the integrated fronthaul/backhaul

H2020 5G-Crosshaul project
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D2.1: Study and assessment of physical and link layer technologies for Crosshaul

Abstract
This document studies the application of different physical and link layer technologies to the 5G-Crosshaul network, critically reviewing relevant features such as connectivity, capacity, link distance, energy efficiency, latency, cost, etc. Application space and use cases will be identified for each technology.

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List of Acronyms

Acronym	Description
A/D RoF	Mixed Analogue & Digital Radio over Fibre
AWG	Arrayed Waveguide Grating filter
BER	Bit Error Rate
BBU	Baseband Unit
BS	Base Station
CapEx	Capital Expenditure
CBR	Constant Bit Rate
CPRI	Common Public Radio Interface
CoMP	Coordinated Multi-Point
C-RAN	Centralized Radio Access Network
DEI	Drop Eligible Indicator
DFB	Distributed Feedback laser
DMT	Discrete Multi-Tone
DP-QPSK	Dual-Polarization Quadrature Shift Keying
D-RoF	Digital Radio over fibre
DS	Downstream
DSP	Digital Signal Processor
EE	Energy Efficiency
ECMP	Equal Cost Multiple Paths
EDP	Ethertype Protocol Discriminator
EIRP	Equivalent Isotropically Radiated Power
EVM	Error Vector Magnitude
FP	Fabry Perot laser
FPGA	Field-Programmable Gate Array
FSO	Free Space Optics
GBR	Guaranteed Bit Rate
GPON	Gigabit-capable Passive Optical Network
GPS	Global Positioning System
HEU	Head-End Unit

Acronym	Description
IFOF	Intermediate Frequency over Fibre
IL-FP	Injection Locked Fabry Perot laser
IR	Internal Report
IR-LED	Infrared LED
LED	Light Emitting Diode
LLC	Logical Link Control
LOS	Line-of-Sight
LPD	LLC Protocol Discriminator
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MEF	Metro Ethernet Forum
MIMO	Multiple-Input Multiple-Output
MPLS-TP	Multiprotocol Label Switching - Transport Profile
µWave	Microwave
mmWave	Millimetre Wave
NG-PON2	40-Gigabit-capable Passive Optical Networks
NGFI	Next Generation Fronthaul Interface
NRZ	Non-Return to Zero
OAM	Operations Administration and Maintenance
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
OpEx	Operational Expenditures
OTDR	Optical Time-Domain Reflectometry
OTN	Optical Transport Network
OW	Optical Wireless
PA	Power Amplifier
PAA	Phased array antenna
PAM	Pulse Amplitude Modulation
PBB-TE	Provider Backbone Bridge – Traffic Engineering

Acronym	Description
PCP	Priority Code Point
PLC	Power Line Copper
PoE	Power over Ethernet
PtP	Point-to-Point
PON	Passive Optical Network
QoS	Quality of Service
RAN	Radio Access Network
RAU	Remote Antenna Unit
RE	Reach Extender
RF	Radio Frequency (RF)
RLC	Radio Link Control layer
ROADM	Reconfigurable Optical Add and Drop Multiplexer
RoF	Radio over Fibre
RRH	Remote Radio Head
RRU	Remote Radio Unit
RSOA	Reflective Semiconductor Optical Amplifiers
SBI	Southbound Interface
SFP	Small Form-factor Pluggable
SLA	Service Level Agreement
SMF	Single-Mode Fibre
SMSR	Side Mode Suppression Ratio
SoC	System-on-a-Chip
TCO	Total cost of Ownership
TDM	Time-Division Multiplexing
TTL	Time To Live
TWDM	Time and Wavelength Division Multiplexing
US	Upstream
VCSEL	Vertical-Cavity Surface-Emitting Laser
VLAN	Virtual Local Area Network
VLC	Visible Light Communications
VRAN	Virtualized Radio Access Network

Acronym	Description
WDM	Wavelength-Division Multiplexing
WDM-PON	Wavelength-Division Multiplexing Passive Optical Network
WFH	Wireless Fronthaul
WR	Wavelength-Routed
WR-WDM-PON	Wavelength-Routed Wavelength Division Multiplexing Passive Optical Network
WS	Wavelength-Selective
WS-WDM-PON	Wavelength-Selective Wavelength-Division Multiplexing Passive Optical Network
XCF	5G-Crosshaul Common Frame
XCSE	5G-Crosshaul Circuit Switching Element
XFE	5G-Crosshaul Forwarding Element
XPFE	5G-Crosshaul Packet Forwarding Element
XFP	10-Gigabit Small Form Factor Pluggable Module
XG-PON	10-Gigabit-capable Passive Optical Network
XGS-PON	10-Gigabit-capable Symmetric Passive Optical Network

1 Executive Summary

The 5G-Crosshaul project aims at developing a 5G integrated fronthaul and backhaul transport network solution, enabling a flexible interconnection of the radio access with the core network by software-defined reconfiguration of all network elements. In order to achieve this goal, there is a need for high capacity and low latency transmission techniques and novel unified data and control plane mechanisms.

For this purpose, this document identifies and analyses physical and link layer technologies that are suitable, as regards cost and performance, for use in a 5G transport network. The technologies are grouped in three families, corresponding to different realistic deployment situations: green-field installations of optical fibre cables, where new optical technologies, such as Silicon Photonics, can be used without constraints coming from legacy infrastructure; upgrade of existing fixed access networks, both over fibre and copper cables; and wireless transport in situations where deploying new cables is not economically viable. The technology analysis is performed in terms of quantitative parameters (capacity, network density, achievable link distance, link budget, energy efficiency, latency) and qualitative aspects.

Besides the identification and analysis of the technologies, a logical architecture of the data plane, compatible with all the aforementioned scenarios, is presented. A unified multilayer data plane architecture is adopted, where the coexistence of circuit- and packet-switched paths enables to accommodate the various latency requirements of pure fronthaul and backhaul traffic, as well as those arising with new functional split options going to be introduced in 5G. The document also describes and proposes multiplexing mechanisms at physical, time slot and packet level to implement the aforementioned multi-layer architecture. On the packet level, we define the 5G-Crosshaul Common Frame, used as frame format across the crosshaul network. Due to the nature of the subjects, the definition of data plane architecture and related multiplexing mechanisms are activities that were carried out in tight collaboration with WP3.

Finally, again in collaboration with WP3, a model is provided for the South-Bound Interface of the Crosshaul Control Infrastructure (XCI), in order to manage heterogeneous physical and link layer technologies while hiding unnecessary details to upper control layers, which are in charge of service provisioning and network optimization. The definition of the protocol extensions to support the Crosshaul technologies is also provided. The model is based on a set of parameters, independent of the adopted protocol to control forwarding, for the configuration, monitoring and inventory of network nodes and transmission technologies.

2 Key Achievements

The three key achievements reported in this document are summarized in the following.

The first important achievement is the **identification and analysis of physical and link layer technologies**. This task has been performed by the analysis of both quantitative parameters (capacity, network density, achievable link distance, link budget, energy efficiency, latency) and qualitative aspects (synchronization, cost considerations, operational aspects). It is highlighted what technologies that can be used in the short term, albeit with a significant innovation effort, and what technologies that are require more long-term technology advances to become practical.

A second important achievement was the definition of a **multilayer data plane architecture, including circuit- and packet-switched paths.** The packet switching path is the primary path for the transport of most delay-tolerant fronthaul and backhaul traffic, whereas the circuit switching path is there to complement the packet switching path for those particular traffic profiles that are not suited for packet-based transporting, e.g. legacy CPRI or traffic with extremely low delay tolerance, or for capacity offloading. This two-path switching architecture is able to combine bandwidth efficiency, through statistical multiplexing in the packet switch, with deterministic latency ensured by the circuit switch. The modular framework of the 5G-Crosshaul switch (i.e. layers may be added and removed) enables various deployment scenarios with traffic segregation at multiple levels, from dedicated wavelengths to VPN, which is particularly desirable for multi-tenancy support, one of the key features identified.

Finally, a **model of the South-Bound Interface (SBI) and definition of the protocol extensions to support the 5G-Crosshaul technologies** is provided. The novelty of this SBI modelling is that it is based on the definition of a protocol-agnostic set of parameters to model network nodes and transmission technologies. This enables applications, such as optimization of resource allocation and energy, to run over the whole network infrastructure. The choice of the parameter sets was carefully made, neither too small to inhibit some applications nor too wide to negatively affect solution cost and scalability.

3 Introduction

This document provides an analysis of the state-of-the art and novel physical and link layer technologies that fit all the requirements of a 5G-Crosshaul network. It proposes a unified multilayer data plane encompassing innovative high-capacity transmission technologies and novel deterministic-latency switch architectures with the 5G-Crosshaul Packet Forwarding Element (XFE). Furthermore the definitions of the unified 5G-Crosshaul Common Frame (XCF) format and the South Bound Interface (SBI) are provided.

Chapter 4 describes the 5G-Crosshaul technology map, data plane infrastructure and clarifies the main terminology.

Chapter 5 provides an assessment of the point-to-point radio and optical wireless, fixed access and optical access network technologies suitable for 5G-Crosshaul detailing quantitative (capacity, network density, achievable link distance, link budget, energy efficiency, latency) and qualitative aspects (synchronization, cost considerations, operational aspects).

Chapter 6 describes deterministic-delay multiplexing mechanisms for fronthaul and backhaul, as CPRI over OTN and the novel 5G-Crosshaul circuit framing protocol over WDM.

Chapter 7 provides the design of the XFE, the key novelty of the 5G-Crosshaul data plane architecture. The XFE enables a unified and harmonized traffic management over various types of fronthaul and backhaul traffic supported by the novel XCF format, described in Chapter 8.

Finally, the novel SBI is illustrated in Chapter 9, where technology specific parameters and extensions are defined in order to ensure the communication and management between the network's resources and their Software Defined Networking (SDN) controller.

4 5G-Crosshaul technology map and data plane architecture

This section will first identify the 5G-Crosshaul network segment, also providing terminology clarifications. Then it will be discussed how different technologies apply to that segment in a variety of real deployment scenarios (indoor small cell with existing copper infrastructure, migration of fibre access networks, wireless connections in fibre-poor scenarios, fibre-rich scenarios, etc.). Finally, a logical architecture of the data plane, underlying all these scenarios, will be presented.

4.1 Scope and terminology

A Radio Access Network (RAN) encompasses different levels of interconnection between base stations, baseband processing units and remote radio units. The interconnection types can be categorized in backhaul, midhaul and fronthaul (Figure 1[1]).

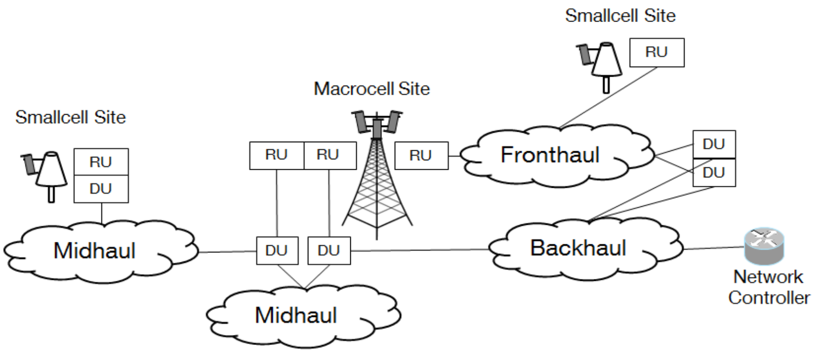


Figure 1: Mobile Backhaul, Midhaul and Fronthaul according to the MEF

(DU: Digital Units; RU: Radio Units)

According to the Metro Ethernet Forum (MEF) terminology:

- The term “Backhaul” refers to the network or links between radio base station sites (or digital units) and network controller/gateway sites;
- The term “Midhaul” refers to the carrier Ethernet network between radio base station sites (or digital units), especially when one site is a small cell site;
- The term “Fronthaul” refers to the connection from a radio base station site (or digital unit) to a remote radio unit.

The scope of 5G-Crosshaul is a reconfigurable transport network architecture common to backhaul, midhaul and fronthaul.

In typical remote radio deployments, the Baseband Unit (BBU or DU) is split into two parts: a “low part”, managed by dedicated hardware, as DSP, FPGA or SoC and a “high part”, managed by General Purpose Processors (GPP). Figure 2 presents different

[1] In the document we will use the term baseband unit (BBU) in place of Digital Unit (DU) and Remote Radio Head (RRH) in place of Radio Unit (RU)

options for the splitting border: moving from option A to E, more functionalities are moved to the RRH; this decreases bandwidth and latency requirements but increases RRH energy consumption and cost and decreases BBU coordination capabilities

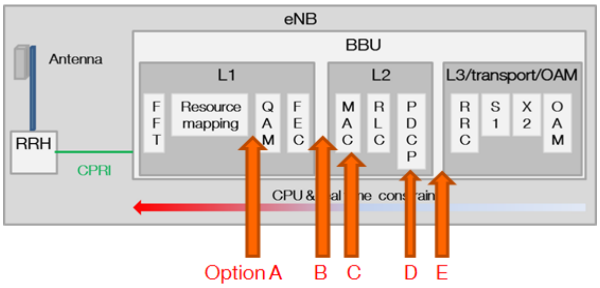


Figure 2: Radio protocol splitting options

Where to split the BBU is not within the scope of 5G-Crosshaul and is open to different implementations, depending on aspects such as: partition between dedicated and virtualized processing; optimization of server size, power consumption and cost; support of features that require multicell or beamforming using L1 processing; bandwidth needed on fronthaul/midhaul links.

To make the transport network as independent as possible on the specific radio implementation, the 5G-Crosshaul network supports any splitting of the 5G radio protocols between remote and processing sites.

4.2 Data plane technology map

To achieve the goal of a unified and radio-technology independent transport architecture, the 5G-Crosshaul network consists of high-capacity switches, as instances of the 5G-Crosshaul Forwarding Element (XFEs), interconnected by heterogeneous transmission links, that can be either wired (e.g. fibre and copper) or wireless (e.g. mmWave and optical wireless). Heterogeneous links can also interconnect the switches to the Remote Radio Heads (RRHs), macro and small cells, centralized-processing units and points-of-presence of the core networks of one or multiple service providers.

The XFE is the central part of the 5G-Crosshaul infrastructure, allowing the integration of different physical access technologies through a common data frame and forwarding behaviour. In general, several XFEs are present in the network: an example is reported in Figure 3 where large XFEs are placed at a second aggregation stage, close to centralized processing sites, and smaller XFEs are placed closer to the edge, in order to collect traffic originated by multiple RRHs.

A necessary step for the definition of the 5G-Crosshaul network is the identification of the required transmission technologies in order to understand how they can be adapted and combined with the purpose of fulfilling the 5G network requirements, especially in terms of latency, bandwidth and deployment density. A one-fits-all approach does not work, but different technologies apply to different deployment scenarios. With reference to Figure 3, three main scenarios will be considered for the first aggregation stage, from the radio terminals to the first XFE.

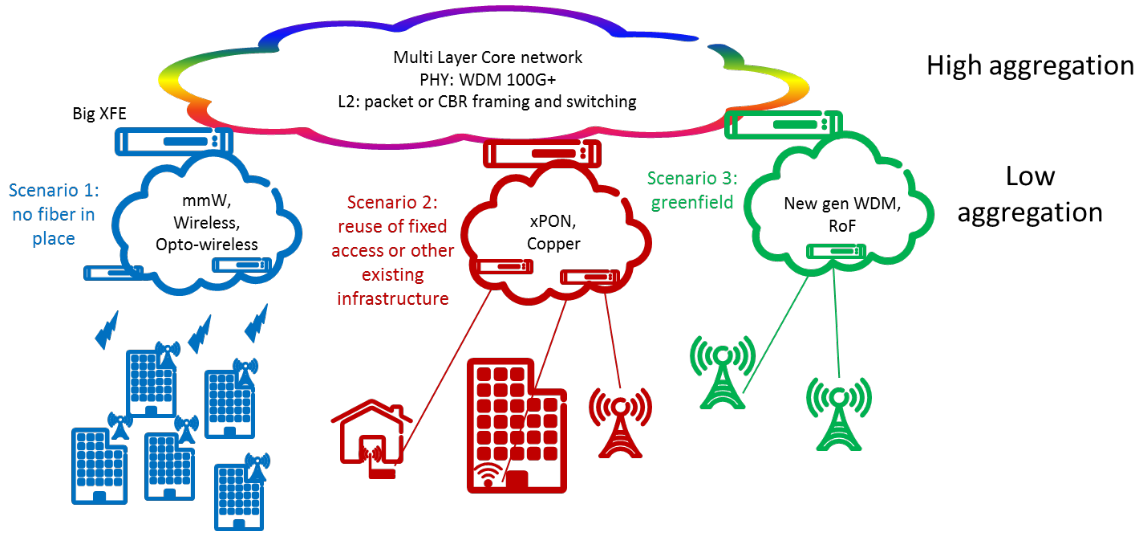


Figure 3: Technology map in the 5G-Crosshaul network, identifying three technological scenarios

In Scenario 1, radio or optical wireless links are used when optical fibre or copper connections cannot be set-up. This scenario applies e.g. to the two opposite cases of a) rural areas, where the cost of new installations could never be amortized, and b) densely populated cities, where performing new cables installations could either be impossible for logistic reasons or not convenient due to high administrative costs for digging and roadworks.

When a fixed access network is already in place (Scenario 2), operators might want to reuse it for 5G-Crosshaul purposes. This is not a trivial task because the fixed infrastructure is typically designed for lower bandwidth than in 5G, and without taking into considerations new requirements like low latency and symmetric upstream and downstream delay, enabling new real-time services. In a typical migration path, cables and distribution nodes will be reused while the old equipment can either be replaced by general purpose data centres able to process both fixed and mobile users or upgraded by adding new 5G BBUs by means of coexistence-enabling devices (e.g. optical band-split filters). The reuse of existing copper infrastructure is especially important for the massive and easy deployment of indoor Small Cells.

Finally, greenfield installations (Scenario 3) open the door, in absence of any legacy constraint, to completely new technologies and architectural concepts, to dramatically increase performance. Integrated photonics is an example of new technology that allows the implementation of optical transceivers, switches or broadband Radio over Fibre (RoF) terminals.

4.3 Data plane logical architecture

The logical architecture of the 5G-Crosshaul data plane is illustrated in Figure 4

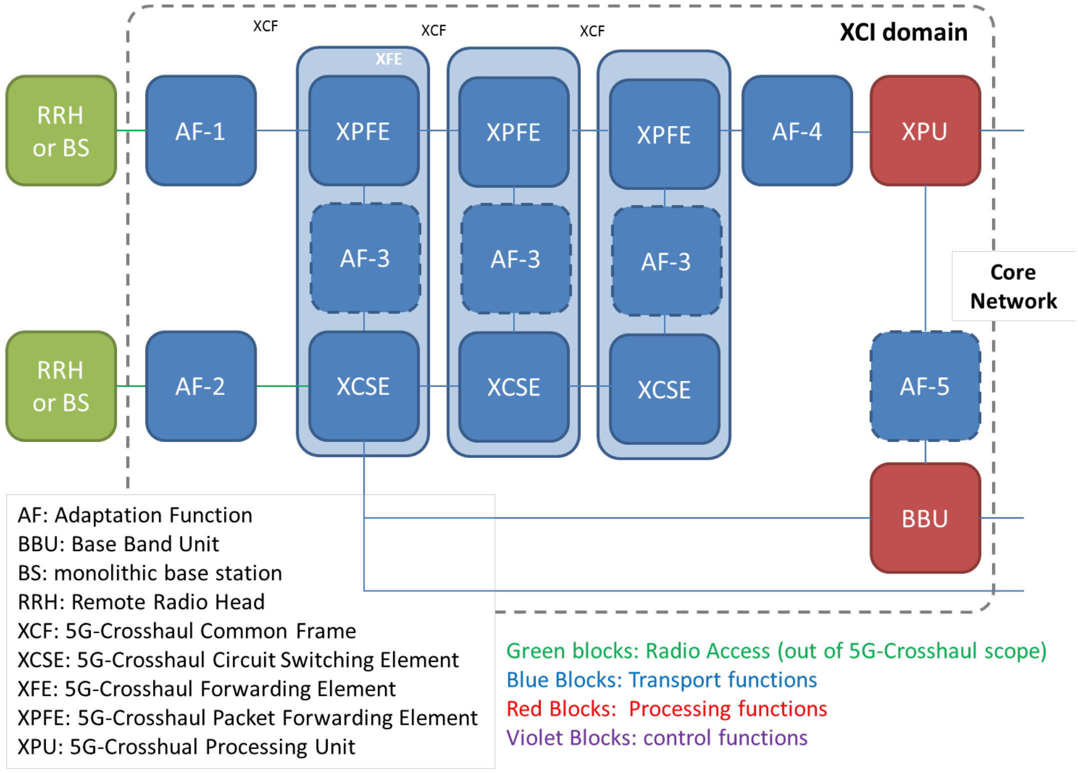


Figure 4: 5G-Crosshaul data plane architecture.

The fundamental block of the data plane architecture is the XFE that, in the most general implementation, is a multi-layer switch, made up of a packet switch called the 5G-Crosshaul Packet Forwarding Element (XPFE) and a circuit switch called the 5G-Crosshaul Circuit Switching Element (XCSE).

The packet switching path is the primary path for the transport of most delay-tolerant fronthaul and backhaul traffic, whereas the circuit switching path is there to complement the packet switching path for those particular traffic profiles that are not suited for packet-based transporting (e.g. legacy CPRI or traffic with extremely low delay tolerance) or just for capacity offloading. This two-path switching architecture is able to combine bandwidth efficiency through statistical multiplexing in the packet switch, with deterministic latency ensured by the circuit switch. The modular structure of the 5G-Crosshaul switch, where layers may be added and removed, enables various deployment scenarios with traffic segregation at multiple levels, from dedicated wavelengths to VPN, which is particularly desirable for multi-tenancy support.

The radio access units (the green blocks in Figure 4) support a flexible functional split, with some functions of the access interface virtualized and placed at the cell site, and their complementary functions virtualized and pushed to the baseband processing nodes.

The fronthaul interface between the remote access unit and the central access unit for a base station can be any existing or new interface, such as CPRI or future packet based fronthaul interfaces.

Although it is not made explicit in Figure 4, some aggregation may be performed by the radio units before interfacing the XFE in order to decrease the number of data flows, increase the bit rate on the XFE ports and simplify the XFE implementation. A first example is provided by a cascade of RRHs, where CPRI traffic is added and time-multiplexed at each RHH. In a second example, client signals at different radio carrier frequencies are multiplexed in a RoF system and the aggregate signal is converted from analogue to digital.

The radio units are connected to the XFE by means of adaptation functions that perform media and protocol adaptation.

The purpose of the adaptation function AF-1 is media adaptation (e.g. from air to fibre) and translation of the radio interface (CPRI, new 5G fronthaul packet interfaces, Ethernet used in backhaul links, mmWave/802.11ad frames, analogue radio over fibre, etc.) into a 5G-Crosshaul Common Frame (XCF), that interface the XPFE. Similar to AF-1, the adaptation function AF-2 maps the radio interface into the protocol used by the XCSE, e.g. OTN or the simpler circuit framing protocol described in Section 6.2.

The XCF is a packet interface based on an evolution of the Ethernet MAC-in-MAC standard, adding mechanisms to deal with time sensitive applications. The XPFEs talk to each other using the XCF. XCF is also the interface between XPFE and 5G-Crosshaul Processing Unit (XPU), the virtualized unit in charge of hosting baseband processing and other virtual functions. An adaptation function, AF-4, could be needed.

The XPFE may be connected to the XCSE, through the adaptation function AF-3 that maps the XCF into the protocol used by the XCSE. As a further advantage, this connection can be used to offload the XPFE, avoiding overload situations and therefore decreasing the probability of discarded packets.

Another adaptation function, AF-5, will also be necessary if pre-existing BBUs needs to be interfaced with 5G XPUs. However, this possibility is out of the scope of the project.

5 Assessment of technologies suitable for 5G-Crosshaul and their evolution

This chapter provides a qualitative overview of the different candidate technologies that fulfil the transport needs of 5G networks. The variety of requirements and deployments scenarios makes a one-fits-all approach unable to deliver all backhaul, midhaul and fronthaul in all networks, hence promoting the combination of diverse technologies to make up the 5G transport network.

These technologies have been classified into three groups. First, wireless technologies, which are expected to provide a cost-effective and fast 5G-Crosshaul deployment. Second, 5G-Crosshaul explores the potential of reusing the current installed base of fibre and copper infrastructures in the access network. Finally, high-capacity optical technologies for aggregation of traffic from edge to core are also reviewed.

For each technology, a discussion of the following parameters is provided in order to evaluate its suitability for 5G-Crosshaul deployment: network density and capacity, achievable link distance and budget, energy efficiency, synchronization and latency, cost considerations, and operational aspects (e.g., reliability, troubleshooting, automatic reconfiguration, and deployment issues).

5.1 Technologies for 5G-Crosshaul wireless networks

As presented in the project technology map (Figure 3), the role of wireless solutions in 5G-Crosshaul is to cover the scenarios where wireline technologies cannot be deployed or their deployment would be too expensive.

Fixed point-to-point wireless backhaul and fronthaul links, using spectrum up to the millimetre-wave frequency bands, have been used for supporting current generation (4G/3G/2G) of high capacity mobile networks. However, as the requirements for 5G emerge, the wireless backhaul and fronthaul technologies face new challenges: a 1000 times increase of capacity, small cell densification, and a significant reduction of allowed latency down to 1 ms end-to-end for some scenarios.

The frequencies below 50 GHz are already very crowded and fragmented, hence the trend in the industry today is to focus on higher frequency bands, 50 to 90 GHz, where large unused continuous bands exist. Along this line, ETSI has recently established an industry specification group with a focus on mmWave transmission in the V-band (57-66 GHz) and E-band (71-76 GHz and 81-86 GHz) [1], suitable for dense deployment of backhaul and fronthaul networks.

On the other hand, with a completely license free spectrum and its immunity to electromagnetic interference, optical wireless communications (OWC) have attracted high interest recently. Since the connection distances in backhaul/fronthaul networks will be shorter, the probability of Line-of-Sight (LOS) increases and bad visibility is considered harmless as well. The term OWC encompass Free Space Optics (FSO) communications, where laser diode transmitters are used for high capacity inter-building optical wireless connections, and the novel technology, Visible Light Communications (VLC) where LED-based illumination systems equipped with low-cost high-power LEDs are used for indoor communications.

5.1.1 Millimetre wave packetized fronthaul and backhaul

A promising technology for small cells is a mesh-like mmWave point-to-multipoint backhaul using electrically steerable antennas. The deployment and cost advantages of point-to-multipoint non-line-of-sight backhaul systems can be retained while the vast bandwidth of mmWave frequencies is utilized to provide high capacity.

The mmWave spectrum is defined as the wide range from 30 to 300 GHz. However, in the following, we focus on the frequency bands between 50-90 GHz, which is aligned with the ETSI mWT ISG as well as the observed trends of frequencies choices made by various vendors for their mmWave backhaul and fronthaul products.

A mesh topology, as illustrated in Figure 5, is in the sequel assumed for performance figures for the mmWave small cells packetized fronthaul/backhaul networks, but other topologies (e.g. daisy chain or star) are also possible.

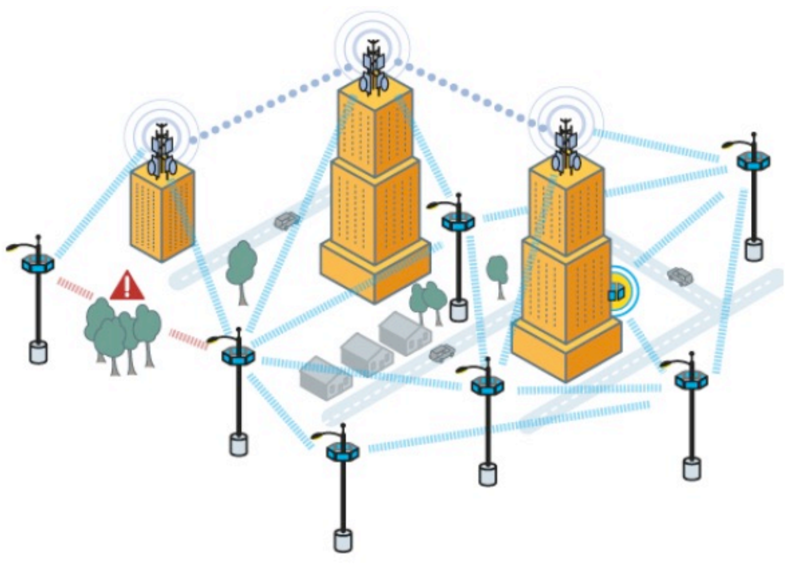


Figure 5: mmWave small cells mesh backhaul [2]

The achievable peak **data rate** of a mmWave link is strongly dependent on the chosen frequency. For example, in the E-Band several commercial products are capable of 1-1.25 Gbit/s. In the V-Band, rates ranging from 450 Mbit/s to 1 Gbit/s have been reported [3]. Within the 5G-Crosshaul project, 1 Gbit/s per sector has been shown for the commercial device EdgeHaul and with four sectors then up to 4 Gbit/s per node [4].

The **network density** depends on the inter-site distance and topology. Generally speaking, in a mesh deployment with a typical inter-site distance of around 150 m, the traffic area capacity may be in the order of a few tens of Gbit/s/km^2, which gives a user density in the order of few thousands of users per km^2 [2].

The mmWave **link distance** also depends on the frequency band. In the E-Band, link distances range from hundreds of meters to several kilometres (e.g. the commercial product [5] can achieve a link distance of up to 20 km when mounting a parabolic antenna dish). In the V-Band, link distances are much shorter, ranging from 50 m to 1000 m. Link distances varies from 50 m to 600 m depending on the antenna technology, whether it is Phased Array Antenna (PAA) or electrical beam steering, the Modulation and Coding Scheme (MCS) and the weather and steering conditions amongst others factors.

According to the datasheet of mmWave products from different vendors, the **power consumption** in the E-Band is typically between 35 W [6] and 45 W [7]. In the V-Band, the values are in the range of 20 W [3] to 25 W [8].

The key components contributing to the power consumption are: the Power Amplifier (PA), the Radio Frequency (RF) transceiver section, the BBU, and the AC-DC unit (mains supply) for connection to the electrical power grid. Conventionally, the power consumption depends on the traffic load and transmission power. An approximate linear model can be based on the percentage of time in which the device is transmitting and on the bandwidth used.

Most of the mmWave solutions surveyed (in both E-Band and V-Band) account for Synchronous Ethernet (physical-method) and IEEE1588v2 (protocol-based-method) to achieve the system **synchronization**. From the datasheets of these surveyed mmWave products, the **node latency** spans from less than 40 µs to 50 µs, suitable for the creation of multi-hop networks transporting LTE traffic.

As an example, in EdgeHaul, the network synchronization is achieved through a master clock provided by the EdgeHaul gateway node and distributed through a time distribution tree. Additionally, each EdgeHaul node benefits from a GPS system. The EdgeHaul node latency is less than 1 ms, due to the use of a fully scheduled, synchronized and Time Division Multiplex (TDM) based multi-hop directional-mesh MAC and the use of electrically steerable antenna arrays.

There are several elements that impact the Total Cost of Ownership (TCO) for a wireless packetized fronthaul/backhaul network [9], such as equipment cost, planning, deployment and installation, spectrum license costs, building/tower lease expenses, pole lease expenses, power expenses, or maintenance and support. The main conclusion from this study is that mesh mmWave backhaul networks in the V-Band can be much less expensive than fixed point-to-point backhaul deployments, arriving saving of up to $750 M in TCO for a mmWave mesh backhaul deployment in a city like London.

The assessment of packetized mmWave technology finishes with a list of **operational aspects** that affect the deployment of packetized mmWave backhaul and fronthaul networks:

- With respect to reliability issues and focusing on weather conditions, trials in the E-Band have reported four nines of link availability for distances around 2-4 km. Similar figures apply in the V-Band, but at shorter link distances of less than 1 km.
- Most of mmWave equipment uses Power over Ethernet (PoE), requiring less wiring.
- Compact design in dimensions and weight and easy installation process (approx..30 min [10]) make nodes suitable for mounting on street furniture, such as lamp posts. For instance, EdgeHaul node dimensions (H x W x D) are: 18cm x 18cm x 8cm.
- Equipment allowing mesh topologies, are introducing self-organizing capabilities, such as self-discovery and automatic rerouting. In EdgeHaul, 10 seconds are reported as the node bring-up time (time from power on to mesh formation).
- IEEE 802.11ad [11] is an off-the-shelf mmWave technology to form mesh network for packetized backhaul and fronthaul, which is low-cost and widely available due to mass production. Inter-working with other IEEE 802 family networks such as Ethernet is discussed later in this document.

5.1.2 Microwave and millimetre wave fronthaul

Compared to LTE/LTE-A, 5G should achieve a tenfold data rate growth up to 10 Gbit/s for each sector. Wireless fronthaul (WFH) technology using microwave (μWave) and mmWave transmission bands emerges as a suitable solution for providing the required network density. An example is depicted in Figure 6 for a cloud RAN (C-RAN) architecture.

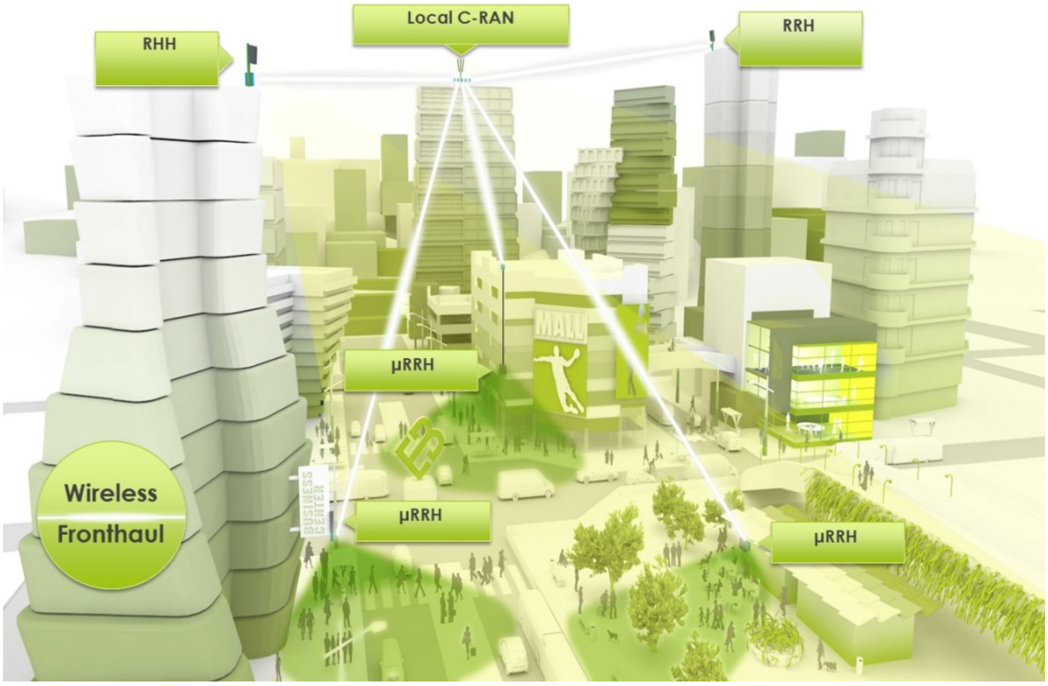


Figure 6: µWawe/mmWave wireless fronthaul as an enabler of local C-RAN in a dense area

As commented before, the **link data rate** required for fronthaul transmission is very high compared to backhaul and depends on the radio access bandwidth and the number of sectors and RRHs.

