (optional) video signals from each player to all other players. • Duration of a session in the range between minutes and hours. Performance: • It is important to maintain the roundtrip latency within a few tens of milliseconds. • Transmission of high fidelity acoustic signals. Estimated data rate is 576 kbps for a 48 ksps, 12 bit AD-converted signal. This allows an audio frequency range up to above 20 kHz. • Optionally, video signals can be transmitted to allow for visual synchronisation between the players. Other: • To reduce latency, avoidance of a central multicast server would be beneficial with signal combination close to the baseband unit (BBU).
Constraints/ Restrictions/ Challenges	• Signal processing in the radio access part of the network consumes a large amount of the allowed round-trip-latency • Besides the latency in the access part of the network, the core network latency contributes to the overall round-trip-latency. Physical propagation speeds of 10 µs per km (in fibre) will pose a (relaxed) limit of approximately 1000 km between the most remote players. However, latency introduced in routers should be minimised in the core network. • Ideally, each player is connected to each other player via a separate stream to reduce processing latency and to improve optical signal integrity / fidelity. This increases the downlink traffic by a factor of N-1 for N distributed players.
Relevance within 5G-XHaul	• A unified network control enables the choice of lowest-latency routing. • Optical routing in the BH and core networks avoids high-latency electrical buffering and routing. • Signal processing delay should be minimised by using low-latency processing. • Maintaining the BH and FH signals in the optical domain (avoiding OEO conversion) can help to reduce latency. • Multi-casting capability for each uplink signal.

3.3 5G-XHaul Use Cases vs. Performance Parameters

The purpose of this section is to establish a first link between the end user use cases and the specific requirements that should be taken into account in the design of the 5G-XHaul system.

In Figure 3.2, the use cases selected are classified according to the main BH/FH network parameter(s) characterising the 5G-XHaul system performance. More specifically, the network parameters that have been taken into account are: (a) capacity (at base station level), (b) mobility, (c) e2e Latency, (d) e2e jitter, (e) reliability (BER, packet loss) and (f) device' density (measured at the base station level).

One can see, for each use case, the level of criticality of each one of the aforementioned parameters, highlighting (in red) the most significant one. It is obvious that more than one "factor" may play a significant role for a given use case. For example, UC2 has major requirements in terms of capacity (grade = 5), mobility (grade =5), e2e latency (grade =5 for VoIP service), e2e jitter (grade =5 for VoIP service) and reliability (grade =5 for VoIP service).

At the same time, it is easy to deduce the impact of a use case on each network performance parameter. For example, UC1, 2, 5, 7, 8, 9, 10, 12 and 13 seem to have major impact (grade >= 3) on the cell capacity.

It is evident that the transport network should take into account the specific QoS/QoE requirements of each application (use case) and reconfigure itself accordingly so as to fulfill them concurrently.

No	UC Title	Capacity (eNB level)	Mobility	Latency (e2e)	Jitter (e2e)	Packet Loss / BER (e2e)	Devices Density (BS level)
1	Cloud Services	●●● (depends on the area)	●	● (depends on content type)	● (video/audio only)	●● (video/audio only)	●
2	High Speed Train & Vehicular data services	●●●●●	●●●●●	●●●●● (VoIP)	●●●●● (VoIP)	●●●●● (VoIP)	●●●
3	Intelligent Transport Services (including safety Applications)	●	●●●●●	●●	●●●● (safety Apps)	●●●●● (safety Apps)	●●●●
4	Large No. of sensors with relatively low data traffic requirements	●●	●● (ITS only)	●● (e.g., commands)	●	●●●● (e.g., commands)	●●●●●
5	Medium No. of sensors with high data traffic requirements	●●●●●	-	●	●● (video/audio only)	-	●●●
6	On-line Gaming	●	●●	●●●●●	●●●●	●●●●	●
7	Tactile internet	●●●●	-	●●●●●	●●●●	●●●●	●●
8	Natural Disaster Occasions	●●●●●	●●	●●●●● (VoIP)	●●●●● (VoIP)	●●●●● (VoIP)	●●●●
9	Public Safety communications - Mission Critical Video Apps	●●●●	●●●	●●●●	●●●●●	●●●●● (VoIP)	●●●●
10	m-Health Applications	●●●●●	●	●●●●	●●●●	●●●●	●●
11	Industrial Control/ Factory automation	-	-	●●●●	●●●	●●●●	●●
12	UHD Video/Photo Sharing in Heavily Crowded Spots	●●●●●	-	●●●●	●●●●	●●●●	●●●●●
13	TV programs broadcasting	●●●●	●●●	●●●●	●●●●	●●●	●●
14	Distributed Virtual Orchestra	●●	-	●●●●●	●●●●●	●●●●	●

Figure 3.2: 5G-XHaul Use Cases Categorisation vs. Main Performance Indicators

4 Operator Use Cases

This section introduces a set of Operator use cases, which will be used to define the interactions between the 5G-XHaul Tenant and 5G-XHaul Operator, actors defined in Figure 2.2. Following the methodology introduced in Chapter 2, the Operator use cases are derived from the transport requirements summarised in Figure 3.2, which are in turn derived from the end user use cases.

A first conclusion drawn from Chapter 3 is that there exists a high variety of use cases that will be target within the context of 5G, not focusing solely on mobile broadband like 4G but, instead, targeting several verticals, such as Factory Automation or ITS. Thus, this use case heterogeneity translates into two fundamental requirements in the context of 5G transport networks:

- **Multi-tenancy**, whereby a 5G-XHaul operator has to be able to instantiate as many independent service instances as possible over a single physical transport infrastructure.
- **Transport Slicing**, whereby a 5G-XHaul tenant has to be able to host a custom control plane to control a virtual representation of the transport resources allocated to it. This requirement is relevant for instance in the End User Use Case UC1: “Cloud Services”, where a Cloud Service provider could interconnect several data centres by leasing connectivity services from a 5G-XHaul operator. In this context the Cloud Service Provider would like to have certain control over the transport infrastructure, instead of relying on pure overlay solutions as those available today [11], in order to take optimal Virtual Machine (VM) placement decisions.

A second conclusion drawn from Figure 3.2 is that several use cases require different amount of transport capacity. Indeed, some use cases, such as those dealing with natural disasters or public safety, require capacity to be allocated only upon certain events; and others may require capacity varying in time and space, such as those dealing with high mobility or very crowded environments. Therefore, a 5G-XHaul operator needs to be able to provision capacity in a dynamic and scalable way, namely offer “Transport Capacity as a Service”.

Another conclusion drawn from Figure 3.2 is that the considered use cases are very diverse in terms of Quality of Service (QoS) requirements, such as Latency, Jitter, Bit Error Rate (BER), and Device density. We envision that this heterogeneity will lead to multiple types of RATs coexisting in the context of 5G. Indeed, this vision is shared by other projects like METIS-II that are studying how to implement multiple 5G RATs for below and above 6 GHz, which will even coexist with 4G [12]. The multi-RAT trend is also justified by the introduction of novel low power WAN technologies specifically tailored to the IoT, such as LoRa [13], SIGFOX [14] or the adaptations of LTE for the support of IoT services introduced in Release 13. Hence, one can envision that, in 5G, different types of services will be addressed by different RATs. Indeed, each RAT could benefit from a different implementation in terms of degree of centralisation. For example, RATs addressing very dense scenarios will require highly coordinated base stations and will therefore benefit from a certain level of the radio protocol stack being centralised. Thus, a 5G-XHaul Operator will require a transport infrastructure able to serve simultaneously multiple RAN implementations with different degrees of centralisation.

Finally, not directly captured in Figure 3.2 but directly coupled to the economics of transport networks, is the fact that a 5G-XHaul operator needs to be able to easily integrate 5G-XHaul infrastructure with legacy transport equipment.

Next, we present a set of Operator use cases that define the previous uses of the 5G-XHaul transport network. Each of the provided use cases include: 1) the type of actor involved according to Figure 2.2, 2) a description of the use case, and 3) a set of functional and performance requirements derived from this use case. The following 5G-XHaul Operator Use Cases have been identified:

- Op-UC1: Transport Capacity as a Service
- Op-UC2: Multi-Tenancy
- Op-UC3: Transport Network Slicing
- Op-UC4: Multiple-split RAN implementation support
- Op-UC5: Seamless Integration with legacy Transport technologies

In the following section, the operator use cases are described in detail.

4.1 5G-XHaul Operator Use Cases

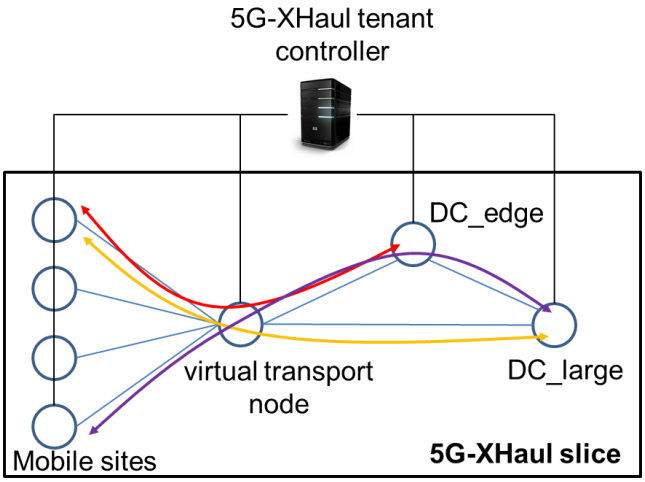
Op-UC1	Transport Capacity as a Service
Actor	5G-XHaul Tenant
Goal/Objective	This use case describes the ability of a 5G-XHaul Tenant to dynamically set the capacity/QoS being provisioned by the 5G-XHaul system, according to foreseeable/planned or unforeseeable events.
Description	A 5G-XHaul tenant deploying a 5G mobile network has contracted transport connectivity services from a 5G-XHaul Operator. The transport bandwidth needs of the 5G-XHaul tenant are not static, and thus the 5G-XHaul tenant is interested in contracting only the required capacity following a "Transport Capacity as a Service" model. Transport capacity variations can occur due to: • Typical day-to-night or seasonal patterns in mobile traffic demand. • Foreseeable smooth traffic increase due to expected events such as national holidays, athletic events, etc. • Foreseeable sharp traffic increase, e.g. New Year's Eve. • Unexpected sharp traffic increase due to e.g. earthquakes, floods, terrorist acts, etc. • Unexpected sharp traffic decrease due to e.g. BS malfunction, vandalism, etc. The 5G-XHaul operator offers a Service Level Agreement (SLA) to the 5G-XHaul Tenant, which allows the tenant to dynamically scale its contracted capacity and to pay for the capacity that the tenant is actually using.

Op-UC1	Transport Capacity as a Service
Requirements	<u>Functional Requirements</u> The 5G-XHaul transport network SLA will, at least, be composed of the following parameters: • Service interface definition: Specifying how input traffic is identified at the customer ingress demarcation point. 5G-XHaul will allow a flexible service interface definition to each customer. In the slicing service the service interface definition also specifies the type of control interface available to the tenant to control the virtual slice. • QoS parameters applied to the transported customer traffic including, at least: throughput (defined by a Committed Information Rate), latency, jitter (delay variation), packet loss. • Allowed service disruption: Specifying for how long the customer can experience loss of service. 5G-XHaul will provide very high reliability with minimal service disruption. • Service definition: In the Multi-tenancy service the service definition comprises the type of connectivity the tenant requires between his sites (e.g. tree, LAN emulation, private line). In the Slicing service the service definition comprises the connectivity between sites, and the required topology of the virtual transport slice. • Statistics/Events: The tenant will be able to specify statistics/events that he wishes to receive to monitor the performance of his connectivity services. The statistics/events may be received in real-time or periodically. A 5G-XHaul SLA will be dynamic and specified by an API that allows for automation. For example, a 5G-XHaul tenant could define an SLA, monitor the performance of its traffic, and automatically request a modified SLA without human intervention. Automatic SLA request and enforcement will be enabled in 5G-XHaul. A 5G-XHaul Transport network shall include Self-X functionalities that will monitor SLA enforcement in the network, and re-configure the network accordingly. Self-X functionalities may include: • Forecast demand variations, in time and space, and re-configure the transport links (wireless and optical) accordingly. • Detect transport link outages or congestion, and quickly re-configure the network giving priority to those services specifying higher reliability requirements in their SLA. • Dynamically prioritising service traffic in the transport network. <u>Performance Requirements</u> A modified SLA submitted to the network through the 5G-XHaul API should enter into effect in less than 5 minutes.

Op-UC2	Multi-Tenancy
Actor	5G-XHaul Operator
Goal/Objective	A 5G-XHaul Operator should be able to sell transport connectivity services to various 5G-XHaul tenants, e.g., MNOs, content distribution companies, large enterprises with dispersed branches/offices, etc.
Description	A 5G-XHaul operator deploys a 5G-XHaul Transport Network and provides connectivity services to multiple 5G-XHaul tenants. For example, the following tenants access the network:

Op-UC2	Multi-Tenancy
	• A mobile operator deploying 4G LTE, which intends to connect multiple eNodeB sites with the data centre hosting the Evolved Packet Core (EPC) functions. The 5G-XHaul Tenant is servicing the business district in a city and, therefore, is very interested in having low delay X2 interfaces between adjacent eNodeBs in order to implement interference management strategies. This tenant requires IP connectivity between its sites. • A content distribution company having a set of small data centers scattered through several high access locations, which cache popular content in order to provide low delay services, as well as few large data centers hosting the whole content collection as well as business related functions. This tenant requires IP connectivity between its sites. • A large company connecting its branches with headquarters. This tenant requires L2 connectivity between all sites. • A mobile operator providing 5G services, using a 5G RAT that benefits from centralised processing. This tenant requires fixed capacity services from the 5G-XHaul transport network.