For example, a 20 MHz LTE bandwidth requires CPRI option 3 (2.5 Gbit/s). This may be reduced to 1Gbit/s if the CPRI traffic is compressed, making the transmission of CPRI traffic over wireless feasible in the µWave band (sub 6 GHz – 42 GHz). Some commercial solutions are able to transmit compressed CPRI for fronthauling purposes using a single 28 MHz channel in the µWave band [12]. Within 5G-Crosshaul, EBlink proposes a new wireless system working in sub-6 GHz band [13], the FrontLink™58, which is able to transmit the entire structure of 3 CPRI option 3 (3 x 2.5 Gbit/s) using a proprietary wireless fronthaul technique [14] employing less than 70 MHz bandwidth rather than using traffic compression.

Nevertheless, to achieve higher data rate, larger bandwidths may be required. Such bandwidth is available in the mmWave spectrum such as in the V-Band (50 to 70 GHz) and E-Band (70 to 80 GHz). Currently, several wireless fronthaul products [15],[16],[17],[18] working in the E-band are available. In particular, commercial products [15] product report up to 10 Gbit/s of peak **data rate** (CPRI option 6) when using 1000 MHz of bandwidth. Within 5G-Crosshaul, there are plans to further develop [13] to transmit in the E-band and targeting 30 Gbit/s (3 x 10 Gbit/s) to align with 5G objectives.

The **link distance** depends on the frequency band and the regulation in terms of gain and maximum Equivalent Isotropically Radiated Power (EIRP) allowed. In the µWave band, the link distance is in the order of two kilometres. In the E-Band, link distance ranges from hundreds of meters [16] up to a 10 km range [18], depending on the required capacity, the gain of the mounted antenna and the radio environment conditions.

According to the datasheet of µWave fronthaul solutions [13],[12], the **power consumption** depends on the working frequency band, spanning from 40 W to 75 W. In the case of the E-Band, reported power consumption values are placed between 20 W [18] and 45 W [14].

Transporting the CPRI protocol, wireless fronthaul equipment can obtain **synchronization** and timing information from BBU CPRI synchronization plane data. Additionally, the datasheets of some vendors report that their products [14],[18] can also obtain synchronization by means of Synchronous Ethernet and IEEE1588v2 methods. According to product datasheets, reported values of equipment latency span from less than 30 µs to 50 µs (one way) [14]. It is worth mentioning the extremely low node latency presented by the equipment in [18], measured in less than 10 ns. However, this product works in the E-Band using CPRI compression to transmit 1 Gbit/s.

Mobile operators wrestle with many unknowns as they develop new strategies to modernize their networks. The potential offered by the C-RAN architecture is huge. In [19], a thorough analysis of the TCO of different fronthaul alternatives can be found. Wireless fronthaul solutions can provide cost-effective implementations for the C-RAN architecture, as depicted in Figure 7.

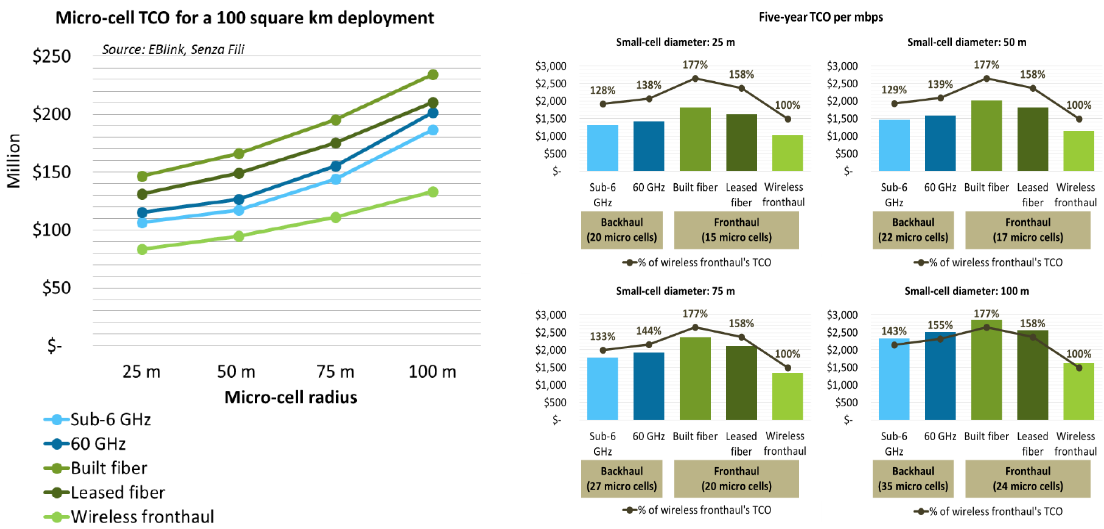


Figure 7: Comparison of per-bit TCO of different alternatives for wireless fronthaul

5.1.3 Optical wireless

Optical Wireless links allow connectivity over various distances, from the ultra-short range for inter-chip interconnects and in-body networks; short-range for optical WiFi, in-flight communications and car-to-car; and medium-/long-range for mobile backhaul, inter-building networks; to ultra-long-range for Tbit/s satellite feeder links and satellite-to-satellite communication. In general, the larger the connection distance, the less divergent light beam is needed in order to maintain the power budget against the atmospheric attenuation and achieve sufficient power density at the receiver side. With beam controlling optics, novel LED-based optical wireless connections are feasible up to several hundred meters, whereas longer distances from more than 200 m require laser links.

LED-based Optical Wireless

As an example of LED-based systems for mobile backhaul connections, the FhG-HHI is developing an LED-based, low cost optical wireless system, shown in Figure 8.

Figure 8: The LED-backhaul link bevice by Fraunhofer-HHI

In the electrical domain, Orthogonal Frequency Division Multiplexing (OFDM) is used with **data rates** up to 1 Gbit/s per link. Moreover, closed-loop adaptive bit-loading is used to adapt the throughput instantaneously to the weather conditions. In general, the achievable data rate depends logarithmically on the received electrical SNR, which is related to the square of the optical power at the receiver.

An infrared-LED (IR-LED) at 850 nm is used. The prototype achieves gross data rates of 500 Mbit/s over 100 m and 250 Mbit/s over 200 m [20].

Power consumption depends on the traffic load, as the LED driver is the main sink and can be switched off when no data is transmitted. With maximum throughput, less than 20 W was measured, whereas in idle mode, power consumption is less than 10 W.

The **latency** depends on the frame size and flow control. In current prototype, the measured one-way latency is of 2 ms ± 1 ms almost independent of the frame size [21].

The LED-backhaul link is designed and assembled with **low-cost** off-the-shelf components, such as LEDs, silicon photodiodes and a digital signal processing chipset. The most expensive component in the current prototype is the weatherproof housing.

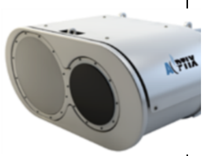
An **automatic reconfiguration** mechanism is implemented, which ensures an immediate reconnection after a signal loss. It also has a real-time data rate adaptation, which improves availability during various weather conditions, as shown in a long term study over 11 months [22]. An optimized system will be taking part in a similar measurement campaign during the winter 2016-2017, where the performance of the optical wireless link will be monitored in parallel with a commercial 60 GHz link over the same link distance and in identical weather conditions. The objective is to study potential synergy between radio and optical transmission when operated as a hybrid link in diverse weather conditions.

Laser-based Optical Wireless - Free Space Optics

With a low divergent propagation of the light beam emitted by a laser diode, long- and ultra-long transmission distances have been achieved. With the laser-based Free Space Optics (FSO) technology, satellite feeder links and inter-satellite communication are operated already today. However, for terrestrial transmission the atmospheric attenuation is the most limiting factor. Today's commercially available systems and their characteristics are listed in the Table 1 below. Note that the data rates can be reached over the specified distance only in clear sight.

Table 1: Current available laser-based Free Space Optics (FSO) on market

	LightPointe (USA)	**fSONA (Canada)**	**AOptix (USA)**	**Artolink (Russia)**
Model	LXR-5	1250-M	MB-2000	M1-10GE
Wavelength	850 nm	1550 nm	1550 nm	1550 nm
Data rate	**1.25 Gbit/s**	**1.25 Gbit/s**	**2 Gbit/s**	**10 Gbit/s**
Apertures	4 Tx + 4 Rx	4 Tx + 1 Rx (20 cm)	1 Tx/Rx	1 Tx + 1 Rx
Tx-Power	4 x 10 mW (VCSELs)	4 x 160 mW	500 mW	n/s
Laser class	1M	1M	1M	1M
Distance	1.6 km (17 dB/km)	3.9 km (3 dB/km)	10 km (carrier class)	500 m 99,9% availability
Auto tracking	Yes	No (?)	Yes	Yes
Weight	15 kg	28 kg	82 kg	8 kg
Interface	Electrical: 1000Base-T RJ45	Optical: SM, MM LC	Optical: SFP, 1000Base SM, MM LC	20-Port GbE (100M/1G)SFP 4 TP/(100/1G) SFP

	LightPointe (USA)	fSONA (Canada)	AOptix (USA)	Artolink (Russia)
	Optical: 1000Base-SX/LX			Combo 3-Port 1G/10G SFP+
Price (approx.)	10 k€	30 k€	100 k€	n/s
				

The **data rates** depend on the optical power and the **transmission distance**. In the terrestrial applications, they range from 1.25 Gbit/s with an achievable link distance of 10 km and up to 10 Gbit/s over 500 m. In terrestrial transmission scenarios, as mobile backhaul or inter-building connections, an availability of 99.99 % over 200 m was measured at HHI in Berlin [22].

According to Table 1, the **transmission power** of the laser is in the range from 10 mW up to 500 mW and depends on the transmission distance. The system **power consumption** is usually less than 50 W. The **costs** per link are from 10 k€ up to 100 k€ depending on the vendor and the required use case. The LightPoint link already shows that laser-based FSO can compete with radio-based solutions if the system is designed for low cost. We assume that the same concept as in the present LED-backhaul device can be maintained with a laser diode instead of an LED. Lasers can be very cheap in large volumes, as it has been exemplified e.g. in DVD and blue-ray writers. Instead of spontaneous light emission in an LED, stimulated light emission and optical feedback in a laser results in a much larger native modulation bandwidth so that similar link distances can be reached with much higher data rates. Moreover, compared with the LED driver, the laser driver design can be even more power-efficient.

The critical component today is the availability of suitable rate-adaptive baseband chips achieving more than 2 Gbit/s. First discussions to scale the technology up to 10 Gbit/s are already ongoing.

Synchronization support using IEEE 1588 precision time protocol is straightforward as the links functionally replace an Ethernet cable with an additional small latency. In this way, the current requirements for LTE-Advanced can already be satisfied. It has been identified that further development is needed for synchronous Ethernet support via rate-adaptive baseband processing, which is needed to provide a precise frequency reference for 5G.

In general, OW solutions are robust to EMI and highly tap-proof, which makes them a good choice in security-aware environments. Furthermore, using the light as a communication signal has the key advantage of an unlicensed optical spectrum. In outdoor environments, it is expected to be more sensitive to haze and fog, while mmWave faces more challenges in rain. It is therefore expected that a hybrid solution could increase the sum data rate and improve the link availability up to 99.999 %. These promising results are often hinted at in the academic literature; however, little experimental evidence has been given so far.

5.2 Technologies to enable 5G-Crosshaul on fixed access networks

As commented previously, reusing the copper or optical fixed access networks can enable a fast and economical deployment of 5G. The following subsections present the current and future technologies used in this kind of networks and how they align with the purposes of the 5G-Crosshaul project.

5.2.1 Technologies working on optical fixed access infrastructure

In the context of 5G-Crosshaul, the overlay of mobile backhaul and fronthaul links over point-to-multipoint Passive Optical Networks (PONs) can provide a cost-effective way to realize a converged fixed-mobile optical access network infrastructure. Currently, there are several candidate technologies, namely GPON, XG-PON, XGS-PON, NG-PON2. However, PON technologies are evolving and it is expected that next generation of passive PON networks are going to be based on Wavelength Division Multiplexing (WDM).

Current PON technologies to enable 5G-Crosshaul on fixed access networks

A detailed description of current PON technologies can be found in the different ITU-T recommendations as detailed in Table 2, which also provides a summary of the main features of each technology, such as **capacity and link distance.**

Table 2: Summary of the main features of standard PON technologies

	GPON	**XG-PON**	**NG-PON2 (TWDM) Shared spectrum**	**XGS-PON**	**WDM-PON (seeded variant)**
ITU-T Recommendation	G.984	G.987	G.989	G.9807	G.698.3
Availability	In market	In market	In market	ITU-T approved	In market
Aggregate Rate	2.5G/1.25G	10G/2.5G coming 10/10	40G/10G 40G/40G	10G/10G	32G/32G

	GPON	XG-PON	NG-PON2 (TWDM) Shared spectrum	XGS-PON	WDM-PON (seeded variant)
Access Peak Rate	2.5G/1.25G	10G/2.5G	10G/2.5G	10G/10G	1G/1G
MAC	TDM	TDM	TWDM and PtP WDM	TDM	WDM
Multipoint device	Splitter	Splitter	Splitter (but use of Wavelength filters allowed)	Splitter	Wavelength filter (AWG)
ODN type	WS	WS	WS/WR	WS	WR
Split ratio	1:32/1:64	1:64 (128)	1:64 (256)	1:128	1:32
Physical reach	20 km	40 km	20 km (for 1:64)	20 km	20 km
Price	Low	Medium	High	Medium	Very High
Max. budget	28 dB	35 dB	38.5 dB	35 dB	15 dB
Transmission Capacity for Digital RoF transport[2]	Little	Medium	High	Medium	High

GPON is currently being used for residential access and offers an aggregate **capacity** of 2.5/1.25 Gbit/s for downstream/upstream links which is shared among typically 32/64 different users. These capacity figures are not adequate for fronthaul links based on Common Public Radio Interface (CPRI). However, GPON could be considered as a suitable technology for the next generation packetized fronthaul interface of 5G-Crosshaul in e.g. dense urban areas, especially for particular cases in which low fronthaul rates below 1 Gbit/s are required. The main reason is the ability of different bandwidth assignment methods (fixed, assured, non-assured) of the Medium Access Control (MAC) layer of Time Division Multiplexing (TDM) based PON technologies (including GPON). However, this is challenging due to the expected required latency for these fronthaul links which may also imply the need for lower splitting ratios in the fibre deployment. This is not very feasible for operators that have already deployed GPON.

[2] Only bitrates are considered in this preliminary analysis, since no standard PON technology can fulfil all current requirements of DRoF systems such as CPRI in terms of delay, jitter and synchronization.

XG-PON, also a TDM-based PON technology, offers 2.5 Gbit/s in the US and 10 Gbit/s in the DS. In this case, 2.5G upstream capacity may be even used to carry up to CPRI-option 3 streams, thus making XG-PON a more suitable technology for the next generation packetized fronthaul interface of 5G-Crosshaul than GPON. However, the recent approval for a new symmetric 10G PON standard (XGS-PON) will limit demands for XG-PON systems, as it is further discussed. Summarizing, GPON and XG-PON are not found to be long-term suitable options for the 5G-Crosshaul network mostly due to their relatively limited capacity.

A more suitable technology for the next generation packetized fronthaul interface of 5G-Crosshaul in terms of capacity than the abovementioned is NG-PON2. The typical NG-PON2 technology configuration comprises 4-8 channel pairs using Time and Wavelength Division Multiplexing (TWDM). Per-channel-pair TWDM bit rates are 10 Gbit/s DS and 10 Gbit/s US; 10 Gbit/s DS and 2.5 Gbit/s US; or 2.5 Gbit/s DS and 2.5 Gbit/s US, respectively.

Several Optical Distribution Network (ODN) **power budget** classes have been defined for NG-PON2, where the maximum allowed is 35dB for the E2 NG-PON2 ODN budget class and a typical fibre length of 20km. In addition to the 4-8 TWDM channel pairs, so-called point-to-point (PtP) WDM channel pairs are an option. These PtP WDM channels must be based on tuneable lasers. The PtP WDM channels have to support all relevant bit rates ranging from Ethernet to three bit-rate classes of CPRI (1.25 Gbit/s, 2.5 Gbit/s, and 10 Gbit/s) for pure fronthaul transport purposes. NG-PON2 must allow co-existence with legacy PON systems, also including the RF video overlay channel and an Optical Time-Domain Reflectometry (OTDR) monitoring band. Since NG-PON2 is a technology thought for wavelength selective (WS) ODNs (WS-ODN) with power splitters, which perform broadcast of all wavelengths in downstream, the Optical Network Units (ONUs) must be equipped with wavelength-selective receivers, e.g. based on tuneable filters. This NG-PON2 variant is also referred to as Shared Spectrum with regard to the wavelength allocation in particular of the PtP WDM channels. Wavelength bands are 1596 to 1603 nm for TWDM downstream operation and 1524 to 1540/1544 for upstream operation. The PtP WDM channels can use the wavelength range of 1603-1625 nm.

In March 2016, ITU-T Study Group 15 has given first-stage approval of Recommendations for next-generation symmetric XGS-PON[3]. XGS-PON will offer symmetrical 10 Gbit/s optical transmission capacity, making it appropriate for business services and mobile backhaul and fronthaul applications. The physical layer of XGS-PON follows XG-PON, which means that is TDM based and systems can be designed using existing 10 Gbit/s symmetrical optical transceiver components. The XGS-PON protocol layer is based on NG-PON2 and XG-PON, and its ONU management and control mechanism is specified in ITU-T G.988. XGS-PON likely will be used as an

[3] www.lightwaveonline.com/content/lw/en/fttx/pon-systems.htm

intermediate step between GPON and NG-PON2, enabling operators to support symmetrical 10 Gbit/s applications that may not require the multi-wavelength future-proofing of NG-PON2 or where immediate competitive situations demand a lower-cost, more immediate approach. The lower expected cost versus the use of a single-wavelength NG-PON2 implementation is due to the use of fixed-wavelength optical transceivers, rather than the tuneable optics the NG-PON2 specifications will codify. Typical distance between an XGS-PON optical line terminal (OLT) and an optical network unit (ONU) will be 20 km, and one OLT XGS-PON is capable of supporting up to 128 ONUs. The availability of XGS-PON systems likely will limit, if not eliminate, the demand for XG-PON systems, which offer 10 Gbit/s only in the downstream direction.

Seeded WDM-PON systems use passive temperature-hardened Dense WDM optical filters in the remote node and colourless ONUs based on Reflective Semiconductor Optical Amplifiers (RSOA) optical modules or injection-locked Fabry Perot lasers (IL-FP). Seeded WDM-PON then operates in Wavelength Routed ODNs (WR-ODN) with wavelength filters, e.g. Arrayed Waveguides Grating filter (AWG), which provides several point-to-point wavelength channels over the same physical infrastructure thanks to its WDM nature. The main advantage of this technology lies on the fact that it provides a guaranteed secured symmetric but limited capacity per user (1 Gbit/s), and modest power budget of about 15 dB for a typical 20 km fibre length. This is yet too little to become a general mechanism to transport pure CPRI fronthaul traffic, but promising. WDM-PON would be the best choice in terms of delay and jitter compared to TDM and TWDM based PON technologies for fronthaul purposes. WDM has much lower latency than TDM. WDM is often used in applications where latency is of utmost priority, such as those that 5G-Crosshaul is targeting.

Table 3 summarizes the suitability of PON technologies for both CPRI fronthaul and Next generation packetized 5G-Crosshaul fronthaul.

Table 3: Summary of suitability of PON technologies for CPRI and packetized fronthaul

	GPON	**XG-PON1**	**NG-PON2**	**XGS-PON**	**Seeded WDM-PON**
CPRI fronthaul capacity	No	No	Yes (PtP WDM)	No	Yes (but 1G commercial)
Next generation packetized 5G-Crosshaul fronthaul capacity	No	Limited (2.5G US)	Yes (10G US/DS)	Yes (10G US/DS)	Yes. Lower latency and jitter than TDM and TWDM. But higher capacity required (1G commercial)

Table 4 contains the typical **power consumption figures** of the equipment used for each PON technology presented previously.

Table 4: OLT and ONU power [23]

	GPON	XGPON	NG-PON2	XGS-PON	WDM-PON
OLT power/port	2W	5W	20W	5W	19W
ONU power	1.8W	3.1W	3.4W	3.1W	15W

PON technologies require the **synchronization** of both OLT and ONUs to a common reference for maintaining frame alignment in order to achieve a Constant Bit Rate (CBR) for upstream traffic. A ranging technique is also required to support collision avoidance in TDM-based PONs. A pure WDM-PON approach, where signal having heterogeneous timing requirements are segregated at a wavelength level, offers lower latency and jitter compared to a TDM-based approach, where client signals can experience conflicts and need to be aligned in time and clock frequency. TDM could anyway be appealing for bandwidth efficiency reasons, allocating time slots to avoid conflicts and assuming input signals have similar timing characteristics.

A recent study authored by 5G-Crosshaul partners has evaluated the **techno-economic cost of PON** technologies when deploying 1 Gbit/s services to residential customers in a greenfield deployment [24]. This analysis, which can be used as a reference to estimate backhauling costs for small cell scenarios, shows that WDM-PON has the highest deployment cost, while GPON and NG-PON2 take advantage of the economics of aggregating multiple users. In particular, the NG-PON2 with split 1:64 offers 1 Gbit/s to the users for 56% of the time and represents a cost of around 65% of the cost of WDM-PON. More details about this analysis can be found in [24].

To finish with the assessment of PON technologies, it is worth mentioning a number of **operational and maintenance aspects** appealing for 5G-Crosshaul purposes, namely:

- Mechanisms for error detection and correction, including scrambling, hybrid error correction decoding and FEC mechanisms implemented with powerful Reed-Solomon codes.
- Network Security, including mechanisms for authentication, key management and data encryption.
- Performance monitoring and continuous supervision of physical and link layer parameters to facilitate troubleshooting and maintenance of PON networks.

Next generation of WDM-PON technologies to enable 5G-Crosshaul on fixed access networks

As explained in the previous section, WDM-PON technology would be the best choice in terms of delay and jitter compared to TDM and TWDM based PONs for fronthaul purposes in 5G-Crosshaul. However, the current commercial seeded WDM-PON technology offers only symmetric 1 Gbit/s links in most cases due to component limitations. It is possible to achieve higher bit rates by using tuneable distributed feedback (DFB) lasers instead of reflective optical components. In this light, tunable WDM-PON has recently attracted the attention of vendors and operators [25] for the development of next generation high capacity tunable WDM-PON systems, which are very suitable for the 5G-Crosshaul. This tunable WDM-PON approach can been seen as an Expanded-Spectrum variant for the PtP WDM part of NG-PON2.

With regards to **optical band, capacity and reach, WDM-PON** uses PtP WDM channels in full C+L bands wavelength range (1524 to 1625 nm) operating at 10Gbit/s rates symmetrically in optical fibre lengths higher than 20km. If we assume WDM-PON systems with 32-40 wavelength pairs for upstream (US) and downstream (DS) in C-band (US) and L-band (DS), respectively, then there is overlap of this WDM-PON definition and one possible NG-PON2 variant which includes PtP WDM. Co-existence with TWDM or legacy systems needs not to be supported in this case.

WS-ODN support is still required, but WDM-filtered, or Wavelength Routed (WR) ODN is allowed. Hence, ODN can for example be based on Cyclic AWGs with a wavelength grid according to ITU-T Recommendation G.698.3. This configuration can be regarded as wavelength-routed (WR-) WDM-PON. The lasers in the ONUs should now be full-band tuneable, across the whole C-band. The downstream uses the L-band. Similarly, an Expanded-Spectrum variant for the PtP WDM part of NG-PON2 for WS-ODN is also possible (so-called WS-WDM-PON). Due to the WS-ODN operation, WS-WDM-PON ONUs must be equipped with wavelength-selective receivers as well. Up to now, no further strict standards for WDM-PON exist, apart from the G.989.x series of Recommendations, G.980.2 and the draft recommendation G.metro.

The question of WR-ODN versus WS-ODN is relevant for both NG-PON2 and (generic, non-NG-PON2) WDM-PON. Wavelength-routed infrastructure is used for most of today's WDM transport systems, where wavelength routing is either performed by static WDM filters (e.g., Optical Add/Drop Multiplexers, OADMs) or by ROADMs. WS-ODN is in use in almost all PONs (GPON, XG-PON, and soon XGS-PON) which, apart from the separation of upstream and downstream, do not make use of WDM. The question is how easily WS-ODN can be used for WDM-PON, in particular if higher numbers of wavelengths are required.

A comprehensive survey of WS- and WR- WDM-PON technologies has been developed in the context of FP7-COMBO project, particularly by some of the partners of the 5G-Crosshaul project [26]. The differences between WS-WDM-PON and WR-WDM-PON can be split into operation-related aspects which lead to contributions to Operational Expenditures (OpEx), and performance-related aspects which lead to further OpEx differences and contributions to Capital Expenditure (CapEx).

Operations-related aspects in WR- and WS- WDM-PON include [26]:

- *Support of legacy ODN*: The ability to support legacy ODN without restriction is given for WS-WDM-PON only.
- *Wavelength-agnostic bandwidth provisioning*: Full wavelength flexibility basically requires WS-ODN, so that it is only natively achievable by WS-WDM-PON.
- *Flexibility of ODN (fan-out) configurations*: for WS-WDM-PON, such flexibility can easily be achieved since cascaded power splitters with different split ratios (1:2, 1:4, 1:8, 1:16, 1:32, etc.) can be used. Not that easy for the WR-WDM-PON case.
- *Energy consumption*: WS-WDM-PON would require active Reach Extenders (RE) like optical amplifiers in the ODN for distances larger than 20 km and large number of channels. Such bi-directional amplifiers may account for extra ~20 W power consumption.
- *Fibre-count requirements*: WS-WDM-PON has lower reach due to higher power budget required caused by passive splitter insertion losses, which has to be compensated either by using REs as explained before, or by reducing the split ratio.
- *Operations and maintenance cost*: In WS-WDM-PON, OpEx for RE maintenance evolves, and due to higher complexity, ONUs in WS-WDM-PON may have somewhat lower availability because of difficulties to integrate the required tunable receiver (which translates into a similar OpEx contribution).

Performance-related aspects in WR- and WS- WDM-PON include [26]:

- *Reach*: Reach between WR- and WS-WDM-PON variants differs significantly. Main reason for this is the insertion loss of power splitters. In [26], significantly higher reach of unamplified WR-WDM-PON (40 km) was observed compared to typical 20 km reach of WS-WDM-PON. OLT-based reach extender (RE) only gives a moderate reach increase for the WDM-PON variants (shifting, however, WR-WDM-PON into the 50-60 km region). However, with ODN-based RE, WS-WDM-PON can heavily benefit in reach, achieving similar distances to WR-WDM-PON.
- *WDM channel count*: The aspect possibly leading to the strongest difference between WR-ODN and WS-ODN is intra-channel interferometric crosstalk, specifically in the upstream direction in a multi-channel PON, caused by the side mode suppression ratio (SMSR) of tuneable lasers of the ONUs in WS-WDM-PON variant. In [26], the upper limit of channel count in WS-WDM-PON without further SMSR improvement is only N = 8 channels, for typical SMSR values of 45-50dB of commercial tuneable DFB lasers.
- *Required transceiver complexity and resulting CapEx*: For improving the WDM channel count, WS-WDM-PON make use of additional tuneable filters in the ONUs for the US (transmit) direction to improve the SMSR. This means that in general (for N > 8), ONUs in WS-WDM-PON have tuneable filters for both transmit and receive. This increases cost, complexity of the ONU tuning procedures, energy consumption, and it decreases availability (because a tuneable component is added in both directions) and also ODN power budget (because now tuneable filters have to be inserted in both directions). However, if equipped with these tuneable transmitter filters, WS-WDM-PON can support any channel count. If further equipped with reach extenders, it can also support reach which is sufficient in long reach fronthaul and site-consolidation scenarios, i.e., up to 50 km.

OFDM Flex PONs

The advent of elastic optical networking, enabled by the adoption of the flexible channel grid and programmable transceivers, opens the door to a truly dynamic management of PONs. This is especially interesting for achieving the integration between fixed access and back- and front-haul networks. To approach this paradigm, channels can be set up according to the requirements of the services to deliver. In these Flexible PONs, programmable sliceable bandwidth variable transceivers (S-BVTs) are present at each OLT in order to concurrently serve different ONUs for delivering the different services.

At the other end of the network, the ONUs have programmable bandwidth variable transceivers (BVTs). Cost-effective solutions based on the aggregation of multiple **data streams** (10 Gbit/s) featuring the lowest possible **bandwidth** (e.g. a 12.5 GHz slot) have been experimentally demonstrated in the last years. Among all the options for implementing the optical (S-)BVTs, those based on orthogonal frequency Division multiplexing (OFDM) are the most interesting for coping with the flexibility requirements of elastic optical networks. OFDM provides **advanced spectrum manipulation** capabilities, including arbitrary sub-carrier suppression and bit/power loading. Thanks to these features, OFDM transceivers can be ad hoc configured for achieving a certain **reach** and/or coping with a targeted data rate, making them suitable for elastic optical networks. Even if the optical OFDM (O-OFDM) approach is significantly improving the flexibility of the transceivers and the network subsystems, it is still regarded as a long-term solution. In fact, there are several points to be further investigated, some of which are within the scope of the 5G-Crosshaul project.

In terms of the **expected performance figures**, the targeted typical capacities will be of 10Gbit/s per flow, coping with the typical distances and power budget associated to PONs (20-50km and 20-30dB). There, latency will be largely contributed by propagation, DSP and transmission, which depends on the design of the (S-)BVTs and the network subsystems.

5.2.2 Technologies working on copper fixed access infrastructure

Copper was very early recognized as a great carrier of electricity and electrical signals. As it is a metal found in some abundance, reasonably priced and an excellent conductor, it has been deployed in large amounts since the invention of the telegraph and electrical powering. Many of these copper infrastructures are still functional and copper infrastructures in various forms are deployed today on a massive scale. For the purpose of carrying 5G-Crosshaul backhaul or fronthaul, there are four copper infrastructures of interest:

- Telephony wiring (nowadays DSL cables)
- Cable-TV coax (the DOCSIS family)
- Power lines (mainly for in-house communication)

- LAN/Ethernet cabling (Cat 5 and upwards)

As a first order approximation, attenuation in dB over copper cables is proportional to length and to the square root of frequency. This means that the usable bandwidth increases approximately four times if the cable length is reduced by a factor of two. The DSL family utilizes this by allowing increased bandwidth when fibre is deployed closer to the end-user (the copper part becomes shorter). Ethernet over Cat 5 and upwards cables on the other hand is typically designed for a given reach of 100 m.

Table 5 lists the most common technologies for communication over copper infrastructures and summarizes their main features.

Table 5: Parameters for the most common tecnology over copper infrastructure

	DSL	DOCSIS	PLC	Ethernet xBASE-T
Standard(s)	ADSL: G.992.x VDSL: G993.x G.fast: G.9701	CableLabs + ITU-T J.112, J.122, J.222	G.hn: G.9960, HomePlug AV, IEEE 1901	IEEE 802.3
Media	Twisted-pair (POTS grade)	Coaxial cable	Power wires	Twisted-pair, Cat5e or better
Topology	PtP	PtMP (star)	any	PtP
Peak rates	ADSL2plus: 24/3 Mbit/s VDSL2: 200/100 Mbit/s G.fast: 1 Gbit/s aggregated	DOCSIS 3 1.6G/0.2G DOCSIS 3.1 10G/1G	Up to ~1G in theory but highly dependent on wiring and noise	Today: 1/1G, 10/10G Soon: 2.5/2.5G and 5/5G Also coming: 25 G, 40 G
Duplex mode	ADSL, VDSL: FDD G.fast: TDD	FDD	TDD (G.hn)	Full duplex (echo cancel.)

Out of the copper technologies, the project's main focus is on using Ethernet xBASE-T technologies for the combination of fronthaul and backhaul due to its wide use in enterprises, homes and data centres. We also provide a brief overview of other copper technologies.

Ethernet xBASE-T

For the traditional 100 m **reach** between active nodes, there are already Ethernet standards working at **data rates** of 1 Gbit/s and 10 Gbit/s. Work is ongoing in IEEE regarding 2.5 Gbit/s and 5 Gbit/s. Even higher rates of 25 Gbit/s, and 40 Gbit/s are being standardized but mainly for datacentre applications with a maximum **reach** of 30 m.

IEEE 802.3az (Energy-Efficient Ethernet, EEE) allows **power savings** during periods with low or no data traffic by disabling the transmitter. EEE can work fine for backhaul traffic. However, traditional fronthaul traffic is not load-dependent, which means that the corresponding cell or sector would have to be disabled in order to achieve any power savings.

With respect to synchronization, it can be achieved with solutions such as the Synchronous Ethernet (SyncE) and the Precision Time Protocol (PTP), e.g. IEEE 1588v2. The synchronization accuracy provided by the state-of-the-art solutions like IEEE 1588v2 based is sufficient to meet fronthaul requirements. Ethernet uses single-carrier technology and has a **latency** in the order of few microseconds.

1 Gbit/s Ethernet is very cheap due to extremely large volumes and prices for 10 Gbit/s chips have come down to acceptable levels for enterprise and similar applications. It is expected that 2.5 Gbit/s will not be much more expensive than 1 Gbit/s due to high demand for backhaul of IEEE 802.11ac, while the cost for 5 Gbit/s will be closer to that of 10 Gbit/s. In addition, Ethernet xBASE-T technology present other interesting **operational aspects,** such as Power over Ethernet (PoE) and built-in diagnostic funtions.

PoE can be an attractive solution in the indoor environment, supplying power over the same physical medium as the data. IEEE 802.3af currently supports up to 13 W, increasing to 25 W with IEEE 802.3at (PoE+). Ongoing work in IEEE 802.3bt aims at increasing the PoE power level further and also to standardize PoE in combination with 10 GBASE-T, which was not the case with earlier PoE standards. Due to cable resistance, PoE may have lower efficiency than AC (mains) powered solutions but it can save cost since there is no need to deploy power cabling. Also, reliability is increased since there are fewer points of failure. When PoE is shut down, there are no idle losses in the end nodes.

Most Ethernet PHY vendors have built-in proprietary diagnostic functions, which can be used to detect and identify faults. Since there is no standard regarding the measurements and data formats, the functionality is not widely used. This is an area that needs improvement from a 5G-Crosshaul perspective.

Other copper technologies (DSL, DOCSIS and PLC)

Telephony wiring has since the nineties become the dominating media for broadband services through the **DSL-family** of broadband standards. The older standards, such as the ADSLfamily, are intended to be deployed at the telephone exchange and operate over long cables, sometimes more than 5 km. As the signal attenuation increases with wire length and frequency, the usable frequency and the resulting transport capacity in Mbit/s is comparatively low. They typically deliver in the range of 2–20 Mbit/s, which is not suitable from a 5G-Crosshaul perspective. The newer technology VDSL operates over shorter lines and can deliver up to about 100 Mbit/s, making it a fairly potent backhaul technology but still unsuitable for fronthaul. The recently standardized G.fast, described in ITU-T G.9700 and G.9701, the latter accepted as recently as December 2014, has not yet been deployed at a large scale. However, as it operates over short copper lines, say 20–45 m, it can deliver several hundred megabits per second closing in on 1 Gbit/s. Future versions may double this figure, making G.fast a possible (but limited) candidate for both 5G-Crosshaul backhaul and fronthaul. In addition, it is mostly interesting for a residential use case.

The coaxial cables of the cable-TV networks have excellent signalling characteristics captured by the **DOCSIS** family of broadband systems. The most recent version D3.1 delivers 10 Gbit/s downstream and 1 Gbit/s upstream. Again, this copper infrastructure is mostly interesting for a residential use case, but can be considered for both 5G-Crosshaul backhaul and fronthaul.

The power line copper (**PLC**) infrastructure is also extensive but not easily used for broadband access. The power distribution network with its transformers and noisy signal environments essentially prevents any reasonable broadband access from a 5G-Crosshaul perspective. However, various standards exist for in-house communication and can there offer hundreds of megabits per second. One advantage is of course that power is also offered over the same copper. Nonetheless, power line communication is not central for 5G-Crosshaul as it mostly offers short-range in-house connectivity.

However, to fulfil the fronthaul requirements latency can be a challenge for the previous three technologies (with the exception of G.fast). As DOCSIS3.1, the DSL family and G.hn (PLC standard) use OFDM-like technologies, they present unavoidable latencies in the order of milliseconds, generated by the interleaving between frames and the encapsulation in the physical layer of the data into OFDM symbol period, the frame structure, and the amount of coding and interleaving.

5.3 Technologies for 5G-Crosshaul optical networks

Leaving the legacy networks and moving into greenfield deployments, optical networks become most appealing for 5G-Crosshaul due to their high aggregate capacity, high link distance and low latency. Passive solutions based on CWDM are especially suitable for cost effective outdoor installations with moderate aggregate capacity. DWDM provides instead a future proof platform for capacity expansion and deep centralization. The two technologies will be discussed in the following.

5.3.1 Passive multiplexing solutions based on CWDM

Passive WDM consists of a wavelength multiplexing/demultiplexing approach devoid of any powered component. It can be both Coarse (CWDM) and Dense (DWDM) with respect to the number of used wavelengths and the spacing between them. Next paragraphs present a summary of the main features of passive CWDM solutions.

CWDM appears as a good technical choice for installations with low or moderate aggregate capacity since it is simple to install and highly reliable. Eighteen CWDM channels separated by 20 nm are defined by ITU-T [27]. Since CWDM transceivers working with CPRI Option 9 (12.16512 Gbit/s) are increasingly common nowadays, the **total capacity** of the link can be pushed to about 219 Gbit/s per fibre with 18 CWDM channels. We should notice that regular CWDM devices need two fibres, one for the upstream and one for the downstream direction, as shown in Figure 9a. Transmission on a single fibre using bidirectional transceivers is, however, possible and helps simplifying operation in the field by avoiding wrong way connections. Recent single fibre solutions are based on wavelength sub-multiplexing over the CWDM grid, which consists on dividing the CWDM channel slot width (+/-6.5nm) into two sub-channels, one per direction. Thus, the total **bit rate per** fibre can be doubled, up to 438 Gbit/s (Figure 9b). However, bit rates defined in [28] are not yet standardized by ITU-T Recommendation [27] and, therefore, still need to be evaluated (e.g. bit rate vs length).

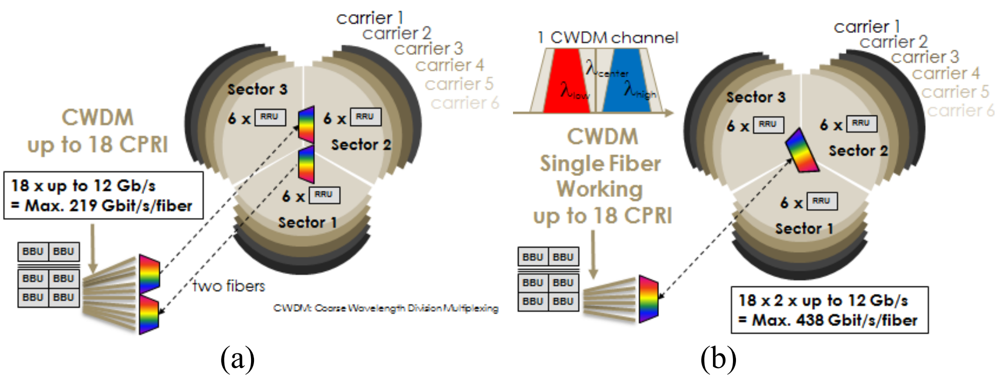


Figure 9 5G-Crosshaul centralized network realized with (a) two-fibre CWDM and (b) single fibre CWDM

Achievable CWDM **reach** is lower than 40 km (typically 20 km) due to fibre chromatic dispersion and laser chirp limitations. Furthermore, CWDM is by its nature the most **energy efficient** solution due to the fact that CWDM multiplexers are passive. The **power consumption** of CWDM transceivers is the same as grey transceivers (1310 nm upstream, 1490 nm or 1550 nm downstream).

Since passive CWDM does not change the transported frames, no special **synchronization** features are required. Concerning **latency**, using single-fibre CWDM inherently allows to solve the issue of unbalanced delays between up and downstream (no difference of cable lengths). CWDM provides the same performances as dark fibre in terms of **delay** and **jitter**, i.e. 5us/km delay and no jitter.

CWDM is the **cheapest** WDM technology for both passive devices (Mux/Demux) and transceivers. The "pay as you grow" possibility is another advantage for the transceiver part, meaning that only the number of passive ports of the Mux/Demux has to be planned in advance. It requires coloured operation (at standardized wavelengths) at the RRH and BBU, which is provided by pluggable transceivers (SFP, SFP+ or XFP). Studies on the market availability of transceivers compliant with the CWDM grid are still being carried out.

One key advantage of CWDM is that it is one of the few solutions compatible with **outdoor operation** conditions (-40/+70°C) for bit rates up to 10 Gbit/s. Another interesting aspect is the fact that passive CWDM devices can be **plug & play** in current or future RAN equipment, compatible with **Ethernet** or **new functional split interfaces**. However, pure passive optical transport does not provide fibre and **channel administration and management**. Indeed, it lacks basic **OAM** functionalities such as monitoring, remote configuration and fault management. This is the reason almost all passive solutions have been proposed with optical transponders that are able to manage and report the status of each wavelength channel pair and fibre infrastructure. This solution can be developed with passive devices at the cell site by introducing remote channel monitoring features per wavelength channel with a semi-active transponder at the BBU side (Figure 10). Finally, we should notice that in order to avoid **compatibility issues** that may arise when SFP/XFPs from one vendor are installed on equipment from another, the choice of RRH and BBU radio equipment must also take into account the underlying passive WDM transport equipment.

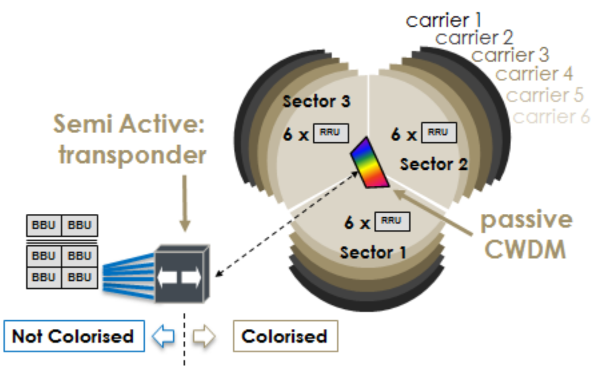


Figure 10: 5G-Crosshaul centralized network realized with single fibre CWDM and wavelength management/ monitoring features

5.3.2 5G-Crosshaul on DWDM metro networks

The number of optical channels for commercial DWDM systems operating over the C-Band (1530-1565 nm) is 48, 100 GHz spaced, or 96, 50 GHz spaced. This leads to formidable **aggregate capacity** over a single optical fibre, as high as 960 Gbit/s with

100 Gbit/s channels, 50 GHz spaced. Further increase will be possible with the introduction of 1 Tbit/s channels [29]. In the extreme case of Tbit/s transmission over both C and L bands, the aggregate capacity can be as high as 67.2 Tbit/s over a single optical fibre. The high aggregate capacity makes DWDM especially suitable to support broadband services and the densely populated scenarios that 5G has to support. Examples of test cases where **traffic volume per area** can be several hundreds of Gbit/s/km^2 are defined in METIS [1] and in the "*dense urban society*" use case provided by 5G-Crosshaul WP1, which presents an average traffic volume/area density of about 700 Gbit/s/km^2.

The **achievable distance** with DWDM spans over a very wide range, from thousands of kilometres for ultra-long haul amplified systems to a few tens of kilometres for non-amplified systems like those defined in [30]. The availability of a plethora of compact and pluggable DWDM transceivers makes possible to trade off cost with target distance and capacity. For example, commercial small form-factor pluggable (SFP+) devices can transmit over 80km of single mode fibre (SMF) at a maximum bit rate of 11.3 Gbit/s, with a **link budget** higher than 22 dB.

In the 5G-Crosshaul network, high distance and link budget make this type of transceivers suitable for centralized scenarios, where RRHs are connected to the same BBU through a chain or a ring of passive OADMs. An example of link budget for a passive optical link is reported in Table 6.

Table 6: Link budget for a 10 Gbit/s passive system

	Optical link parameters	Value
A	Available link budget, including path penalty	22 dB
B	Link distance	20 km
C	Fibre attenuation coefficient	0.25 dB/km
D	Fibre attenuation D=AxB	5 dB
E	OADM add/drop loss	2 dB
F	OADM pass-through loss	2 dB
G	Add/drop loss at the BBU node	5 dB
H	Number of OADM nodes A=D+E+(H-1)xF+G	6

In the high aggregation stages of the 5G-Crosshaul network, 100 Gbit/s optical channels are the most suitable choice to tackle the required aggregate capacity with a low number of wavelengths, i.e. few optical transceivers. However, current 100 Gbit/s DWDM optical transceivers based on coherent DP-QPSK are designed for long distance, in the order of 1000 km, and are too costly for the 5G-Crosshaul network segment. This is the reason why optical transceivers industry and academic community are working on 100 Gbit/s solutions that, having a shorter target distance, like a few tens of kilometres, can be more cost effective. Multi-level modulation formats suitable of direct detection, like pulse amplitude modulation-4 (PAM-4) and discrete multi-tone (DMT) [31], are promising but they still present unsolved issues such as limited link budget (from 2 to 7 dB) and low tolerance to the optical amplification noise, an aspect that makes it difficult to increase the link budget even by using optical amplifiers. This issue will be investigated further in the 5G-Crosshaul project but we anticipate that it could be necessary to split the 100 Gbit/s channel in two 50 Gbit/s channels and use novel modulation formats, possibly helped by dispersion compensation devices realized in Silicon Photonics [32]. The necessity to avoid or reduce power consuming DSP, makes optical compensation techniques appealing: novel solutions based on integrated photonics will be investigated during the project.

Current tuneable 10 Gbit/s SFP+ can guarantee 2W power consumption operating over the 50 GHz grid, which is already a satisfactory value. New technologies are being introduced to reduce size and **energy consumption** of 100 Gbit/s optical pluggable modules, as illustrated in Figure 11. Starting from the current CFP (24W power consumption), CFP2/4 (6W power consumption) are expected within 2016 and QSFP28 (3.5W power consumption) during 2017.

Figure 11: 100G optical modules: size and power consumption

Improving the power consumption figures of optical transceivers is however a minor advantage compared to the great opportunity that DWDM offers to realize energy efficient network designs, enabled by optical switches, ROADMs [33], which consume much less power compared to electrical switches.

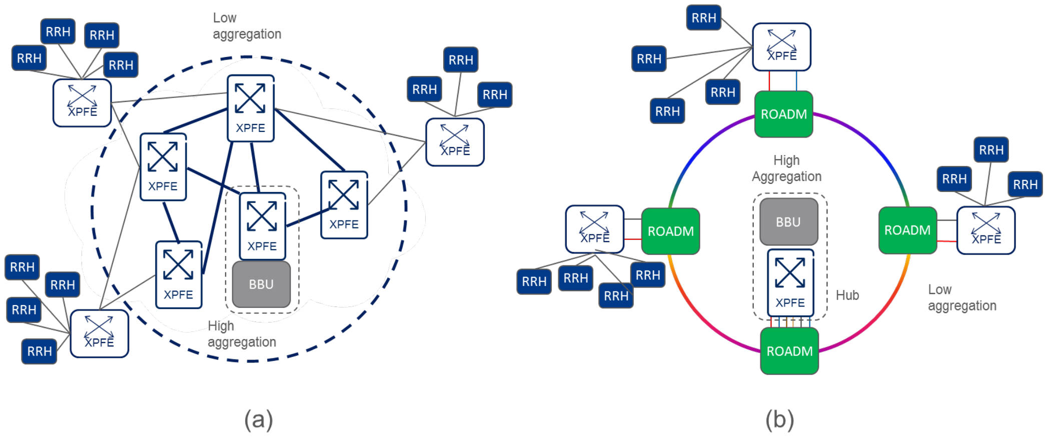


Figure 12: 5G-Crosshaul centralized network realized with (a) grey optics and (b) DWDM

Figure 12 shows two implementations of a centralized 5G-Crosshaul network with electrical switches and grey transceivers (Figure 12a) and ROADMs and DWDM transceivers (Figure 12b). The low aggregation stage is the same for both the networks, with clusters of RRHs connected to XPFEs. At the high aggregation stage in Figure 12a, a mesh of bigger XPFEs acts as transport network, with a hub node for baseband processing. Each XPFE in the low aggregation stage is dual homed for protection purposes. The number of XPFEs and the mesh degree must be high enough to avoid congestion and ensure resiliency. Moreover, the XPFEs are to be dimensioned to support both traffic generated by the connected XPFEs in the low aggregation stage and pass-through traffic from other high aggregation XPFEs. Such an increase of number and size of XPFEs lead to unnecessary power consumption. In Figure 12b, the mesh of XPFEs is replaced by a ring of ROADMs, whose power consumption is negligible. Moreover, just one ROADM is needed for each XPFE in the low aggregation stage. This saves the energy consumed by all the high aggregation XPFEs but the hub node.

Another advantage of DWDM is the possibility to realize a complex network by maintaining a point to point logical topology (Figure 12b is an example) so that any **synchronization** information can be managed at the network terminations, with no intermediate processing, which is a potential cause of performance degradation. Moreover, DWDM is a solution for the case when multiplexing signals with very heterogeneous clock and clock accuracy characteristics leads to excess latency caused by buffering, bit stuffing and justification mechanisms. In this case, segregating the two signals on dedicated wavelengths could be the only solution.

It is a common understanding that **cost** is the main drawback of DWDM technology. Efforts to reduce the cost of the transceivers are ongoing, introducing new technologies such as cost effective modulation formats [31], low cost tuneable lasers [34] and new solutions for ROADMs based on Silicon Photonics [35] that promise to cut down the cost by two orders of magnitude. The higher cost of DWDM optical devices is anyway compensated by the opportunity DWDM offers to save equipment cost overall, as can be seen comparing Figure 12a and b. This holds even more considering the plenty of optical cables needed to be installed or leased to set up point-to-point or meshed physical topologies.

Regarding **operational** aspects, the capability to support multiple physical topologies (linear, ring, point-to-multipoint) using the same technology and keeping a point-to-point logical connectivity is one of the biggest advantages of DWDM. Such a degree of flexibility is increased by the availability of reconfigurable devices like tuneable lasers and ROADMs that also offer the opportunity to reduce equipment inventory costs.

5.3.3 Analogue radio over fibre technologies for 5G-Crosshaul

Analogue Radio over Fibre (RoF) technology allows optical fibres to carry Radio Frequency (RF) signals between base station (BS) and remote antenna units (RAU) instead of coaxial cables. Analogue RoF technology today supports up to 16 optical channels on a single fibre using the CWDM grid [36] with 20 nm channel spacing in the 1270 – 1610 nm wavelength range. The higher capacity can be achieved by using DWDM which provides 48 channels at 100 GHz frequency spacing.

With analogue RoF technology, RF signals can propagate over a long distance with low degradation. The **link distance** for CWDM transmission can be up to 80 km, corresponding to a delay of 0.4 ms, considering ~5 us/km of propagation delay in fibre. In LTE, the delay tolerance between downlink and uplink is 1 ms for FDD, which also holds for the maximum delay of LTE-A coordinated multi-point (CoMP) transmission and reception. This implies that the propagation delay for downlink or uplink should not exceed 0.5 ms and a link distance of 80 km is thus possible.

Taking 4 RAUs for 2x2 multiple-input multiple-output (MIMO) transmission as an example, 1x4 CWDM modules are used at both the head-end unit (HEU) and the RAU for the downlink and uplink of 2 antenna ports. To connect with 4 RAUs, a 1x4 power splitter is applied at the HEU. **A link budget** of analogue RoF with 4 RAUs for 2x2 MIMO transmission is shown in Table 7.

Table 7: Link budget for analogue RoF with 4 RAUs for 2x2 MIMO transmission

	Optical link parameters	Value (S/C/L-Band)	Value (O/E/U-Band)
A	Available link budget, including path penalty A=D+E+F+G	12 dB	16dB
B	Link distance	16 km	16 km
C	Fibre attenuation coefficient	0.25 dB/km	0.5 dB/km
D	Fibre attenuation D=BxC	4 dB	8dB

	Optical link parameters	Value (S/C/L-Band)	Value (O/E/U-Band)
E	1x4 CWDM loss (HEU)	1 dB	1 dB
F	1x4 CWDM loss (RAU)	1 dB	1 dB
G	1x4 power spliter	6 dB	6 dB

Analogue RoF can be an **energy-efficient** alternative to provide wireless service from base stations to mobile stations. In [28], it is shown that the analogue RoF is an energy-efficient scheme for urban areas using micro base stations (transmitting power is less than 25 dBm). A typical power consumption of RoF modules supporting MIMO operation, including a 30dB gain power amplifier, is 36W over 12V and 3A.

The fibres connecting an HEU to several RAUs generally have different length, which results in unequal **latency** and may degrade the reception performance. LTE base stations can compensate the latency difference via signal processing. Alternatively, redundant fibres can be deployed to equalize the propagation delay for each RAU.

Analogue RoF can be a **cost efficient** solution for extending the cell coverage: RoF only consists of an electrical/optical conversion module and RF circuits. For the cost considerations of RoF components, the direct modulation of a laser diode has lower cost than using additional optical modulators. However, the operating frequency of laser diodes with direct modulation is lower than using optical modulator. It is not applicable to very high frequency, such as mmWave. Regarding the laser diode, vertical-cavity surface-emitting lasers (VCSEL) are more cost-effective than distributed feedback (DFB) lasers but leads to lower data rate, higher optical fibre loss, and chromatic dispersion. CWDM is usually used for the coexistence of multiple RF signals in a fibre with low cost. The cost of analogue RoF and digitized RoF was reported in [20] and [21]. The deployment cost of analogue RoF and digitized RoF was further compared in [37].

In the 5G-Crosshual project, the analogue RoF will be mainly **deployed** inside the tunnels along the high speed rail to extend the coverage of base stations, as shown in Figure 13. The downlink and uplink attenuation as well as on/off power switching can be **controlled** by the XCI if a 5G-Crosshaul agent is developed and installed. Besides, to improve the reliability, real-time error and fault detection can be enabled by **monitoring** the status of critical components, and the modular design facilitates quick replacement instead of on-site troubleshooting.

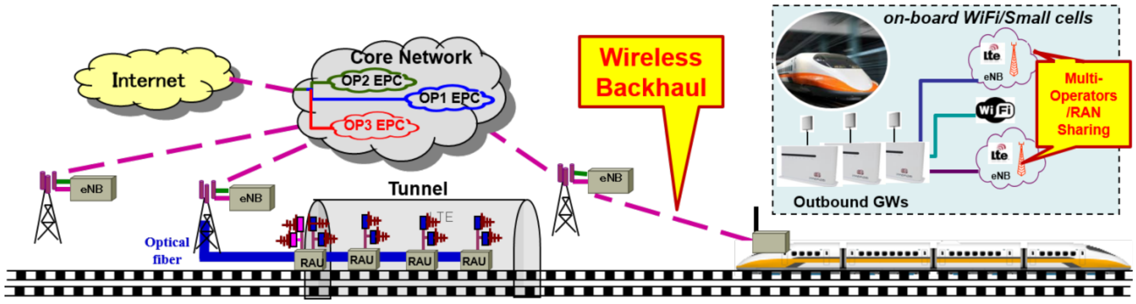


Figure 13: The deployment of analogue RoF along high speed rail

5.3.4 Mixed analogue/digital radio over fibre

In this context, we refer to A/D RoF as the case when we introduce an analogue RoF-link in an otherwise standard system as an extension of the fronthaul over fibre-optics [13], as depicted in Figure 14. The standard wireless fronthaul modules are used to process the digital signal (CPRI) of the BBU before the transmission of its native waveform with embedded BB's information and the C&M (Ethernet) to fibre-optic media. In addition, an Intermediate Frequency over the Fibre (IFOF) is used to reduce the bandwidth (PHY interface: IF vs 5.8 GHz RF).

To do so, it is not possible to make use of commercially available SFP/XFP modules since they are accompanied by electronic components (limiting amplifiers, decision circuitry, etc) based on NRZ modulation. Transmission has to be made using lasers and photodiode modules that can be transparently used with any modulation. In addition, in order to avoid the generation of harmonics and intermodulation products in the electro-optical and opto-electrical conversions, it is essential that those components can operate under a sufficiently linear regime. We should also remark that in order to fully benefit from the available bandwidths of the optical devices, the signals are transposed to intermediate frequencies (lower than the RF frequencies on the radio front) [18].

A/D RoF tests have been carried out recently between Orange and Eblink, partners in 5G-Crosshaul project, with very promising results. Those consisted on a proof-of-concepts demonstration of the transmission of 6 x 64QAM CPRI1 (614.4 Mb/s each) signals using a total bandwidth of only 63 MHz (6 x 10 MHz bands spaced by 500 kHz). In order to attain the same performance using a standard D-RoF transmission, we would need to compress the CPRI signal by approximately 98% which is unfeasible using state-of-art compression approaches.

Figure 14 depicts a possible experimental setup for the A/D-RoF demonstration. Such a technique can also be applied to fibre by mixing digital and analogue radio signals over a fibre. Figure 15 shows the summary of Error Vector Magnitude (EVM) measurement results which using a 3GPP test model.

Generally the **distance/latency** (5 µs/km) between RRH and BBU must not exceed 15-40 km [18].

In order to fulfil the LTE/C-RAN/5G timing requirements without any compromise, very low latency transport systems are required. This applies in particular to support some features such as Cooperative Multi-Point (CoMP).

Working with the CPRI protocol, A/D RoF equipment can obtain **synchronization** and timing information from BBU CPRI synchronization plane data.

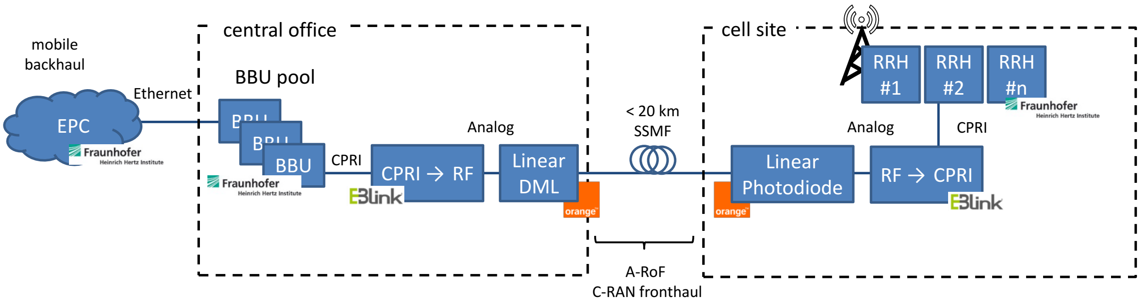
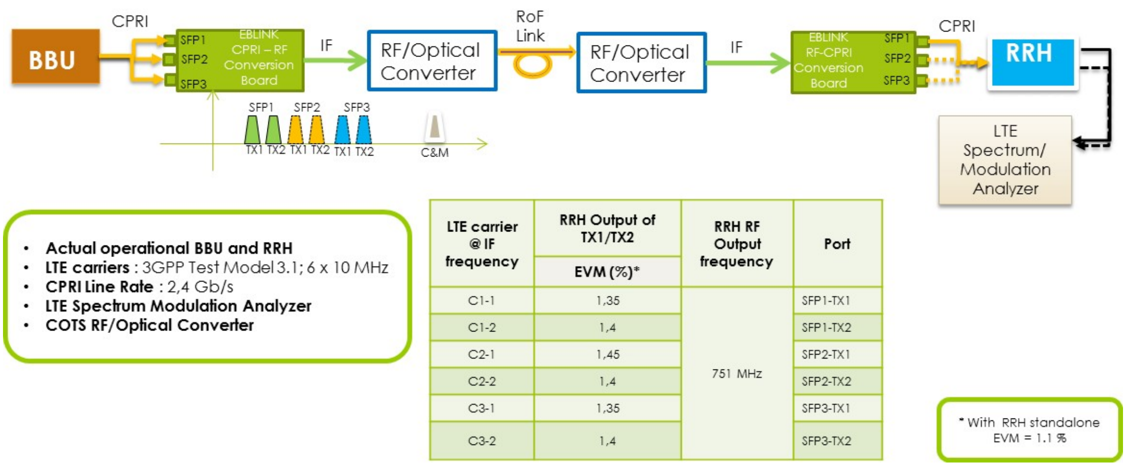


Figure 14 A/D RoF experimental setup



LTE carrier @ IF frequency	RRH Output of TX1/TX2 EVM (%)*	RRH RF Output frequency	Port
C1-1	1,35	751 MHz	SFP1-TX1
C1-2	1,4		SFP1-TX2
C2-1	1,45		SFP2-TX1
C2-2	1,4		SFP2-TX2
C3-1	1,35		SFP3-TX1
C3-2	1,4		SFP3-TX2

Figure 15 EVM measurement results of the A/D RoF system under test

6 Deterministic delay multiplexing technologies for fronthaul and backhaul

Multiplexing backhaul and fronthaul traffic is advantageous since it enables the use of the same infrastructure and a common control for multiple purposes, with a consequent decrease of the total cost of ownership. This holds even more in 5G, where new functional split schemes of the radio interface add a plethora of possible intermediate cases in between the pure fronthaul and backhaul scenarios, which is costly to manage with dedicated infrastructures.

Three multiplexing levels, physical layer, time division, and packet multiplexing, are possible. Physical layer and time division multiplexing ensure deterministic delays and especially fit time-sensitive fronthaul signals with high and constant bit rate (CBR) like CPRI.

The most immediate solution for RAN centralization is to provide point-to-point fibre connectivity between each cell site and BBU hotel. However, fibre is often a rare resource and reaching antenna sites with fibre requires time and operational costs, making it advantageous to multiplex several 5G-Crosshaul links in the same fibre.

Different flavours of multiplexing schemes exist. One is natively proposed by CPRI [27]. It is a time division multiplexing scheme that, for example, allocates two CPRI Option 1 tributary signals in one CPRI Option 2 frame. A similar scheme is envisaged for other bit rate options.

Multiplexing performed according to CPRI is usually controlled within the RAN but it could be moved to the transport network or it could be an integrated radio-transport solution. The choice depends on the use case and the operators' requirements for setting a demarcation point between radio and transport networks. For example, moving the multiplexing function to the transport network could be preferred when it is needed to carry CPRI signals with different vendor specific implementation options on the same transport network.

In the following, we will describe two multiplexing techniques in the transport network.

6.1 CPRI over OTN

OTN [38] is an optical transport standard developed by the ITU-T. It is also known as ITU G.709 and "digital wrapper". In OTN, the ITU defined the payload encapsulation, OAM overhead, forward error correction (FEC) and multiplexing hierarchy. The result is a transport standard that includes the benefits of SDH (such as resiliency and manageability) but with the improvements for transporting data payloads. OTN standards includes a standard multiplexing hierarchy, defining exactly how the lower rate signals map into the higher-rate payloads. This allows any OTN switch and any WDM platform to electronically groom and switch lower-rate services within 10 Gbit/s, 40 Gbit/s, or 100 Gbit/s wavelengths.

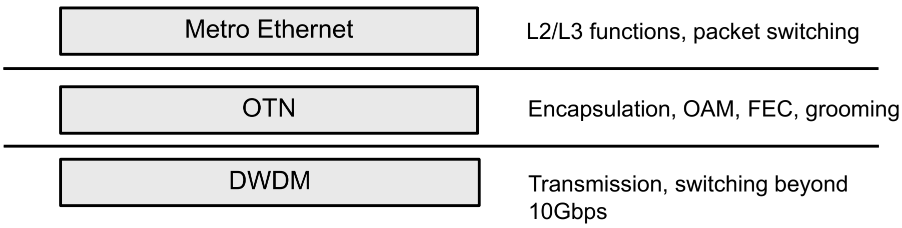


Figure 16: Network layers in Metro OTN/DWDM networks

CPRI mapping over OTN has recently been included in the ITU-T supplement [39]: CPRI options 1 to 3 are mapped into an OPUk via the generic mapping procedure while CPRI options 4 to 8 are mapped into an OPUk via the bit-synchronous mapping procedure. OPU2r is defined as a new container for either 6 Option-3, or 3 Option-4 or 3 Option-5 CPRI signals. The OTU2r frame structure may or may not include the FEC area. The bit rates are as summarized in Table 8.

Table 8: CPRI over OTN bit rates and bit rate tolerances

Signal Type	Nominal bit rate	Tolerance
OTU2r	255/238 x 128 x 24 x 3840 kbit/s	±100 ppm
OTU2r no FEC	239/238 x 128 x 24 x 3840 kbit/s	±100 ppm
ODU2r	239/238 x 128 x 24 x 3840 kbit/s	±100 ppm
OPU2r	128 x 24 x 3840 kbit/s	±100 ppm
NOTE 1 – The nominal OTU2r rate is approximately 12639085.714 kbit/s NOTE 2 – The nominal OTU2r without FEC and ODU2r rates are approximately 11846045.042 kbit/s NOTE 3 – The nominal OPU2r rate is 11796480 kbit/s		

The following figures (Figure 17, Figure 18, Figure 19) show examples of CPRI mapping and OTN multiplexing schemes.

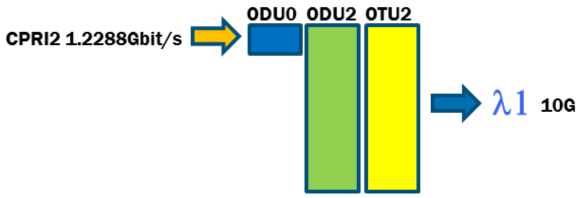


Figure 17: A CPRI2 flow into 10Gbit/s lambda multiplexing scheme.

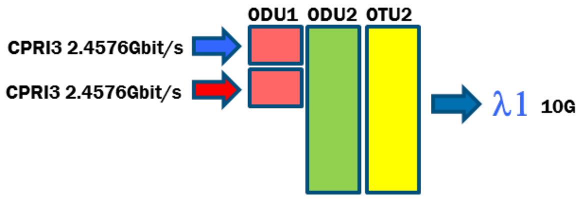


Figure 18: Two CPRI3 flows into 10Gbit/s lambda multiplexing scheme.

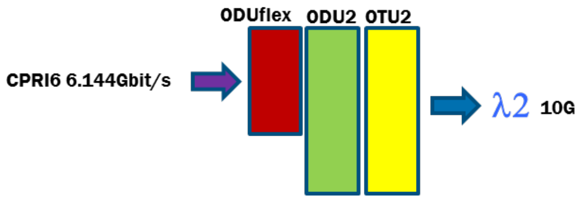


Figure 19: A CPRI6 flows into 10Gbit/s lambda multiplexing scheme

The main challenge of transporting CPRI or any time-sensitive fronthaul interface over OTN is to limit the jitter and wander introduced while mapping and de-mapping CPRI to OTN. Simulation analyses of the frequency offset ("jitter") and Mean Time Interval Error was performed by ITU-T [39] showing that to meet 2 ppb, as specified by the CPRI standard, stringent desynchronizer bandwidth is required, much lower than 300 Hz normally used in OTN. This would lead either to design RRHs capable to tolerate higher input noise or to redesign the OTN equipment including very stable oscillators and sharp filters. Another issue, still under discussion, is the compensation of a possible unbalance of latency times in up- and down-stream, which might not be compatible with CPRI. As a conclusion, today the practical use of CPRI over OTN appears to be limited to the case of synchronous mapping of CPRI signals belonging to a single synchronization domain, quite in contrast with the 5G-Crosshaul concept of fronthaul and backhaul coexistence.

6.2 5G-Crosshaul circuit framing protocol over WDM

To overcome the issues that arise when mapping time sensitive fronthaul interfaces over OTN, an alternative multiplexing methodology is presented in the following which could also be extended to Ethernet client signals to fulfil the 5G-Crosshaul case. Though the discussion focus is on optical channels, the methodology can be applied to wireless signals as well. For a cost effective implementation, the proposed method makes the realistic assumption that fronthaul signals are transported over short reach links (a few tens of kilometres) so that there is no need for advanced features such as the complex multiplexing hierarchy and protection mechanisms envisaged in [38].

The proposed framing procedure is synchronous to the CPRI client to avoid any degradation of the synchronization accuracy.