Requirements	<u>Functional Requirements</u>
	• A single 5G-XHaul physical infrastructure is shared among all tenants.
	• The connectivity services delivered to each tenant are described by a dynamic API-driven SLA (defined in Op-UC1).
	• By default, a 5G-XHaul operator will offer each tenant an SDN based service abstraction, meaning that each tenant will see its different sites directly connected to a virtual SDN agent (e.g. an OpenFlow switch). Each tenant will be able to dynamically control the traffic forwarding behavior between its sites by programming the SDN agent abstraction through the 5G-XHaul North-Bound Interface (NBI). Configurability of the SDN agent includes:
	  ○ Flexibly define input traffic flows.
	  ○ For each defined flow, specify the corresponding destination tenant site.
	  ○ For each defined flow, specify a class of service.
	• A 5G-XHaul operator will be able to define service templates for common service definition. For example:
	  ○ A L2 service template will instantiate an SDN agent behaving like an Ethernet bridge.
	  ○ A L3 service template will instantiate an SDN agent behaving like a L3 router running a configurable IGP or EGP.
	• The traffic from one tenant must not be visible to other tenants (traffic isolation).
	• A 5G-XHaul Tenant will receive quasi real-time notifications, events and alarms about the performance of the connectivity service affecting his transport flows.
	<u>Performance Requirements</u>
	The 5G-XHaul transport network will allow to instantiate, at least, 2^{24} independent service instances.

Op-UC3	Transport Network slicing
Actor	5G-XHaul Tenant
Goal/Objective	A 5G-XHaul Operator should be able to create slices of his transport network that can be directly controlled by a 5G-XHaul Tenant. A 5G-XHaul transport slice is composed of a virtual representation of (a subset of) the physical network elements composing the 5G-XHaul transport network. A NBI is provided to the 5G-XHaul tenant to control his virtual slice. The difference between the Multi-Tenancy service and the Slicing service in 5G-XHaul is that, in the Multi-tenancy service, the tenant is only allowed to control the behavior of the e2e flows between his sites. However the paths that these flows follow on the transport network are under the control of the 5G-XHaul Operator. Instead, in the Slicing service the 5G-XHaul tenant controls a virtual representation of (a subset of) the transport network connecting its sites, thus being able to exert a more granular control on the traffic flowing between its sites.
Description	A 5G-XHaul Tenant providing mobile services wants to connect a set of mobile sites with two data centers hosting Mobile Core and Service related functions. One Data Centre, DC_edge, is located closer to the mobile sites and is therefore appropriate for low latency services, while the other Data Centre, DC_large, is located deeper in the network. The 5G-XHaul Tenant wants to be able to decide, according to its own business logic, which data flows are forwarded to DC_edge and which ones are forwarded to DC_centre. The 5G-XHaul Tenant requests a 5G-XHaul transport slice containing a node representing the mobile sites, DC_edge and DC_centre, as well as a virtual transport node aggregating the mobile sites and connecting them to the Data Centres. Forwarding through the 5G-XHaul slice is controlled by a controller located in the tenant premises, which implements forwarding according the tenant's business logic. The following figure illustrates the 5G-XHaul slice as perceived by the tenant. 

Op-UC3	Transport Network slicing

Requirements	Functional Requirements
	• A 5G-XHaul Operator will be able to simultaneously provide different virtual slices to different tenants.
	• A 5G-XHaul Tenant will be able to define an arbitrary transport slice layout connecting its sites. Each node in the transport slice will behave as a programmable SDN agent.
	• A 5G-XHaul Operator will be able to isolate traffic between different transport slices in terms of:
	  ○ Visibility: Traffic from one transport slice should never be visible to other transport slices.
	  ○ Network/Compute Resource isolation: Performance of the networking and compute resources allocated to one transport slice should not be affected by the behavior of other transport slices.
	• In order to minimise costs, a 5G-XHaul Operator should be able to multiplex as many transport slices as possible over a single physical networking element.
	• A 5G-XHaul Tenant will receive quasi real-time notifications, events and alarms about the performance of his transport slice.
	Performance Requirements
	A 5G-XHaul network will allow the deployment of as many slices as service instances (see Op-UC3).

Op-UC4	Multiple-split RAN implementations support
Actor	5G-XHaul Operator
Goal/Objective	The main goal of 5G-XHaul Operator will be to provide connectivity services to Mobile Network Operators (MNOs), which may use a heterogeneous set of RAN technologies (2G/3G/4G/5G). In particular, different MNOs may implement different functional splits, where a functional split defines the functionality implemented in a Remote Unit (RU) deployed in the field and a Centralised Unit (CU) centralised in a Data Centre, and possibly virtualised.

Op-UC4	Multiple-split RAN implementations support
Description	A 5G-XHaul Operator provides connectivity services to the following MNOs: • A 5G MNO offering high capacity services/applications in dense urban areas by deploying mmWave based RATs. Each mmWave base station embeds the complete signal processing chain and transmits IP packets to the transport network. Individual user data rate can be in excess of 1 Gbps, but delay requirements are in the order of various tens of milliseconds. • A MNO deploying a 4G LTE-A RAN deployed as small RRUs with a CPRI interface in each cell site, and a set of BBUs hosted in a remote data centre. This MNO requires per cell-site bandwidths in the order of 10 Gbps, latencies below 200 us and delay jitter below 16ns. • A MNO deploying Massive Multiple-Input Multiple-Output (MIMO) BSs to serve dense urban areas. In the employed RAN technology data stream to antenna mapping is performed at the RU, thereby reducing the requirements on the transport network. In particular, this operator maps 8 CPRI like streams to a 64 antenna array operating below 6 GHz. • A 5G MNO deploying a new 5G RAT operating below 6 GHz. This 5G RAN is implemented through a novel functional split that enables centralised cooperative signal processing and scheduling, whilst requiring load dependent capacity from the transport network.
Requirements	<u>Functional Requirements</u> • A 5G-XHaul transport network will be able to provide connectivity services simultaneously to multiple RAN functional splits over a converged transport infrastructure. • Multiple splits will be supported over a packet based network that can benefit from statistical multiplexing gains to optimise transport resources. • A 5G-XHaul transport network will contain synchronisation functions that are required to support some of the considered multiple splits. • Traffic generated by multiple functional splits will be mapped to different transport flows/classes in the 5G-XHaul transport network. • RAN functional split flows/classes will have guaranteed performance in terms of throughput, delay, jitter and synchronisation. • The end points of a transport flow carrying traffic from a given RAN functional splits, may dynamically move. Notice that the end point functions may be virtual functions orchestrated by an NFV management framework. A 5G-XHaul transport network will implement SDN functionalities to re-route transport flows as required, as well as a North Bound API for a tenant to notify about the relocation of a transport endpoint. <u>Performance Requirements</u> A 5G-XHaul transport network will support a functional split transporting IQ samples such as CPRI, along with its associated requirements, as well as traditional backhaul services, over a converged infrastructure.

Op-UC5	Seamless Integration with legacy transport technologies
Actor	5G-XHaul Operator
Goal/Objective	A 5G-XHaul Operator should be able to deploy 5G-XHaul network components in a gradual manner, and these components should integrate to legacy transport network components.
Description	A transport operator has a transport network containing an aggregation segment connecting mobile sites to a regional Data Centre, implemented using Ethernet Provider Backbone Bridge (PBB) technology. Then, regional Data Centers are connected to the operator backbone using IP/MPLS. The transport operator wants to gradually deploy 5G-XHaul functionality in order to increase the flexibility of its transport network and expand his service offering. For this purpose, the transport operator follows these steps: • First, leveraging a planned street level deployment to backhaul Small Cells, the operator deploys a street level wireless segment based on 5G-XHaul technology. This street level segment allows to flexibly connect the street level Small Cells to the macro-sites where the operator has its PBB connectivity. • As a second step, the transport operator gradually replaces its PBB segment with 5G-XHaul packet and optical switches. The 5G-XHaul segments provide increased flexibility and offer redundant paths in order to improve reliability. • As a final step, the transport operator replaces the IP/MPLS segment by 5G-XHaul SDN controlled optical segment, which among other things increases the efficiency of the used optical resources and simplifies the provisioning of connectivity services.
Requirements	<u>Functional Requirements</u> R5.1: A 5G-XHaul Operator will be able to integrate a 5G-XHaul transport “cloud” with an Ethernet PBB-based transport network. R5.2: A 5G-XHaul Operator will be able to integrate a 5G-XHaul transport “cloud” with an IP/MPLS-based transport network. R5.3: A 5G-XHaul Operator will be able to independently deploy wireless and wired 5G-XHaul transport components. R5.4: The benefits provided by a 5G-XHaul transport network should increase proportionally to the number of deployed 5G-XHaul components.

5 Transport requirements for 5G Radio Access Technologies

The end-user use cases introduced in Chapter 3 will have to be supported by all parts of the 5G radio access network, including both RATs and transport networks as designed by 5G-XHaul. In particular, to cope with the stringent requirements derived from the end user use cases introduced in Chapter 3, new 5G RATs such as massive MIMO or mmWave communication are currently under study by the 5G community [12]. The objective of the 5G-XHaul transport network is to support these underlying 5G RATs. Hence, specific performance requirements for 5G-XHaul such as latency, jitter, and overall capacity will be defined by the novel 5G RATs. In this chapter, we first present the state of the art in fronthaul/backhaul technologies and the related requirements. Then, we analyse the effect that several potential 5G RATs might have on the transport network, both from a single link perspective as well as from an aggregation network point of view. The obtained performance requirements will provide important guidelines for the overall design of the 5G-XHaul transport network.

5.1 State-of-the-Art Technologies and Requirements

5.1.1 Transport Technologies Overview

The demand for higher date rates has grown exponentially over the recent years, and the use of smartphones, laptops and other data hungry devices have created unprecedented challenges for wireless service providers. However, the average revenue per unit (ARPU) is either flat or even decreasing slowly. On the other hand, the cost to build, operate and upgrade the RAN is becoming more and more expensive [15]. This has made operators to tread carefully before switching to newer technologies. However, existing technologies cannot meet future demands and hence operators must find cost effective ways to maintain profitability and growth. As we will analyse next, this is especially important in the context of C-RAN.

Traditional 4th generation mobile networks such as 3GPP LTE employ decentralised RAN architectures with baseband units (BBUs) being physically co-located with remote radio units (RRUs) inside a BS, where the BS performs the complete baseband processing including physical (PHY) layer, medium access (MAC) layer and parts of the network layer processing. The IP layer user data is then forwarded between the BS and core network through a transport network known as BH network. In practice, BH networks consist of a combination of mmWave, microwave and fibre, typically offering Ethernet or IP/MPLS interfaces. The BH transport requirements for 4G networks are well established in the industry [16] and are in the order of 100 Mbps per Base Station, and e2e latencies of tens of milliseconds.

Traditional RANs suffer from several limitations including: i) increased CApital EXpenditure (CAPEX) to acquire new BSs, and increased Operational Expenditure (OPEX) due to underutilised resources and increased management costs, ii) limited scalability and flexibility, iii) lack of modularity and limited density as the system is complex to resize after deployment, and iv) inefficient power delivery as the BSs processing power cannot be shared.

An alternative to a decentralised approach is to centralise the RAN functionalities as in the C-RAN approach, where “C” stands for centralised, cloud, collaborative and clean [15]. In a C-RAN architecture, digital processing is performed by a central BBU, while a Remote Radio Head (RRH) containing the radio frequency (RF) transmit and receive components performs analogue processing, and is connected to the antenna. C-RAN has drawn great interest and is already deployed by some operators in China, Japan and South Korea.

A centralised architecture delivers several advantages over the traditional decentralised architecture. One of the main advantages of C-RAN is the reduced CAPEX and OPEX. By reducing the size of the BS, sites can be smaller and energy consumption is reduced due to less energy losses in the coaxial cable and, particularly, because no active cooling is required. RRUs are much smaller, cheaper and their functionalities are also simpler than full-scale BSs. Further, since all BBUs and site support equipment are placed in a centralised location, operation and maintenance becomes easier. C-RAN also enables a flexible deployment of the mobile network and provides improved physical security to the BBUs.

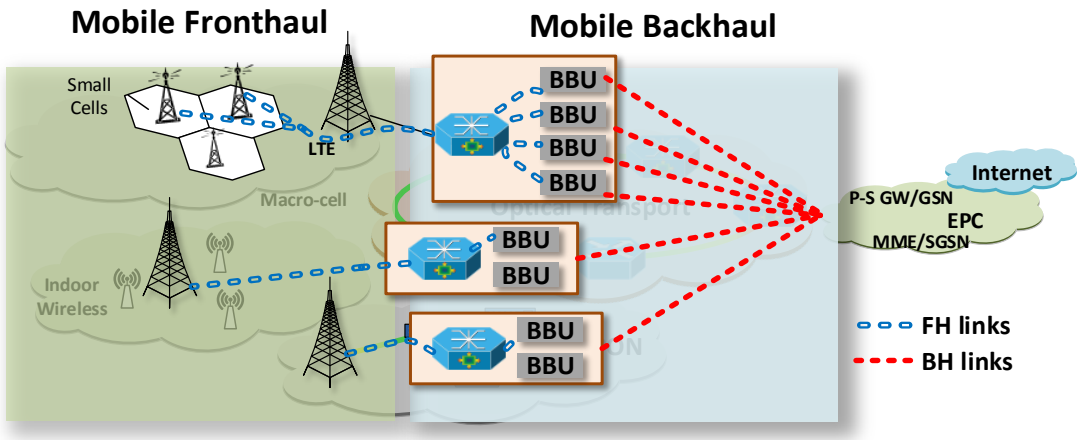


Figure 5.1: Mobile fronthaul and backhaul

Furthermore, the C-RAN architecture enables a more efficient implementation of coordinated multipoint (CoMP), an LTE feature that provides higher capacity and improved cell edge performance [17][5]. The fact that the same BBU can be shared between small cells and parent macro cell in the same coverage area allows to more efficiently manage interference in heterogeneous networks.

In C-RAN, RRHs are connected to the BBU pool through high bandwidth transport links known as FH (left part of Figure 5.1). The interface between the RRH and BBU is standardised as the common public radio interface (CPRI) [18], open base architecture initiative (OBSAI) and open radio interface (ORI). However, CPRI is currently the most common technology used by C-RAN vendors. FH is responsible to carry the RRH wireless signals, typically over an optical transport network, using either digitised form based on protocols such as the CPRI, or in analogue form through radio-over-fibre technology [19]. The main advantage of digitised transmission is the reduced signal degradation, allowing data transmission over longer distances and enabling the adoption of longer reach optics offering higher degree of BBU consolidation. The common FH solution in C-RAN is to use dedicated fibre. However, centralisation requires consumption of a large number of fibre cores which are scarce and much more expensive to deploy. Alternative solutions include the use of other transport technologies such as wavelength-division multiplexing (WDM) and optical transport network (OTN) or even the transmission of FH data using microwave or mmWave frequency bands.