Optional FEC is provided, based on RS (255, 239) as in [38] but the number of interleaved codecs can optionally be reduced to limit the additional latency. First experiments showed a FEC latency lower than 4µs with 9 interleaved codes, with no appreciable degradation of the FEC gain with respect to the OTN case.

The bandwidth efficiency compared to CPRI is improved replacing spectrally inefficient line codes such as 8B/10B, code with more efficient scramblers, e.g. using as generating polynomial $1+ x + x^3 + x^{12} + x^{16}$, leaving space to FEC overhead and in-band signalling.

The transmitter scheme is outlined in Figure 20, taking CPRI Option-7 (9.8304 Gbit/s) as an example.

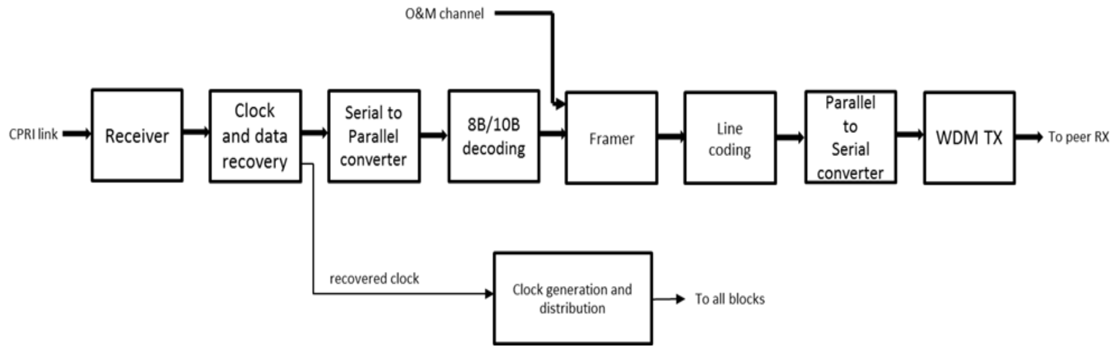


Figure 20: Transmitter scheme

The clock signal is extracted from the received CPRI signal and distributed to all the transmitter blocks. After serial to parallel conversion, the 8B/10B redundant bits are removed with the exception of the control bits which identify the K-codes. Then, a framer block (Figure 21) applies FEC to data, control and any other OAM bit. If desirable, different FEC codes or interleaving could be used for data and OAM bits. The framer includes also a buffer for the compensation of the difference between upstream and downstream delays, as required by the CPRI client. Finally, the assembled frame is scrambled.

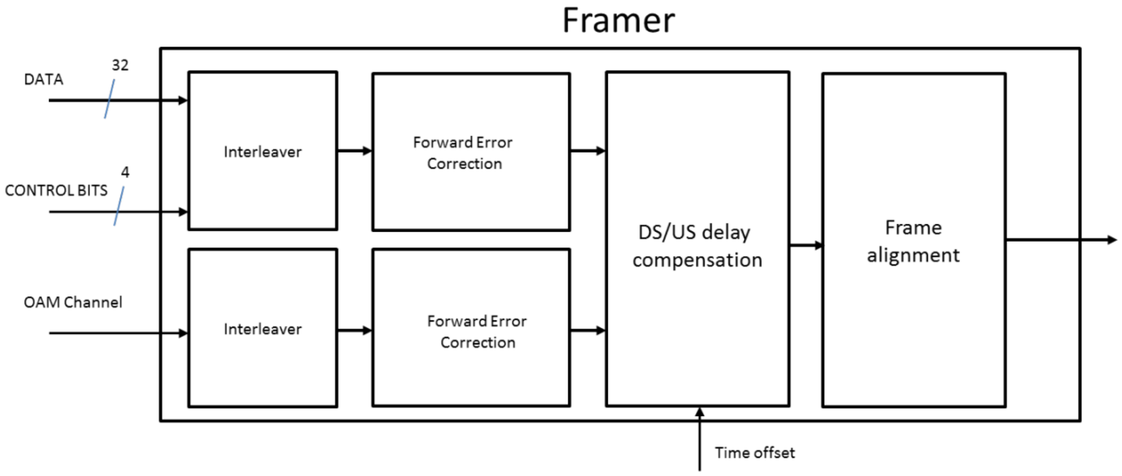


Figure 21: Framer scheme

The inverse operation is performed at the receiver (Figure 22 and Figure 23).

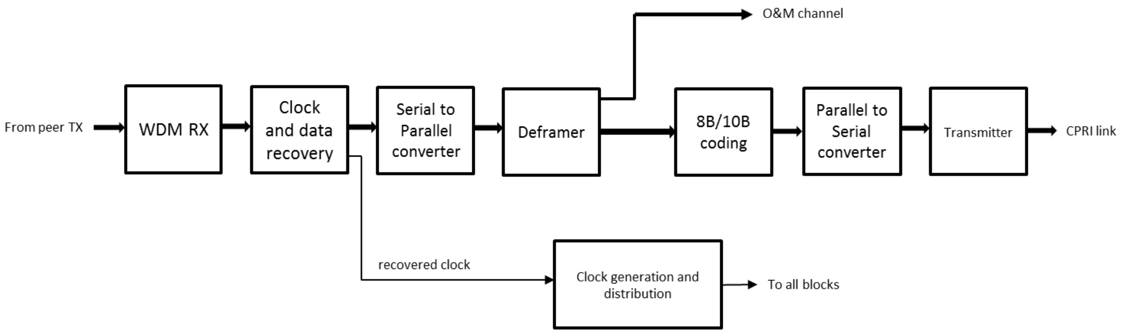


Figure 22: Receiver Scheme

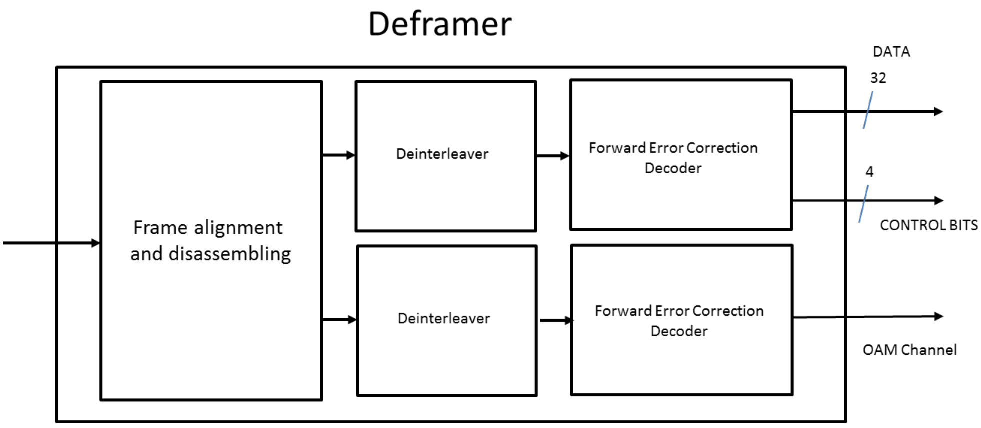


Figure 23: Deframer scheme

An example of frame structure is illustrated in Figure 24:

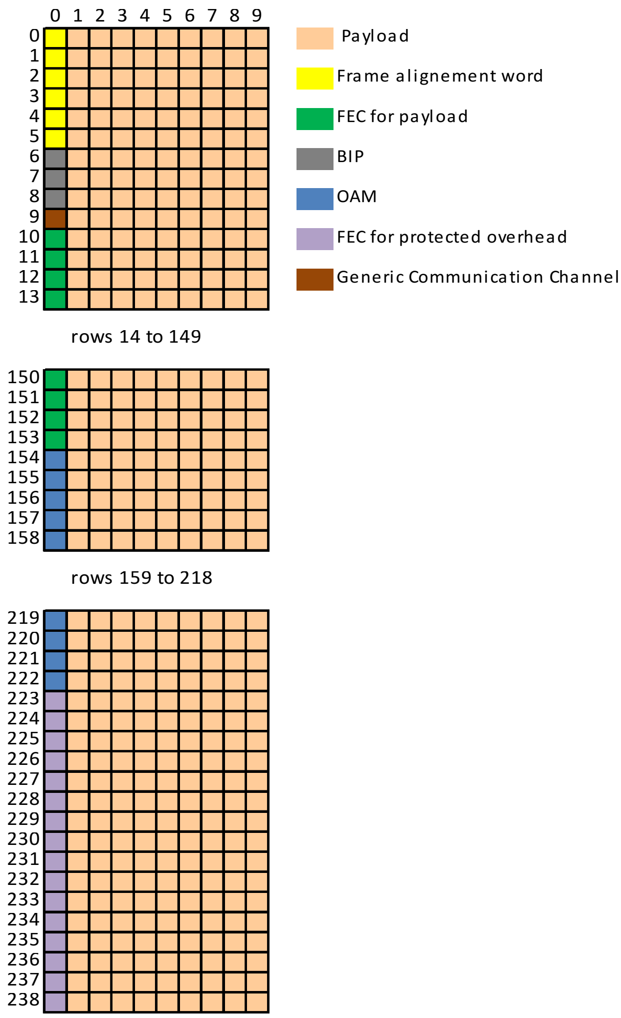


Figure 24: Example of frame structure (239 rows by 10 columns)

The frame is 2390 octets long, arranged in 239 rows by 10 columns. Columns 1 to 9 are for payload while column 0 is reserved for overhead: Frame alignment word (distributed in rows 0 to 5), FEC codes for payload (rows 10 to 153), Bit Interleaved Parity (rows 6 to 8), Generic communication channel (row 9), OAM channel (rows 154 to 222), FEC code for protected overhead (rows 223 to 238).

In this, like in other framing structures, it is necessary to consider the potential time asymmetry of the fronthaul segment between downlink and uplink. This time asymmetry is due to:

- optical fibre cable length difference when two fibre cables are used in up and down link (7 m corresponds to approximatively 34 ns delay in SSMF)
- the difference of wavelength propagation delays when transmission wavelengths at DU and RRH are not similar (typically 1.3µm and 1.55µm wavelength duplex causes 33ns time difference over 20 km of standard single mode fibre)
- the difference of processing time (including functions such as time multiplexing,

encapsulation, compression) at OLT and ONT.

Any time difference can be compensated for by adequate buffering, possibly helped by a measurement of the latency in the two directions.

When number and bit rate of the fronthaul client signals are not sufficient to “fill” a wavelength up to the maximum supported bit rate, the unutilized bits can be used to transport other type of clients. Especially Ethernet (e.g. the MAC-in-MAC frames of use in the XCF) is of interest so that the same DWDM channel can serve fronthaul and backhaul connections.

The proposed frame cannot provide all the set of features ensured by OTN but it is intended to target a simpler scenario, where point-to-point logical connections are the most frequent case.

The basic concept is very simple and consists of allocating two separate portions of the same frame to Ethernet and CPRI (or CPRI-like) clients. Size and position of the portions within the frame are known as well as the frame size, making very easy to separate Ethernet packets from CPRI frames. The concept is illustrated in Figure 25.

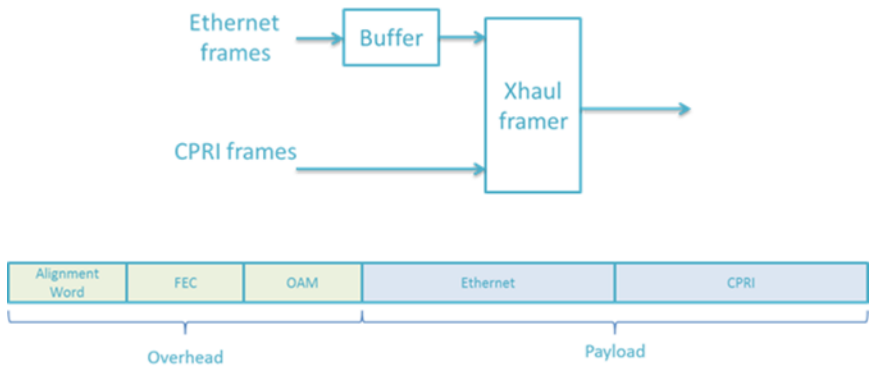


Figure 25: CPRI and Ethernet over the same DWDM channel

Portion size and position can be programmable, e.g. via XCI, depending on network configuration and planned traffic load. The frame is synchronous to the CPRI clock in order to minimize the impact on delay and jitter sensitive CPRI frames while ingress Ethernet packets are buffered to absorb differences in clock value and accuracy. A possible way to map Ethernet frames in the dedicated timeslots of the frame is the use of the Generic Framing Procedure (GFP).

7 Design of the multi-layer 5G-Crosshaul Forwarding Element

The key novelty of the 5G-Crosshaul data plane architecture lies in the 5G-Crosshaul Forwarding Element (XFE) design and related adaptations in order to provide a common switching layer for enabling a unified and harmonized traffic management. This common switching layer supports the 5G-Crosshaul Common Frame (XCF) format across various types of fronthaul and backhaul traffic and the various link technologies in the forwarding network. The common switching layer in the XFEs falls under the control of the 5G-Crosshual Common interface, XCI, which is another key part of the proposed architecture, as described in Section 9.

In its generic implementation (Figure 26), the 5G-Crosshaul switching node encompasses two macro layers: a packet layer and a circuit layer.

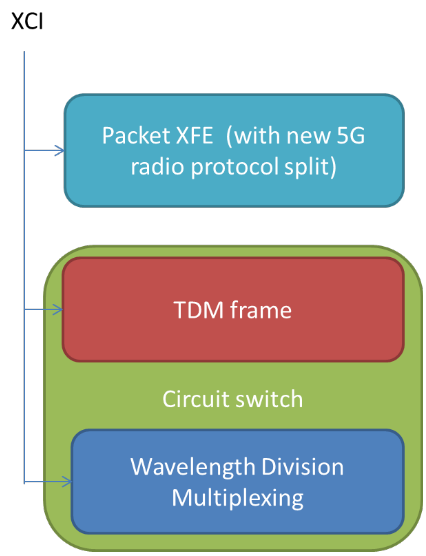


Figure 26: Generic implementation of the 5G-Crosshaul switching node

It is not necessary that all the layers always coexist but one or two could be skipped depending on the type of deployed network. Examples are: a mesh of packet switches connected by dark fibres (where only the packet layer is exploited); 5G RRHs, based on new radio protocol split and packetized fronthaul interface, connected to a DWDM network (where only wavelength and packet switch are present); the same network where also CPRI tributaries are carried and multiplexed over time-slots in a wavelength, so that a TDM switch needs to be added.

In summary, the layered switch architecture is able to combine bandwidth efficiency, through statistical multiplexing in the packet switch, with deterministic latency ensured by the circuit switch. The modular structure of the Crosshaul switch, where layers can be added or removed, also allows to deal with a diversified deployment scenario and to guarantee traffic segregation at multiple level, from dedicated wavelengths to VPN, which is especially desirable in the multi-tenancy use case.

7.1 Circuit Switching

For latency demanding applications and protocol splits where re-transmission from main and remote sites is maintained, jitter and queuing delay occurring in a packet switch may not be acceptable, especially when more than one packet switch is cascaded. In these situations, packets having strict timing requirements can be sent to the circuit switch, which assigns them fixed time slots in a frame, ensuring a deterministic latency. The circuit switch can also be used for offloading the packet switch, avoiding overload and overprovisioning situations: packets addressed to the same destination node can be aggregated in a single constant bit rate frame, as happens today for GbE and 10GbE, so that such big pipes can be more easily cross-connected by the circuit switch. All this requires a common control for the switching layer, which is performed by the XCI similarly to what happens today in packet-optical network [40]

The XCSE circuit switching layer may be composed of two sub-layers of different granularities. As previously mentioned, it is not necessary that both sub-layers always coexist. In optical networks, the sub-layers correspond to wavelengths and time slots in a wavelength, as in current reconfigurable add-drop multiplexers (ROADMs) and according to OTN as described in Sections 5.3.2 and 6.1, respectively.

Figure 5 illustrates an alternative XCSE implementation based on the TDM frame presented in Section 6.2.

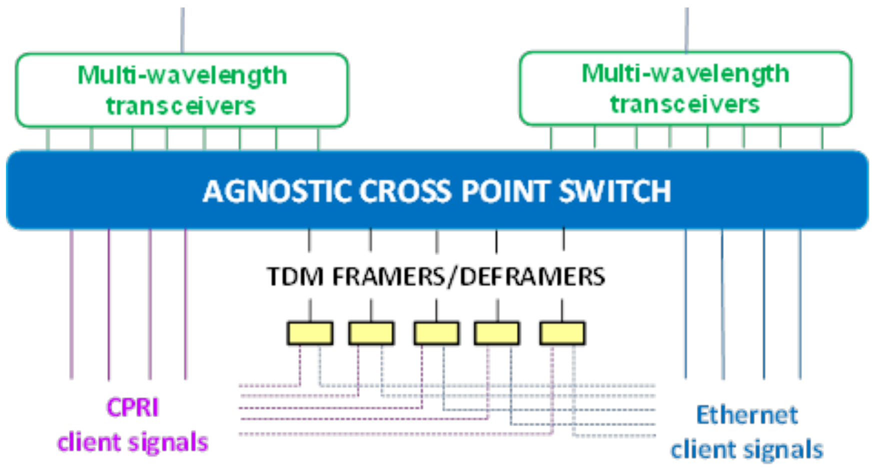


Figure 27: Generic implementation of the 5G-Crosshaul switching node

Wavelength channels, which are generated and received by multi-wavelengths integrated transceivers, are first optical-to-electrical converted and then cross-connected by a protocol-agnostic cross-point switch. Wavelengths that carry only CPRI or Ethernet signals undergo no further processing. Wavelengths where CPRI and Ethernet are multiplexed together are instead sent to de-framers that use the framing protocol presented in Chapter 6. The de-framers use pointers in the frame header to separate CPRI and Ethernet CBR client signals. Programmability of slots size and position of the client signals can be achieved by using the pointers subject to network configuration and traffic load planning. This implementation relies on cost effective devices, as integrated multi-wavelength transceivers and high capacity cross-point switches (e.g. 160x160 ports), to achieve modularity and enhanced flexibility, offering the possibility of wavelength reuse over multiple ports.

7.2 Packet Switching

Packet switching enables statistical multiplexing when the peak to average radio access traffic load in 5G is high enough. It is also particularly suitable for protocol split options, where MAC and partly RLC are moved back to the remote access unit so that HARQ re-transmission, which is a major source of latency, is performed locally.

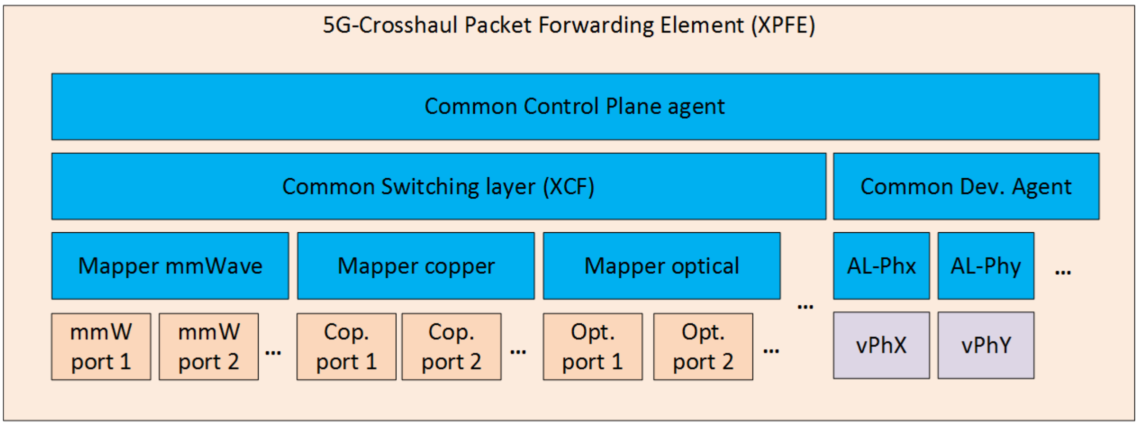


Figure 28: XPFE functional architecture

Figure 28 depicts an initial functional architecture for the 5G-Crosshaul Packet Forwarding Element (XPFE). It includes the following key functions:

- A common control-plane agent to talk to the common control infrastructure (XCI).
- A common switching layer based on a common frame (XCF) to forward packets between interfaces. The switching engine is technology-agnostic and relies on (i) an abstract resource model (e.g. bandwidth, latency, BER, jitter, latency, etc.) of the underlying interfaces (e.g. mmWave, Optical, etc.), and on (ii) traffic requirements (e.g. fronthaul/backhaul, jitter tolerance, packet loss, etc.) that could be carried in the XCF. As a result, the common switching layer enables forwarding between heterogeneous protocols, interfaces and physical technologies.
- A device agent common to all peripheral systems to talk with system components. This agent exposes device-related information like CPU usage, RAM occupancy, battery status, GPS position, etc, to the control infrastructure.

- Mappers for each physical interface. XCF can be mapped on any physical interface as long as the XCF traffic requirements are satisfied. For example, NGFI digital samples could be carried by XCF and transmitted over a copper interface if a low-bandwidth-demanding functional split is adopted. If a more demanding functional split is adopted, a different interface (e.g. optical, mmWave) could be chosen.
- Physical interfaces to transmit the data on the link. Multiple physical interfaces can coexist in the unit including different technologies (fibre optic, mmWave, µWave, copper, etc.).

The **control-plane agent** is in charge of communicating with the control-plane entity (XCI). The following is a non-exhaustive list of functions envisioned for the control-plane agent:

- The protocol that governs the exchange between the forwarding node and the control-plane entity.
- Exposition of device capabilities to the south-bound interface. The control-plane agent informs the control-plane entity regarding the node's capabilities. An example of reported capabilities is: south-bound version support, data-plane version support, device-agent version support, number of ports, port technology, available rates, number of flow tables, flow table size, available RAM, CPU capabilities, battery status, etc.
- Mapping of south-bound interface to data-plane agent. The control-plane agent interacts with the data-plane agent in order to configure the common frame format being used and the matching rules.
- Mapping of south-bound interface to device agent. The control-plane agent interacts with the device agent in order to configure the device itself or some peripheral. For example, the control-plane entity might instruct the device (through the control-plane agent) to go in power-saving mode.

The **data-plane agent**, also called the **common switching layer**, is in charge of communicating with the control-plane agent. The following is a non-exhaustive list of functions envisioned for the data-plane agent:

- The common frame format that governs the forwarding between different interfaces in order to support heterogeneous technologies.
- The available operations regarding the common frame format. For example, the data-plane agent might support multi-tenancy, QoS enforcement, field lookup and modification, and header options push and pop.
- Mapping of data-plane capabilities to the control-agent interface. The data-plane agent informs the control-plane agent regarding the data-plane capabilities. An example of reported capabilities is: SBI version support, data-plane version support, number of ports, port technology, available rates, number of flow tables, and flow table size.
- Mapping of the control-plane agent interface to the technology mappers underneath. The data-plane agent identifies and contacts the mapper layer required to enforce the control-plane agent commands.

The **device agent** is in charge of communicating with the control-plane agent. The following is a non-exhaustive list of functions that will be defined in the device agent:

- The common interface that governs the information exchange regarding device-related parameters.
- The available operations regarding the device. For example, the device agent might support several power states, resource slicing, and statistics collection.
- Mapping of device capabilities to the control-agent interface. The device agent informs the control-plane agent regarding the device capabilities. An example of reported capabilities is: device agent version support, available RAM, CPU usage, battery support, battery status, GPS support, and GPS position.
- Mapping of the control-plane agent interface to adaptation layers. The data-plane agent identifies and contacts the adaptation layers required to enforce the control-plane agent commands.

The **mapping layers** are in charge of enforcing the control-plane by mapping the commands to protocol and technology-specific interfaces/peripherals. The following is a non-exhaustive list of functions that will be defined in the mapping layers:

- The common interface that governs the information exchange between the data-plane and device agents.
- The technology-specific interface that governs the information exchange between the mapper layer and the interface/peripheral;
- Mapping of technology-specific capabilities to data-plane and device agent interfaces. The mapping layers abstract and hide the low-level details of the interfaces and peripherals. For example, a mapper layer may abstract the status of the physical channel in more generic terms like available bandwidth, bit error rate, jitter, etc. In this case, the abstraction layer hides low-level details (e.g. employed MCS) to the higher layers.
- Mapping of common data-plane and device agent interfaces to technology-specific parameters. The mapping layers translate the control-plane instructions into technology-specific parameters. For example, the mapping layers translate the common data frame requirements (e.g. QoS) to the technology-specific parameters (e.g. IEEE 802.11e Enhanced Distributed Channel Access Traffic Categories).

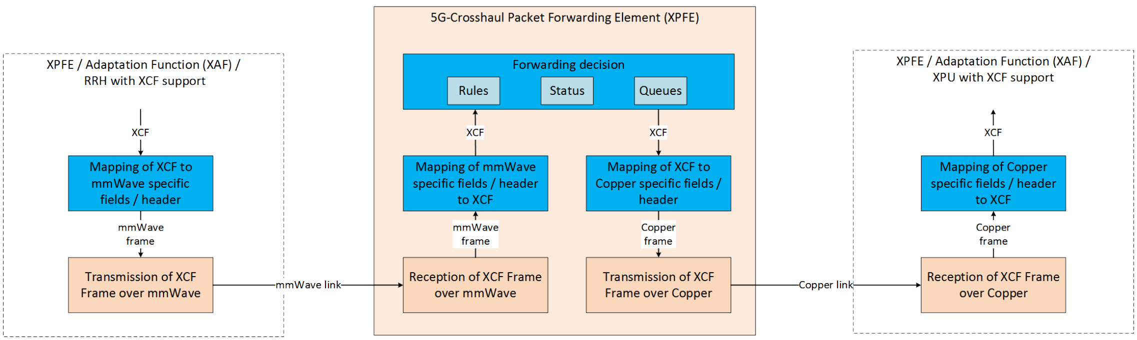


Figure 29: XPFE forwarding example

Figure 29 shows an example of an XPFE forwarding element receiving an XCF frame over a mmWave link and forwarding it over copper. Here, the XPFE receives first a frame over the mmWave link and maps it to XCF. Next, the XPFE uses XCF information to decide how and where to forward the packet. Finally, the XCF is mapped onto a copper frame and sent over the copper link.

As mentioned above, the XPFE common switching layer (and hence the forwarding decision) is based on XCF and on the abstract resource model of the underlying physical interfaces (e.g. mmWave and copper in the above example). Therefore, XPFEs manage only XCF frames at switching level and an adaptation function is required to interoperate with non-XCF switching devices (e.g. legacy switches). This adaptation function is (at least logically) separated from the XPFE.

Figure 30 depicts an initial functional architecture for the 5G-Crosshaul Adaptation Function (XAF). It includes the following key functions:

- A common control-plane agent, a common switching layer, a common device agent, mappers, and physical interfaces like in XPFE case.
- Adaptation layers from/to the common switching layer to/from the specific fronthaul and backhaul protocols.
- Fronthaul and backhaul protocols (Ethernet, NGFI, CPRI, etc.).

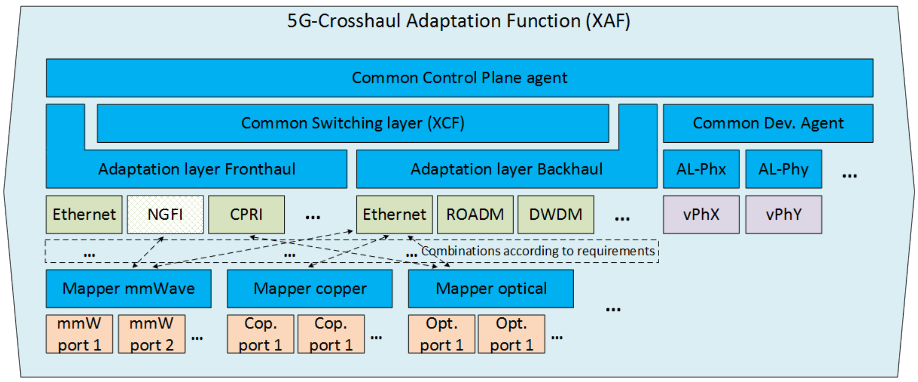


Figure 30: XAF functional architecture

The **adaptation layers** are in charge of translating/adapting fronthaul and backhaul protocols to XCF and enforcing the XCF forwarding control by adapting/translating the commands to specific protocol interfaces. The following is a non-exhaustive list of functions that will be defined in the adaptation layers:

- Mapping of fronthaul/backhaul traffic characteristics to the XCF format.
- Encapsulation and decapsulation of fronthaul and backhaul while dejittering and retiming the associated traffic.
- Framing of fronthaul and backhaul traffic with particular attention to the frame size in order to minimize delay, jitter, and to avoid fragmentation.

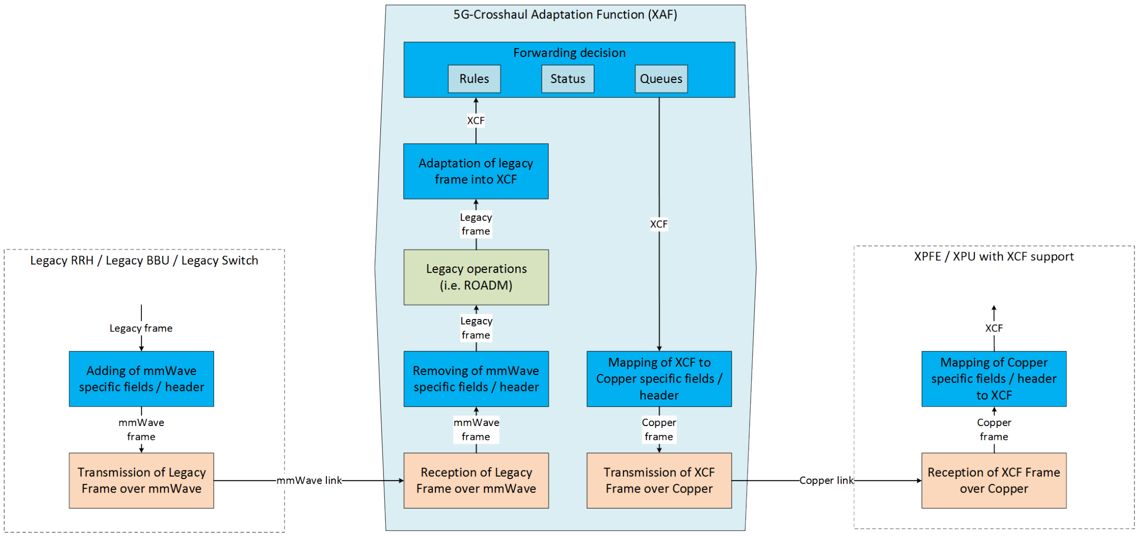


Figure 31: XAF adaptation example

Figure 31 shows an example of an XAF adaptation function where a legacy fronthaul traffic (e.g. CPRI) is received over a mmWave link, adapted next to XCF, and finally forwarded over a copper link. The XAF receives first the fronthaul signal over the mmWave link. It then adapts it to XCF by framing, encapsulating, and mapping traffic requirement to XCF. The XAF uses the XCF information to decide how and where to forward the packet. Finally, it maps the XCF into a copper frame and transmits it over a copper link for the next hop.

8 Design of the 5G-Crosshaul Common Frame

The XFEs provide a common switching layer for enabling a unified and harmonized traffic management. This common switching layer supports the 5G-Crosshaul Common Frame (XCF) format in the packet switching path across the various traffic types (of fronthaul and backhaul) and the various link technologies in the forwarding network as described in previous paragraphs of this document.

Requirements on the XCF and the chosen frame format are described in Section 8.1, and an alternative frame format is described in Section 8.2 for the sake of completeness.

8.1 XCF Requirements and structure

The XCF is a frame format that defines the control information used by the XPFE to perform the forwarding. The control information to use is decided by the XCI which is the entity in charge of instructing the XPFEs.

Several network deployment options for LTE backhaul traffic are described in [1], while considering different protocol stacks for different physical topologies. For instance, the backhaul traffic is IP-based in case of LTE while the fronthaul traffic in 5G can be packet based depending on the functional split and its implementation, see [41] as an example of packet based radio data. Therefore, the XCF shall support a larger variety of services for both fronthaul and backhaul traffic.

8.1.1 Requirements

The XCF has to provide sufficiently rich information in the frame headers so that the common switching layer of the XPFEs can fulfil the requirements for both fronthaul and backhaul traffic.

The requirements identified for the XCF are listed in the following table. According to the project objectives, different functional splits, as well as multiple tenants, have to be supported. Moreover, to support the migration to a 5G-Crosshaul network, it must be possible to interact with legacy devices. For this purpose, the XCF should allow making efficient use of the available bandwidth and it has to support different media. In addition to the service data, additional frames to support OAM have to be exchanged as well.

Table 9: XCF Requirements

Req.ID	Requirement	Explanation
Functional splits		
XCF-R1	Support multiple functional splits	The XCF shall support traffic of different functional splits of the radio protocol stack, ranging from CPRI-like fronthaul traffic to backhaul traffic
Multi-tenancy		

Req.ID	Requirement	Explanation
XCF-R2	Isolate traffic	Provide guaranteed QoS to traffic of different tenants. Traffic of one tenant shall not impact the QoS of the traffic of other tenants.
XCF-R3	Separate traffic	Guarantee the privacy of each individual tenant. One tenant shall not be able to eavesdrop traffic of another tenant.
XCF-R4	Differentiation of forwarding traffic	Traffic of different tenants may be forwarded using different policies.
XCF-R5	Multiplexing gain	It shall be possible to exploit statistical multiplexing gains among the traffic of different tenants.
XCF-R6	Tenant ID	The traffic of each tenant shall be identifiable.
	Coexistence	
XCF-R7	Ethernet	Compatibility with legacy Ethernet switches.
XCF-R8	Security support	Encryption and/or authentication shall be supported for XCF data frames. Securing access to the network itself is considered a control-plane issue.
XCF-R9	Compatible with IEEE 1588v2 or IEEE 802.1AS	It shall be possible to carry synchronization information on the same links as the data traffic using XCF.
	Transport Efficiency	
XCF-R10	Short overhead	The additional headers introduced by the XCF shall be short, in order to minimize the overhead.
XCF-R11	Multi-path	The XCF shall allow carrying traffic towards one destination on different paths, but keeping individual flows on the same path. This is useful in meshed wireless networks.
XCF-R12	Flow differentiation	The frame format shall provide flow-basis QoS support in addition to traffic classes.
XCF-R13	Class of Service differentiation	XFEs shall support different classes of service for different types of traffic.

Req.ID	Requirement	Explanation
		Management
XCF-R14	In-band control traffic (OAM)	It shall be possible to carry OAM traffic on the same links as the data traffic using XCF
		Support of multiple media
XCF-R15	IEEE 802.3	XCF shall support 802.3
XCF-R16	IEEE 802.11ad	XCF shall support 802.11ad
XCF-R17	mmWave	XCF shall support mmWave
Energy efficiency		
XCF-R18	Energy usage proportional to handled traffic	XCF shall support energy efficiency by providing the required control information to allow XFEs to use features such as sleep modes, reduced line rates, etc.
		Miscellaneous
XCF-R19	No vendor lock-in	The XCF shall be based on standards, such that no vendor lock-in may happen.

These requirements are on the frame format, i.e. on what information is contained in individual frames. The control, i.e. how this information is used in the XPFEs for the forwarding decisions, is a control-plane issue related to the XCI. For example, it is not relevant to the frame format whether point-to-point or multipoint-to-multipoint services are established. These questions are important, but independent of the frame format, as long as the frames contain sufficient information to establish the corresponding services.

8.1.2 MAC-in-MAC XCF as baseline

The XCF has to provide sufficient information for the XPFEs to forward the packets towards their destination while satisfying the requirements on latency and jitter. To ensure interoperability with legacy devices and to benefit from previous research, the XCF was based on an existing packet format. Starting from the ubiquitous availability of Ethernet, its widespread deployment in datacentres, and recent developments for Radio over Ethernet [41], the XCF is based on Ethernet. To better support multi-tenancy PBB-TE (Provider Backbone Bridge-Traffic Engineering), better known as MAC-in-MAC, is chosen as the baseline format for the XCF.

A frame format based on MPLS-TP would be a viable alternative as XCF format, see Section 8.2. But within 5G-Crosshaul, we focus on one format to a keep developments aligned among partners. From a technical perspective, no clear advantages or disadvantages of MAC-in-MAC or MPLS-TP as XCF have been identified.

Frame format

MAC-in-MAC encapsulates the tenant's data-link frames by adding one or two additional headers. This allows the tenant's frames to be transported unchanged across the provided network. The first additional header consists of the actual MAC-in-MAC header while the second additional header consists of the optional F-Tag (Flow-Filtering Tag) to support Equal Cost Multiple Path (ECMP).

The MAC-in-MAC header contains a new Ethernet header with Source and Destination MAC addresses, a B-TAG (Backbone VLAN Tag) to support VLANs, and an I-TAG (Backbone Service Instance Tag) to support further service differentiation. The frame format is shown in Figure 32.

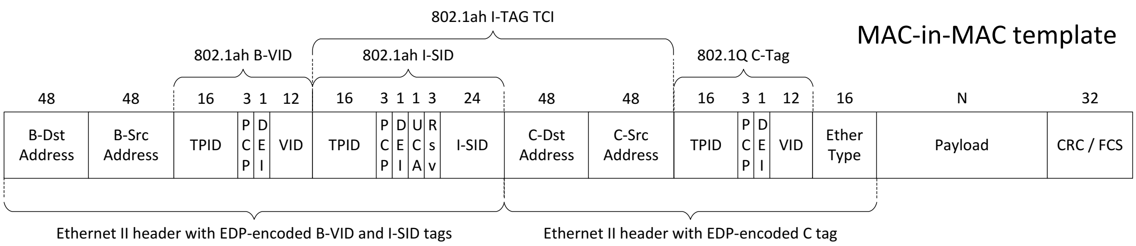


Figure 32: MAC-in-MAC header

The outer MAC addresses are used to address the XPFEs. The destination B-MAC address is the MAC address of the XPFE to which the tenant device, identified by the C-Dst address, is connected. The B-VLAN tag contains the VLAN-ID in the provider network as well as the Priority Code Points (PCP) used to prioritize the packets appropriately. The Use Customer Address (UCA) is used to indicate whether the addresses in the inner header are actual client addresses or whether the frame is an OAM frame.

In the 5G-Crosshaul System Architecture, the concept of multi-tenancy is of primary importance. Specifically, a different portion of a virtual slice of the physical network is assigned to each tenant. Moreover, each tenant could offer some services but not necessarily all of them, so it is also important to differentiate the services. Finally, different types of traffic need to be differentiated in the network accordingly to the assigned priority. Therefore, the labels of each packet must contain fields for all these requirements.

The B-VID tag is used to identify the tenant thanks to the VID field which is 12 bits long and allows to identify 2^{12} = 4096 different tenants. Based on the instructions received from the control plane, the adaptation function configures the PCP and DEI fields to preserve traffic isolation and support SLAs within the 5G-Crosshaul transport network. A Credit/Time shaper might be associated to each traffic class, identified by the PCP.

The I-SID tag is used to differentiate the service thanks to the I-SID field that can be used as a Service ID. The I-SID scope can be global or local: in case of global scope, the I-SID values are shared among all the tenants and defined by the infrastructure owner; alternatively each tenant defines its own values. In addition, the flow may be identified by combining the I-SID, C-Dst and C-Src addresses.

ECMP can be supported by providing a value per end user flow. This value can be used to calculate which of the available paths should be used to forward the frames. If individual flows have different values, this allows distributing flows to different paths while keeping all packets of one flow on the same path. This value is contained in the F-Tag for flow filtering, see [42] and Figure 33.

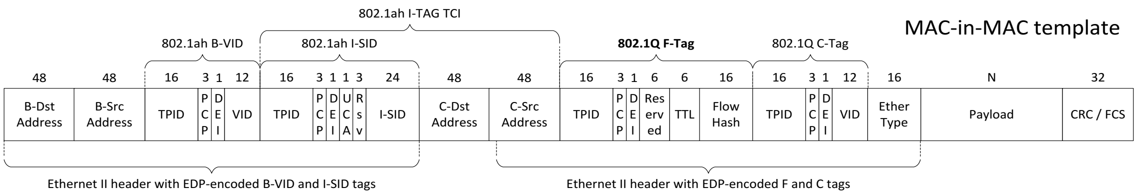


Figure 33: MAC-in-MAC header with F-Tag

The Time to live (TTL) value can be used to prevent forwarding loops. But as the F-Tag is considered optional within 5G-Crosshaul, this mechanism will not be used. Indeed, the use of such tag will imply that packet is modified at each hop in order to decrement the TTL field. The modification of the header has a negative impact on the forwarding latency, which might be critical for time-sensitive fronthaul traffic. The flow hash field in the F-Tag is to support ECMP.

Gap analysis

The XCF has been compared against the requirements identified in Table 9 and most of them are satisfied by the XCF design. Details are provided in Table 10.

Table 10: XCF requirement fulfilment

ReqId	Requirement	Explanation
Functional splits		
XCF-R1	Support multiple functional splits	All functional splits with packetized transport can be supported by the XCF, see also XCF-R2
Multi-tenancy		
XCF-R2	Isolate traffic	QoS provided by PCP.
XCF-R3	Separate traffic	Traffic of different tenants can be distinguished by the B-Tag and the I-Tag.
XCF-R4	Differentiation of forwarding traffic	XCF supports multiple priorities and traffic classes that map on XPFE queues. However, the

ReqId	Requirement	Explanation
		mapping task is devoted to the XCI.
XCF-R5	Multiplexing gain	Packet-based technology multiplexing gains can be achieved.
XCF-R6	Tenant ID	B-Tag and I-Tag.
Coexistence		
XCF-R7	Ethernet	Legacy Ethernet switches can forward frames based on the information of the outer header.[4]
XCF-R8	Security support	Either payload has to be encrypted e.g. by IPsec or encrypted links have to be used, e.g. 802.1AE MACSec.
XCF-R9	Compatible with IEEE 1588v2 or IEEE 802.1AS	IEEE 1588 packets can be carried as any other IP packet as payload. XCF frames and 802.1AS (gPTP) can be carried on the same link.
Transport Efficiency		
XCF-R10	Short overhead	B-tag + I-Tag: 22B, (optional) F-Tag: 6B
XCF-R11	Multi-path	Based on F-Tag.
XCF-R12	Flow differentiation	Individual services can be identified by I-SID and classified to dedicated queues, although PCP is considered sufficient.
XCF-R13	Class of Service differentiation	QoS provided by PCP.
Management		
XCF-R14	In-band control traffic (OAM)	OAM traffic is under control of XCI. OAM traffic can be distinguished by using Ethertype or dedicated multicast addresses.
Support of multiple media		
XCF-R15	802.3	Yes.

[4] Legacy Ethernet switches consider only Destination and Source Addresses. 802.1Q-compliant switches will also consider the VLAN tags during the forwarding. The consistency of forwarding rules (e.g., VLAN-switch port mapping) is delegated to the XCI.

ReqId	Requirement	Explanation
XCF-R16	802.11ad	Yes.
XCF-R17	mmWave	Same frame format as 802.11ad.
	Energy efficiency	
XCF-R18	Energy usage proportional to handled traffic	N/A
	Miscellaneous	
XCF-R19	No vendor lock-in	Based on MAC-in-MAC standard.

Support of IEEE 802.11ad links

Historically, transport links based on IEEE 802.11 did not support the transmission of VLAN tagged frames and as such would have not been able to support the XCF. The 802.2 LLC (Logical Link Control) sublayer uses two different methods for encoding the higher layer protocol:

- EPD: Ethertype Protocol Discriminator
- LPD: LLC Protocol Discriminator.

VLAN tags are inserted in both cases with a protocol discriminator, but the format of the protocol discriminator is different, as shown by the examples in Table 11.

Lately, IEEE 802.1Q and IEEE 802.1AC have been aligned with IEEE 802.1Qbz, in order to use the same Length/Type encoding. For instance, the header of a VLAN-tagged LPD frame, Ethertype 08-00, priority 0, and VLAN 0123 using EPD for the inner frame, is encoded as AA-AA-03-00-00-00-81-00-01-23-08-00.

This adoption allows using 802.11ak [43] and specifically 802.11ad [44] links as links within an 802.1Q conformant network. Correspondingly, frames according to the XCF can be transported over such links. The mapping of a MAC-in-MAC frame onto an 802.11 frame is shown in Figure 34.

Table 11: EPD and LPD headers for higher layer protocols

Protocol	EPD	LPD
IPv4	08-00	AA-AA-03-00-00-00-08-00
IPv6	86-DD	AA-AA-03-00-00-00-86-DD
C-VLAN tagged IPv4	81-00-xy-zw-08-00	AA-AA-03-00-00-00-81-00-xy-zw-08-00

Protocol	EPD	LPD
S-VLAN and C-VLAN tagged IPv6	88-A8-st-uv-81-00-xy-zw-86-DD	AA-AA-03-00-00-00-88-A8-st-uv-81-00-xy-zw-86-DD

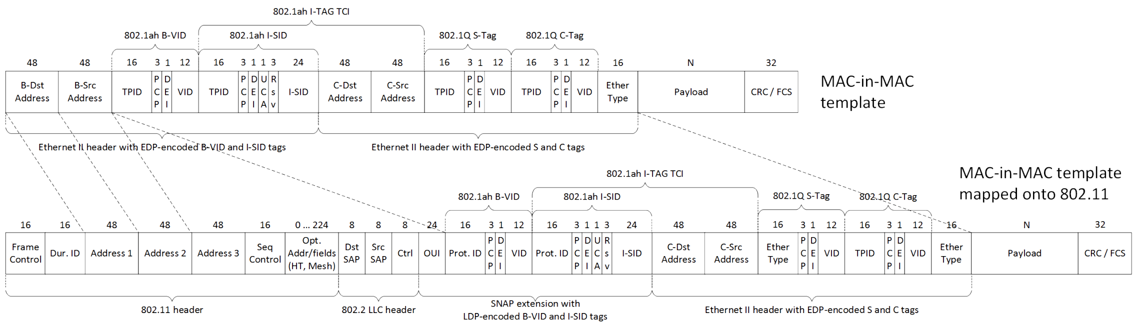


Figure 34: MAC-in-MAC frame mapped onto 802.11 frame

Quality of service

XPFEs need to distinguish different types of traffic and schedule frames for transmission according the SLA requirements of the frames. The XCF provides 3 bits to encode priority information, allowing XPFEs to distinguish 8 different traffic classes. In turn, XPFEs should provide 8 queues per port, one per each traffic class, to prevent head of line blocking by low-priority traffic. Based on these traffic classes, the 5G-Crosshaul network can provide four major service classes: ultra-low latency, control, low latency and regular. The latter two service classes are divided further into subclasses for GBR (guaranteed bit rate), nGBR (non-GBR) premium, and nGBR best effort traffic. Table 12 presents a mapping of traffic types to priorities. Additional traffic classes would provide even more fine granular control, but the three types of service classes for end user traffic are considered sufficient. The service classes – ideal, near/sub ideal, non-ideal – are taken from [45].

Table 12: Traffic Classes

PCP	Traffic class	Service class / Priority	Comment
7	Radio over Ethernet (RoE), CPRI-like	Ideal	May pre-empt other frames; committed bit rate; ensure there remains sufficient bandwidth for control.
6	Control (sync, network control, FH radio control, BH radio control)	Near/sub ideal	Traffic volume not sufficient to starve other traffic classes; split bandwidth further for the different types of control traffic.

PCP	Traffic class	Service class / Priority	Comment
5	FH data GBR, mission critical	Near/sub ideal/GBR high	Committed bit rate; priority of mission critical traffic over GBR traffic can be ensured by admission control on application level.
4	BH GBR, mission critical, tactile, voice video	Non-ideal/ GBR high	N/A
3	FH nGBR premium, mission critical	Near/sub ideal/nGBR high	Just a part of the bit rate may be committed, the service has to adapt to the available bit rate.
2	FH nGBR best effort	Near/sub ideal/nGBR low	Just a part of the bit rate may be committed, the service has to adapt to the available bit rate.
1	BH nGBR premium, mission critical	non ideal/nGBR high	Just a part of the bit rate may be committed, the service has to adapt to the available bit rate.
0	BH nGBR best effort	non ideal/nGBR low	Just a part of the bit rate may be committed, the service has to adapt to the available bit rate.

The traffic class with the highest priority may pre-empt the transmission of other frames to reduce the jitter [46]. Instead of having to wait for the transmission of a frame, a high priority frame could be sent already after waiting for the minimum fragment size. Frame pre-emption is applicable to copper or fibre Ethernet links but it is not applicable to 802.11 based transport links. Extending 802.11 with frame pre-emption is out of scope of this project.

Synchronisation

IEEE 802.1AS [47] and ongoing revisions define a mechanism to ensure the synchronization requirements are met for time-sensitive applications across networks. IEEE 802.1AS is based on IEEE 1588v2 [48], and was originally specified for audio and video like traffic, but it can be applied to provide synchronisation between the XFE in the 5G-Crosshaul network.

In 802.1AS, nodes are referred to as Time-Aware Systems (TAS). Using 802.1AS, two of such TASs are synchronised within a +/- 500 ns accuracy, which may not be sufficient for CPRI traffic but works fine for other functional splits. 802.1AS is plug-and-play, that is, the Grand Master clock is selected automatically. After this, a clock tree reconfigures automatically and bridges in the tree propagate time towards the leaves. The master periodically broadcasts the time reference to the other clocks (up to 10 messages per second are permitted in PTPv2 – Precision Time Protocol [48]).

OAM

To support OAM, the XCF has to allow the distinction of OAM frames and regular data frames. This distinction is possible by setting the UCA bit to one or by using specific MAC addresses for OAM functionality.

8.2 Alternatives and extensions

In this section the MPLS Transport Profile (MPLS-TP) is described as a possible alternative to MAC-in-MAC. Similarly to MAC-in-MAC, the forwarding is based on the control information stored in the XPFEs.

MPLS-TP is based on MPLS, but differs from the latter since the configuration is provided via management commands and not via routing protocols such as the Label Distribution Protocol (LDP). Typically, nodes are connected via either point-to-point pseudo-wires or multipoint-to-multipoint networks, implementing a mesh of pseudo-wires. MPLS-TP has a typical frame structure with an outer label for a label switched path (LSP), and inner label for a pseudo-wire (PW), and an optional PW control word. ITU-T and IETF standards allow the possibility of an unlimited number of indented labels, corresponding to an unlimited LSP hierarchy.

Figure 35 shows an MPLS-TP header, using Ethernet as data link layer technology. As usual in MPLS, each label contains the actual label, a 3-bit traffic class (TC), a 1-bit indication whether the bottom of the label stack has been reached (EOS), and an 8-bit time to live field (TTL).

The label in the LSP label might be used for distinguishing different tenants. The LSP label has 20 bits of length and has a local scope, enabling the identification of 2^{20}=1048576 different tenants. Prioritization of different services can be based on the Traffic Class field (TC bits), while the PW can be used to transport different services, both packet and circuit oriented.

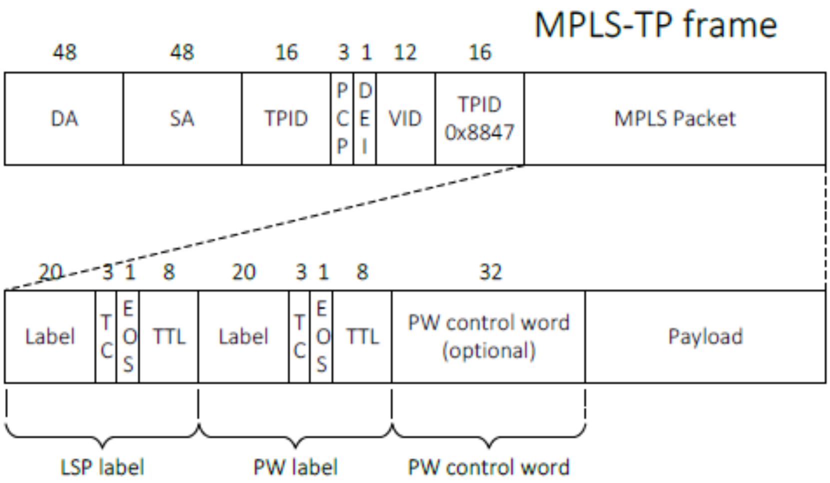


Figure 35: MPLS-TP frame structure

According to IETF RFC 3270, MPLS(-TP) can differentiate traffic based on EXP-Inferred-PSC LSPs (E-LSP) or Label-Only-Inferred-PSC LSPs (L-LSP). In the first case the TC field is used by the XPFE to determine the Per-Hop Behaviour (PHB) to be applied to the packet making possible to have a maximum number of eight PHB scheduling classes, in the other case PHB scheduling class is explicitly assigned at the time of label establishment supporting an unlimited number of scheduling classes.

Different LSPs can be provisioned to transport different flows. Edge nodes or adaptation functions are in charge of classifying the incoming traffic and assigning it to the correct LSP while intermediate nodes need to analyse only the LSP label of the incoming packets and use the forwarding behaviour associated with the E-LSP or L-LSP. As such, multiple tenants can be supported over the same infrastructure without interfering. Indeed, by adding the previous information in the tags, the traffic flows can be easily differentiated from each other.

MPLS-TP satisfies the XCF requirements similarly to MAC-in-MAC. It supports multiple functional splits and multi-tenancy, guaranteeing possibility to separate and differentiate traffic and to define each tenant as described before.

Ethernet can be used as link layer technology, security support is provided by different mechanism e.g. IPsec for payload or 802.1AE MACsec for encrypted links. On Ethernet links, MPLS-TP is compatible with synchronization protocols such as synchronous Ethernet or IEEE 802.1AS. MPLS-TP is equally compatible with security mechanisms such as IEEE 802.1X and IEEE 802.1AE and provides a rich set of OAM functionalities.

Segment routing is another alternative briefly proposed in this paragraph regarding the forwarding mechanism. It actually includes the forwarding information in the header of each frame . Instead of carrying just endpoint addresses in the frames and each XPFE knowing how to reach the endpoint, the path to be taken is contained in the header and XPFEs would just have to know how to reach the next hop. The network is then seen as a set of segments that the packets have to traverse.

Segment routing leverages the source routing paradigm [49], where the source chooses the path and encodes it in the packet header as an ordered list of segment IDs. The intelligence for routing is kept on the source routers only while the rest of the routers are kept as simple as possible. Actually, there is no single router in a network acting as source router for all traffic flows, but many routers will be source routers and each of them has to control the routing of its flows.

The source router intelligence is programmed by an external controller, which fits well with a software-defined networking approach and the XCI design. As one possibility, segment routing leverages MPLS, where each router adds a label or a label stack, pops some label, or swaps a label. The label stack may be incomplete; it is not necessary to list all forwarding nodes on a path. This mechanism leaves flexibility within the network to determine local paths or to provide alternative paths in case of link failures.

9 South Bound Interface

The Southbound Interface, SBI, is the interface that, in software-defined networking (SDN), provides communication and management between network's SDN controller and physical or virtual resources. In this chapter, we report the main south bound protocols for controlling and switch management and propose parameter extensions for the 5G-Crosshaul capable technologies described in Chapter 5.

9.1 SBIs for controlling the forwarding and for switch management

There are two differentiated types of southbound protocols depending on their purpose. The Control protocols primarily control the forwarding/routing, which is the core functionality of the switches and routers in the network. The Management protocols convey information regarding the configuration and administration of the elements. In a complex SDN network both control and management protocols are present. In some cases, there are control protocols that have their partner management protocol but they are still distinct and decoupled, permitting a higher degree of flexibility.

9.1.1 SBIs for controlling the forwarding

In this section, we report the main southbound interfaces intended to control the forwarding tables on the switches.

OpenFlow Protocol

OpenFlow is a communications protocol standardized by Open Networking Foundation (ONF)[5] that gives access to the forwarding plane of a network switch or router over the network. It is the main representative of the *Control* protocols options for the southbound interface and it is supported by the main SDN controllers, such as OpenDaylight (ODL) and ONOS. OpenFlow has influenced the definition of SDN by describing three fundamental paradigms of SDN. The most prominent one is the network architecture with a split user plane and control plane. The second one is a model for rules definition based on packet match and actions. The third one is the OpenFlow protocol itself. The SDN network implements these three paradigms through a central network controller that interacts using OpenFlow with networking devices that implement the match action model.

In addition to network controller/switch communication interface, OpenFlow protocol defines the internal architecture of an OpenFlow-enabled Ethernet packet-based switch. The complete switch architecture is composed of several components, among them the main ones are:

[5] https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow/openflow-switch-v1.5.1.pdf

1. One or more flow tables that contain one or more flow entries
2. Each flow entry consists of:
    a. Matching fields: set of fields in the header used to match ingress packets
    b. Actions: set of available actions applied to matching packets
3. Pipeline: defines how matching packets interact with the flow tables

The number of components, the behaviour of the switch, and the interaction with network controllers may vary depending on the adopted OpenFlow protocol version.

The first OpenFlow specification limited the protocol to a very concrete scope. Ever since, each subsequent specification of OpenFlow added additional features to the protocol. Table 13 summarizes the main features supported by each OpenFlow versions. *Match fields* and *Actions* table's rows show clearly how OpenFlow has been extended over time to support a greater number of headers, fields, and network protocols. For instance, IPv6 support was first introduced in OpenFlow 1.2, while Provider Backbone Bridge (PBB) support was introduced in OpenFlow 1.3.

Table 13: Openflow versions comparison

Parameter	**Description**	**OpenFlow version support**					
		1.0	1.1	1.2	1.3	1.4	1.5
Released	Publication date	Dec 2009	Feb 201 1	Dec 201 1	Jun 201 2	Oct 201 3	Dec 201 4
Multiple controllers	A switch could be controlled by multiple network controllers	-	-	Y	Y	Y	Y
Auxiliary connections	A switch could have multiple active connections towards the same network controller	-	-	-	Y	Y	Y
Multiple Flow tables	OpenFlow pipeline could have more than one flow table	-	Y	Y	Y	Y	Y
Group table	Contains group entries which affect group of flows	-	Y	Y	Y	Y	Y
Meter table	A meter table consists of meter entries which implement simple QoS operations, such as rate-limiting	-	-	-	Y	Y	Y
Configurable Table-miss	Describes how to manage a packet with no matching rules	-	-	-	Y	Y	Y
Flow table synch.	The content is automatically updated by the switch to reflect changes in the flow table it is	-	-	-	-	Y	Y

Parameter	Description	OpenFlow version support					
	synchronized with						
Bundle messages	A bundle is a sequence of modification requests that is applied as a single OpenFlow operation meeting ACID requirements (Haerder & Reuter, 1983)	-	-	-	-	Y	Y
Ingr/Egr pipelines	Flow tables can be used for ingress or egress processing	-	-	-	-	-	Y
Match fields	Packet match fields used for table lookups, e.g. Ethernet source address or IPv4/IPv6 destination address	12	22	35	39	41	44
Actions	Actions executed on the packet, e.g. push/pop-VLAN, decrement TTL	10	22	28	30	30	30
Counters	Counters are maintained per-table, per-flow, per-port and per-queue, e.g. bytes received, rx/tx error, etc.	22	27	27	40	40	40

Forwarding and Control Element Separation Protocol

Forwarding and Control Element Separation (ForCES) defines an architectural framework and associated protocols to standardize information exchange between the control plane and the forwarding plane in a ForCES Network Element (NE). RFC 3654[6] defines the ForCES requirements, RFC 3746[7] defines the ForCES framework, and RFC 5810 specifies the protocol.

The ForCES Forwarding Element (FE) is defined by RFC 5812[8] and is a logical entity that implements the ForCES Protocol and uses the underlying hardware to provide per-packet processing and handling as directed by a Control Element. A Control Element (CE) is a logical entity that implements the ForCES Protocol and uses it to instruct one or more FEs on how to process packets. CEs handle functionality such as the execution of control and signaling protocols.

Logical Function Block (LFB) is the basic building block that is operated on by the ForCES protocol. The LFB is a well-defined, logically separable functional block that resides in an FE and is controlled by the CE via the ForCES protocol. The LFB may

[6] Requirements for Separation of IP Control and Forwarding, https://tools.ietf.org/html/rfc3654
[7] Forwarding and Control Element Separation (ForCES) Framework, https://tools.ietf.org/html/rfc3746
[8] Forwarding and Control Element Separation (ForCES) Forwarding Element Model, https://tools.ietf.org/html/rfc5812

reside at the FE's data path and process packets or may be purely an FE control or configuration entity that is operated on by the CE. Note that the LFB is a functionally accurate abstraction of the FE's processing capabilities, but not a hardware-accurate representation of the FE implementation.

The RFC 3654 defines requirements that must be satisfied by a ForCES FE model. To summarize, an FE model must define:

- Logically separable and distinct packet forwarding operations in an FE data path (Logical Functional Blocks or LFBs);
- The possible topological relationships (and hence the sequence of packet forwarding operations) between the various LFBs;
- The possible operational capabilities (e.g., capacity limits, constraints, optional features, granularity of configuration) of each type of LFB;
- The possible configurable parameters (e.g., components) of each type of LFB; and
- Metadata that may be exchanged between LFBs.

Packets coming into the FE from ingress ports generally flow through one or more LFBs before leaving out of the egress ports. The result of LFB processing may have an impact on how the packet is to be treated in downstream LFBs. This differentiation of packet treatment downstream can be conceptualized as having alternative data paths in the FE. For example, the result of a 6-tuple classification performed by a classifier LFB could control which rate meter is applied to the packet by a rate meter LFB in a later stage in the data path. LFB topology is a directed graph representation of the logical data paths within an FE, with the nodes representing the LFB instances and the directed link depicting the packet flow direction from one LFB to the next.

In addition to FE model, ForCES defines 3 execution modes that can be requested for a batch of operations: execute-all-or-none, continue-execute-on-failure, and execute-until-failure. By use of the *execute-all-or-none* mode, the protocol provides a mechanism for transactional operations within one stand-alone message meeting the ACID requirements [50]. LFB processing, the transaction mechanism, and the different modes of operation are of particular interest for 5G-Crosshaul since they can be used to implement complex operations at switching level. ForCES represents an alternative to OpenFlow but is not supported by current SDN controllers.

9.1.2 SBIs for switch management

In this section, we report the southbound interfaces devoted to the device configuration. The parameters that can be configured through these interfaces are not related to the forwarding itself but rather to the device.

OF-Config Protocol

The OF-Config[9] protocol is a *Management* protocol that addresses the following controller-switch components:

- OpenFlow configuration point: The OF-Config point issues OF-Config commands;
- OpenFlow capable switch: A physical or virtual switching device containing a number of ports and queues;
- OpenFlow logical switch: A logical switch within the OpenFlow capable switch allocates a subset of the ports and queues that make up an OpenFlow capable switch.

The OF-Config protocol enables configuration of essential artefacts of an OpenFlow Logical Switch so that an OpenFlow controller can communicate and control the OpenFlow Logical switch via the OpenFlow protocol. An OpenFlow Capable Switch is intended to be equivalent to an actual physical or virtual network element (e.g. an Ethernet switch) which is hosting one or more OpenFlow data paths by partitioning a set of OpenFlow related resources such as ports and queues among the hosted OpenFlow data paths.

The OF-Config protocol enables dynamic association of the OpenFlow related resources of an OpenFlow Capable Switch with specific OpenFlow Logical Switches which are being hosted on the OpenFlow Capable Switch. OF-Config does not specify or report how the partitioning of resources in an OpenFlow Capable Switch is achieved. OF-Config assumes that resources such as ports and queues are partitioned amongst multiple OpenFlow Logical Switches such that each OpenFlow Logical Switch can assume full control over the resources that is assigned to it.

Open vSwitch Database Management Protocol

The Open vSwitch Database Management (OVSDB) is a *Management* protocol described in IETF RFC 7047[10]. Open vSwitch is an open-source software switch designed to be used as a vSwitch (virtual switch) in virtualized server environments. A vSwitch forwards traffic between different virtual machines (VMs) on the same physical host and also forwards traffic between VMs and the physical network. Open vSwitch is open to programmatic extension and control using OpenFlow and the OVSDB (Open vSwitch Database) management protocol which provides an imperative programmatic access.

The OVSDB management interface is used to perform management and configuration operations on the OVS instance. Compared to OpenFlow, OVSDB management

[9] https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow-config/of-config-1.2.pdf

[10] The Open vSwitch Database Management Protocol, https://tools.ietf.org/html/rfc7047

operations occur on a relatively long timescale. Examples of operations that are supported by OVSDB include:

- Creation, modification, and deletion of OpenFlow datapaths (bridges), of which there may be many in a single OVS instance;
- Configuration of the set of controllers to which an OpenFlow datapath should connect;
- Configuration of the set of managers to which the OVSDB server should connect;
- Creation, modification, and deletion of ports on OpenFlow datapaths;
- Creation, modification, and deletion of tunnel interfaces on OpenFlow datapaths;
- Creation, modification, and deletion of queues;
- Configuration of QoS (quality of service) policies and attachment of those policies to queues; and
- Collection of statistics.

Thus, OVSDB is a complementary protocol to OpenFlow focusing on the configuration data which is stored in the database of the switch instead of the flow information in the forwarding tables of the vSwitch which is configured by OpenFlow.

Simple Network Management Protocol

Simple Network Management Protocol (SNMP) is an "Internet-standard protocol for managing devices on IP networks" and is described in RFC 1157[11] (Case, Fedor, Schoffstall, & Davin, 1990). SNMP exposes management data in the form of variables on the managed systems, which describe the system configuration. These variables can then be queried and set by managing applications. SNMP itself does not define which information (which variables) a managed system should offer. Rather, SNMP uses an extensible design, where the available information is defined by management information bases (MIBs). MIBs describe the structure of the management data of a device subsystem; they use a hierarchical namespace containing object identifiers (OID). Each OID identifies a variable that can be read or set via SNMP.

The MIB hierarchy can be depicted as a tree with a nameless root, the levels of which are assigned by different organizations. The top-level MIB OIDs belong to different standards organizations, while lower-level object IDs are allocated by associated organizations. A managed object is one of any number of specific characteristics of a managed device. Managed objects are made up of one or more object instances (identified by their OIDs), which are essentially variables. Two types of managed objects exist:

- Scalar objects define a single object instance.

[11] A Simple Network Management Protocol (SNMP), https://www.ietf.org/rfc/rfc1157.txt

- Tabular objects define multiple related object instances that are grouped in MIB tables.

There are several versions of SNMP. SNMP v1 is the initial implementation with the most fundamental operations, including Get, GetNext, Set, and Trap. SNMP v2 is a direct update to SNMP v1. New protocols, such as GetBulk and Inform, are added to handle large amounts of data. SNMP v2c, as a sub-protocol of SNMP v2, can be seen as lighter version of SNMP v2. SNMP v3 adds security and remote configuration capabilities to the previous versions.

SNMP is still the most widely used protocol for network equipment fault management (FM) and also widely used for performance management (PM) and configuration management (CM). SNMP has demonstrated some advantages over time but it is also showing limitations. Particularly for PM and CM it may not provide the same level of flexibility and capabilities as more modern protocols like NETCONF.

Network Configuration Protocol

The Network Configuration Protocol (NETCONF) is a network management protocol developed and standardized by the IETF. It was developed in the NETCONF working group and published in December 2006 as RFC 4741[12] and later revised in RFC 6241[13] and RFC 7803[14].

NETCONF provides mechanisms to install, manipulate, and delete the configuration of network devices. Its operations are realized on top of a simple remote procedure call (RPC) layer. The NETCONF protocol can be conceptually partitioned into four layers:

- The Content layer consists of configuration data and notification data.
- The Operations layer defines a set of base protocol operations to retrieve and edit the configuration data.
- The Messages layer provides a mechanism for encoding remote procedure calls (RPCs) and notifications.
- The Secure Transport layer provides a secure and reliable transport of messages between a client and a server.

One particular strength of NETCONF is its support for robust configuration change transactions involving a number of devices. NETCONF has support for a significant part of the networking equipment manufacturers as a substitute of SNMP for Configuration Management (CM) and also for Performance Management (PM). One of the main advantages of using NETCONF is its support for transactions and, combined with YANG[15], its generic applicability. Understanding SDN as a broader concept than

[12] NETCONF Configuration Protocol, https://tools.ietf.org/html/rfc4741
[13] Network Configuration Protocol (NETCONF), https://tools.ietf.org/html/rfc6241
[14] Changing the Registration Policy for the NETCONF Capability URNs Registry, https://tools.ietf.org/html/rfc7803
[15] YANG - A Data Modeling Language for the Network Configuration Protocol (NETCONF)

just user plane and control plane separation, NETCONF is very relevant when considering the generic programmability and ability of forwarding devices to be remotely configured and managed.

9.1.3 SBIs for interacting with legacy systems

In this section, we report the southbound interfaces devoted to the interaction with legacy systems covering both device and forwarding management.

Border Gateway Protocol

Border Gateway Protocol (BGP) is a standardized exterior gateway protocol[16] designed to exchange routing and reachability information between autonomous systems (AS) on the Internet. The BGP makes routing decisions based on paths, network policies, or rule-sets configured by a network administrator and is involved in making core routing decisions.