However, CPRI induces very strict requirements on the FH network. These requirements make the FH network very expensive to deploy, thereby counteracting the cost saving expected from C-RAN. It can therefore be argued that the FH network could become the bottleneck of 5G mobile networks. Detailed CPRI FH requirements are discussed in the next section.

5.1.2 CPRI PHY Layer Requirements

CPRI requirements are discussed below in terms of e2e latency, data rate, timing accuracy and reliability.

5.1.2.1 End to end Latency

CPRI requires a round trip latency of 5 µs, excluding propagation delay. More importantly, the total delay including propagation delay is limited by LTE's Hybrid Automatic Repeat reQuest (HARQ) timing. As HARQ acknowledgements have to be received at the UEs after 3 ms and BB processing takes about 2.8 ms [20], only around 200 µs are available for total FH latency. Considering typical speed of light of 200,000 km/s in fibre, CPRI maximum transmission distance is limited to about 20 km.

5.1.2.2 Data rate

CPRI is a constant data rate interface where the data rate depends only on the cell setup and is given as [21]:

[5] CoMP is also possible in a traditional, distributed RAN with a fast X2 interface. Although performance most likely will be worse.

$$D = N_A \cdot f_S \cdot N_q \cdot 2 \cdot \gamma, \quad (5.1)$$

where N_A is the number of antennas per sector, f_S is the sampling rate (sample/s/carrier), N_q is sample width (bits/sample), *2* is multiplication factor for in-phase and quadrature-phase, and γ is an overhead factor accounting both for control signalling and line coding. For example, for a 20 MHz LTE carrier with a 2x2 MIMO configuration, the required CPRI date rate is approximately 2.5 Gbps. Notice that the CPRI data rate requirement increases linearly with the number of antennas per sector and with the bandwidth, both of which will potentially increase in 5G.

According to CPRI section 4.2.1 [18], CPRI line bit rate options 1 through 10 are defined as depicted in Table 5.1, where options 1 through 7 use 8B/10B line coding and options 7A through 10 use 64B/66B line coding. In the future, higher line rates may be defined. In most of cases, 10G, 25G or even higher rate interfaces should be considered for CPRI transport.

Table 5.1: CPRI Line Rates

CPRI Option	CPRI Line Rate (Mbit/s)	Carrier Spectrum Size (MHz)
1	614.4	5
2	1228.8	10
3	2457.6	20
4	3072.0	30
5	4915.2	40
6	6144.0	50
7	9830.4	80
7A	8110.08	80
8	10137.6	100
9	12165.12	120
10	24330.24	240

5.1.2.3 Frequency Synchronisation and Timing accuracy

The CPRI requirements on timing accuracy and synchronisation are based on the requirements of the RATs that are supported, i.e. GSM, UTRA and E-UTRA. Table 5.2 and Table 5.3 list these requirements, respectively.

Table 5.2: Timing Accuracy Requirements for CPRI

Tech Type	Timing Accuracy Req.	3GPP Reference	Remark
GSM	¼ normal symbol periods (about 65.1ns)	TS-45.010 Section 5.3	timing difference between the different carriers measured at the BS antenna
UTRA-FDD	¼ Tc (about 65.1ns)	TS-25.104 Section 6.8.4	MIMO or TX diversity transmissions
E-UTRA	2 Ts (65 ns)	TS-36.133 Section 10.3	Timing advance resolution

Table 5.3: Frequency Synchronisation Requirements for CPRI

Tech Type	Frequency Sync. Req.	3GPP Reference	Remark
GSM	±50 ppb	TS-45.010 Section 5.1	The BS shall use a single frequency source of absolute accuracy better than 0.05 ppm for both RF frequency generation and clocking the timebase
UTRA-FDD	±50 ppb	TS-25.104 Section 6.3	Wide Area BS
E-UTRA	±50 ppb	TS-36.104 Section 6.5.1	Wide Area BS

The FH link must only contribute a fraction of these inaccuracies and, hence, CPRI requires a clock jitter of 2 ppb (parts per billion, 4 % of the total inaccuracy) and a round-trip timing accuracy of ±16 ns (25 % of the total inaccuracy). It is important to note that the frequency accuracy is relative to the clock frequency, while the timing accuracy is based on sample duration. These dependencies will have an impact on the requirements for 5G FH networks, as will be analysed in Section 5.2.

5.1.2.4 Reliability

CPRI requires very high reliability with bit error rates (BER) of less than or equal to10^{-12}.

5.2 5G Radio Access and Impact on the Transport Network

5.2.1 Overview of Functional Split Options in 5G Radio Access

As described in the previous section it is very complex to scale the CPRI technology to RATs with large number of antennas or large bandwidth, like the ones considered for 5G. Hence, several options have been proposed to reduce the requirements imposed on the FH network. Compression schemes [22] can reduce the data rate by up to a factor of 3, thereby reducing the fibre capacity to be deployed. Opportunistic [23] and suspended HARQ [20] are options to increase the total delay requirement, hence enabling larger distances or more time for, e.g. intelligent routing algorithms. However, the most promising approach so far is the introduction of different functional splits [20],[24],[25]. A functional split refers to the splitting of processing that is performed at the central unit (CU) versus the processing that is performed at the Remote Unit (RU), where in the case of CPRI the CU corresponds to the BBU and the RU to the RRH. Thus, the stringent requirements on FH can be reduced by only centralising a part of the processing chain while still maintaining benefits from partial centralisation.

Figure 5.2 shows a detailed signal processing chain in the BS of an LTE mobile network. We take the 4G LTE processing chain as reference, while assuming that 5G RAN technologies will implement a functionally similar chain. We can see in Figure 5.2, that in the downlink (DL), packetised data is processed on the packet data convergence protocol (PDCP) layer and on the MAC layer, thereby adding appropriate headers, and performing scheduling. Automatic repeat request (ARQ) and forward error correction (FEC) encoding is added, followed by modulation and precoding. These operations are performed according to the current channel quality and channel state information, which are continuously made available to the BS by measurements. Next, user and control data are mapped to physical resources, namely subcarriers and time slots. Additional signals for synchronisation and channel measurements are added at this stage as well. In LTE, resource mapping is performed in the frequency domain. Subsequently, a cyclic prefix (CP) is added after transforming the signal to the time domain and the data is then digitally filtered. Finally, the data is converted to analogue domain using a digital-to-analogue converter (DAC), up-converted to the carrier frequency, and then transmitted via the antennas.

In the uplink (UL), the process is reversed. The radio frequency signal received from the UEs is first down-converted to BB, then digitised by sampling and quantisation, and digitally filtered. After the CP has been removed, the data is transformed to the frequency domain, where the different channels are de-mapped from the physical resources and the signals are equalised. After converting the signals back to the time domain, the symbols are detected and decoded. The resulting MAC data is then forwarded to the higher layers, where HARQ, and ARQ is performed, and the data is packetised for transmission on the BH network [4].

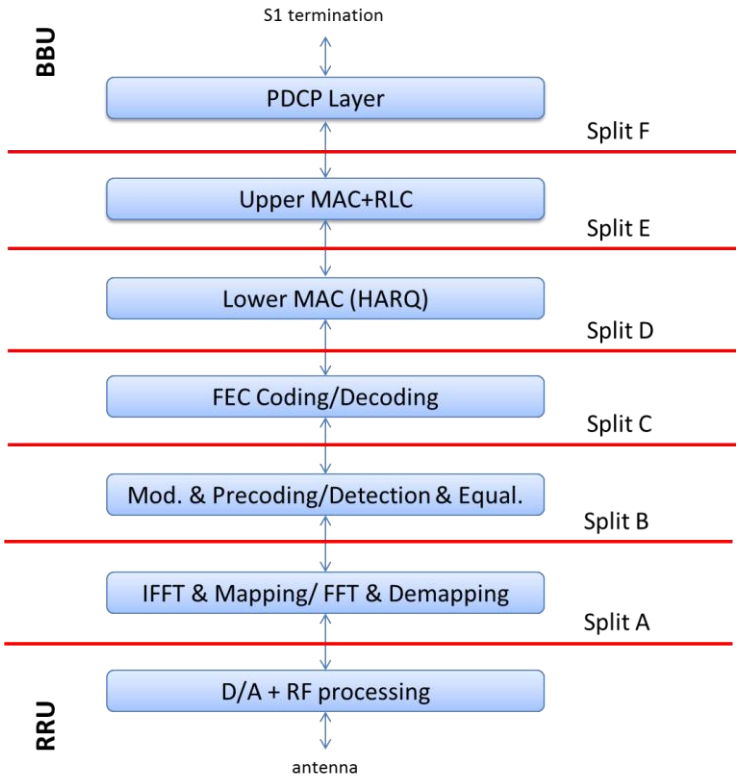


Figure 5.2: Functional split options [26]

In order to relax the stringent FH requirements of C-RAN architectures, while still taking advantage of pooling and coordination gains, alternative architectures incorporating different functional splits could be proposed. Novel potential functional splits are depicted in Figure 5.2 and discussed next.

Split A

Split option A corresponds to the classical FH split in CPRI. Split A marks a clear demarcation point between RF processing and digital signal processing. In split A, the FH data rate can be calculated using (5.1) and it depends on the number of antennas, sampling frequency, quantiser resolution and number of ADC chains. Future mobile networks employing massive MIMO techniques will incorporate a large number of transmitting and receiving antennas. This will linearly scale up the FH data rate since the data rate is proportional to the number of antennas. Similarly, sampling frequency depends on the total bandwidth, which is also foreseen to increase in future networks. The quantiser resolution needs to be quite high, usually around 15 bits per dimension, due to the high dynamics of the time domain signal in LTE. Therefore, the main disadvantage of this split is that FH data rate is of constant rate and it does not depend on the actual user traffic, i.e., even when no user is connected to the BS, the full FH data rate needs to be forwarded.

Further, in order to enable CoMP and distributed MIMO techniques, one must ensure that samples of different BSs are correctly aligned and that the timing advance, i.e., the different propagation times of different UEs, is known precisely. Hence, the total delay on the FH must be measured and jitter must be kept low.

Split B

In split option B, the resource mapping/demapping is decentralised to the RU. Thus, the data exchanged in split option B corresponds to frequency domain samples. Additionally, the different physical channels can be separated by demapping them from the resource elements. These different channels carry data responsible for, e.g. synchronisation, channel estimation, control signals, or user data. Thus, an advantage of this split is that some of these channels, e.g. synchronisation and reference symbols, do not have to be carried by the FH as they can be generated locally at the RU.

Split B offers the option of performing channel estimation in a distributed way, as the reference symbols are available after demapping. This removes the power control constraints on latency for this split, as

Signal to Interference plus Noise Ratio (SINR) can be calculated in the RU. However, centralised precoding still requires up-to-date channel information available at the CU. Therefore, latency requirements could be slightly relaxed, depending on the coherence time of the channel. In addition, jitter is less critical for the higher layer splits, as the samples are aligned at the RU.

The distinct advantage of split B compared to split A is that only the resources currently utilised need to be forwarded. In other words, FH data rate depends on user traffic and it is not constant as in split A.

Split C

For split option C, modulation and precoding are also distributed in the DL. Accordingly, bit-level data instead of complex modulated symbols need to be forwarded from the central processing unit to the RU. Split C is the only split that exhibits a significant asymmetry between UL and DL. In the DL, encoded user bits are transported, while in the UL, Log-Likelihood Ratio (LLR) values are forwarded back to the CU to enable turbo decoding.

The main advantage of this split is that the number of antennas is mapped to spatial streams and vice versa. For example, if a BS is equipped with four antennas but, due to the channel state, can only transmit one spatial stream to a user, only this stream has to be forwarded to the RU instead of one stream for each of the four antennas. This becomes critical in massive MIMO systems if a high number of antennas are mostly used for beamforming, and only a limited number of independent user streams are transmitted concurrently. As channel decoding is still performed centrally, the HARQ scheme of LTE is still a limiting factor as UEs require an acknowledgement to be sent within 3 ms, so split C needs to meet this latency requirement.

Split D

In split option D, coding and decoding are also performed at the RU, i.e. all PHY-layer processing is performed at the RUs. Accordingly, centralisation gains are only possible from higher layer processing. Techniques like joint scheduling or connection control still offer benefits from such a partly centralised architecture. Split D terminates PHY-layer processing. Hence, latency requirements are determined by the higher layers. The data rate for this split is close to the actual data rate seen by the user, because the coding overhead is removed.

Split E

Split E consists of centralising upper MAC layer and RLC functions, whereas the Lower MAC (HARQ) is distributed to the RU. This split has the advantage that the strict timing requirement of LTE's HARQ no longer applies. Otherwise, it is very similar to split D. This Split E would be similar to the light access point P split used in enterprise-level WLANs.

Split F

Split F closely resembles the classical BH split and, in this case, centralised scheduling is no longer available. The only advantage it offers is that it encompasses a somewhat cleaner cut between the Radio Link Control (RLC) and PDCP layers, as well as a minimum impact on the transport network. In addition, centralising PDCP to a secure location may result in enhanced security, because PDCP stores the security credentials used by the UE.

The advantages and disadvantages of each split are summarised in Table 5.4.

Table 5.4: Advantages and Disadvantages of Functional Splits

No.	Advantages/Disadvantages
F	• Clean cut • No centralised scheduling
E	• No HARQ delay requirement for FH
D	• Data rate depends on code rate per user • Clean cut • Potentially no hardware acc. at BBU • No centralised joint decoding

No.	Advantages/Disadvantages
C	• Data rate depends on modulation scheme, layers per user • No centralised CoMP, MU-MIMO
B	• Only utilised Resource Block (RB) (enables stat. mux.) • No CP, GC on FH • Potentially no RS, SS on FH • Frequency domain (lower ADC res.) • Additional hardware at RU required (FFT)
A	• CPRI • No limitation in centralised processing • Very little digital hardware at RU • Very high, static data rate • Low latency and jitter required

As analysed above, several splits are quite similar in the benefits and disadvantages they offer. Thus, to keep complexity of the transport networks low, it is expected that not all splits will be employed in future transport networks. In fact, China Mobile is currently leading an industry group investigating the definition of the Next Generation Fronthaul Interface (NGFI), which will recommend one, or a subset, of the previous splits [25]. Therefore, from the six splits discussed, we have selected the three which offer enough diversity to cover the most important design trade-offs: namely splits A, B, and E. Split A represents the fully centralised option with all its advantages and disadvantages. Split B still allows for sample-based cooperative processing, but the data rate in the transport network depends on the actual cell load, thereby enabling statistical multiplexing among several cells. Split E is close to the classical BH but retains centralised scheduling. Thus, Split A represents the current FH interface, e.g. CPRI, whereas splits B and E are potential candidates for the NGFI interface [25]. In addition, classical BH also needs to be considered for legacy eNBs.