Currently, some vendors[17] are claiming that the southbound protocol is less important than the operational agility and programmability that SDN architecture aims to offer. These vendors have identified BGP as a potential SDN protocol that can enable network programmability. The controller uses BGP as a *Control* plane protocol and leverages NETCONF as a *Management* plane protocol to interact with physical routers, switches and networking services like firewalls. This approach enables SDN to exist in a multi-vendor environment without requiring infrastructure upgrades.

The controller operates on multiple levels of abstraction, from routing and bridging topologies to flow based. BGP does not include program flows, but operates at a higher level of state like physical and virtual topologies (L2 and L3), security policies, etc. BGP for SDN can offer capital expense savings by allowing network operators to seamlessly integrate existing networks and deployed infrastructure components. Also, the reuse of existing protocols prevents the need for lower-performance software gateways to bridge the physical and virtual worlds. Reducing network complexity and integrating SDN systems with their existing business logic and processes built around years of experience with BGP.

Extensible Messaging and Presence Protocol

Extensible Messaging and Presence Protocol (XMPP) is a communications protocol for message-oriented middleware based on XML (Extensible Mark-up Language) and defined in RFC 6120. It enables the near-real-time exchange of structured yet extensible data between any two or more network entities (like SDN controller and switches/routers). XMPP provides a general framework for messaging across a network

https://tools.ietf.org/html/rfc6020
[16] A Border Gateway Protocol 4 (BGP-4), https://www.ietf.org/rfc/rfc4271.txt
[17] http://searchsdn.techtarget.com/feature/Border-Gateway-Protocol-as-a-hybrid-SDN-protocol

and was originally developed for instant messaging and online presence detection. Not surprisingly, this has a multitude of applications beyond traditional Instant Messaging (IM) and the distribution of Presence data. Indeed, XMPP is emerging as an alternative software-defined networking (SDN) protocol.

XMPP can be used by the controller to distribute both control plane and management plane information to the server endpoints, and to manage information at all levels of abstraction down to the flow. Traditional protocols are considered necessary for interoperability with legacy networks and systems. Integrating existing protocols that have matured through industry-wide cooperation and standardization can help speed the transition to SDN systems.

CoAP

The Constrained Application Protocol (CoAP) is defined in RFC 7252[18] and is an application protocol that can be used to provide RESTful APIs in devices with battery, processing, memory and other types of constraints like those in M2M networks. CoAP is a possible *control* or *management* protocol. CoAP provides a request/response interaction model between application endpoints, supports built-in discovery of services and resources, and includes key concepts of the Web such as URIs and Internet media types. CoAP is designed to easily interface with HTTP for integration with the Web while meeting specialized requirements such as multicast support, very low overhead, and simplicity for constrained environments. CoAP uses UDP as transport although it adds optional reliability features when required. Since 5G-Crosshaul is not directly addressing IoT and M2M scenarios CoAP does not seem a relevant candidate for the SBI.

PCEP

The Path Computation Element Protocol (PCEP) is defined in RFC 5440[19] to fulfil the needs of path computation in large MPLS or GMPLS networks. The PCEP protocol has been kept generic enough to apply to other path computation problems not exclusive to MPLS. PCEP supports communication between two Path Computation Elements (PCE) and between a Path Computation Client (PCC) and a PCE. PCEP is transported over TCP, optionally through an IPSec tunnel to provide additional security layer. PCEP defines a request/reply message scheme with variable objects carrying the requirements for path computation in the request and the path computation results in the reply.

PCEP has recently received great attention as a protocol to be used for the SBI applied to MPLS and GMPLS networks thanks to the definition of new extensions proposed to support stateful path computation and Label Switched Paths (LSP) instantiation. The first extensions allow the PCE to maintain a database of all active LSPs that can be used

[18] The Constrained Application Protocol (CoAP), https://tools.ietf.org/html/rfc7252
[19] Path Computation Element (PCE) Communication Protocol (PCEP), https://tools.ietf.org/html/rfc5440

as input for new path computation, while by means of the latter the PCE can directly control LSP instantiation and modification (rerouting, bandwidth changes, etc.). Despite the fact that the standardization process is still on-going, a large number of implementations are already available. OpenDaylight supports PCEP for the southbound protocol towards networking elements. In 5G-Crosshaul architectures the northbound interface may offer path computation capabilities; which makes PCEP as a possible candidate for the northbound protocol.

ALTO

The Application Layer Traffic Optimization (ALTO) protocol is described in IETF RFC 7285 (Alimi, et al., 2014). ALTO defines a protocol to share network information to applications. The network information exposed can be network locations, costs and properties that permit the applications to choose the connectivity achieving an optimized used of resources and avoiding bottleneck creation. ALTO uses a RESTful protocol over HTTP. The main SDN controllers support ALTO in the southbound but its capabilities are most relevant in the northbound interface from a 5G-Crosshaul perspective.

CAPWAP

The Control and Provisioning of Wireless Access Point (CAPWAP) is a protocol defined by IETF in RFC 5415[20]. CAPWAP uses UDP and DTLS and defines its own transport layer messages. CAPWAP has been designed with independence of the radio layer of the access points but its current applicability is in WLAN networks where a controller manages the configuration of several access points using CAPWAP. The main SDN controllers support CAPWAP in the SBI but from the 5G-Crosshaul perspective it does not fulfil the requirements to be included as a southbound protocol.

PCMM/COPS

COPS is a standard protocol defined by IETF in RFC 4261[21], 2748 and used as part of the CableLabs PacketCable 2.0 multimedia architecture (PCMM). COPS is used in the pkt-mm-2 interface between the policy server and the CMTS for transferring policy and gating information. It is only relevant in cable networks. The main SDN controllers support PCMM/COPS in the southbound but it is not relevant for the 5G-Crosshaul scenarios and architecture.

[20] Control And Provisioning of Wireless Access Points (CAPWAP) Protocol Specification https://tools.ietf.org/html/rfc5415
[21] Common Open Policy Service (COPS) Over Transport Layer Security (TLS) https://tools.ietf.org/html/rfc4261

SXP

The Source Group Tag eXchange Protocol (SXP) [22] is described in an IETF informational draft. SXP is transported over TCP between two hosts that are source-group tag-aware. SXP is a protocol from Cisco to deliver bindings between IP Addresses and tags. Tags are used for network policies selection at networking devices. The bindings between IP Addresses and tags are assigned dynamically and permit the application of policies to groups of equipment accessing the network (source groups).

9.1.4 Modelling methodology

In the last years, there have been several initiatives to abstract the forwarding behaviour, abstract the node concept and model them in such a way that it enables programmability of the network. In 5G-Crosshaul we are currently focused on the analysis of the two main abstractions most noted in the literature: the IETF approach to SDN, ForCES; and the standard SDN approach pushed by the Open Network Foundation, OpenFlow.

Node Abstraction

This section is devoted to the analysis of the node abstraction used by IETF Forwarding and Control Element Separation (ForCES) and OpenFlow.

The *ForCES* model includes capability and state abstraction, the Forwarding Element (FE) and Logic Functional Block (LFB) model construction, and the unique addressing of the different model structures. The FE/LFB capability model describes the capabilities and capacities of an FE/LFB by specifying the variation in functions supported and any limitations. The state model describes the current state of the FE/LFB, that is, the instantaneous values or operational behaviour of the FE/ LFB. The ForCES model includes the constructions for defining the class of LFBs that an FE may support. The definition of such a class provides the information content for monitoring and controlling instances of the LFB class for ForCES purposes. Each LFB model class formally defines the operational LFB components, LFB capabilities, and LFB events. The FE model also provides the construction necessary to monitor and control the FE as a whole. For consistency of operation and simplicity, this information is represented as an LFB. The FE Object LFB class defines the required components to provide coarse-grain information at the FE level, i.e., not all possible capabilities or all details about the capabilities of the FE.

Part of the FE-level information is the LFB topology, which expresses the logical inter-connection between the LFB instances along the data path(s) within the FE. The FE Object also includes information about what LFB classes the FE can support. The ForCES model allows for unique identification of the different constructs it defines. This includes identification of the LFB classes, and of LFB instances within those

[22] http://tools.ietf.org/html/draft-smith-kandula-sxp-03

classes, as well as identification of components within those instances. Conceptually, the FE capability model tells the Control Element (CE) which states are allowed on an FE, with capacity information indicating certain quantitative limits or constraints. Thus, the CE has general knowledge about configurations that are applicable to a particular FE.

The FE capability model may be used to describe an FE at a coarse level. For example, an FE might be defined as follows:

- FE can handle IPv4 and IPv6 forwarding;
- FE can perform classification based on the following fields: source IP address, destination IP address, source port number, destination port number, etc.;
- FE can perform metering;
- FE can handle up to *N* queues (capacity); and the FE can add and remove encapsulating headers of types including IPsec, GRE, and L2TP.

While one could try to build an object model to fully represent the FE capabilities, other efforts found this approach to be a significant undertaking. The main difficulty arises in describing detailed limits, such as the maximum number of classifiers, queues, buffer pools, and meters that the FE can provide. A good balance between simplicity and flexibility can be achieved for the FE model by combining coarse-level-capability reporting with an error reporting mechanism. That is, if the CE attempts to instruct the FE to set up some specific behaviour it cannot support, the FE will return an error indicating the problem. Examples of similar approaches include Diffserv PIB RFC 3317[23] and framework PIB RFC 3318[24]. The FE state model presents the snapshot view of the FE to the CE. Both LFB capability and state information are defined formally using the LFB modelling XML schema. Capability information at the LFB level is an integral part of the LFB model and provides for powerful semantics. For example, when certain features of an LFB class are optional, the CE needs to be able to determine if those optional features are supported by a given LFB instance. The schema for the definition of LFB classes provides a means for identifying such components.

OpenFlow uses a completely different approach for node abstraction. An OpenFlow Logical Switch consists of one or more *flow tables* and a *group table*, which perform packet lookups and forwarding, and one or more *OpenFlow channels* to an external controller. The switch communicates with the controller and the controller manages the switch via the OpenFlow switch protocol. Using the OpenFlow switch protocol, the controller can add, update, and delete *flow entries* in flow tables, both reactively (in response to packets) and proactively. Each flow table in the switch contains a set of flow entries; each flow entry consists of *match fields*, *counters*, and a set of *instructions* to apply to matching packets. Flow entries may forward to a *port*. This is usually a

[23] Differentiated Services Quality of Service Policy Information Base, https://tools.ietf.org/html/rfc3317
[24] Framework Policy Information Base, https://tools.ietf.org/html/rfc3318

physical port, but it may also be a logical port defined by the switch or a reserved port defined by this specification. Reserved ports may specify generic forwarding actions such as sending to the controller, flooding, or forwarding using non-OpenFlow methods, such as "normal" switch processing, while switch-defined logical ports may specify link aggregation groups, tunnels or loopback interfaces.

OpenFlow ports are the network interfaces for passing packets between OpenFlow processing and the rest of the network. OpenFlow switches connect logically to each other via their OpenFlow ports, and a packet can be forwarded from one OpenFlow switch to another OpenFlow switch only via an output OpenFlow port on the first switch and an ingress OpenFlow port on the second switch. Hence, the abstraction of a switch promoted by OpenFlow relies on the concept of port. In fact this is one of the main limitations of OpenFlow since for each new technology that is added to OpenFlow, the definition of a new type of port is needed. Currently only Ethernet and Optical ports are defined. It is important to note that this abstraction also has a strong limitation when used for technologies that do not follow the traditional concept of IEEE 802.1 port such as IEEE 802.11. This technology connects a complete IEEE 802.11 network, which may contain multiple access points and stations in any possible configuration, through a portal or integration service which is seen as a single port by switches. This means that the complexity of the topology within the IEEE 802.11 network is completely hidden from OpenFlow, reducing the set of possible actions that can be applied to nodes within the IEEE 802.11 network.

Forwarding Abstraction

ForCES aims to define a framework and associated protocols to standardize information exchange between the control and forwarding plane. Network elements usually expose their functionality to external entities as a single and monolithic instance with a set of defined inputs and expected outputs. In reality, this is not the case and each network element can be dissected in numerous logically separated entities or functionalities that cooperate to provide a given functionality. In the ForCES concept, network elements can be divided in two broad sets of components: *i*) control elements (CEs) in control plane and *ii*) forwarding elements (FE) in forwarding plane (or data plane). By defining the communication mechanisms between CEs and FEs, ForCES enables them to be physically separated. This physical separation accrues several benefits to the ForCES architecture. Separate components would allow component vendors to specialize in one component without having to become experts in all components. Standard protocol also allows the CEs and FEs from different component vendors to interoperate with each other and hence it becomes possible for system vendors to integrate together the CEs and FEs from different component suppliers. This interoperability translates into increased design choices and flexibility for the system vendors. Overall, ForCES will enable rapid innovation in both the control and forwarding planes while maintaining interoperability. Scalability is also easily provided by this architecture in that additional forwarding or control capacity can be added to existing network elements without the need for forklift upgrades.

The FE model proposed in ForCES is based on an abstraction using distinct Logical Functional Blocks (LFBs) that are interconnected in a directed graph, and receive, process, modify, and transmit packets along with metadata. The FE and LFB models are designed so that different implementations of the forwarding data path can be logically mapped onto the model with the functionality and sequence of operations correctly captured. The LFB topology model for a particular data path implementation must correctly capture the sequence of operations on the packet. The FE model is designed to model the logical processing functions of an FE. The FE model proposed in ForCES includes three components; the LFB modelling of individual Logical Functional Block (LFB model), the logical interconnection between LFBs (LFB topology), and the FE-level attributes, including FE capabilities. The most important block of the ForCES forwarding model is the LFB Class (or type). The LFB is a template that represents a fine-grained, logically separable aspect of FE processing. Most LFBs relate to packet processing in the data path. LFB classes are the basic building blocks of the FE model, which basically interconnects them to obtain a complex behaviour. An example of a complex behaviour built out of the coordination of LFBs is presented in Figure 36. The complex behaviour shown in Figure 36 is built by graphically interconnecting the different LFBs supported by the NE. This forwarding abstraction used to build complex functionalities requires that the CE is aware of the limitations and capabilities of each NE, since each NE needs to tell the CE which LFBs can be implemented on its hardware. In addition, with all the information of the different LFBs per NE and their desired interconnection, the CE needs to decide which LFBs are implemented on each NE and how to connect everything together so the desired forwarding behaviour is created. This complex procedure may lead to the need of new algorithmic approaches.

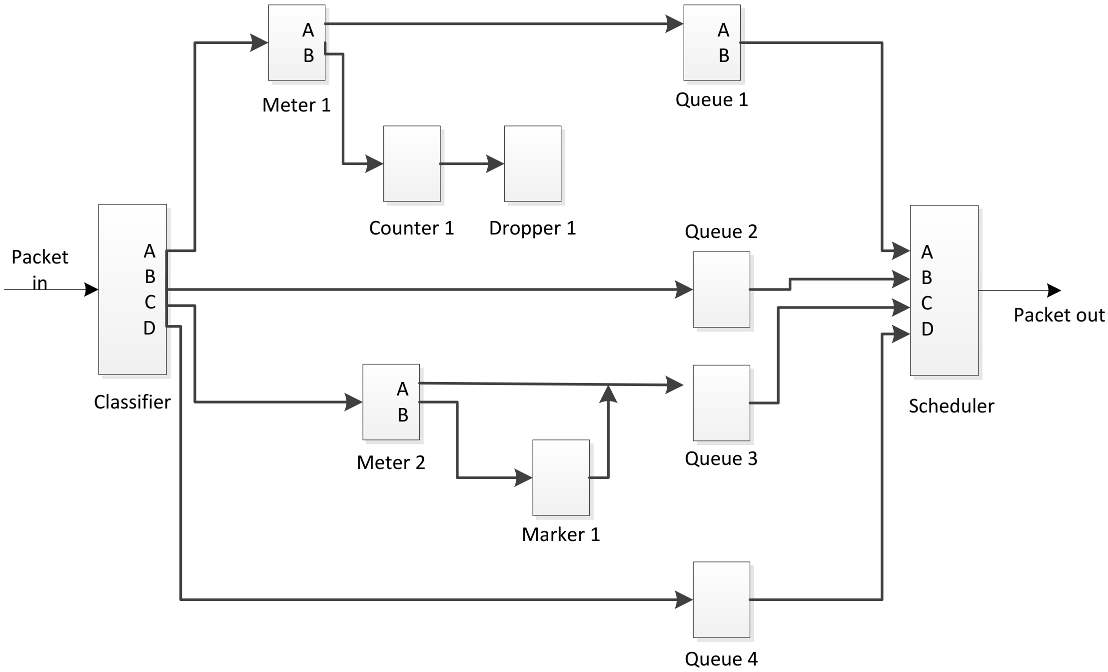


Figure 36: Complex behavior build on multple LFBs

OpenFlow defines two kinds of switches: *i*) OpenFlow-only which can only process packets following the OpenFlow pipeline and *ii*) OpenFlow-hybrid which support OpenFlow and normal switch operation in parallel. These switches should provide an external (not OF based) classification mechanism that routes traffic to either the OpenFlow pipeline or the normal pipeline. For example, a switch may use the VLAN tag or input port of the packet to decide whether to process the packet using one pipeline or the other, or it may direct all packets to the OpenFlow pipeline. The OpenFlow pipeline, shown in Figure 37, is composed of a set of ingress and egress Flow Tables, each of them consisting of multiple flow entries. An OpenFlow switch must include at least one ingress Flow Table. How a packet travels through the OpenFlow pipeline and the set of actions applied to it while traversing them defines the packet operation of the OpenFlow switch and the different forwarding behaviours applied to the different flows.

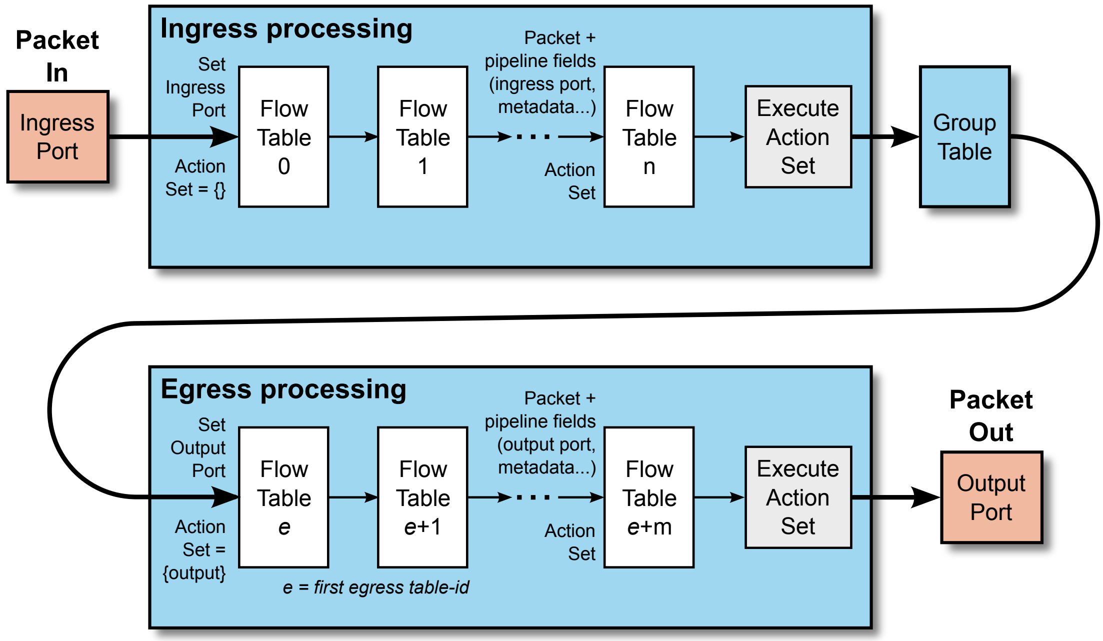


Figure 37: OpenFlow Pipeline processing (Open Networking Foundation, 2015)

The flow tables of an OpenFlow switch are sequentially numbered, starting at 0. Pipeline processing happens in two stages, *ingress processing* and *egress processing*. The separation of the two stages is indicated by the first egress table. Pipeline processing always starts with ingress processing at the first flow table: the packet must be first matched against flow entries of flow table 0. Based on the matching result the packet may be forwarded to an output port or to a different ingress Flow Table. In case the packet is forwarded to an output port, it may be processed by the first egress Flow Table assigned to the output port. The use of multiple ingress and egress Flow Tables allows to implement complex behaviours in a simpler way than having just one single Flow Table. Each Flow Table is a collection of flow entries and each flow entry contains the following elements:

- Match fields: used to match against packet headers and optionally metadata provided by a previous Flow Table processing result;
- Priority: matching precedence of the flow entry;
- Counters: updated when packets are matched;
- Instructions: to modify the action set or pipeline processing;
- Timeouts: maximum lifetime of the flow entry.

A flow table entry is identified by its match fields and priority: the match fields and priority taken together identify a unique flow entry in a specific flow table. A flow entry instruction may contain actions to be performed on the packet at some point of the pipeline.

This section has presented the two most relevant forwarding abstractions currently present in the literature, IETF ForCES and OpenFlow processing pipeline. Both alternatives implement the concept of Software Defined Networking by separating the control and data paths, although each of them does it in a different way. Regarding ForCES, it seems that their approach is quite powerful and flexible, since each LFB can be allocated/implemented in a variety of hardware and then interconnected as suits the complex functionality desired. The problem of this approach is two-fold. On the one hand, the interconnection graph used to build the complex network functionality by interconnecting LFBs requires new software tools able to transform the graph-based representation to real commands that can be applied to the NEs. On the other hand, the ForCES approach is so flexible that it does not mandate or standardize any mechanisms for implementing the LFBs/NEs in real hardware. This is a clear limitation since right now there is no hardware implementing ForCES. In contrast, the limitations of the OpenFlow forwarding abstraction do not come of the lack of hardware, whose availability is increasing every day, but it comes from speed limitations on the match and pipeline processing. In order to perform the matching in the OpenFlow Flow Tables, it is required to process the complete header of the packet. For fronthaul traffic with strict delay requirements, the standard OpenFlow pipeline processing may be too slow. In 5G-Crosshaul we are studying modifications to this pipeline processing in order to increase the packet processing speed, for example by just reading a very low quantity of bits of the header and perform the switching decision based on partial information.

Measurements, Reporting, Event Triggering

The XCI needs to collect, from the data plane, any information or measurement required by the applications. The XCI also needs to adapt its internal procedure to the current data plane status in order not to disrupt the services provided to the upper layers. 5G-Crosshaul scenario has a strong asynchronous connotation, where multiple uncorrelated and independent events can occur in the network at any time. Link disruption, switch congestion, and XFE failure are examples of events that cannot be predicted in advance and, thus, must be managed in a timely manner by XCI. Therefore, XCI and XFEs should employ a communication paradigm able to guarantee such timeliness.

An event-driven architecture is a software architecture pattern promoting the production, detection, consumption of, and reaction to events. An event can be defined as *a significant change in state* in the system. From a formal perspective, what is produced, published, propagated, detected or consumed is typically an asynchronous message called the event notification, and not the event itself, which is the state change that triggered the message emission. An event-driven system typically consists of event emitters, event consumers, and event channels. Usually, XFEs play the role of emitters and have the responsibility to detect, gather, and transfer events. XCI plays the role of consumer and has the responsibility of applying a reaction when an event is presented.

SBI is the event channel where the events are transmitted on from XFE to XCI and vice versa. Building applications and systems around an event-driven architecture allows these applications and systems to be constructed in a manner that facilitates responsiveness, because event-driven systems are, by design, suited to unpredictable and asynchronous environments. Indeed, an event-driven architecture is loosely coupled and well distributed. The resilient distribution of this architecture exists because an event can be almost anything and exist almost anywhere. The architecture is loosely coupled because the event itself does not know about its consequences. E.g., an XFE communicating a link failure does not know what decision the XCI will take. However, event-architectures are tightly coupled, via event subscriptions and patterns, to the semantics of the underlying event schema and values, which is the semantic defined by the SBI.

Table 14 and Table 15, and Table 16 report the information, measurements, and events required by the applications residing on top of XCI. Such information is gathered from the data plane by the XCI that forwards it to the applications according to the event-driven paradigm.

Table 14: SBI reporting parameters

Type	Details

Abstraction of underlying topology (virtual or physical):	• List of nodes
	  ○ Type of node (XFE, XPU, legacy switch, etc.)
	  ○ List of ports (active, inactive, busy, free).
	  ○ Computing capacity [op/s]
	  ○ Memory capacity [bytes]
	  ○ Available VLAN tags
	  ○ Physical location [GPS coordinates]
	• List of links
	  ○ Type of link (microwave, optical, etc.).
	  ○ Configurable parameters, e.g. if wireless:
	- Set of channels and widths
	- Set of transmission powers
	- Set of modulations and coding schema
	  ○ Endpoint nodes and ports [node Id/port Id]
	  ○ Link capacity [Mbit/s]
	  ○ Length [m]

Type	Details
Energy-related capabilities	• Type of harvesting and energy storage • Set of power states and node/link abstraction for each state
RAN configuration	• RAN functional split • BBU/XPU associated to each RRH • Set of RAN functions that can be offloaded into BBUs and XPUs
Routing	• Optimum path between any two nodes for a set of criteria (e.g. minimum number of hops, minimum delay, maximum capacity, etc.)

Table 15: SBI measurement parameters

Type	Details
Link performance monitoring	• Estimation on distribution of links' throughput load (e.g. max, min, mean, variance) • Estimation on distribution of links' delay (e.g. max, min, mean, variance) • Estimation on distribution of packet loss rate • Monitoring of the above distribution per flow type
XPU performance monitoring	• Estimation on distribution of nodes' computational load (e.g. max, min, mean, variance) • Estimation on distribution of memory usage
Energy measurements	• Amount of harvested energy • Power state of nodes
RAN measurements	• Distribution of interference levels • Distribution of RAN user load [Mbit/s]

Table 16: SBI event triggering parameters

Type	Details

Type	Details
Link performance events	• Sudden change in distribution of links' throughput loads • Sudden change in distribution of links' delay • Sudden change in distribution of packet loss rate
XPU performance events	• Sudden change in distribution of computational load (e.g. max, min, mean, variance) • Sudden change in distribution of memory usage
(Virtual/physical) Link state	• Link failure and type • Link up • Link down
(Virtual/physical) Node state	• Node failure and type • Node up • Node down

9.1.5 OpenFlow and MAC-in-MAC XCF baseline compliance

Section 9.1.1 considered several Southbound Interface candidates for controlling the forwarding, switch management, and interaction with legacy systems. This section focuses on OpenFlow that is considered as the main candidate for 5G-Crosshaul. We described the OpenFlow node and forwarding modelling for XPFE architecture. The following sections analyse how OpenFlow 1.5.1 specifications (the latest available OpenFlow specification at the time of writing) can fulfil the XPFE, AF, and XCF design requirements (reported in Section 8.1) for the MAC-in-MAC baseline.

OpenFlow and Adaptation Function compliance

The Adaptation function is in charge of en/decapsulating the customer fronthaul/backhaul traffic as shown in Figure 32. OpenFlow supports MAC-in-MAC since version 1.3 by defining the `PUSH_PBB` and `POP_PBB` actions for encapsulation and decapsulation.

The `PUSH_PBB` header action logically pushes a new PBB service instance header onto the packet (I-TAG TCI), and copies the original Ethernet addresses of the packet into the customer addresses (C-DA and C-SA) of the tag. The PBB service instance header should be the outermost tag inserted, immediately after the Ethernet header and before other tags. The customer addresses of the I-TAG are in the location of the original Ethernet addresses of the encapsulated packet. Therefore, this action can be seen as adding both the backbone MAC-in-MAC header and the I-SID field to the front of the packet. The Push PBB header action does not add a backbone VLAN header (B-TAG) to the packet, it can be added via the `PUSH_VLAN` header action after the `PUSH_PBB` header operation. After this operation, regular `set-field` actions can be used to modify the outer Ethernet addresses (B-DA and B-SA).

A `POP_PBB` header action logically pops the outer-most PBB service instance header from the packet (I-TAG TCI) and copies the customer addresses (C-DA and C-SA) in the Ethernet addresses of the packet. This action can be seen as removing the backbone MAC-in-MAC header and the I-SID field from the front of the packet. The `POP_PBB` header action does not remove the backbone VLAN header (B-TAG) from the packet; it should be removed prior to this operation via the `POP_VLAN` header action.

In case the inner header has to be evaluated after popping the outer header, the frame has to be resubmitted to the beginning of the pipeline for further processing. It is not possible to match at the same time against the addresses and VLAN information in the outer and inner header. In case the further handling of the frame, e.g. forwarding via a specific port, can be decided based on the I-SID, such resubmission to the pipeline is not needed.

The F-Tag is considered optional within 5G-Crosshaul as described in Section 8.1.2. The OpenFlow 1.5.1 specification does not support the F-Tag in `PUSH_VLAN` and `POP_VLAN` actions. Therefore, in case of optionally employing the F-Tag within 5G-Crosshaul, OpenFlow extensions need to be defined. Despite the F-Tag, OpenFlow supports since the version 1.3 all the required functions envisioned for the Adaptation Function in case of having MAC-in-MAC as XCF baseline. Clearly, the XCI is in charge of defining the matching rules against the incoming customer frames and to define which values to assign to each of the PBB fields (e.g., B-DA, B-SA, B-VID, and I-SID).

OpenFlow and XPFE compliance

XPFEs forward the XCF traffic based on the information contained in the MAC-in-MAC header according to the OpenFlow forwarding model. The first operation performed by an XFE for XCF forwarding is to match the incoming packets against the flow entries of the flow tables. Table 17 reports the MAC-in-MAC header fields that can be matched by using different OpenFlow versions.

Table 17: OpenFlow support for MAC-in-MAC fields: match and set-fields

Field	OF version	Comment
Backbone Destination Address	OF-1.0	Same as Ethernet Destination Address

Field	OF version	Comment
Backbone Source Address	OF-1.0	Same as Ethernet Source Address
Backbone VID: TPID	OF-1.1	Same as S-TAG Ethertype: 0x88a8
Backbone VID: PCP	OF-1.1	Same as S-TAG PCP
Backbone VID: DEI	N/A	Not supported
Backbone VID: VID	OF-1.1	Same as S-TAG VID
Instance SID: TPID	OF-1.3	Ethertype: 0x88E7
Instance SID: PCP	OF-1.3	
Instance SID: DEI	N/A	Not supported
Instance SID: UCA	OF-1.4	
Instance SID: I-SID	OF-1.3	
Optional: F-TAG: TPID	N/A	Not supported
Optional: F-TAG: PCP	N/A	Not supported
Optional: F-TAG: DEI	N/A	Not supported
Optional: F-TAG: TTL	N/A	Not supported
Optional: F-TAG: Hash	N/A	Not supported

As it can be noticed, even the latest OpenFlow version (1.5.1 at the time of writing) does not support the matching and the configuration of the DEI field. Such field may be used separately or in conjunction with PCP to indicate frames eligible to be dropped in the presence of congestion. Therefore, OpenFlow needs to be extended to support matching and configuration of DEI field. Additionally, the F-TAG is not supported by the current version of OpenFlow. Since the adoption of the F-TAG is optional within 5G-Crosshaul, OpenFlow extensions are needed.

As described in the previous section, a flow entry is composed of a match and an action set. The action set of the incoming matched XCF packets will contain the output instruction, or the *DROP* action alternatively, including the port and queue the XCF frame should be forwarded to. XCF frames are directed to one of the queues based on the packet output port and the packet queue id, set using the *output* action and *set-queue* action respectively. According to the OpenFlow 1.5.1 specification, an OpenFlow switch may support only queues that are tied to specific PCP bits. As mentioned in

Section 8.1.2, XPFEs should provide eight queues per port, one per each traffic class, to prevent head of line blocking by low-priority traffic. A specific PCP value is associated to each queue as reported in Table 12.

In general, an OpenFlow switch provides limited QoS support. A switch can optionally have more than one queue attached to a specific output port, and those queues can be used to schedule packet transmission. Packets mapped to a specific queue will be treated according to that queue's configuration. Queue processing happens logically after all OpenFlow pipeline processing. Packet scheduling using queues is not defined by the OpenFlow specification and it is switch-dependent; in particular, no priority between queue IDs is assumed. Hence, queue configuration takes place outside the OpenFlow switch protocol, either through a command line tool or through an external dedicated configuration protocol. This topic will be further investigated in the 5G-Crosshaul project.

9.2 SBI Technology specific parameters and extensions

The SBI is able to collect and demand information about network topology, node and link capabilities (nominal and available bandwidth, latency, availability, etc.) so that upper layers in the SDN architecture can use this information to calculate appropriate paths taking into account the different technology performance in the XFEs.

For this purpose, we adopt a novel approach where a set of parameters is defined to model network nodes and transmission technologies, in order to enable the proper operation of applications, such as optimization of resource allocation and energy, to run over the whole network infrastructure. The right choice of the parameters is crucial in so far a too small set could inhibit some applications while a too wide set, exposing unnecessary technology details, could negatively affect solution cost and scalability.

For each transmission technology identified as suitable for the 5G-Crosshaul data plane, a list of parameters that can be notified to the control plane for configuration, monitoring or during the inventory phase will be provided in the form of a corresponding table. On this basis, the relevant list of parameters to include in the SBI both at transmission level and node model level will be defined. Configuration parameters are those parameters that can be set by the SBI; the transmitter power being a typical example. The monitoring-parameters are the parameters that can or need to be tracked and whose value is communicated through SBI to the SDN controller; the BER being a typical example. Inventory parameters are descriptive parameters which cannot be modified but contains useful information that can be put at disposal for optimization algorithm; e.g. wavelength values of optical transmitters in a DWDM system.

Once the parameters have been defined, they need to be mapped in the protocol stacks used in 5G-Crosshaul, e.g. Open Flow. This is the second step of the SBI modelling methodology and is aimed at identifying the extensions that are required to the protocols for enabling the proper operation of the applications running on top of the infrastructure.

9.2.1 Millimeter wave packetized fronthaul and backhaul

IEEE 802.11ad [44] defines standardized modifications to both the IEEE 802.11 physical layers (PHYs) and the IEEE 802.11 medium access control layer (MAC) to enable operation in frequencies around 60 GHz and capable of very high throughput.

IEEE 802.11 organizes the medium access through periodically recurring Beacon Intervals (BIs) that are initiated by a single beacon frame transmitted omnidirectionally by the Access Point (AP) or coordinating station. The beacon announces the existence of a wireless network and carries further management data. The rest of the BI is used for data transmissions between stations, usually following a contention-based access scheme. The IEEE 802.11ad extends this concept as shown in Figure 38. First, a BI is initiated with the Beacon Header Interval (BHI), which replaces the single beacon frame of legacy Wi-Fi networks. The BHI facilitates the exchange of management information and network announcements using a sweep of multiple directionally transmitted frames. The BHI is followed by a Data Transmission Interval (DTI), which can implement different types of medium access. The central network coordinator announces the schedule and medium access parameters, which are necessary for stations to participate in a BI, the Personal Basic Service Set (PBSS) Control Point (PCP) or AP, during the BHI.