While the idea of functional splits has been extensively discussed for 4G networks, the introduction of new RAN technologies in 5G networks, especially massive MIMO, larger spectrum and mmWave RANs, will determine the impact that the selected functional split will have on the transport network. Therefore, in the next section we analyse in depth the impact of potential future 5G RANs on the transport network.

5.2.2 Impact of potential 5G RATs on Transport Networks

In addition to the used functional split, a major impact on the transport network will come from the introduction of higher carrier frequencies in the 5G RAN, which is currently a likely target for the second phase of 5G standardisation [12]. Currently deployed frequency spectrum lies in the range of 700 MHz to 3 GHz, which is already overcrowded. Fortunately, substantial amount of new spectrum is available in higher frequency bands such as cmWave and mmWave. The use of new spectrum in licensed and unlicensed bands will enable higher data rates and capacity. Moreover, massive MIMO is well suited for higher frequency bands. However, it should be noted that, as frequency increases, it undergoes higher penetration losses and cannot propagate to larger distances. Thus, due to the different properties of cmWave and mmWave spectrum, concepts such as C/U-plane path split and UL/DL split are required that optimise the use of spectra [2].

The introduction of higher carrier frequencies and the accompanying higher bandwidths and increased number of antennas will impact the transport network strongly, especially if low level functional splits are considered. In addition, several other RAN technologies are being discussed in the context of 5G including higher order modulation schemes, new waveforms and technologies supporting the use cases of improved latency and resilience, as well as machine type communications. The general impact of these technologies on the transport network is discussed in Table 5.5. A more detailed analysis can be found in [27].

Table 5.5: Impact of candidate 5G RAN technologies on transport networks

Technology	Effect on air interface	Impact on transport data rate	Impact on transport latency	Other
Higher Carrier Frequency [28]	More bandwidth available, see below Increased pathloss requires beamforming	Higher bandwidth leads to increased transport data rates, see below	Shorter channel coherence time Latency for centralised scheduling or adaptive modulation and coding should be less then channel coherence time	-
Higher bandwidth [28]	Increased user data rates	Increases data rate in all split options	Lower sample duration requires more precise latency estimation	Clock synchronisation is more challenging
Massive MIMO [29]	Increased user data rates by multi-user MIMO Beamforming to overcome increased pathloss	Would lead to massive increase in capacity for per-antenna-CPRI Antenna pre-processing required at RU	For mmWave beamforming, latency must be short enough to allow for user tracking	-
Higher order modulation schemes [30]	Increased user data rates by higher spectral efficiency	Increased data rates for splits C or higher Potentially higher quantiser resolution required, increases data rates for splits A and B	-	-
New waveforms [31]	More flexible air interface for different use cases Reduced out-of-band (OOB) radiation, i.e. less inter-carrier interference	Closer carrier spacing could lead to increased rates for split B and above Potentially higher quantiser resolution required to keep quantisation noise below OOB radiation	-	-
Low Latency [32]	Support of low latency application	-	Transport latency must be considerably lower than required e2e latency	-
High resilience [2]	Support of safety critical applications, automation	-	Transport latency must be low enough to support application	Transport latency must not reduce e2e resilience
Machine Type Communications [2]	Support of new applications Low energy consumption	Potentially large number of small packets	-	-

5.3 Quantitative Requirements for the 5G-XHaul Transport Network

5.3.1 Single Link Requirements

Current 5G research and standardisation efforts [12] are looking as 5G as a multi-RAT system with an air interface operating below 6 GHz, and another air interface operating above 6 GHz in cmWave or mmWave spectrum. Thus, 5G should be capable of a flexible and efficient use of all available air interfaces. In particular, the World Radio Conference (WRC) 2015 focused on frequencies below 6 GHz, which will be considered by the first 5G phase of 3GPP standardisation. Consequently, it is planned that WRC 2019 will allocate frequencies above 6 GHz, e.g. 6 GHz-100 GHz, which will be considered in a 2nd phase of 5G standardisation. It is expected that the higher frequency bands will be complementary bands to 5G, whereas the bands below 6 GHz will continue to be the primary bands of 5G spectrum [7]. As a matter of example some of the currently researched frequency bands above 6 GHz are 28 GHz, 30 GHz, 60 GHz, 70GHz, 72 GHz, and 73 GHz [33].

Notice that the variety of potential spectrum bands and technologies considered for 5G make it difficult to derive the requirements that these technologies will impose on the future transport network. Therefore, in order to progress on the derivation of concrete data rate, delay, jitter, and synchronisation requirements for the 5G transport, we identify three distinct potential 5G RAN air interfaces, encompassing phase 1 and 2, which we consider to be good representatives of the technologies being discussed, namely:

- **"Sub 6":** a 2 GHz carrier with a 100 MHz bandwidth,
- **"Low mmWave":** a 30 GHz carrier with 500 MHz bandwidth, and
- **"High mmWave":** an 80 GHz carrier with 2 GHz bandwidth

Further, in order to capture the most significant architectural options, we focus on three relevant functional splits, namely:

- Split A,
- Split B, and
- Split E,

where the different functional splits have been introduced in Section 5.2.1. Figure 5.3 illustrates the signal processing chain assumed for the Sub 6 as well as both mmWave RATs. For the considered analysis, it has been assumed that mmWave air interfaces employ a multi-carrier waveform, an approach that is still under discussion both in academia and industry. However, the subsequent analysis also applies for a single-carrier system, with the difference that the subcarriers would correspond to time-domain sub-symbols in such a case. In any case, the signal processing steps for both Sub 6 and mmWave are expected to be quite similar, as depicted in Figure 5.2. The only likely difference is that digital beamforming will be preferred in Sub 6 GHz whereas analogue beamforming will be used in mmWave. However, since split A, depicted in Figure 5.2, is placed before the corresponding antenna mapping, the impact on the transport network is negligible.

Table 5.6 summarises all relevant parameters for each considered candidate 5G RAT and the values assumed in the estimation of the throughput for each RAT and all functional splits.

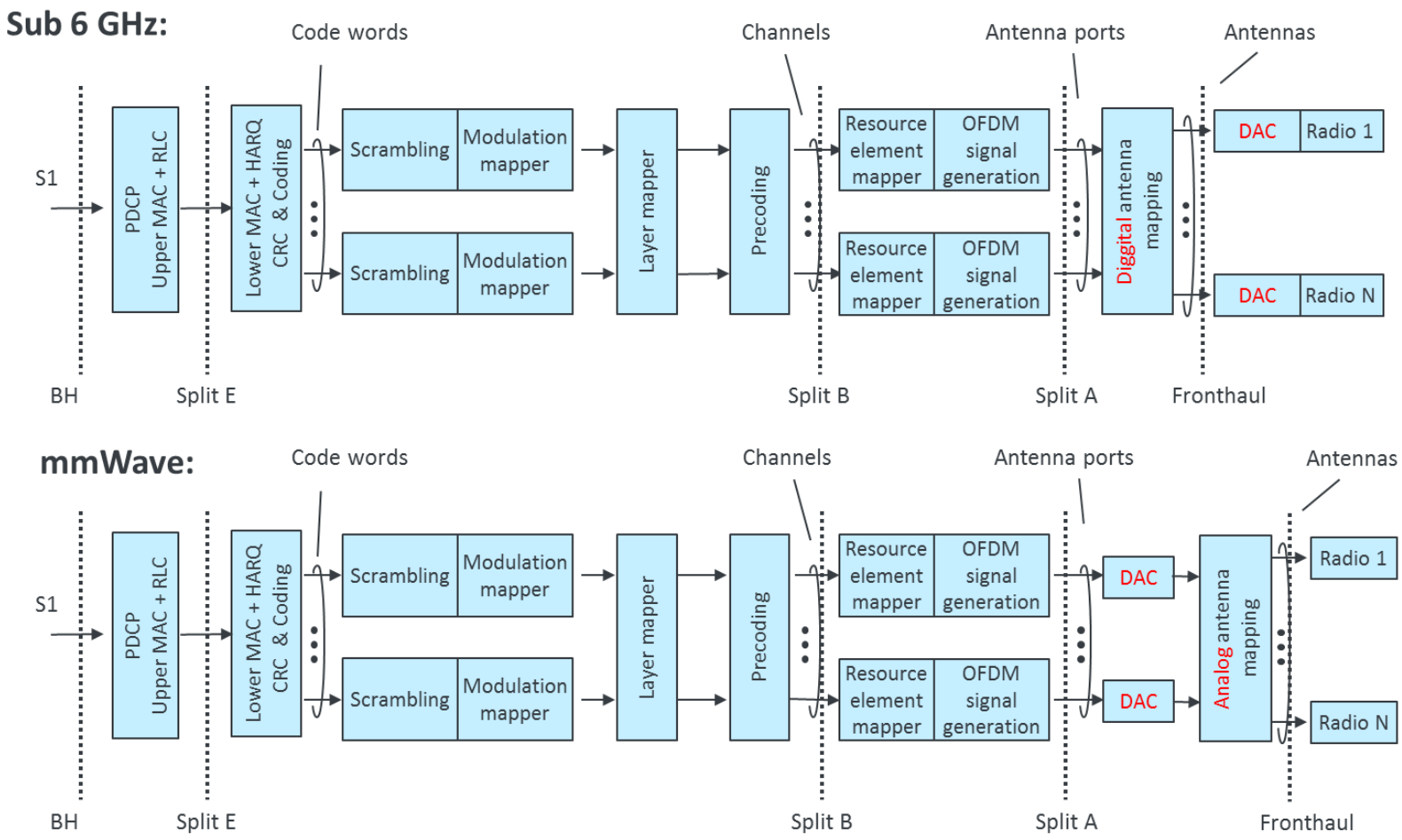


Figure 5.3: Signal processing in Sub 6 GHz and mmWave

Table 5.6: 5G RAT parameters assumed to derive transport requirements [27]

Parameter	Symbol	Sub-6	Low mmWave	High mmWave
Carrier Frequency [GHz]	f_C	2	30	80
Channel Size [MHz]	BW	100	500	2000
Sampling Rate [MHz]	f_S	150	750	3000
# Antennas	N_A	96	128	512
# ADC/DAC chains	N_P	8	4	4
# Layers	N_L	8	4	4
Overhead	γ	1.33	1.33	1.33
Quantiser resolution time domain	$N_{Q,T}$	15	9	7
Quantiser resolution frequency domain	$N_{Q,F}$	9	7	7
Modulation order	M	256	64	64
Max. code rate	R_C	0.85	0.85	0.85
Frame duration [ms]	T_F	1	0.1	0.1
FFT size	N_{FFT}	$5 \cdot 2048$	2048	2048
# Active subcarriers	$N_{SC,act}$	$5 \cdot 1200$	1200	1200
# Data symbols per frame	N_{Sy}	14	35	120
Peak utilisation	μ	1	1	1
Formula for channel coherence time [26]	$T_C = \sqrt{\frac{9}{16\,\pi}\frac{c}{v \cdot f_C}}$			
Channel coherence time at 3 km/h [ms]	$T_{C,3}$	**76.14**	**5.08**	**1.90**
Channel coherence time at 250 km/h [ms]	$T_{C,250}$	**0.91**	**0.06**	**0.02**
Timing accuracy for split A, B (1/2 sample duration) [ns]	T_j	**3.33**	**0.66**	**0.17**
Formula data rate split A	$D_A = 2 \cdot N_P \cdot f_S \cdot N_{Q,T} \cdot \gamma$			
Formula data rate split B	$D_B = 2 \cdot N_P \cdot N_{SC,act} \cdot N_{Sy} \cdot N_{Q,F} \cdot T_F^{-1} \cdot \mu \cdot \gamma$			
Formula data rate split E	$D_E = N_L \cdot N_{SC,act} \cdot N_{Sy} \cdot R_c \cdot \log_2 M \cdot T_F^{-1} \cdot \mu \cdot \gamma$			
Peak data rate split A [Gbps]	D_A	**47.9**	**71.8**	**223.4**
Peak data rate split B [Gbps]	D_B	**16.1**	**31.3**	**107.3**
Peak data rate split E [Gbps]	D_E	**6.1**	**11.4**	**39.1**

The resulting peak transport data rates are summarised in Figure 5.4 for all three considered 5G RATs and functional splits.

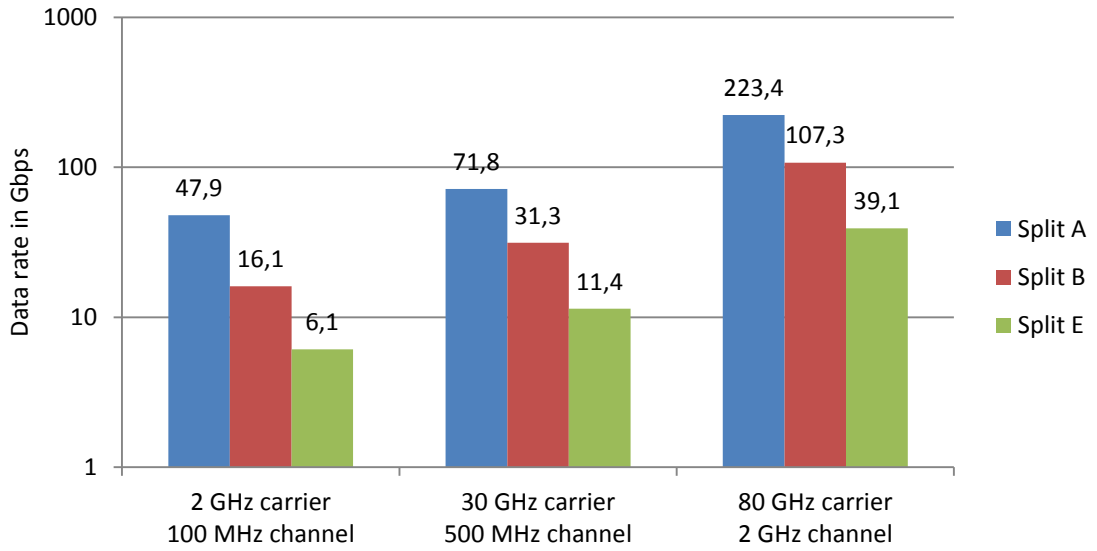


Figure 5.4: Transport data rate for different splits and RAN parameterisations

One of the key benefits of splits B and C, however, is that their data rates depend on the actual load of the network. This is especially important for the dimensioning of the aggregation segment of the transport network, as not all cells in a given network will exhibit peak rates at the same time instance. This fact is commonly referred to as statistical multiplexing, and as a result, transport networks need not to be dimensioned in practice for the sum peak traffic of all cells. In the next section we provide a study based on real traces to evaluate the statistical multiplexing gains achievable with different RATs and functional splits.

Finally, the “single-cell” transport requirements for the different RATs and functional splits considered are summarised in Table 5.7, Table 5.8, and Table 5.9 below, including the “conventional” splits of FH and BH for comparison.

The data rates for split A to E are taken from Table 5.6. The data rate for FH assumes that one stream per antenna element is transported instead of one stream per ADC chain as for split A. For BH it was assumed that the overhead compared to split E is negligible and hence the data rates are the same.

For the delays, it is assumed that the splits below B need to meet the same HARQ requirements as CPRI, as discussed in Section 5.1.2.1. For split E, it was assumed that HARQ is decentralised and, hence, the channel coherence time is the limiting factor. For Sub-6 GHz the channel coherence time at 250 km/h was taken into account, while for the mmWave technologies it was considered that only slow moving users of about 3 km/h will be supported due to the low range of mmWave technology. The delay for the BH is based on the value typically observed in 4G BH networks [34].

The timing accuracy was also taken from Table 5.6, accounting for ½ of the sample duration, following the CPRI requirement discussed in Section 5.1.2.1. Since splits above E do not require an alignment of samples, no requirement on timing accuracy applies.

Finally, the clock jitter is also based on the CPRI requirement. However, as it is relative to the clock frequency, the total value will be higher for the considered 5G RATs according to their higher sampling frequencies. Again, the splits above B do not require synchronous clocks from the RAN perspective.

Clearly, the data rates given for FH, which considers one stream per antenna element, are prohibitively high, making this type of split infeasible. At the same time, the requirements of BH are very similar to those of split E. As a result, splits A, B and E were chosen as options being both viable and representative.

Table 5.7: PHY layer requirements for transport of a "Sub 6" access link

Sub 6	FH	Split A	Split B	Split E	BH
Peak Throughput	574.6 Gbps	47.9 Gbps	16.1 Gbps	6.1 Gbps	6.1 Gbps
Delay	200 us	200 us	200 us	200 ms	30 ms
Timing accuracy	3.3 ns	3.3 ns	3.3 ns	-	-
Clock jitter	2 ppb	2 ppb	2 ppb	-	-

Table 5.8: PHY layer requirements for transport of a "Low mmWave" access link

Low mmWave	FH	Split A	Split B	Split E	BH
Peak Throughput	2.3 Tbps	71.8 Gbps	31.3 Gbps	11.4 Gbps	11.4 Gbps
Delay	200 us	200 us	200 us	30 ms	30 ms
Timing accuracy	0.3 ns	0.3 ns	0.3 ns	-	-
Clock jitter	2 ppb	2 ppb	2 ppb	-	-

Table 5.9: PHY layer requirements for transport of a "High mmWave" access link

High mmWave	FH	Split A	Split B	Split E	BH
Peak Throughput	286 Tbps	223.4 Gbps	107.3 Gbps	39.1 Gbps	39.1 Gbps
Delay	200 us	200 us	200 us	200 ms	30 ms
Timing accuracy	0.167 ns	0.167 ns	0.167 ns	-	-
Clock jitter	2 ppb	2 ppb	2 ppb	-	-

5.3.2 Throughput Requirements for Aggregated Links

As previously discussed, peak traffic is not a good measure to dimension transport networks. Therefore, in order to properly assess the effect of the load-dependent functional splits, actual traffic measurements gathered from an operational LTE network in Greece (provided by COSMOTE) have been evaluated. In particular, COSMOTE gathered data from 10 sites with $\mathrm{C} = 33$ cells in total, over a period of $\mathrm{D} = 15$ days on a 15 minute basis. For the purpose of this study, the following measurements have been used (for each cell c and 15-minute time instance $t = (d, m)$, d being the day and m the 15-min interval):

- the percentage of utilised Physical Resource Blocks (PRBs) relative to the total number of PRBs, for UL and DL, $\mu_{UL}(c,t), \mu_{DL}(c,t)$
- the MCS distribution, $p(MCS_i, c\ t)$
- the maximum cell throughput, for UL and DL, $D_{\max}(c,t)$
- the maximum number of UEs per cell, for UL and DL, $N_{\mathrm{UE}}(c,t)$

Figure 5.5 shows the maximum and average utilisation measured for the UL and DL, i.e,

$$\mu_{max}(t) = \max_{c} \mu(c,t) \tag{5.2}$$

and

$$\mu_{avrg}(t) = \frac{1}{C}\sum_{c} \mu(c,t) \tag{5.3}$$

Clear day-night patterns can be observed in Figure 5.5, where it is worth noticing that both average and maximum loads tend to be quite low in the measured LTE production network. Note that it is difficult to assess how representative the measured "low-load" scenario will be for future 5G networks, as one would have to measure the effect of both the increased demand and the new RAN technologies on the network load. Therefore, in order to cover a wide range of scenarios, we consider in our study the "low load" scenario obtained through the measurements performed by COSMOTE, and a synthetic "high load" scenario that has been obtained by scaling up the COSMOTE traces. Figure 5.6 depicts a sample of the scaled up traces.

In order to derive the "high load" traces it was assumed that each user generates an average traffic demand of $D_{5G,DL} = 300$ Mbps for the DL and $D_{5G,UL} = 50$ Mbps for the UL, as recommended by the NGMN alliance for broadband access in dense areas in [2], and that the spectral efficiency of a 5G network would be approximately 5 times higher than in a current LTE network. Accordingly, the loads for a high load scenario were computed as:

$$\mu'(c,t) = \mu(c,t)\frac{D_{5G}}{D_{\max}(c,t)\cdot 5} \tag{5.4}$$

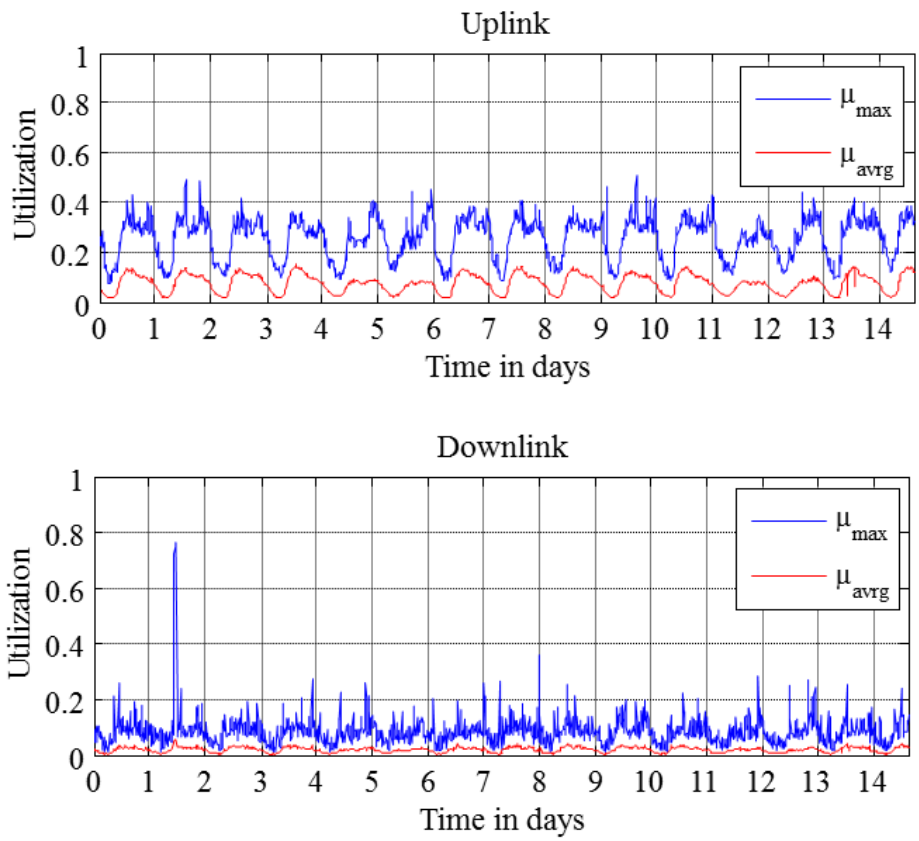


Figure 5.5: Average and maximum cell utilisation from real-life network measurements (low load)

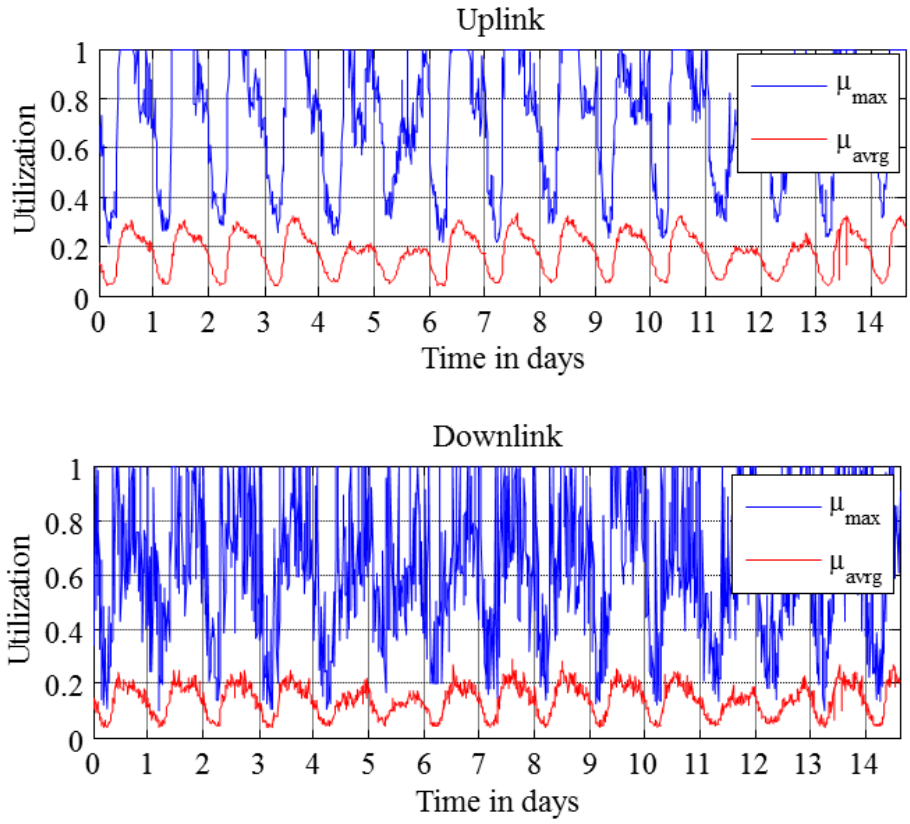


Figure 5.6: Average and maximum cell utilisation of scaled measurements (high load)

As observed in Figure 5.5 and Figure 5.6, load in the network is time dependent; therefore, the concept of Busy Hour (BH) is introduced to dimension the transport network. In particular, based on the methodology introduced by the NGMN alliance in [35], we have analyzed BH requirements for 5G transport networks by combining the measurements with the exemplary parameter set from [27] using the methodology described next.

The busy hour is selected as the hour with the highest sum utilisation among all cells, i.e.

$$t_{busy} = \underset{m}{\operatorname{argmax}} \sum_{c} \sum_{d} \sum_{m}^{m+3} \mu(c,t) \tag{5.5}$$

Following this approach, the busy hour was found to span from 12:15 to 13:15, both for UL and DL. Next, a busy hour MCS distribution was computed as the average MCS distribution in that hour, i.e.:

$$p_{busy}(MCS_i) = \frac{1}{C \cdot D} \sum_{c} \sum_{d} p(MCS_i, c, t_{busy}) \tag{5.6}$$

The MCS distribution is depicted in Figure 5.7. Note that MCS 10 and 17 are very close to their adjacent MCS in terms of spectral efficiency and thus were not utilised.

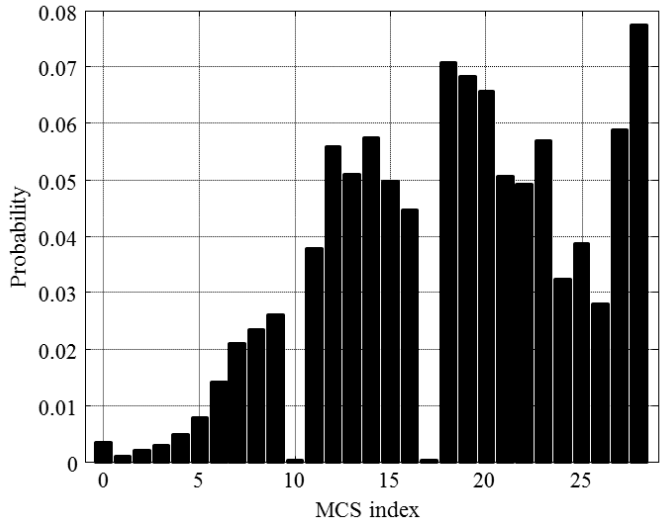


Figure 5.7: Busy hour MCS distribution

Next, all loads observed in the busy hour across all cells, were used to accumulate a discrete busy hour load distribution:

$$p_{busy}\left(\mu \in \bigcup_{d,c} \mu(c, t_{busy})\right) = \frac{1}{4 \cdot C \cdot D} \tag{5.7}$$

with the factor 4 accounting for the four 15-min traces per hour.

Figure 5.8 depicts the CDFs of the busy hour utilisation for both the low load and high load scenarios.