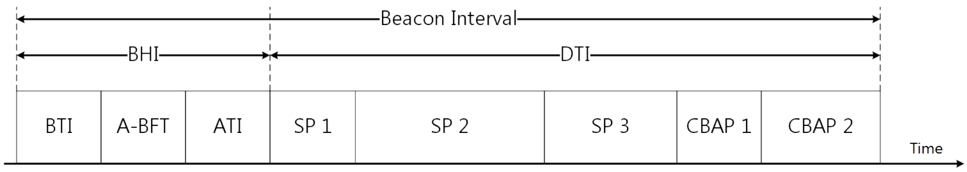


Figure 38: IEEE 802.11ad super-frame

The BHI consists of up to three sub-intervals. First, the beacon transmission interval (BTI) comprises multiple beacon frames, each transmitted by the PCP/AP on a different sector to cover all possible directions. This interval is used for network announcement and beamforming training of the PCP/AP's antenna sectors. Second, the association beamforming training (A-BFT) is used by stations to train their antenna sector for communication with the PCP/AP. Third, during the Announcement Transmission Interval (ATI), the PCP/AP exchanges management information with associated and beam-trained stations.

The DTI comprises one or more Contention Based Access Periods (CBAPs) and scheduled Service Periods (SPs) where stations exchange data frames. While in CBAP, multiple stations can contend for the channel according to the IEEE 802.11ad enhanced distributed coordination function (EDCF). An SP is assigned for communication between a dedicated pair of nodes with a contention-free period creating a pseudo-static channel time allocation. Accessing the channel using this TDMA mechanism provides reliability and complies with quality of service demands. The IEEE 802.11ad amendment defines stations to use traffic specifications to request scheduling of pseudo-static channel allocations at the PCP/AP. A requesting station defines the properties of its traffic demand in terms of allocation duration and isochronous or asynchronous traffic characteristic. The actual schedule that includes the requested allocations is broadcasted by the PCP/AP in an extended schedule element in the next BTI or ATI.

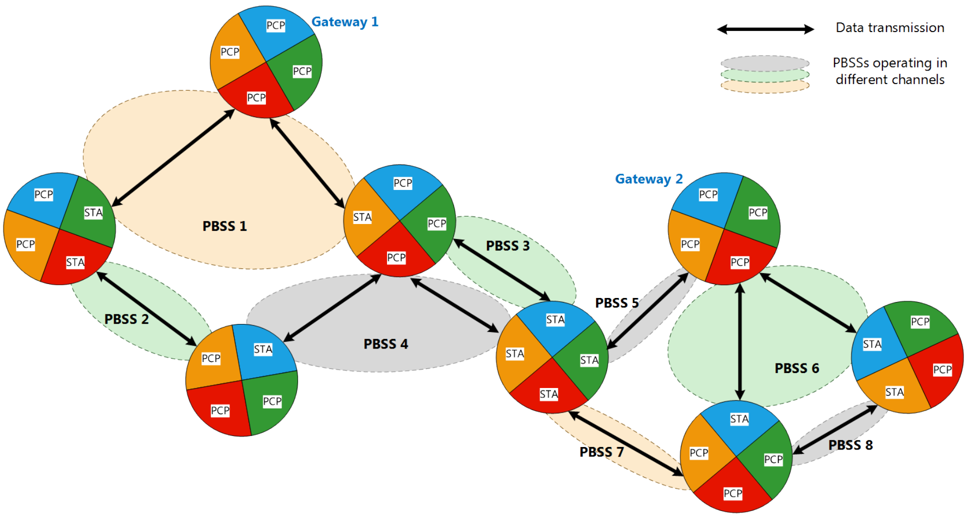


Figure 39: Example of IEEE 802.11ad mesh network

IEEE 802.11ad introduces the personal basic service set (PBSS), where nodes communicate in an ad hoc like manner. However, one of the participating nodes takes the role of the PCP. This PCP acts like an AP, announcing the network and organizing medium access. This centralized approach allows the directional network and schedule announcement process to be used for an ad hoc like network. When selecting between a set of possible PCPs, the unique capabilities of PCP candidate stations are considered to choose the PCP providing the most complete number of services to the network. Multiple sectors and multiple PBSS can be combined together to form an IEEE 802.11ad mesh network by properly assigning PCP and STA roles to each sector as shown in Figure 39.

Based on IEEE 802.11ad, the list of parameters to model a mmWave mesh network in 5G-Crosshaul is reported in Table 18. Table 18 also indicates parameters that can be configured or just monitored, and those used for inventory purposes.

Table 18: mmWave mesh network SBI parameters

Parameter	Units	Config.	Monitor	Inventory	Notes
General information					
GPS coordinates	-		x	x	
Number of sectors	-			x	
Sector-level sweep protocol	-	x		x	
QoS support	-	x		x	
Synchronization protocol	-	x		x	
Time distribution tree	-	x		x	
Sector information					
Horizontal coordinates (Azimuth, Altitude)	deg.		x	x	Identifies the orientation of the sector
Supported channels	-			x	
Channel bandwidth	MHz	x		x	
Central channel frequency	MHz	x		x	
Links Per Sector When Operating as STA	-			x	
Links Per Sector When Operating as AP/PCP	-			x	
Link status	-		x		
Electronically steerable Phased Array Antenna	-			x	
Beam refinement protocol	-	x		x	
Beam switching period	ns		x	x	
Beam steering coverage	deg.			x	
Beam width	deg.			x	
Noise threshold	dB	x	x		
Supported Modulation Coding Schemes (MCS)	Mbit/s	x		x	MCS can be either configured by the control plane or dynamically selected by a rate-control algorithm running on the mmWave node

Parameter	Units	Config.	Monitor	Inventory	Notes
Achievable range (per MCS)	m		x	x	
High Throughput capabilities	-	x		x	
Beaconing	-	x			Defines the beacon interval and the parameters to be included
Retransmission policy	-	x		x	Multiple retransmission policies can be configured: No Ack, Ack, Block Ack
Scheduling	-	x			In case of phased array antennas and multiple neighbours associated to the same sector, the scheduling determines the split of the total available bandwidth among the associated/selected neighbours
Reassembling and reordering	-	x			
Aggregation (A-MSDU and A-MPDU)	-	x			
Neighbour selection/association	-	x	x		
SNR (per neighbour)	dB		x		
Interference Management	-	x	x		mmWave nodes perform periodic interference measurements to evaluate the interference in the mesh network

9.2.2 Microwave and millimetre wave fronthaul

Figure 40 depicts the µWave/mmWave wireless fronthaul that is being developed within the 5G-Crosshaul project. Each wireless fronthaul module (WFM) is composed of a digital part and a RF part. The inputs of the central and the remote modules are optical ports (BBU-WFM, WFM-RRU) that carry the digital signal. The central module transmits the RF signal over the air to the remote module. Each µWave/mmWave Wireless Fronthaul node may have to feed multiple sectors/RRHs connected to BBUs/C-RAN/V-RAN as depicted in Figure 40. To manage the data flow from both legacy and 5G RAN, some inputs parameters are required by the herein considered wireless fronthaul system.

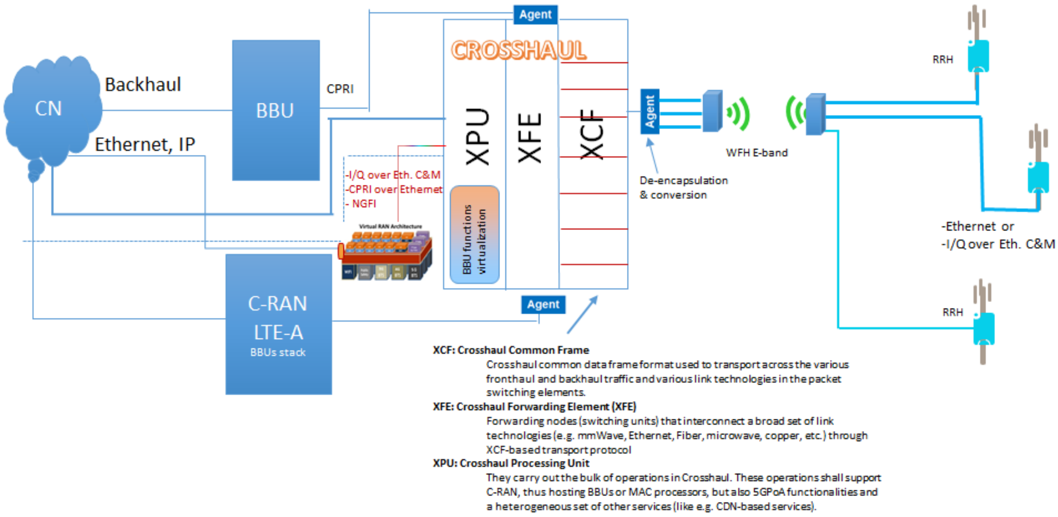


Figure 40: µmwave - mmWave fronthaul scenario in 5G-Crosshaul

These parameters are valid for both microwave and millimetrewave fronthaul links, but different constraints can be applied depending on the frequency range and administration regulation. A tentative but non-exhaustive list of the most relevant parameters is illustrated below, for CPRI (legacy), RF and Crosshaul nodes.

Table 19: µWwave mmWave fronthaul SBI parameters

Parameters	Units	Config.	Monitor	Inventory	Notes
CPRI (Legacy) related Parameters					
Wireless link			x	x	Report about the link quality
Vendor ID	-				To manage multiple OEM
CPRI version	-				
Line Rate: 1 to 10	Gbit/s	x	x		
CPRI maximum latency	µs		x		
CPRI Compression :Y/N	-				
Compression type	-				
HDLC: Y/N	-				
Fast C&M (Ethernet): Y/N	-		x		

Vendor specific used: Y/N	-				
Passive mode: Y/N	-				
RAT: 3G, 4G, 5G	-				
LTE BW: 5, 10, 15, 20, …	MHz				
MIMO: 2x2, 4x4, …	-				
IQ format: 2's complement, mantissa/exponent …	-				
Number of bits per IQ DL			x		
Number of bits per IQ UL			x		
AxC location:					The position of the AxCs in the CPRI Basic Frame
RF related Parameters					
Vendor ID				x	
Channel bandwidth (per sector)		x			
TX power (per sector)	dBm		x		
Polarization (type)		x			
Duplex spacing	MHz				
Frequency Plan information		x			
RRH gain (per sector)	dB	x			
Feeder loss (per sector)	dB		x		
Max composite Tx power	dBm	x			
Max composite EIRP	dBm	x			
Noise threshold (per sector)	dBm		x		
Beam width (per sector)	deg.	x			
Wireless link distance (per sector)	m	x	x		
Fibre link distance		x			

(per sector)					
Rx/Tx sensitivity threshold	dBm	x			
AGC: automatic Gain Control/sector	dB	x			
EIRP max	dBm	x			
RRH EVM	%				
Node related Parameters					
Used Protocol	-				
XCF Protocol encapsulation: CPRI/OBSAI/Ethernet, …	-				
MCS - Modulation Coding Scheme (per sector)	-		x		
Topology :	-				Line-of Sight(LoS), Chain, Tree, Ring
Port number					
Number of ports		x			
SFP/QSFP family	-				
Synchronization information					
BH activation: Y/N	-	x			
FH activation: Y/N	-	x			
Matrix AxC/port	-				
E2E max delay	µs		x		

9.2.3 Optical wireless

A schematic view of the LED-Based Optical Wireless Communication (OWC) Backhaul link to be used in the project demonstration set-up is shown in Figure 41. It has a 1G-DSP-Chip with a 1000BaseT Ethernet interface, a baseband (BB) unit and an analogue frontend (AFE). The chip control interface allows logging and configuring certain parameters on both, the MAC and PHY. The relevant parameters are listed in Table 20.

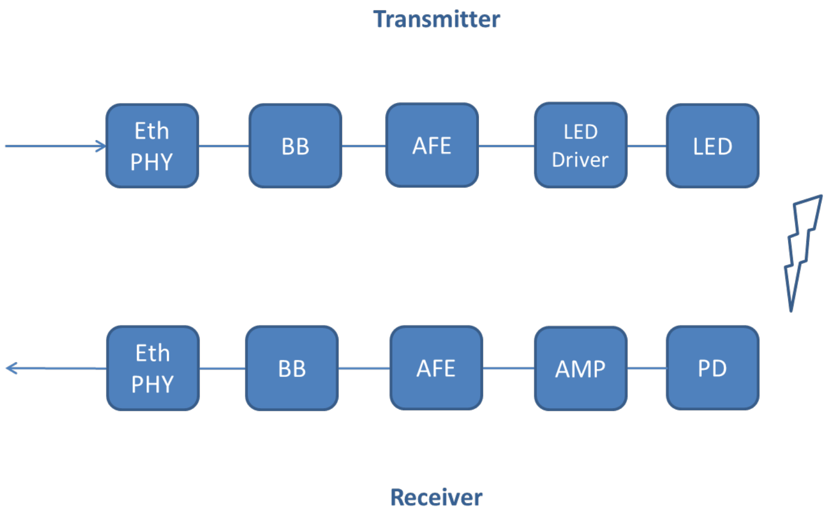


Figure 41: Schematic diagram of the LED backhaul link.

The bit rate is adaptive and is self-controlled by the DSP-Chip. It depends mostly on the visibility of the link. The transmitters bit rate can be limited through the notch filter, setting the attenuation and the upper/lower frequencies and therefore limiting the number of carriers. Reading the current bandwidth is the confirmation, whether the filter is set successfully or not. The current system power consumption can be monitored for energy efficiency issues. In order to save power, a sleep mode is possible for the LED driver and the AFE, but turning on or off the LED-driver introduces a latency of 2µs.

Link availability can be calculated locally or at the controller device. Here, the data rate should be captured over a time interval. Therefore, the availability can be given in percentage and has usually the target of 99.999%.

Table 20: LED-backhaul link SBI parameters

Parameter	Units	Config.	Monitor	Inventory	Notes
Maximum Tx bit rate	MBit/s			x	
Current Tx bit rate	MBit/s		x		The current bit rate varies due to weather conditions and is configurable by varying the bandwidth with the notch filter parameters
Maximum Rx bit rate	MBit/s			x	
Current Rx bit rate	MBit/s		x		
Bit rate adaption interval	ms	x			
Maximal Bandwidth	MHz			x	Maximal available bandwidth
Current Bandwidth	MHz		x		The current bandwidth influences the number of carriers and therefore the bit rate, current bandwidth can be configured via the notch filter parameters
Lower Frequency of Notch filter	kHz	x			
Upper Frequency of Notch filter	kHz	x			
Attenuation of Notch filter	dB	x			
Current electrical SNR	dB		x		
Maximum Power Consumption	W			x	
Current Power Consumption	W			x	

Parameter	Units	Config.	Monitor	Inventory	Notes
LED drivers sleeping mode	Boolean	x			
AFE frontend sleeping mode	Boolean	x			
Input Power	dBm		x		
Receive Sensitivity	dBm		x		It depends on the modulation format per carrier
LED type characteristics					
LED Color/ Wavelength	nm			x	
LED Power Consumption	mW			x	
LED Beam width				x	
Link availability	Percent per time		x		Availability can be calculated with logging the RX data rate over a time interval

9.2.4 Optical fixed access

Recommendation ITU-T G.989.2 [51] specifies the physical media dependent (PMD) layer requirements for a passive optical network (PON) system with a nominal aggregate capacity of 40 Gbit/s in the downstream direction and 10 Gbit/s in the upstream direction, hereinafter referred to as NG-PON2. Essentially, NG-PON2 implements a stacking of 4 x XG-PON operating at 10 Gbit/s downstream and 2.5 Gbit/s upstream on four different wavelengths. Each pair of wavelengths are shared among multiple ONUs via Time division multiplexing (TDM), in a similar fashion as in GPON or XG-PON. For these reasons, this PON technology is often referred to as the TWDM-PON (4 wavelengths at 10/2.5 Gb/s ds/us). OLT ports are often located in a chassis along with other OLT cards. ONUs are colorless, i.e. they can operate on any wavelength (which makes them much more expensive than GPON ONUs).

Regarding data transmission, frames are fragmented and encapsulated into XGEM frames using the XG-PON Encapsulation Method (XGEM). In the downstream, the traffic multiplexing functionality is centralized. The OLT multiplexes XGEM frames onto the transmission medium using XGEM Port-ID as a key to identify XGEM frames that belong to different downstream logical connections. Each ONU filters the downstream XGEM frames based on their XGEM Port-IDs and processes only the XGEM frames that belong to that ONU (see Figure 42 below).

In the upstream direction, the traffic multiplexing functionality is distributed. The OLT grants upstream transmission opportunities, or upstream bandwidth allocations, to the traffic-bearing entities within the subtending ONUs. The ONU's traffic-bearing entities that are recipients of the upstream bandwidth allocations are identified by their allocation IDs (Alloc-IDs). Bandwidth allocations to different Alloc-IDs are multiplexed in time as specified by the OLT in the bandwidth maps transmitted downstream. Within each bandwidth allocation, the ONU uses the XGEM Port-ID as a multiplexing key to identify the XGEM frames that belong to different upstream logical connections (see Figure 42).

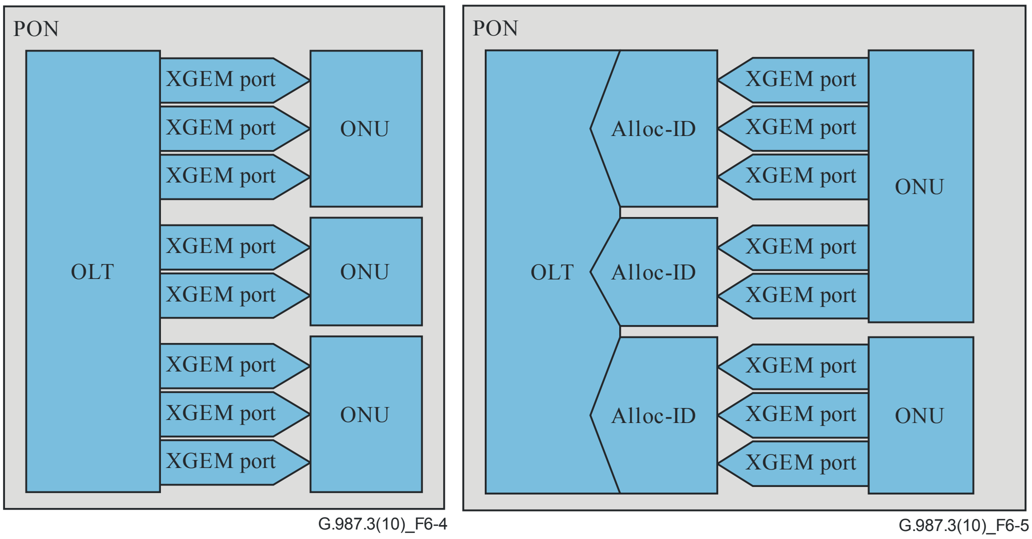


Figure 42: Downstream and upstream multiplexing model of the XG-PON.

- ONU identifier: The ONU-ID is a 10-bit identifier that the OLT assigns to an ONU during the ONU's activation. It is unique across the PON.
- The allocation identifier (Alloc-ID) is a 14-bit number that the OLT assigns to an ONU to identify a traffic-bearing entity that is a recipient of upstream bandwidth allocations within that ONU. Such a traffic-bearing entity can be represented either by a T-CONT or by the upstream OMCC.
- The XGEM port identifier, or XGEM Port-ID, is a 16-bit number that is assigned by the OLT to an individual logical connection. The XGEM Port-ID assignment to the OMCC logical connection is implicit by virtue of the ONU-ID assignment to the given ONU.

Finally, traffic flows are provisioned with a specific set of downstream and upstream service parameters. These parameters may be represented by a traffic descriptor. In the most general case, a traffic descriptor has the form:

$$D = < RF, RA, RM, XAB, P, \omega >$$

RF, RA and RM refer to Fixed bandwidth, Assured bandwidth and Maximum bandwidth respectively.

These parameters related with the operation of OLTs are further studied in section 4.4.1, especially those regarding configuration of OLT cards and XGEM logical ports. Other physical-level parameters related with the optical properties of TWDM-PONs are described in the following table:

Table 21: Optical fixed access SBI parameters

Parameter	Units	Config.	Monitor	Inventory	Notes
OLT transmitter (optical interface S)					
Nominal line rate	Gbit/s	x			
Operating wavelength band	nm	x			Shared spectrum vs dedicated spectrum
Operating central frequency	THz	x			PtP WDM vs TWDM channels
Operating Channel Spacing	GHz	x			From 50GHz to 200GHz
Line code	-	x			Scrambled NRZ is the standard line code
Reflectance at the S/R-CG interface	dB		x	x	
ORL of ODN at S/R-CG	dB		x		
ODN class	-			x	
Channel launch power (at S/R-CG)	dBm	x	x		
ER	dB		x	x	
Dispersion range	ps/nm			x	
SMSR	dB			x	
Jitter generation				x	
ONU receiver (optical interface R)					
OPP	dB		x	x	
Reflectance at the R/S interface	dB		x	x	
Bit error ratio reference level	-		x	x	
Receiver wavelength channel tuning time	us			x	
Maximum tuning granularity	GHz			x	
ODN class	-			x	
Sensitivity	dBm			x	

Parameter	Units	Config.	Monitor	Inventory	Notes
Overload	dBm		x	x	
In-band crosstalk tolerance	dB			x	
Consecutive identical digit immunity	bit			x	
Jitter tolerance	-		x	x	
ONU transmitter (optical interface S)					
Nominal line rate	Gbit/s	x			
Operating wavelength band	nm	x			Shared spectrum vs dedicated spectrum
Operating channel Spacing	GHz	x			From 50 GHz to 200 GHz
Maximum spectral excursion	GHz			x	
Transmitter power wavelength dependency	dB			x	
Minimum tuning window	GHz	x			
Maximum tuning granularity	GHz			x	
Transmitter wavelength channel tuning time	Us			x	
Line code	-	x			
Reflectance at the R/S interface	dB		x	x	
ORL of ODN	dB		x	x	
ODN class	-			x	
Channel launch power	dBm	x	x		
Transmitter enabled transient time	bits			x	
ER	dB		x	x	
Tolerance to reflected optical power	dB			x	
Dispersion range	ps/nm		x	x	
SMSR	dB			x	
Jitter transfer	-			x	
Jitter generation	-		x	x	
OLT receiver (optical interface R)					

Parameter	**Units**	**Config.**	**Monitor**	**Inventory**	**Notes**
ODN class	-			x	
OPP	dB		x	x	
Reflectance at S/R-CG	dB		x	x	
Bit error ratio reference level	-		x	x	
Sensitivity	dBm		x	x	
Overload	dBm		x	x	
In-band crosstalk tolerance	dB			x	
Consecutive identical digit immunity	bit			x	
Jitter tolerance	-		x	x	

9.2.5 Copper fixed access

As a result of the analysis of copper technologies we consider only Ethernet for use with 5G-Crosshaul. The currently available and useful standards are the 1 Gbits/s Ethernet (1000BASE-T or IEEE 802.3ab) and the 10 Gbit/s (10GBASE-T or 802.3an). However, 2.5 Gbits/s and 5 Gbit/s versions are being standardized with the same reach as today's systems, at least 100 meters. A 25 Gbit/s and a 40 Gbit/s system are also being standardized, but their reach is limited to 30 meters.

A common quality of all these standards is the Autonegotiation feature defined in clause 28 of IEEE 802.3. Two communicating devices will automatically detect the highest stable rate they can use. No performance improvement can be achieved by disabling the autonegotiation and manually setting parameters. It is quite the opposite as any manual intervention risks disabling the link altogether. Thus, it is strongly recommended to keep all Ethernet over copper links in the default autonegotiate mode.

Nonetheless, this section provides a list of the most important configurable parameters, but for reference only. Table 22 has a short list of identified configuration parameters for Ethernet over twisted pair (e.g. 10GBASE-T).

Table 22: Ethernet copper link SBI parameters

Parameter	**Units**	**Config.**	**Monitor**	**Inventory**	**Notes**
General information					
Bit-rate	Gbit/s	autodetect			Bit-rate autodetect is recommended over manual override.
Bit-rate	Gbit/s	manual			Currently used standards are 100

Parameter	Units	Config.	Monitor	Inventory	Notes
					Mbits/s, 1 Gbits/s, and 10 Gbits/s.
Master/Slave PHY mode	–	autodetect			Autodetect is recommended.
Master/Slave PHY mode	–	manual			Force master or slave mode.
Energy Efficient Ethernet (EEE)	–	enable			Enable/disable PHY-sleep functionality
Link active	–		x		A flag indicating the status of the link.
Remote powering					
Power over Ethernet (PoE)	W	enable			If the remote side is to be powered over the Ethernet cable.

9.2.6 DWDM/CWDM networks

ITU-T Recommendation G.698.1 [30] can be used as a reference to model passive Dense Wavelength Division Multiplexing (DWDM) 5G-Crosshaul networks. Passive DWDM networks includes fibre spans, wavelength multiplexers/demultiplexers (OM/OD) and optical add-drop multiplexers (OADMs).

This section also encompasses Coarse Wavelength Division Multiplexing (CWDM) networks, which can be modelled by the same set of parameters, although their values (channel frequencies, link attenuation, etc.) are different.

G.698.1 encompasses three possible configurations: linear, bus and bidirectional, which fits well with the 5G-Crosshaul deployment scenarios. These configurations are reported in Figure 43, Figure 44 and Figure 45, where reference points in the link are also indicated.

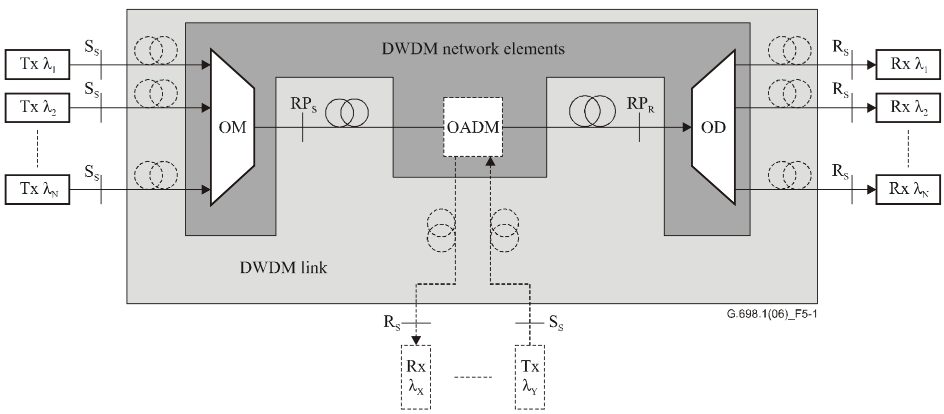


Figure 43: Linear passive DWDM network.

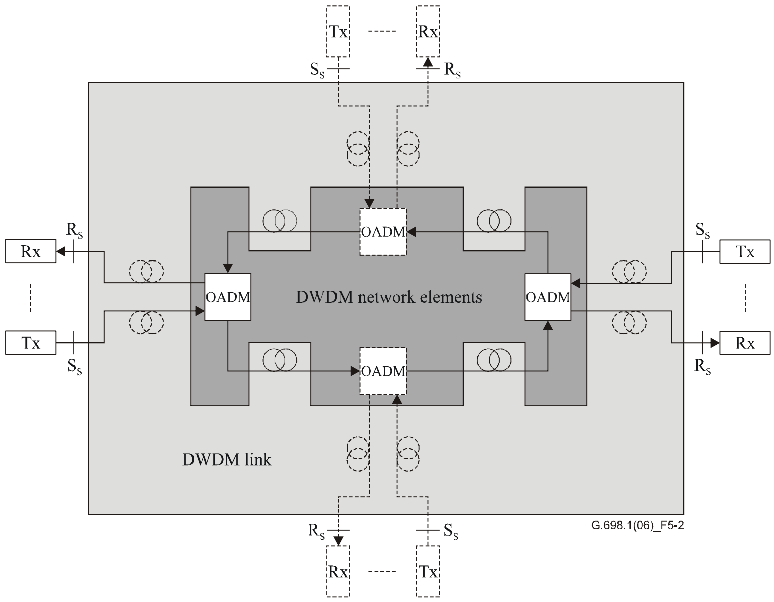


Figure 44: Ring passive DWDM network.

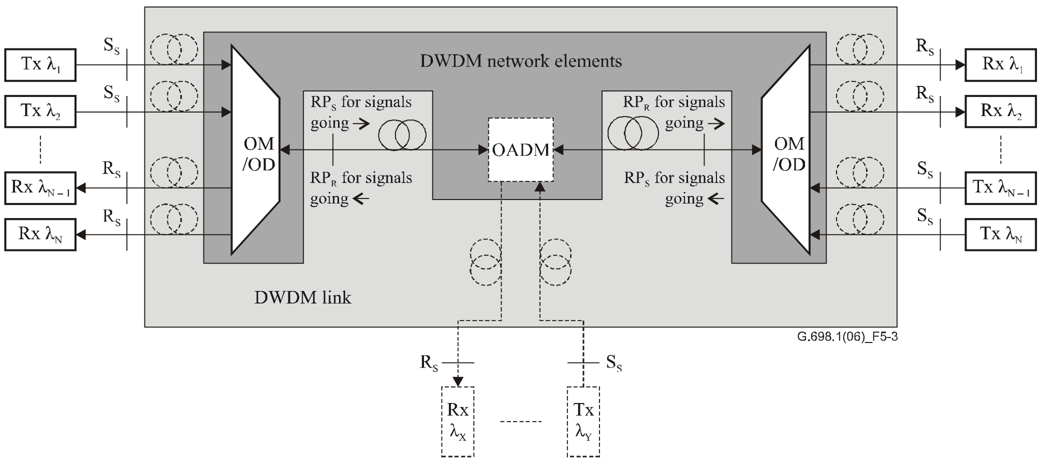


Figure 45. Bidirectional passive DWDM network.

Based on G.698.1, the list of parameters to model passive DWDM links in 5G-Crosshaul is reported in Table 23, which also indicates parameters that can be configured or just monitored, and those used for inventory purposes.

Table 23:Passive DWDM link SBI parameters

Parameter	**Units**	**Config.**	**Monitor**	**Inventory**	**Notes**

General information					
Minimum channel spacing	GHz			x	In future, it could be reconfigurable by using the flexi-grid
Bit-rate	Gbit/s			x	In future, it might configured using advanced modulation schemes (e.g. OFDM)
Line coding or modulation format				x	In future, it could be reconfigurable by using adaptable transceivers
Maximum bit-error ratio (pre-FEC)	–		x		
Maximum bit-error ratio (post-FEC)			x		
Fibre type	–			x	
Interface at point S_S					
Channel output power	dBm	x	x		For some transceivers (e.g. SFP) the output power might be not configurable
Channel central frequency	THz			x	In future, it could be reconfigurable by using the flexi-grid
Optical path from point S_S to R_S					
Channel insertion loss	dB		x		Calculated by monitoring input and output power
Maximum chromatic dispersion	ps/nm			x	Optional - Estimated by design
Minimum optical return loss at S_S	dB			x	Optional - Estimated by design
Maximum discrete reflectance between S_S and R_S	dB				Optional - Estimated by design
Maximum differential group delay	ps			x	Estimated by design
Maximum inter-channel crosstalk at R_S	dB			x	Optional – estimated by design
Maximum interferometric crosstalk at Rs	dB			x	Optional – estimated by design
Latency	ps		x	x	Not included in G.698.1. Estimated by design or measured. e.g. by using time stamps
Interface at point R_S					
Input power	dBm		x		
Receiver sensitivity	dBm			x	
Maximum optical path	dB			x	

penalty					
Maximum reflectance of receiver	dB			x	Optional
Optical Transceiver latency					Not included in G.698.1
Latency from client interface to S_S	ps		x	x	Estimated by design or measured, e.g. by using time stamps
Latency from client interface to S_S	ps		X	x	Estimated by design or measured, e.g. by using time stamps

ITU-T Recommendation G.698.2 [51] can be used as a reference to model DWDM 5G-Crosshaul networks with optical amplification. The reference schemes are reported below, similar to G.698.1.

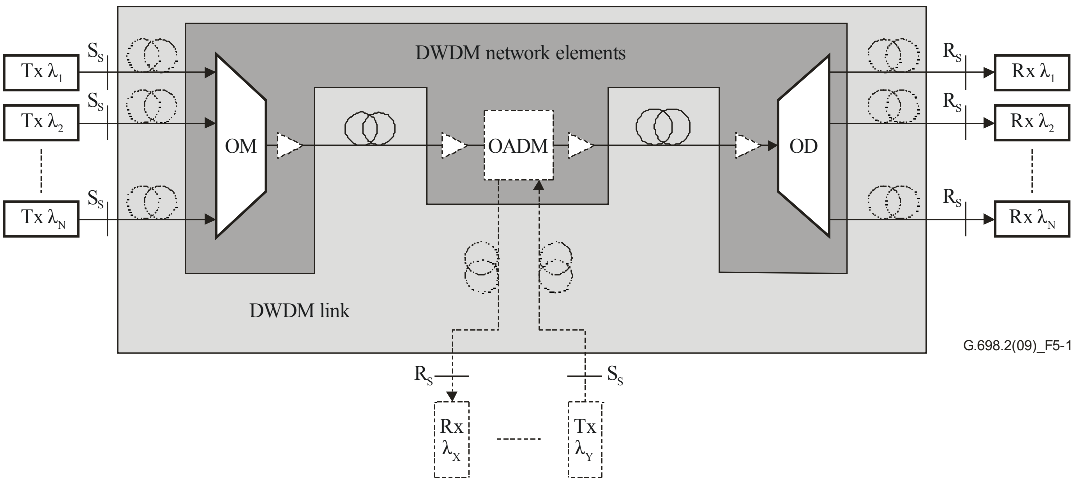


Figure 46: Linear amplified DWDM network.