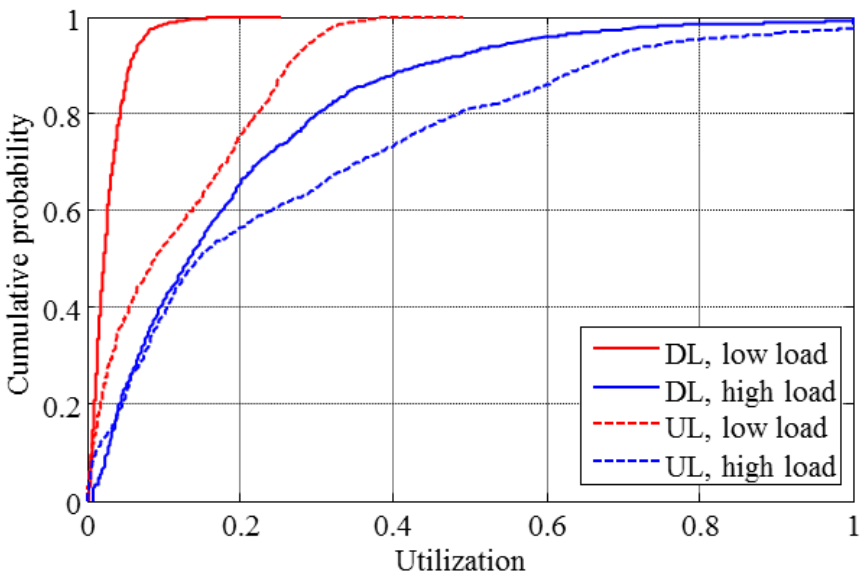


Figure 5.8: Busy hour load distribution for low load and high load scenario

Finally, based on the empirically computed busy hour utilisation and MCS distributions, it is possible to calculate the probability distribution of the transport data rates required by splits A, B and E and for the three different 5G RATs introduced above by using basic probabilistic methodologies, as described in [21]. To account for the fact that, as maximum modulation scheme of 256-QAM was assumed instead of the 64-QAM in the actual measurements, the spectral efficiency of each MCS was scaled by 8/6 for the 2 GHz carrier.

The resulting complementary CDFs of the different data rates are depicted in Figure 5.9 for the low load scenario.

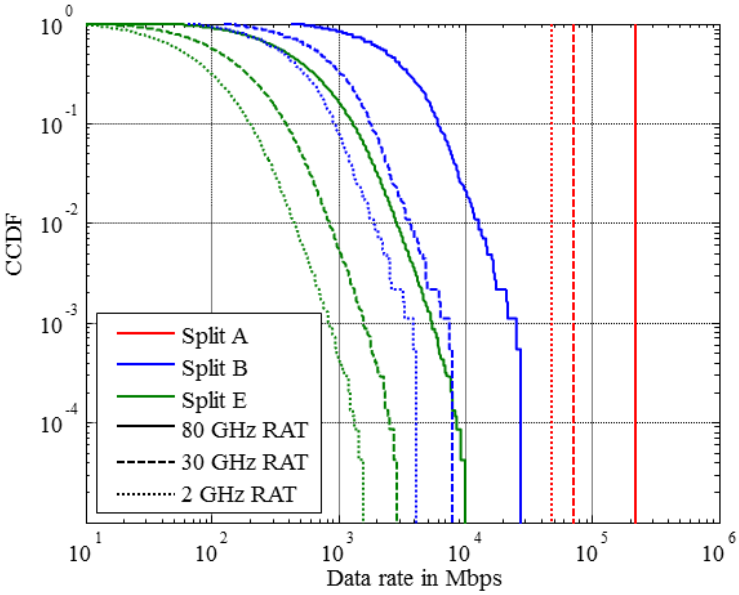


Figure 5.9: Complementary Cumulative Distribution Function (CCDF) of single cell data rates for the DL and low load

Figure 5.9 illustrates the potential statistical multiplexing gains that can be achieved by each 5G RAT and functional split. This is important, as the transport network is typically not dimensioned for peak rates in order to save costs [36]. Instead, it is dimensioned for a certain percentile, e.g. the 95th percentile Q_{95}, i.e. the offered traffic can be transported without delays with a probability of 95%. As an example, consider split E of the 2 GHz RAT: while the peak rate (Q_{100}) is about 1553 Mbps, Q_{95} is only 267 Mbps, i.e. 17 % of the peak capacity, which would very significantly reduce the required transport infrastructure.

When several base stations are aggregated, additional statistical multiplexing gains can be observed, as the distribution, and hence percentiles $Q(C)$ of C cells are different to a simply scaled percentile of one cell $C \cdot Q(1)$ [21]. Intuitively, one can imagine that the peaks of all cells do not happen simultaneously. To illustrate this, Figure 5.10 depicts the aggregated data rates for the 2 GHz carrier for the aggregated peak rates ($C \cdot Q_{100}(1)$), aggregated 95th percentile without accounting for statistical multiplexing ($C \cdot Q_{95}(1)$), and the 95 % percentile of all aggregated cells when considering statistical multiplexing ($Q_{95}(C)$). Following the methodology from [35], the required capacity when using the 95th percentile are calculated as the maximum between the 95th percentile of C cells and the peak capacity required for one cell (see also Figure 5.10):

$$R_{req} = \max(Q_{100}(1), C \cdot Q_{95}(1)) \quad \text{without multiplexing} \tag{5.4}$$

$$R_{req} = \max(Q_{100}(1), Q_{95}(C)) \quad \text{with multiplexing} \tag{5.5}$$

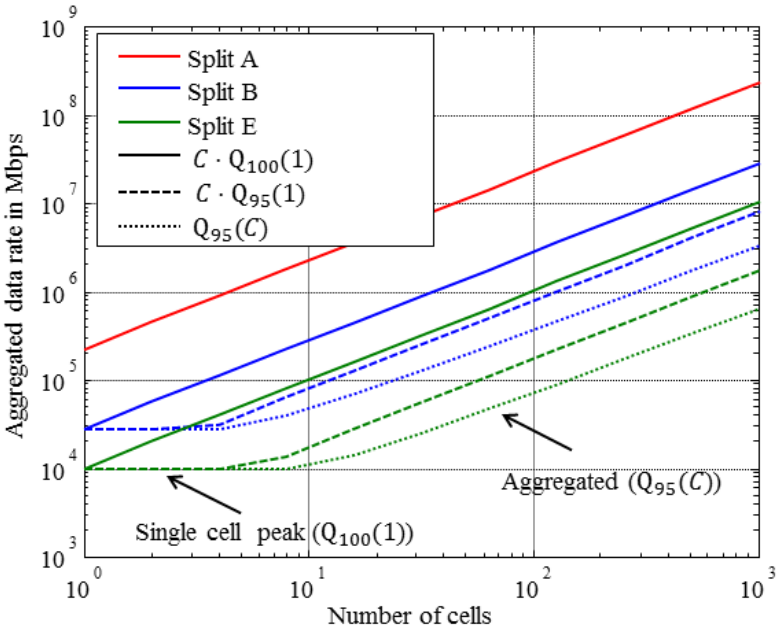


Figure 5.10: Aggregated data rates for 2 GHz RAT and different percentiles

Notice in Figure 5.10 that the gap between the dotted and dashed lines is the gain from statistical multiplexing, and the gap between the dashed and solid lines is the gain from dimensioning only for 95 % of the traffic.

As can be seen in Figure 5.10, the gains can be as large as factor 3 for splits B and E. However, split A does not exhibit gains due to its constant data rate. In summary, Figure 5.10 demonstrates that the required capacity and correspondingly deployment and operational costs can be greatly reduced with load-dependent functional splits and a transport network supporting variable data rates.

Finally, to evaluate the total capacity required for a larger network, Figure 5.11 shows the required capacity for uplink and downlink for the two load scenarios derived from the COSMOTE traces and the parameter set from Table 5.6. As can be seen, the required capacity of, e.g. a core network aggregating 1000 cells, varies between 229 Tbps in the case of split A mmWave RAT, and only 67 Gbps in the case of a split E Sub 6 GHz RAT.

To put this into further perspective, let us consider technologies for packet based transport based on the Ethernet standard. The versions with the highest data rate currently standardised are 802.3.ae, .ak, and .an [37] with a capacity of approximately 10 Gbps. Considering the rates derived in the high load scenario, only 8 cells of split C for the 2 GHz RAT could be transported by these technologies, whereas no single cell of the mmWave RATs could be transported at all. Hence, the currently available technologies will not be able to support 5G technology, which justifies the research on novel wireless and optical transport technologies that will be carried out in 5G-XHaul. For example, higher rates of up to 400 Gbps are currently being investigated by IEEE study groups [38]. Figure 5.12 illustrates the number of cells that could be supported with a 400 Gbps Ethernet link in the DL for the high load scenario. We can see how in this case all functional splits and 5G RAT combinations could be supported in principle.

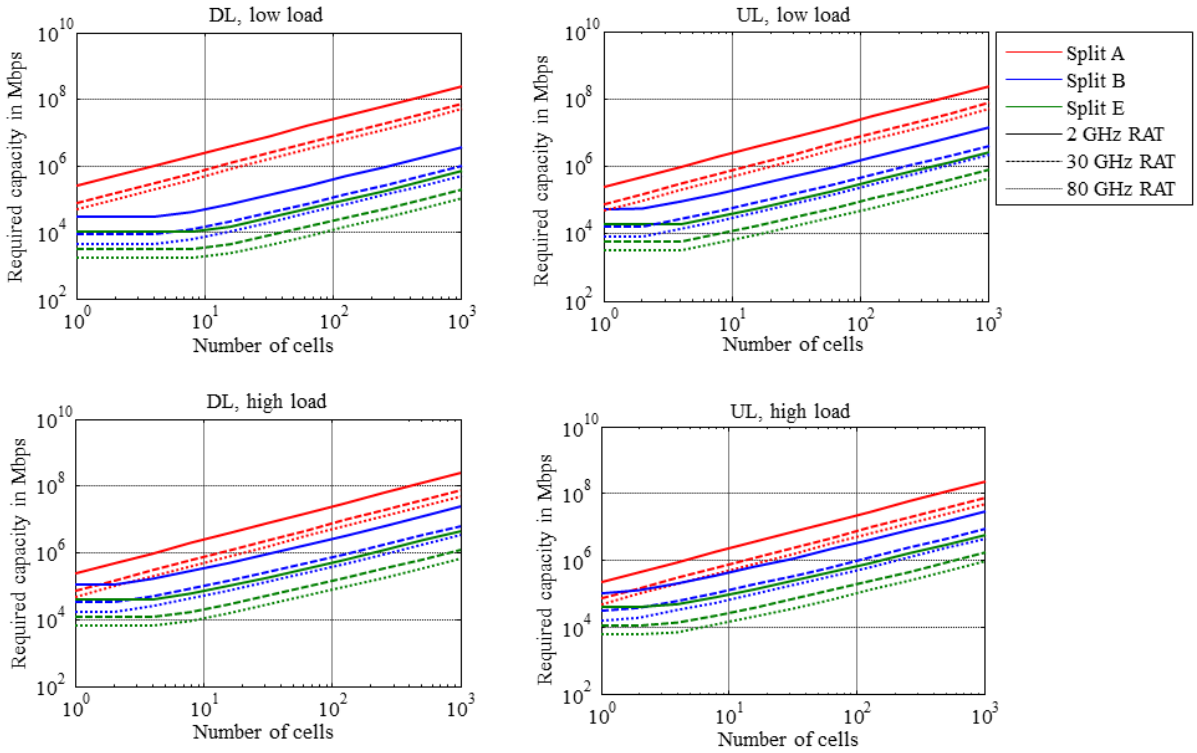


Figure 5.11: Capacity Requirements for Aggregated Network Traffic

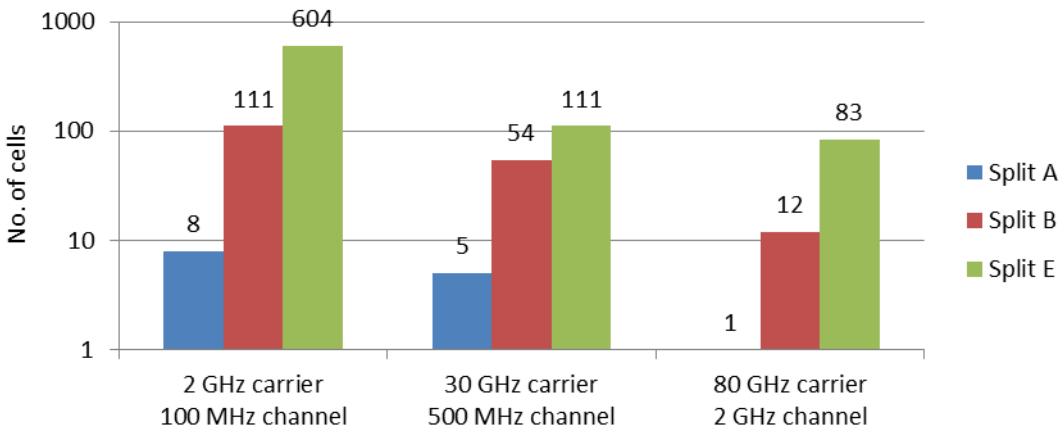


Figure 5.12: Number of cells supported with 400 Gbps Ethernet

6 5G-XHaul Key Performance Indicators

As stated in Section 2, the requirements derived from the intended uses of the overall 5G System have a cascading effect on 5G transport networks and, as a result, on the 5G-XHaul Transport system. Following these lines, the envisioned 5G-PPP global performance KPIs expected by 2020 [6] will have implications on the KPIs to be achieved by our transport network. Even though the quantification of these KPIs at this early stage can be an ambiguous task, we attempt to address those with medium-high relevance, and give an estimation of 5G-XHaul contribution. We also want to point out that the KPI quantification will be adapted over the course of the project.

Table 6.1: 5G-XHaul transport solution planned contributions to help fulfil the expected 5G-PPP KPIs by 2020

KPI	Relevance	Details on planned project contribution towards achieving the KPI
Providing 1000 times higher wireless area capacity and more varied service capabilities compared to 2010.	High	Using a combination of optical technologies and mmWave wireless broadband Point-to-Multipoint (P2MP) links, in conjunction with dynamic network control, 5G-XHaul will support this traffic growth expected from the RAN. 5G-XHaul infrastructure will efficiently support provisioning of both end-user and operational services. The maximum levels of performance will not all apply at the same time for every application or service. Instead, 5G systems will be built to meet a range of performance targets, so that different services with widely varying demands can be deployed on a single infrastructure.
Reducing the average service creation time cycle from 90 hours to 90 minutes.	Medium	5G-XHaul will develop a transport network comprising wireless and optical technologies. Thus, in the context of 5G-XHaul, services are transport related services, such as provisioning connectivity between end points with a given SLA. 5G-XHaul proposal is to use a converged SDN control plane for the transport network (both wireless and optical segments), which should simplify and speed up service provisioning. The northbound API developed in 5G-XHaul will enable instant provisioning of BH connectivity services for different tenants. At the moment, though, it is hard to benchmark the project improvements against the 90 minutes goal.
Facilitating very dense deployments of wireless communication links to connect over 7 trillion wireless devices serving over 7 billion people.	High	The forecasted move to the use of higher frequencies in the RAN will also require smaller coverage areas per cell site – the mobile grid will become much denser than it is today. We contribute to the densification of the wireless access developing P2MP millimetre wave radios for the transport network. These radios will be controllable by an SDN control plane in order to adapt the topology according to the network conditions. We believe SDN controlled P2MP millimetre wave radios are key to reducing the Total Cost of Ownership (TCO) of massive deployments of Small Cells. In terms of physical deployment, this will incorporate the addition of macro cells as well as small cells on poles, towers and rooftops, in addition to mass deployment at the street level, utilising street furniture and light poles as part of the physical infrastructure.

KPI	Relevance	Details on planned project contribution towards achieving the KPI
Creating a secure, reliable and dependable Internet with a “zero perceived” downtime for services provision.	Medium	The SDN control plane on the transport network should improve reliability by allowing to easily establish backup paths. The P2MP millimetre wave technology in Small Cell scenarios improves reliability by providing path diversity, as compared to current static point-to-point links.
Reduction of energy consumption per service up to 90% (as compared to 2010)	Medium	5G-XHaul will contribute to energy reduction on two fronts: 1) On the optical domain the project will investigate innovations to WDM-PON networks that allow an SDN controller to dynamically switch off optical endpoints in order to save energy. 2) In the wireless Small Cell transport segment, one of the use cases considered for the P2MP millimetre wave technology is to switch off Small Cells during periods of low load, and reconfigure the wireless transport accordingly.

7 First System Concept Proposal

7.1 Overview of the 5G-XHaul Architecture

Having identified a wealth of services that need to be supported by 5G infrastructures, as well as the requirements associated with the operational needs of the infrastructure in terms of BB processing described in detail in the sections above, 5G-XHaul is proposing a converged optical-wireless 5G network infrastructure interconnecting computational resources with fixed and mobile users. The objective is to support both operational network (C-RAN) [39] and end-user services, adopting the concept of cloud computing. A layered architecture, inspired by the ETSI Network Function Virtualisation (NFV) standard [40] and the SDN reference architecture [41], is considered to effectively and efficiently provision both end-user and operational services over the proposed infrastructure.

5G-XHaul aims to study a variety of FH and BH options and identify associated trade-offs, spanning from the traditional approach where the two functions are supported separately to solutions involving fully or partially converged FH and BH functions (Figure 7.1). As part of the proposed approach, 5G-XHaul will adopt a holistic view considering jointly mobile FH and BH functions to ensure appropriate allocation of the required resources across all domains. Its objective is twofold: i) to minimise the CAPEX and OPEX of the joint FH and BH network, under the associated delay constraints taking advantage of optimal functional split options of BB processing, as well as through optimal BBU placement [42], and ii) to minimise e2e service delay in the BH.

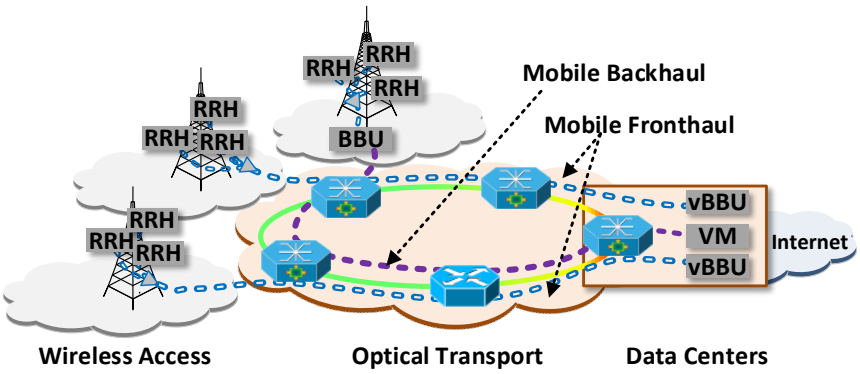


Figure 7.1: Unified mobile BH/FH over converged optical data centre networks

7.2 The 5G-XHaul Data Plane

The 5G-XHaul data-plane architecture considers an integrated optical and wireless network infrastructure. The wireless domain comprises a dense layer of small cells that are located 50-200 m apart [43]. This small cell layer is complemented by a macro cell layer to ensure ubiquitous coverage. Macro-cell sites are around 500 metres apart. Small cells can be wirelessly backhauled to the macro-cell site, using a combination of mmWave and Sub 6 wireless technologies. Alternatively, the 5G-XHaul architecture allows small cells to be directly connected to a central office node using optical network technologies and, more specifically, Passive Optical Networks (PONs) offering enhanced capacity through the deployment of Wavelength Division Multiplexing (WDM). In addition to WDM-PONs, 5G-XHaul adopts the use of a dynamic and flexible/elastic frame based optical network solution that can support more demanding capacity and flexibility requirements for traffic aggregation and transport. Through this architecture 5G-XHaul aims to efficiently support a large variety of end-user services considered in 5G.

A key architectural issue, associated with this type of infrastructure, is the location of BBUs and RUs. In 5G-XHaul, the concept of C-RAN, where RRHs, are connected to BBU pools through high bandwidth transport links (FH), is one of the approaches investigated in order to overcome the limitations associated with the traditional RAN approach. Through the need for FH capability, this architectural choice introduces the requirement to support an additional set of services for operational network purposes. More specifically, the densely distributed BSs/RRHs need to be connected to regional data centres that host BBUs with very stringent delay and synchronisation requirements. 5G-XHaul proposes to use a common network infrastructure to support jointly BH and FH functions maximising the associated sharing bene-

fits, improve efficiency in resource utilisation and provide measurable benefits in terms of overall cost, scalability and sustainability objectives. This can be practically supported through the proposed 5G-XHaul data plane architecture as well as the advanced wireless and optical network technologies that are developed internally within the project.

A key enabler supporting the feasibility of this approach is the adoption of a high capacity, flexible optical transport comprising both passive and active solutions. As well as PON solutions, active solutions will also adopt more flexible and dynamic WDM technologies such as the Time-Shared Optical Network (TSON). TSON has already been developed and deployed to efficiently and effectively demonstrate advanced backhauling capabilities [45]. TSON is designed and implemented as a novel frame-based, time multiplexing metro network solution, offering dynamic connectivity with fine bandwidth granularity [46]. In addition, 5G-XHaul proposes to exploit the benefits of flexible processing splits introduced in Sec. 5.2.1 with the aim of relaxing the stringent requirements in terms of transport capacity, delay and synchronisation discussed. As illustrated in Figure 5.2, the range of “optimal split” options spans between the “traditional distributed RAN” case, where all processing is taking place locally at the AP, to the ”fully-centralised C-RAN” case, where all processing is allocated to a CU. All other options correspond to allocating a particular part of the processing at the RU and the remaining processing remotely at the CU. The optimal allocation of processing functions executed locally or remotely, i.e. the optimal “split”, can be decided during the network design phase, based on a number of factors such as the transport network characteristics, the network topology and scale, as well as the type and volume of services that need to be supported. A high level view of the 5G-XHaul data plane architecture is provided in Figure 7.2.

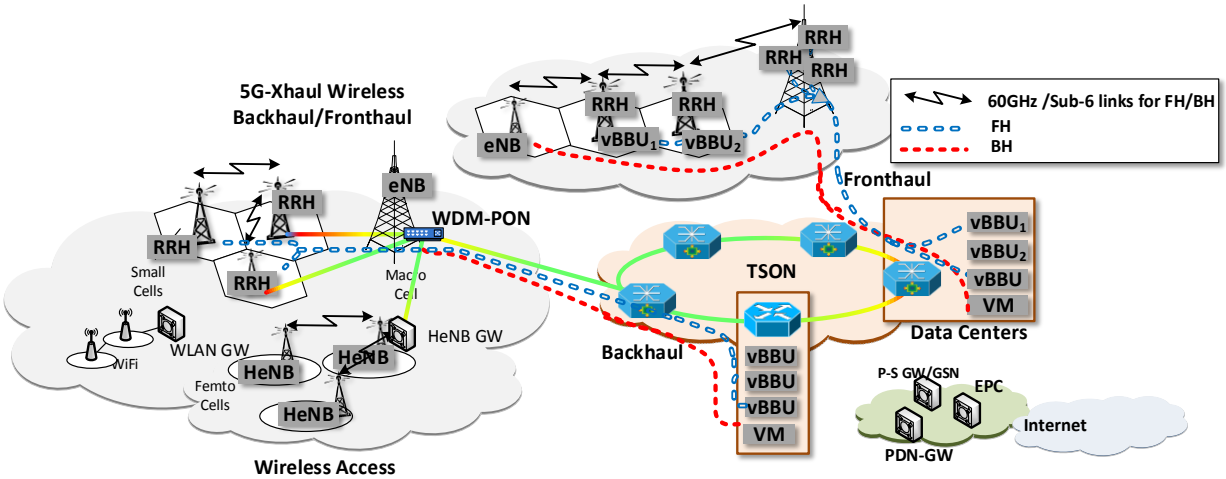


Figure 7.2: The 5G-XHaul physical infrastructures

A pictorial representation of the 5G-XHaul optical transport is shown in Figure 7.3. The TSON framework offers a very flexible optical platform that supports sub-wavelength switching, flexible frame lengths, varying from 64 ns to 25.6 μs and variable bit rates, spanning from of 30 Mbps up to 6 Gbps, with 30 Mbps step. As TSON’s operational characteristics can be dynamically modified, varying service related requirements can be also supported. Extensions planned to be developed in the framework of 5G-XHaul will include elastic bandwidth allocation (Figure 7.4) and more stringent synchronisation capabilities.

As part of the common optical network infrastructure outlined above, we also consider other key enablers for coping with the stringent requirements of a joint BH and FH optimisation. Optical fibre links are so far mostly available in urban environments while, at the time being, their deployment is not fast enough to match the sheer number of small cells required to serve the upcoming demand in mobile data. To address this issue, low cost mmWave links along with Sub 6 GHz systems can be used for this purpose in cases where optical fibre links are not available.

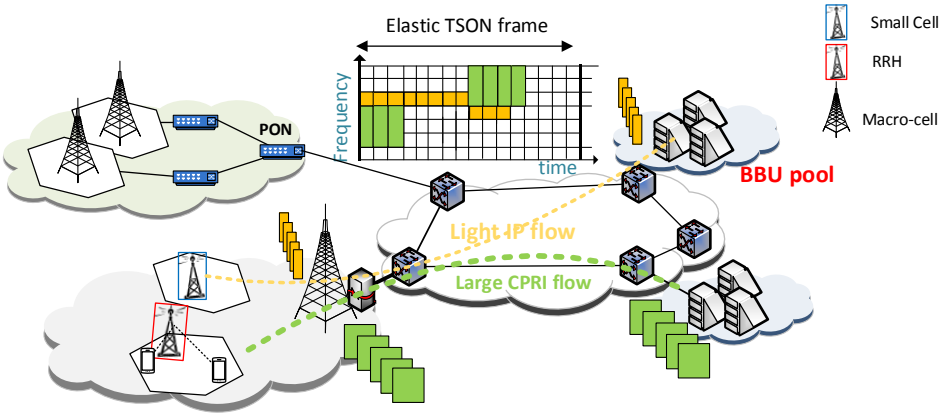


Figure 7.3: 5G-XHaul optical transport

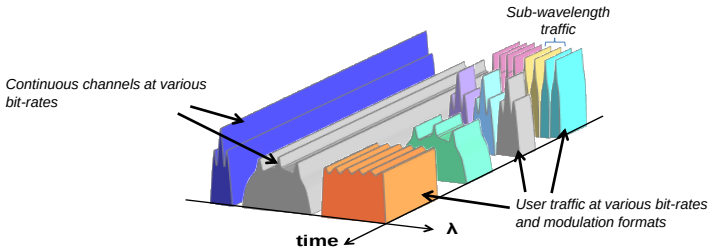


Figure 7.4: Elastic time and bandwidth allocation

In general, the 5G-XHaul infrastructure is expected to support a large variety of traffic types including CPRI, traditional BH, new FH functional splits, and other, e.g., IoT traffic, as shown in Figure 7.5. These various types of traffic can be carried by the same physical network and, in some cases, by the same physical link. Existing mechanisms, such as queuing, store-and-forward etc., make traditional packet networks unable to meet the requirements associated with these services, unless relevant enhancements are performed. Some related work in the industry is currently ongoing, e.g. at the IEEE Time-Sensitive Networking Task Group.

Unlike FH, BH traffic, either from the eNodeB or from the BBU pool to the Service Gateway (S-GW) / Packet Data Network Gateway (P-GW), does not currently impose stringent QoS requirements. However, it is expected that in 5G environments there will be some emerging services that will also have tight requirements in terms of delay and delay jitter. Other types of traffic, associated e.g. with Wi-Fi, do not have explicit QoS requirements and can be treated as best effort traffic taking advantage of statistical multiplexing in packet networks. This type of traffic can traverse the mobile transport network and access internet via P-GW as suggested by the 3GPP LTE architecture [47], or simply via a common router. It should be noted, that adopting an integrated packet based FH and BH network can also make use of the mature Ethernet ecosystem, and help in decreasing the associated CAPEX. In view of this, 5G-XHaul will also consider this option.