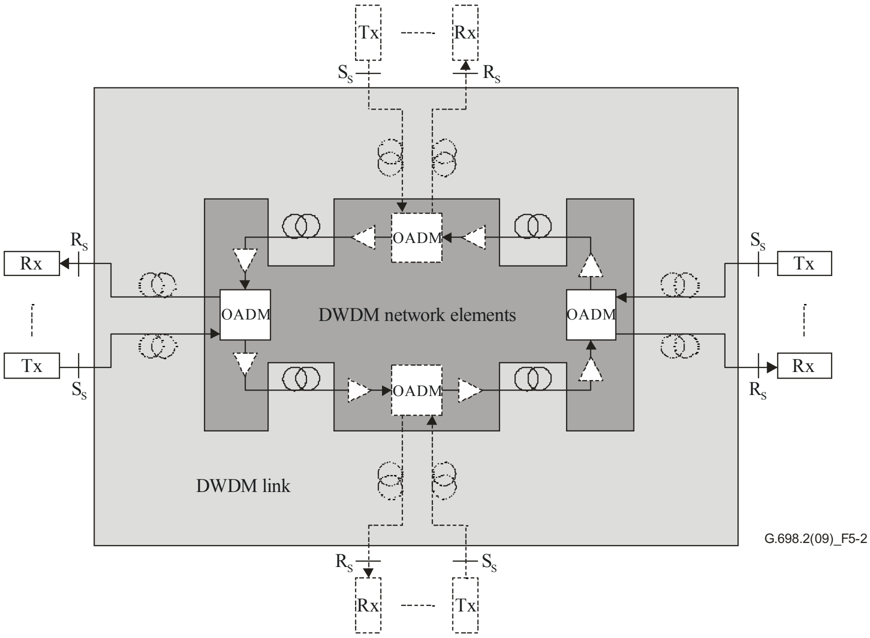


Figure 47: Ring amplified DWDM network.

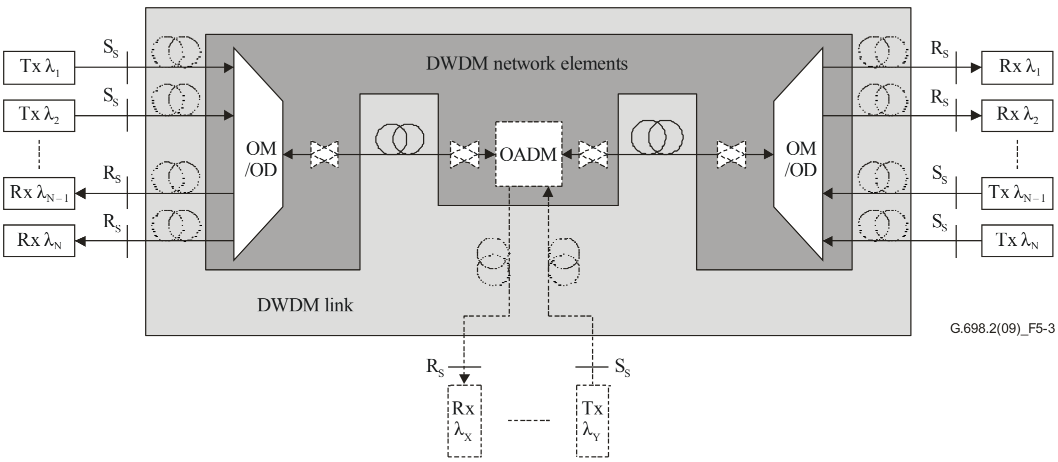


Figure 48: Bidirectional amplified DWDM network.

Table 24: Amplified DWDM link SBI parameters

Parameter	Units	Config.	Monitor	Inventory	Notes
General information					
Minimum channel spacing	GHz			x	In the future, it could be reconfigurable by using the flexi-grid

Parameter	**Units**	**Config.**	**Monitor**	**Inventory**	**Notes**
Bit rate	Gbit/s			x	In the future, it might be configured using advanced modulation schemes (e.g. OFDM)
Line coding or modulation format				x	In future, it could be reconfigurable by using adaptable transceivers
Maximum bit error ratio (pre-FEC)	–		x		
Maximum bit-error ratio (post-FEC)			x		
Fibre type	–			x	
Interface at point S_S					
Channel output power	dBm	x	x		For some transceivers (e.g. SFP) the output power might not be configurable. However, in amplified links the channel output power can also be configured by adjusting the booster amplifier output power.
Minimum central frequency	THz				In the future, it could be reconfigurable by using the flexi-grid
Channel central frequency	THz			x	
Optical path from point S_S to R_S					
Maximum ripple	dB			x	Optionally, it can be monitored by means of an optical spectrum analyser
Residual chromatic dispersion	ps/nm			x	
Minimum optical return loss at S_S	dB			x	Optional - Estimated by design
Maximum discrete reflectance between S_S and R_S	dB			x	Optional - Estimated by design
Maximum differential group delay	ps			x	Estimated by design
Maximum polarization	dB			x	Optional, estimated by

Parameter	**Units**	**Config.**	**Monitor**	**Inventory**	**Notes**
dependent loss					design
Maximum inter-channel crosstalk at R_S	dB			x	Optional, estimated by design
Maximum interferometric crosstalk at R_S	dB			x	Optional, estimated by design
Maximum optical path OSNR penalty	dB			x	
Latency	ps		x	x	Estimated by design or measured by using time stamps
Interface at point R_S					
Input power	dBm	x	x		In amplified links the channel output power can also be configured by adjusting the booster amplifier output power.
OSNR	dB (0.1 nm)		x	x	Optionally, it can be monitored by means of an optical spectrum analyser
Receiver OSNR tolerance	dB (0.1nm)			x	
Maximum reflectance of receiver	dB			x	Optional, estimated by design
Optical Transceiver latency (Not included in G.698.1)					
Latency from client interface to S_S	ps		x	x	Estimated by design or measured using time stamps
Latency from client interface to S_S	ps		x	x	Estimated by design or measured using time stamps

9.2.7 Analogue radio over fibre

The architecture of Analogue Radio-over-Fibre (RoF) transmission system is shown in Figure 49. A head-end unit (HEU) contains a circulator, digital attenuators, a laser diode and a photodiode. The downlink signals are converted to optical signals by HEU. The optical fibre connects HEU with remote antenna unit (RAU), by which the digital attenuator and power amplifier can adjust the RF power to an appropriate level. The uplink signals are processed similarly in the opposite direction. The parameters of RoF systems are listed in Table 25.

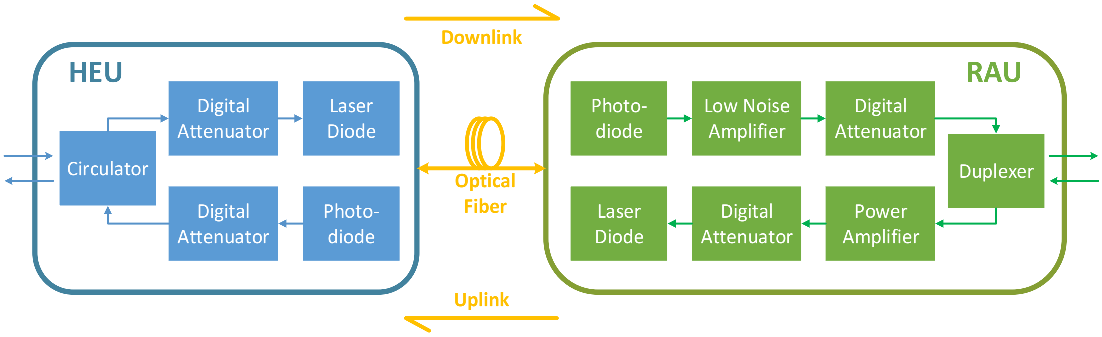


Figure 49: Schematic diagram of the Analogue-RoF.

Table 25: Analogue RoF System SBI parameters

Parameter	Units	Config.	Monitor	Inventory	Notes
Downlink RF Power Uplink RF Power	dBm dBm	x x	x x		RF output power which can be adjusted by digital attenuator (HEU, RAU).
Digital Attenuator	dB	x	x	x	Flexible range for HEU: 0 ~ 31.5dB with 0.5dB granularity. Flexible range for RAU: 0 ~ 7.75dB with 0.25dB granularity.
LD Status	N/A		x		Status of LD connection (HEU, RAU).
PD Status	N/A				Status of PD connection (HEU, RAU).
PA Temperature	Celsius		x		Temperature of PA (RAU).
LD Temperature	Celsius		x		Temperature of LD (HEU, RAU)
Connectivity	N/A		x		Connection status of RoF nodes (HEU, RAU).
LD On/Off	N/A	x			LD on/off switch (RAU)
Power On/Off	N/A	x			Device on/off switch (HEU, RAU)

9.3 ANNEX: Examples of 5G-Crosshaul SBI extension

As an example, this section explains how the parameters for Optical Networks are mapped to the 1.5.1 version of OpenFlow protocol (ONF TS-025) to access configuration, monitoring, and inventory services. Some parameters can be directly mapped to the current OpenFlow 1.5.1 specification. However, there is a set for which there is no such direct mapping. OpenFlow 1.5.1 is the latest release of OpenFlow at the time of writing, and it has become a sort of de-facto standard in SDN development.

The reason to limit the analysis to optical networks is that the ONF, in its wireless transport group, is already working on extensions to OF for supporting wireless transport nodes. Unfortunately, this work is currently not in the public domain but partners of 5G-Crosshaul are part of the standardization process at ONF and can facilitate the cross fertilization between the project and the standardization body. Hence, we expect that 5G-Crosshaul will benefit from this work.

It is reasonable to assume that transport ports of an OpenFlow switch can be extended to wireless technologies based on the built-in features. In particular, Experimenter extensions provide a standard way for OpenFlow switches to offer additional functionality within the OpenFlow message type space. For example, to enable extensions of mmWave ports for OpenFlow switches, the `EXPERIMENTER` properties defined in OpenFlow specification 1.5.1 can be utilized. This is the current process. However, it is likely that in the future, the situation will be similar to the optical case: first integration in the protocol, then defining further extensions.

Finally, an analysis of the parameters in Section 9.2.5 (Copper) concluded that no extension is required there. However, for the Analogue RoF technology (Section 9.2.7), the applicability of OpenFlow is unclear and left for further study.

9.3.1 SBI protocols for CWDM and DWDM

A single analysis covers CWDM and DWDM technologies (Sections 9.2.6) due to their similarities. It is expected that both technologies manage an equivalent set of parameters.

The OpenFlow 1.5.1 specification defines the following properties to provide configuration, monitoring and inventory capabilities to optical transport nodes:

- Optical port description property `ofp_port_desc_prop_optical` to describe optical port capabilities.
- Optical port mod property `ofp_port_mod_prop_optical` to configure optical ports.
- Optical port stats property `ofp_port_stats_prop_optical` to monitor optical ports.

Port description:

```
/* Optical port description property. */
struct ofp_port_desc_prop_optical {
uint16_t type;                  /* OFPPDPT_3OPTICAL. */
uint16_t length;                /* Length in bytes of this property. */
uint8_t  pad[4];                /* Align to 64 bits. */
uint32_t supported;             /* Features supported by the port. */
uint32_t tx_min_freq_lmda;      /* Minimum TX Frequency/Wavelength */
uint32_t tx_max_freq_lmda;      /* Maximum TX Frequency/Wavelength */
uint32_t tx_grid_freq_lmda;     /* TX Grid Spacing Frequency/Wavelength */
uint32_t rx_min_freq_lmda;      /* Minimum RX Frequency/Wavelength */
uint32_t rx_max_freq_lmda;      /* Maximum RX Frequency/Wavelength */
uint32_t rx_grid_freq_lmda;     /* RX Grid Spacing Frequency/Wavelength */
uint16_t tx_pwr_min;            /* Minimum TX power */
uint16_t tx_pwr_max;            /* Maximum TX power */
};
OFP_ASSERT(sizeof(struct ofp_port_desc_prop_optical) == 40);
/* Features of optical ports available in switch. */
enum ofp_optical_port_features {
OFPOPF_RX_TUNE = 1 << 0,        /* Receiver is tunable */
OFPOPF_TX_TUNE = 1 << 1,        /* Transmitter is tunable */
OFPOPF_TX_PWR = 1 << 2,         /* Power is configurable */
OFPOPF_USE_FREQ = 1 << 3,       /* Use Frequency, not wavelength */
};
```

Beyond the basic parameters available in OpenFlow 1.5, the protocol allows to define port attribute extensions using the `ofp_port_desc_prop_experimenter` structure. This structure, available since v1.4, is used to define optical parameters in the "Optical Transport Protocol Extensions" v1.0, March 2015 (ONF TS-022).

Port modification parameters:

```
struct ofp_port_mod_prop_optical {
uint16_t type;                  /* OFPPMPT_OPTICAL. */
uint16_t length;                /* Length in bytes of this property. */
uint32_t configure;             /* Bitmap of OFPOPF_*. */
uint32_t freq_lmda;             /* The "center" frequency */
int32_t  fl_offset;             /* signed frequency offset */
uint32_t grid_span;             /* The size of the grid for this port */
uint32_t tx_pwr;                /* tx power setting */
};
OFP_ASSERT(sizeof(struct ofp_port_mod_prop_optical) == 24);
```

Port statistics:

```
/* Optical port stats property. */
struct ofp_port_stats_prop_optical {
uint16_t type;                  /* OFPPSPT_OPTICAL. */
uint16_t length;                /* Length in bytes of this property. */
uint8_t  pad[4];                /* Align to 64 bits. */
uint32_t flags;                 /* Features enabled by the port. */
uint32_t tx_freq_lmda;          /* Current TX Frequency/Wavelength */
uint32_t tx_offset;             /* TX Offset */
uint32_t tx_grid_span;          /* TX Grid Spacing */
uint32_t rx_freq_lmda;          /* Current RX Frequency/Wavelength */
uint32_t rx_offset;             /* RX Offset */
uint32_t rx_grid_span;          /* RX Grid Spacing */
uint16_t tx_pwr;                /* Current TX power */
uint16_t rx_pwr;                /* Current RX power */
uint16_t bias_current;          /* TX Bias Current */
uint16_t temperature;           /* TX Laser Temperature */
};
OFP_ASSERT(sizeof(struct ofp_port_stats_prop_optical) == 44);
```

```
/* Flags is one of OFPOSF_ below */
enum ofp_port_stats_optical_flags {
OFPOSF_RX_TUNE = 1 << 0,        /* Receiver tune info valid */
OFPOSF_TX_TUNE = 1 << 1,        /* Transmit tune info valid */
OFPOSF_TX_PWR = 1 << 2,         /* TX Power is valid */
OFPOSF_RX_PWR = 1 << 4,         /* RX power is valid */
OFPOSF_TX_BIAS = 1 << 5,        /* Transmit bias is valid */
OFPOSF_TX_TEMP = 1 << 6,        /* TX Temp is valid */
};
```

The following tables provide a detailed analysis of how the parameters defined in Section 9.2.6 are mapped to existing OpenFlow structures (when possible) and provide a suggestion of the possible required extensions.

Table 26: Configuration parameters for CWDM, DWDM technology

5G-Crosshaul parameter	**Scope**	**OpenFlow structure**	**Extension**
Channel output power (dBm)	<Port, Wavelength>	ofp_port_mod_prop_optical -> tx_pwr	--

Table 27: Monitoring parameters for CWDM, DWDM technology

5G-Crosshaul parameter	Scope	OpenFlow structure	Extension
Max BER (pre-FEC)	<Port, Wavelength>	Missing	ofp_port_stats_prop_experimenter -> experimenter_data -> max_ber_pre_fec
Max BER (post-FEC)	<Port, Wavelength>	Missing	ofp_port_stats_prop_experimenter-> experimenter_data -> max_ber_post_fec
Channel output power (dBm)	<Port, Wavelength>	ofp_port_stats_prop_optical -> tx_pwr	--
Channel insertion loss (dBm)	<Input port, output port, wavelength>	Missing[25]	
Latency (ps)	<Input port, output port, wavelength>	Missing	
Input power (dBm)	<Port, Wavelength>	ofp_port_stats_prop_optical -> rx_pwr	--
Transceiver latency (ps)	<Port, Wavelength>	Missing	ofp_port_stats_prop_experimenter -> experimenter_data -> transceiver_latency
OSNR (dB)	<Port, Wavelength>	Missing	ofp_port_stats_prop_experimenter -> experimenter_data -> osnr

The pair <port, wavelength> is identified through the port itself and the `tx_freq_lmda` or the `rx_freq_lmda` parameter.

The additional parameters related to the <port, wavelength> pair are encoded in a new data structure which extends the `ofp_port_stats_prop_experimenter` structure:

```
/* Experimenter port stats property. */
struct ofp_port_stats_prop_experimenter {
uint16_t type;              /* OFPPSPT_EXPERIMENTER. */
uint16_t length;            /* Length in bytes of this property. */
uint32_t experimenter;      /* Experimenter ID which takes the same form as in
       struct ofp_experimenter_header. */
```

[25] How to model this is TBD. Since it is not strictly related to a port/wavelength pair, but depends also on the output port, it would be better to model this as an extension of a flow statistic (where the flow entry corresponds to the cross-connection)

```
uint32_t exp_type;         /* Experimenter defined. */
/* Followed by:
* - Exactly (length - 12) bytes containing the experimenter data, then
* - Exactly (length + 7)/8*8 - (length) (between 0 and 7)
* bytes of all-zero bytes */
uint32_t experimenter_data[0];
};
```

Where:

- experimenter = OFP_OTWG_EXPERIMENTER_ID 0xFF000007
- exp_type = OFPPDPT_OPTICAL_TRANSPORT (To be assigned)
- experimenter_data = ofp_experimenter_optical_port_stats

```
struct ofp_experimenter_optical_port_stats {
uint32_t tx_freq_lmda;          /* Current TX Frequency/Wavelength */
uint32_t rx_freq_lmda;          /* Current RX Frequency/Wavelength */
uint32_t max_ber_pre_fec;
uint32_t max_ber_post_fec;
uint32_t transceiver_latency;
uint32_t osnr;
};
```

Table 28: Inventory parameters for CWDM, DWDM technology

5G-Crosshaul parameter	Scope	OpenFlow structure	Extension
Minimum channel spacing (GHz)	<Port, Wavelength>	ofp_port_desc_prop_optical -> tx_grid_freq_lmda ofp_port_desc_prop_optical -> rx_grid_freq_lmda	--
Bit rate (Gbit/s)	<Port, Wavelength>	Missing	ofp_port_desc_prop_experimenter -> ofp_port_desc_prop_exp_optical_transport-> ofp_port_optical_g698_[1-2]_features ->bitrate
Modulation format	<Port, Wavelength>	Missing	ofp_port_desc_prop_experimenter -> ofp_port_desc_prop_exp_optical_transport-> ofp_port_optical_g698_[1-2]_features -> modulation_format

5G-Crosshaul parameter	**Scope**	**OpenFlow structure**	**Extension**
Fibre type	<Port, Wavelength>	Missing	ofp_port_desc_prop_experimenter -> ofp_port_desc_prop_exp_optical_transport-> ofp_port_optical_g698_[1-2]_features -> fibre_type
Channel central frequency	<Port, Wavelength>	ofp_port_desc_prop_optical -> tx_min_freq_lmda / tx_max_freq_lmda ofp_port_desc_prop_optical -> rx_min_freq_lmda / rx_max_freq_lmda[26]	--
Maximum ripple[27]	<Input port, output port, wavelength>	Missing	
Residual chromatic dispersión	<Input port, output port, wavelength>	Missing	
Minimum optical return loss at S_S	<Input port, output port, wavelength>	Missing	
Maximum discrete reflectance between S_S and R_S	<Input port, output port, wavelength>	Missing	
Maximum differential group delay	<Input port, output port, wavelength>	Missing	
Maximum polarization	<Input port, output port,	Missing	

[26] min and max values are the same
[27] These parameters are related not only to a single pair <port, wavelength>, but depends also on the output port. We could encode them in a further data structure which includes also the output port. However, this would mean to have this structure repeated N(M-1) times where N is the number of <port, wavelength> elements and M is the number of ports.

5G-Crosshaul parameter	Scope	OpenFlow structure	Extension
dependent loss	wavelength>		
Maximum inter-channel crosstalk at R_S	<Input port, output port, wavelength>	Missing	
Maximum interferometric crosstalk at R_S	<Input port, output port, wavelength>	Missing	
Maximum optical path OSNR penalty	<Input port, output port, wavelength>	Missing	
Latency	<Input port, output port, wavelength>	Missing	
OSNR	<Input Port, Wavelength>	Missing	ofp_port_desc_prop_experimenter -> ofp_port_desc_prop_exp_optical_transport -> ofp_port_optical_g698_2_features -> osnr
Receiver OSNR tolerance	<Input Port, Wavelength>	Missing	ofp_port_desc_prop_experimenter -> ofp_port_desc_prop_exp_optical_transport -> ofp_port_optical_g698_2_features -> max_osnr_tolerance
Receiver sensitivity	<Input Port, Wavelength>	Missing	ofp_port_desc_prop_experimenter -> ofp_port_desc_prop_exp_optical_transport -> ofp_port_optical_g698_1_features -> receiver_sensitivity
Maximum optical path penalty	<Input Port, Wavelength>	Missing	ofp_port_desc_prop_experimenter -> ofp_port_desc_prop_exp_optical_transport -> ofp_port_optical_g698_1_features -> max_optical_path_penalty
Maximum Reflectance of Receiver	<Input Port, Wavelength>	Missing	ofp_port_desc_prop_experimenter -> ofp_port_desc_prop_exp_optical_transport ->

5G-Crosshaul parameter	Scope	OpenFlow structure	Extension
			ofp_port_optical_g698_[1-2]_features-> max_receiver_reflectance
Optical transceiver latency	<Port, Wavelength>	Missing	ofp_port_desc_prop_experimenter -> ofp_port_desc_prop_exp_optical_transport -> ofp_port_optical_g698_[1-2]_features -> optical_transceiver_latency

Since some of the inventory parameters are not available in OpenFlow 1.5.1, we refer to the Optical Transport extensions v1.0, March 2015 (ONF TS-022), adopting the approach based on the port attribute extensions available since OF 1.4. These extensions make use of the `ofp_port_desc_prop_experimenter` structure:

```
/* Experimenter port description property. */
struct ofp_port_desc_prop_experimenter {
uint16_t type;             /* OFPPDPT_EXPERIMENTER. */
uint16_t length;           /* Length in bytes of this property. */
uint32_t experimenter;     /* Experimenter ID which takes the same
                              form as in struct ofp_experimenter_header. */
uint32_t exp_type;         /* Experimenter defined. */
/* Followed by:
* - Exactly (length - 12) bytes containing the experimenter data, then
* - Exactly (length + 7)/8*8 - (length) (between 0 and 7)
* bytes of all-zero bytes */
uint32_t experimenter_data[0];
};
OFP_ASSERT(sizeof(struct ofp_port_desc_prop_experimenter) == 12);
```

Where:

- experimenter = OFP_OTWG_EXPERIMENTER_ID 0xFF000007
- exp_type = `OFPPDPT_OPTICAL_TRANSPORT` (To be assigned)

`ofp_port_desc_prop_exp_optical_transport` is based on a sub-TLV structure, as follows:

```
/*Optical Transport port experimenter property. */
struct ofp_port_desc_prop_exp_optical_transport {
uint16_t type;             /* Set to OFPPDPT_EXPERIMENTER. */
```

```
uint16_t length;            /* Length in bytes of this property. */
uint32_t experimenter;      /* OTWG ID */
uint32_t exp_type;          /* Set to OFPPDPT_OPTICAL_TRANSPORT */
uint8_t port_signal_type;   /* Base port layer signal type - OFPOTPT_* */
uint8_t reserved;
uint8_t pad[2];
struct ofp_port_optical_transport_feature_header features[0];
};
OFP_ASSERT(sizeof (struct ofp_port_desc_prop_exp_optical_transport) == 16);
```

Where the possible values for the port_signal_type are:

```
OFPPOTST_OTSn = 1
OFPPOTST_OMSn = 2
OFPPOTST_OPSn = 3
OFPPOTST_OPSM = 4
OFPPOTST_OCH = 5
OFPPOTST_OTU1 = 11
OFPPOTST_OTU2 = 12
OFPPOTST_OTU3 = 13
OFPPOTST_OTU4 = 14
```

And the ofp_port_optical_transport_feature_header structure is as follows:

```
struct ofp_port_optical_transport_feature_header {
uint16_t feature_type; /* OFPOTPF_. */
uint16_t length; /* length of feature excluding padding*/
};
OFP_ASSERT(sizeof(struct ofp_port_optical_transport_feature_header) == 4);
```

The feature type can assume the following values:

```
OFPPOTFT_OPT_INTERFACE_CLASS = 1
OFPPOTFT_LAYER_STACK         = 2
```

In our case we will use the first type to discriminate between the element types, obtaining the following:

```
/* Optical Interface Class Feature Encoding */
struct ofp_port_optical_transport_application_code {
uint16_t feature_type; /* Set to OFPOTPF_OPT_INTERFACE_CLASS */
uint16_t length;
uint8_t oic_type;
char app_code[15];
};
OFP_ASSERT(sizeof(struct ofp_port_optical_transport_application_code) == 20);
```

Where `oic_type` will assume the value `OFPOICT_ITUT_G698_1 = 1` or `OFPOICT_ITUT_G698_2 = 2` for passive DWDM elements and DWDM elements with optical amplification respectively.

Moreover, we will define two new feature types to provide G.698.1 and G.698.2 characteristics:

- OFPPOTFT_G698_1_FEATURE = 3
- OFPPOTFT_G698_1_FEATURE = 4

The associated structures will be the following:

```
/* G698.1 Feature Encoding */
struct ofp_port_optical_g698_1_features {
uint16_t feature_type;          /* Set to OFPPOTFT_G698_1_FEATURE */
uint16_t length;
uint32_t bitrate;
uint32_t tx_freq_lmda;          /* Current TX Frequency/Wavelength */
uint32_t rx_freq_lmda;          /* Current RX Frequency/Wavelength */
uint32_t modulation_format;
uint8_t        fibre_type;
uint32_t receiver_sensitivity;
uint32_t max_optical_path_penalty;
uint32_t max_receiver_reflectance;
uint32_t optical_transceiver_latency;
};
```

```
/* G698.2 Feature Encoding */
struct ofp_port_optical_g698_2_features {
uint16_t feature_type;          /* Set to OFPPOTFT_G698_2_FEATURE */
uint16_t length;
uint32_t tx_freq_lmda;          /* Current TX Frequency/Wavelength */
uint32_t rx_freq_lmda;          /* Current RX Frequency/Wavelength */
uint32_t bitrate;
uint32_t modulation_format;
uint8_t        fibre_type;
uint32_t osnr;
uint32_t max_osnr_tolerance;
uint32_t max_receiver_reflectance;
uint32_t optical_transceiver_latency;
};
```

9.3.2 SBI protocols for fixed access networks

This section discusses about the support of OpenFlow to technologies deployed on optical fixed access infrastructures, with focus on additional extensions required for configuring the TWDM working mode. As mentioned in Section 9.2.4, 9.2.4, the parameter analysis will be made based on the list of parameters defined by the ITU-T G.989 specification to model fibre-optical fixed-access links in 5G-Crosshaul networks.

Two logical port types are necessary to be introduced per PON, namely:

1. NGPON olt_port
2. NGPON xgem_port

The former refers to the actual OLT hardware port in the chassis where multiple OLT cards are allocated. The latter aims to characterize logical L2 connections between the OLT and different ONUs, as explained in Section 3.

Regarding the olt_port, the same physical parameters defined in Section 9.3.1 need to be used but, in addition, some more parameters are necessary to extend the port_mod description and provide configuration capabilities to the controller, namely:

- olt_port_id: identifier of OLT card
- alloc_properties: which identify the traffic profile per alloc_id
    - alloc_id
    - fixed_bandwidth
    - assured_bandwidth
    - maximum_bandwidth
- dba_method: Dynamic Bandwidth Allocation Method. Two options: Status Reporting (SR) and Traffic Monitoring (TM).

Table 29: Configuration parameters for TWDM optical fixed access network

5G-Crosshaul parameter	Scope	OpenFlow structure	Extension
olt_port_id	<olt_port>	Missing	ofp_port_mod_prop_experimenter -> experimenter_data -> olt_port_id
alloc_properties	<olt_port>	Missing	ofp_port_mod_prop_experimenter -> experimenter_data -> alloc_properties
dba_method	<olt_port>	Missing	ofp_port_mod_prop_experimenter -> experimenter_data -> dba_method

These additional parameters related to the <olt_port> value are encoded in a new data structure which extends the `ofp_port_mod_prop_experimenter` structure:

```
/* Experimenter port desc property. */
struct ofp_port_mod_prop_experimenter {
uint16_t type;              /* OFPPSPT_EXPERIMENTER. */
uint16_t length;            /* Length in bytes of this property. */
uint32_t experimenter;      /* Experimenter ID which takes the same form as in
                            struct ofp_experimenter_header. */
uint32_t exp_type;          /* Experimenter defined. */
/* Followed by:
* - Exactly (length - 12) bytes containing the experimenter data, then
* - Exactly (length + 7)/8*8 - (length) (between 0 and 7)
* bytes of all-zero bytes */
uint32_t experimenter_data[0];
};
```

where:

- experimenter = OFP_OTWG_EXPERIMENTER_ID 0xFF000007
- exp_type = OFPPDPT_OPTICAL_NGPON_OLT_TRANSPORT (to be assigned)
- experimenter_data = ofp_experimenter_optical_port_desc_ngpon_olt

```
struct ofp_experimenter_optical_port_mod_ngpon_olt {
uint16_t     olt_port_id;
struct              alloc_id_type[16384];
uint16_t     dba_method;
};
enum dba_method_type {
        TRAFFIC_MONITORING = 0;
        STATUS_REPORTING = 1;
};
struct alloc_id_type {
        uint16_t     alloc_id;
        uint32_t     fixed_bandwidth;
        uint32_t     assured_bandwidth;
        uint32_t     maximum_bandwidth;
};
```

Regarding the NGPON xgem_port, the following parameters are necessary to provide a proper description of the xgem_port to the controller:

- olt_port_id: identifier of the OLT card

- xgem_port_id: identifier of the L2 logical port (Generic Encapsulation Method)
- onu_id: this is the ONU identifier for such xgem_port
- ds_lmda: downstream wavelength
- us_lmda: upstream wavelength
- alloc_id: identifier used by the Dynamic Bandwidth Allocation in the upstream direction

Table 30: Inventory parameters for TWDM optical fixed access network

5G-Crosshaul parameter	Scope	OpenFlow structure	Extension
olt_port_id	<xgem_port>	Missing	ofp_port_desc_prop_experimenter -> experimenter_data -> olt_port_id
xgem_port_id	< xgem _port>	Missing	ofp_port_desc_prop_experimenter -> experimenter_data -> xgem_port_id
onu_id	< xgem _port>	Missing	ofp_port_desc_prop_experimenter -> experimenter_data -> onu_id
ds_lmda	< xgem _port>	Missing	ofp_port_desc_prop_experimenter -> experimenter_data -> ds_lmda
us_lmda	< xgem _port>	Missing	ofp_port_desc_prop_experimenter -> experimenter_data -> us_lmda
alloc_id	< xgem _port>	Missing	ofp_port_desc_prop_experimenter -> experimenter_data -> alloc_id

These additional parameters related to the <xgem_port> are encoded in a new data structure which extends the ofp_port_desc_prop_experimenter structure:

```
/* Experimenter port desc property. */
struct ofp_port_desc_prop_experimenter {
uint16_t type;              /* OFPPSPT_EXPERIMENTER. */
uint16_t length;            /* Length in bytes of this property. */
uint32_t experimenter;      /* Experimenter ID which takes the same form as in
                               struct
ofp_experimenter_header. */
uint32_t exp_type; /* Experimenter defined. */
/* Followed by:
* - Exactly (length - 12) bytes containing the experimenter data, then
* - Exactly (length + 7)/8*8 - (length) (between 0 and 7)
* bytes of all-zero bytes */
```

```
uint32_t experimenter_data[0];
};
```

where:

- experimenter = OFP_OTWG_EXPERIMENTER_ID 0xFF000007
- exp_type = OFPPDPT_OPTICAL_NGPON_TRANSPORT (To be assigned)
- experimenter_data = ofp_experimenter_optical_port_desc_ngpon_xgem

```
struct ofp_experimenter_optical_port_desc_ngpon_xgem {
uint16_t olt_port_id;
uint16_t xgem_port_id;
uint16_t onu_id;
uint32_t ds_lmda;
uint32_t us_lmda;
uint16_t alloc_id;
};
```

Regarding the monitoring parameters, again the same physical monitoring parameters defined in section 9.2.4 shall be used for the olt_port. Regarding the xgem_port, some extra monitoring parameters reporting on the bandwidth requested and consumed per xgem_port are necessary.

Table 31: Monitoring parameters for TWDM optical fixed access network

5G-Crosshaul parameter	**Scope**	**OpenFlow structure**	**Extension**
Bandwidth	<xgem_port>	Missing	ofp_port_stats_prop_experimenter -> experimenter_data -> bandwidth

This additional parameter related to the <xgem_port> is encoded in a new data structure which extends the ofp_port_stats_prop_experimenter structure:

```
/* Experimenter port stats property. */
struct ofp_port_stats_prop_experimenter {
uint16_t type;      /* OFPPSPT_EXPERIMENTER. */
uint16_t length;    /* Length in bytes of this property. */
uint32_t experimenter;    /* Experimenter ID which takes the same form as in struct
ofp_experimenter_header. */
uint32_t exp_type;        /* Experimenter defined. */
/* Followed by:
* - Exactly (length - 12) bytes containing the experimenter data, then
* - Exactly (length + 7)/8*8 - (length) (between 0 and 7)
* bytes of all-zero bytes */
```

```
uint32_t experimenter_data[0];
};
```

where:

- experimenter = OFP_OTWG_EXPERIMENTER_ID 0xFF000007
- exp_type = OFPPDPT_OPTICAL_NGPON_TRANSPORT (To be assigned)
- experimenter_data = ofp_experimenter_optical_port_stats_ngpon_xgem

```
struct ofp_experimenter_optical_port_stats_ngpon_xgem {
uint32_t     bandwidth;
};
```

10 Conclusion

This document provided the identification and analysis of physical and link layer technologies with both quantitative and qualitative parameters. Moreover, the technologies that can be used in the short term where pointed out as well as the innovation effort required to technologies, in order to achieve long-term advantages.

One of the main innovations of the 5G-Crosshaul project, the multilayer data plane architecture, including circuit- and packet-switched paths was defined as a proposal. Here, the packet switching path is the primary path for the transport of most delay-tolerant fronthaul and backhaul traffic, whereas the circuit switching path is there for traffic with extremely low delay tolerance or legacy protocols as CPRI and can be used for capacity offloading. This two-path switching architecture is able to combine packet based bandwidth efficiency with circuit based deterministic latency, while providing adaption functions in between. This modular structure of this switch, the 5G-Crosshaul Forwarding Element (XFE), enables traffic segregation at multiple levels, from dedicated wavelengths to VPN, which is particularly desirable for multi-tenancy support, one of the key features identified.

In order to enable SDN through a control layer, a protocol agnostic abstraction model of the South-Bound Interface (SBI) and definition of the protocol extensions to support the 5G-Crosshaul technologies were described. The novelty of this SBI model is, that it enables applications, such as optimization of resource allocation and energy, to run over the whole network infrastructure by modelling the network nodes and transmission technologies with a protocol-agnostic set of parameters.

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