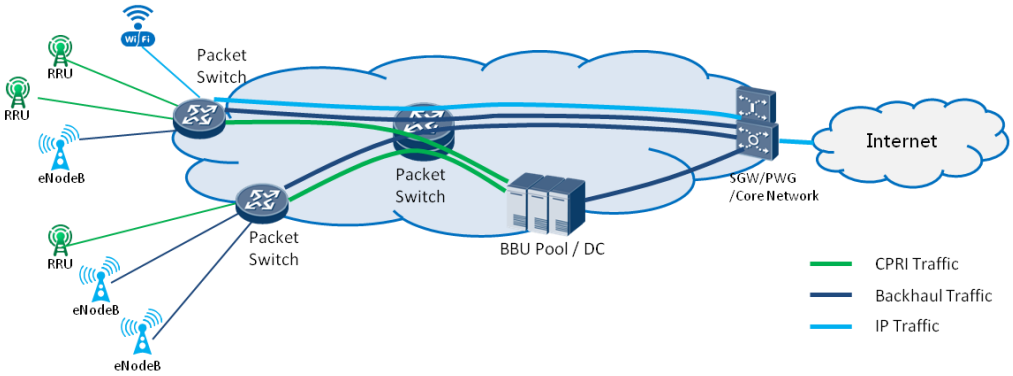


Figure 7.5: Integrated BH/FH/IP transport

5G-XHaul will design techniques to allow dynamic and autonomic reconfiguration of the transport network topology using a P2MP scheme, tightly integrated with Sub 6 technologies. Novel PHY techniques for mmWave wireless technologies will be designed in order to enable the transport of CPRI, and of other functional splits, over wireless. 5G-XHaul will also exploit novel radio signal processing methods in the PHY layer to show how LoS and NLoS performance for mmWave BH and FH systems can be enhanced. Specific examples include Massive MIMO array antenna signal processing where multipath may be exploited to either increase range or QoS (in LoS conditions), or to improve coverage through exploitation of multipath (in NLoS conditions – particularly in urban conditions).

7.3 The 5G-XHaul Control Plane

5G infrastructures will not rely on a single radio access technology, but will support heterogeneous networks, covering the traditional 2G, 3G, 4G, as well as new 5G air interfaces, Wi-Fi solutions, etc. This variety of radio access technologies has very diverse QoS requirements, needs to support different traffic models and relies on different architectures. Building a dedicated network for each of these technologies or applications is very complex and cost inefficient. Network slicing will be a possible solution for this problem. Network slicing will provide e2e network slices in RAN, mobile BH/FH, and also core network, as indicated in [48]. A network slice can be allocated for a specific Radio Access Transport network (RATN), a service, or an operator adopting the Mobile Virtual Network Operator (MVNO) model. Based on such an approach, resources can be added and removed from a network slice dynamically, taking advantage of the principles of SDN. SDN allows the decoupling of the data and control plane and can enable access and allocation of resources as required through suitable SDN controllers.

In order to support network slicing in the mobile transport network, dynamic network resource management and sharing will be necessary, which requires an integrated mobile transport network, including the mobile FH and BH. The required switching capabilities can be provided through packet networks, such as Ethernet, MPLS, or even non-standard solutions such as TSON.

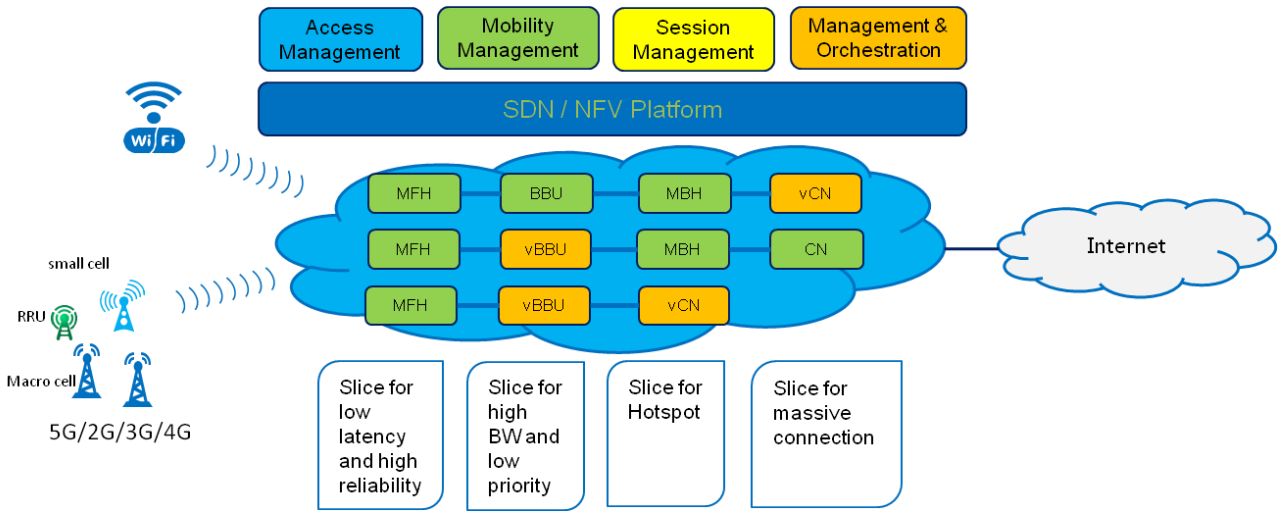


Figure 7.6: Converged SDN/NFV approach

With the use of Network Function Virtualisation (NFV) technology, some of the network functions can be virtualised, such as virtualised Core Network (vCN) and virtualised BBU (vBBU). In network deployments, the virtualised functions can work together with traditional hardware devices. This gives the operators a lot of deployment flexibilities; e.g. a network may comprise a vCN plus a physical BBU, or a vBBU plus a physical CN, or both vBBU and vCU, as shown in Figure 7.6. The virtualised functions can be located in a centralised location, or distributed in several DCs. An integrated FH and BH solution will allow virtualised functions to be flexibly allocated in many locations and ease traffic routing.

An integrated FH and BH, deploying common technology solutions, can facilitate interoperability, and can simplify the network architecture and the network management requirements. On the other hand, NFV functions are usually implemented using common X86 and ARM platforms and located in DCs, where the network is usually Ethernet based. Therefore, a packet based FH and BH will ease integration with the DC network.

To address these requirements and the challenge of managing and operating this type of complex heterogeneous infrastructure in an efficient manner, 5G-XHaul proposes the adoption of SDN and NFV that will be integrated in a seamless manner. As discussed above in SDN, the control plane is decoupled from the data plane and is managed by a logically centralised controller that has a holistic view of the network [44]. At the same time, NFV enables the execution of network functions on commodity hardware (general-purpose servers, standard storage and switches) by leveraging software virtualisation techniques [44]. Through joint consideration of SDN and NFV, significant benefits can be achieved. For example, the separate control plane can be virtualised using NFV, and the SDN controller-related Virtual Network Functions (VNFs) may be deployed dynamically, having the ability to scale up and down on demand based on the associated workloads [49].

As discussed in detail in [49], SDN network elements can be treated as VNFs since they can be implemented as software running on general-purpose platforms in virtualised environments. Both SDN and non-SDN models can be supported by SDN network elements. On the other hand, network applications can include SDN controller functions, or interact with SDN controllers and can themselves provide VNFs. Service chaining is considered to be one possible network application. Network elements controlled by an SDN controller can be either VNFs or Physical Network Functions (PNFs).

7.4 5G-XHaul Basic Transport Classes

As discussed in the sections above, it becomes apparent that the 5G-XHaul transport network will have to carry traffic of different types, according to their end-user use-case and the functional split. Following the observations in Chapter 5, this traffic will be of variable data rates, and the total amount of capacity will depend on the level of aggregation, i.e. on the number of cells. The 5G-XHaul network will hence have to be flexible to support these different types of traffic. SDN has been proposed as a technology to enable re-configuration of the network, which would enable it to adapt to traffic demand variations or different functional splits. However, there are several requirements to be fulfilled in each case, covering different parameters like data rate, latency and synchronisation. In order to reduce the number of possible requirement combination and, hence, simplify overall network management, we have derived four so-called transport classes (TCs) in [27]. Each transport class covers several types of traffic and has a distinct set of requirements. They are intended to be attached to each traffic flow in order to quickly characterise and classify the flows and process them accordingly. The main differentiation is based on latency. Transport classes with a lower identifier will have priority over those with higher identifiers in, e.g. router queues. Latency was chosen as it is expected to be the most critical parameter to meet for a converged transport network; while capacity also plays a main role it depends heavily on the number of aggregated cells and is hence more a question of dimensioning the corresponding network segment.

TC 0 is an enabling transport class. Next to latency, synchronisation is a key requirement, especially for FH-like traffic such as when employing split A or B. Synchronisation and time alignment can be achieved by using, e.g. a combination of synchronous Ethernet and the Precision Time Protocol [50]. This requires the exchange of special packets, exhibiting a low delay variation. In order to ensure a low impact of queues, the corresponding packets of TC 0 would be prioritised above all other TCs. The data rate expected from this TC would be quite low.

TC 1 is designed to support low latency traffic, both imposed by RAN requirements, e.g., legacy CPRI, or imposed by the application layer, e.g. tactile internet traffic. A maximum latency of 200 µs round trip time is proposed for this TC, which should meet both CPRI requirements, as well as support a 1 ms e2e latency for tactile internet applications. In order to support PHY layer joint processing such as CoMP, the flows of this TC would need to be synchronised. Corresponding to the low layer splits such as split A and B, the expected traffic would be very high.

TC 2 encompasses similar traffic as TC 1, but with a relaxed latency requirement of 2 ms. As discussed in Chapter 5, the latency requirement induced by LTE's HARQ can be reduced by several methods. At the same time, the expected channel coherence time of mmWave carriers derived in Table 5.6 is in the same order of magnitude and, hence, a latency of 2 ms will still enable a coordinated beamforming of several mmWave access points. End user applications requiring a lower latency than current networks but not the strict "tactile" latency could also be transported in this TC. The corresponding traffic would depend on the actual split employed. As still lower layer splits are supported, this TC would need to operate synchronously.

TC 3 supports legacy BH-type traffic. The maximum round-trip time proposed is 20 ms, which is in the order of magnitude of today's e2e latencies [34]. Correspondingly, the expected traffic would be of medium intensity and the flows can operate asynchronously.

A summary of the TCs is shown in Table 7.1.

Table 7.1: Basic transport classes for a packet-based and SDN-enabled transport network

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

8 Summary and Conclusions

With this first technical deliverable, the project has established the basis for the design process of the 5G-XHaul solution. For this purpose, the project has adopted the usual methodology, also employed by other projects and SDOs, of identifying relevant use cases, and deriving requirements to start the network architecture design process. However, given the characteristics of 5G-XHaul, which is focused on the transport infrastructure of 5G networks, it has been necessary to adapt the methodology to this circumstance.

In this context, two kinds of use cases have been identified, namely end-user use cases and operator use cases. In the former, the actor that plays the role of the user is the end user consuming 5G services (either a human being or machine), whereas in the latter, the role is adopted by the operator, service provider or enterprise that obtains connectivity services from the transport infrastructure and uses the services developed and provided by 5G-XHaul. For both kinds of use cases the associated requirements have been identified, which help to identify the functionalities that must be supported by the 5G-XHaul transport infrastructure as well as the performance expected from the system in terms of capacity, latency and jitter.

In terms of performance to be supported by the transport network, it should be noticed that the requirements for 5G-XHaul will not only arise directly from the end-user use cases and the operator use cases, but also from the physical layer requirements, such as latency, jitter, and overall capacity, that will be defined by the proposed RATs for 5G systems, currently being designed by other 5G-PPP Projects. In addition, it should be noted that the transport network limitations may become a critical factor when deciding how the network functions are distributed or centralised in the network architecture in order to support different use cases. For this reason, several potential 5G RATs technologies (like the use of massive MIMO or mmWave) have been analysed, both from a single transport link perspective as well as from an aggregation transport network point of view. From these requirements, important guidelines for the overall design of the 5G-XHaul transport network have been identified.

The project has also identified the main Key Performance Indicators (KPIs) that should be used to determine whether the project has been successful in achieving its intended objectives and has contributed to the 5G-PPP global KPIs.

Finally, the project has provided a first sketch of the system concept for a converged optical-wireless 5G transport infrastructure. The system concept outlined in this document improves the one originally specified in the project's Grant Agreement, taking into account the requirements identified in this deliverable and applying the new architectural frameworks, like NFV and SDN, which are expected to play a major role in the future 5G network architecture.

The main outcomes of this deliverable are:

- The **development of a methodology** that, whilst consistent with those adopted by most 5G PPP projects, addresses the specifics of 5G-XHaul, distinguishing between different types of use cases.
- The **identification of a set of end-user use cases** that cover the expected range of 5G experiences and applications. For all of them, the relevance for 5G-XHaul has been evaluated.
- The **identification of a set of operator use cases** that are relevant for the 5G-XHaul system, in order to identify relevant functional and performance requirements.
- The **analysis of the impact of the expected new functionalities to be incorporated in the new 5G RATs** on the requirements of the transport infrastructure. This analysis takes into account different functional splits that may be required to support different use cases.
- The proposal of a **first system concept** for the design of a converged optical-wireless 5G transport infrastructure that is able to support the convergence of BH and FH, as well as the performance requirements that are associated with the new proposed 5G radio access technologies.
- The identification of a **set of KPIs** that may help to evaluate the progress of the project towards its intended objectives.
- The **identification and definition of a set of Transport Classes (TCs)** that may facilitate the support both of the convergence between BH and FH as well as the new physical layer requirements from 5G RATs. These TCs are considered a first step in the definition of a network

architecture that provides the expected functionalities and performance without incurring unnecessary complexity and cost.

Taking these outcomes as a basis, we continue the work towards defining a system concept and network architecture that will allow meeting the objectives of 5G-XHaul project and the targets outlined by the 5G-PPP.

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10 Acronyms

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

KPI	Key Performance Indicator
LLR	Log-Likelihood Ratios
LoS	Line-of-Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MBB	Mobile Broadband
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
mmWave	Millimetre Wave
MNO	Mobile Network Operator
MPLS	Multiprotocol Label Switching
MTC	Machine-Type-Communications
MVNO	Mobile Virtual Network Operator
NBI	North-Bound Interface
NFV	Network Function Virtualisation
NGFI	Next Generation Fronthaul Interface
NGMN	Next Generation Mobile Networks
NloS	Non-Line-of-Sight
OBSAI	Open Base Station Architecture Initiative
OOB	Out-of-band
ORI	Open Radio Interface
OS	Operating System
OTN	Optical Transport Network
OTT	Over-The-Top
P2P	Point-to-Point
P2MP	Point-to-Multipoint
PBB	Provider Backbone Bridge
P-GW	Packet Data Network Gateway
PDCP	Packet Data Convergence Protocol
PON	Passive Optical Network
PTZ	Pan–tilt–zoom
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RATN	Radio Access Transport Network
RB	Resource Block
RF	Radio Frequency

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