D3.4 - Assessment of candidate transport network architectures for structural convergence

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Executive Summary

This deliverable (D3.4) is the final deliverable of Task 3.3 which proposes, defines and assesses candidate architectures for structural convergence. This final deliverable is focused on the assessment and comparison of the proposed architectures and completes the initial assessment work started in D3.3 [1] and partially fulfills COMBO Target 1 to "*define and develop Fixed-Mobile Convergence (FMC) architectures for future networks, which will be technically assessed with respect to FMC use cases defined by the project.*" In particular, this deliverable addresses the Specific Objective SO1.5 to "d*etermine [the] most suitable FMC architectures*".

Structural convergence is driven by several factors. Rapidly increasing traffic volumes in mobile networks are driving the need for radio access network (RAN) densification through large numbers of small cells, which in turn need to be connected in a cost efficient way. This raises the incentives for reusing existing deployed fixed-access infrastructure for connecting small cells, which in turn drives the need for structural convergence. In fixed access, the current trend is that fibre is penetrating further out towards the end-user, with FTTC/B/H deployment becoming more common. This in turn determines the available infrastructure for the convergence scenarios.

RAN transport brings a different set of requirements on connectivity compared to fixed access. Tight radio coordination, which is generally thought to become increasingly important as the RAN is densified, introduces stringent requirements on transport in terms of latency. Furthermore, new deployment models, exploiting fronthaul and/or new RAN splits considered in 5G, bring more stringent requirements on transport in terms of capacity and/or latency.

Given the diverse requirements of fixed access and RAN transport, a major question regarding convergence is whether it is more efficient with a single access/transport system that can meet the requirements of both fixed access and RAN transport, or whether it is more efficient with dedicated solutions tailored for the individual requirements of each domain.

COMBO is primarily focusing on modelling the CapEx of transport, while a complete cost comparison of the convergence scenarios would require modelling additional costs such as CapEx of radio, OpEx, etc. Instead, in this deliverable we present results for a broad range of RAN deployment scenarios where assessments are performed for different assumptions on BBU placement, on the placement of the radio coordination functions (RCC), how the small cells are aggregated, etc. A range of new RAN splits considered for 5G were also included in the analysis as well as the impact of 5G radio technologies in terms of massive antennas, wider spectrum, etc.

A broad range of systems and technologies were analysed with respect to the requirements from different deployment and convergence scenarios. The stringent requirements on connectivity for RAN transport were met in the most cost efficient way through dedicated wavelengths. This suggests that structural convergence should be based on wavelength multiplexing. With that in mind, four main technology options were identified, that in turn provide different degree of structural convergence:

- PtP CWDM (reference technology)
- NG-PON2 with WDM overlay
- WR-WDM-PON (wavelength routed)
- WS-WDM-PON (wavelength selective)

PtP CWDM provides the least structural convergence, with dedicated infrastructure for cabinet backhaul and RAN transport in addition to the legacy FTTH infrastructure. WR-WDM-PON and WS-WDM-PON provide convergence through a common infrastructure for PtP WDM services. NG-PON2 with WDM overlay provides further convergence with a common infrastructure for PtP WDM and TWDM services.

A large range of configurations (splitter/AWG configurations, amplifiers and amplifier placement, dispersion compensation, etc) of the different technology options were considered and optimized for each deployment. Furthermore, a capacity range including 3G, 10G, 25G, 40G and 100G was considered for each of the technology options.

To summarise, the key findings from the investigations in this deliverable are the following – grouped into five categories.

Results on LTE radio scenarios where small cells are aggregated directly to the main CO:

- The reference PtP CWDM solution, with limited convergence potential, is always the most costly solution.
- In an FTTC deployment scenario, WR-WDM-PON always has the lowest cost independently of fibre availability.
- Moderate RAN densities give an advantage to WR-WDM-PON in fibre-rich scenarios, even at high FTTH/FTTC ratios, and especially in the fronthaul case. However, NG-PON2-based converged architecture is the cheapest solution when both the FTTH/FTTC ratio and the RAN density increase.

Results on LTE radio scenarios where small cells are aggregated via the macro sites:

- Compared to the scenario where small cells are aggregated directly to the main CO, the convergence benefits are reduced when small cells are aggregated via the macro sites.
- The WS-WDM solution is always the most costly solution.
- In an FTTC deployment scenario, WR-WDM-PON or PtP-CWDM have the lowest cost independently of RAN density and fibre availability. PtP-CWDM is favorable only for very low RAN densities.
- In the fibre rich deployment scenario, WR-WDM-PON or PtP-CWDM have the lowest cost independently of RAN density and FTTH/FTTC ratio. PtP-CWDM is favorable only at low RAN densities.
- In the fibre poor scenario and for high FTTH/FTTC ratios, low and moderate RAN densities give an advantage to NG-PON2. As the RAN density increases, the cost difference to WR-WDM-PON diminishes. As the FTTH/FTTC ratio decreases, WR-WDM-PON or PtP-CWDM become more favorable depending on RAN density.

Results on 5G radio scenarios:

- For 5G, differences compared to LTE are seen for deployment scenarios that require higher-speed transport (25G, 40G and 100G). In these cases, the overall trends are similar but the convergence benefits of NG-PON2 are reduced gradually with higher interface speed. For fibre-rich scenarios and 100G tranport, there are no more convergence benefits of NG-PON2 and WR-WDM-PON is the most favorable independently of RAN density and FTTH/FTTC ratio.

Results on the impact of the introduction of flexibility at the wavelength level:

- System variants based on flexibility in the WDM layer are feasible for urban and ultra-dense urban scenarios, while sub-urban and rural scenarios require extensive use of optical amplifiers. If no savings are taken into account in terms of resource sharing or facilitated service provisioning, flexible WDM systems lead to an added cost (~20% added to the total transport cost for the corresponding ridged WDM solution). If large dynamicity is expected, savings (in the order of 10-15%) in the total transport cost can be expected by pooling interfaces.

Results on the impact of different protection requirements:

- The FMC architecture should minimize the risk of a total blackout (no fixed and no mobile access) especially for the voice service (emergency calls). Providing protection to the macro basestation sites can be used to guarantee a minimum level of connectivity. All protection architectures allow a significant improvement of the backhaul link availability. It is highly recommended to consider a battery backup at the macro basestation site since the total backhaul link unavailability of all protection architecture variants are dominated by the unavailability of the basestation location powering.
- Dual homing should only be considered in the case of a low Main CO location availability, for example, caused by frequent power failures, climate failures, faulty connections, fire, vandalism etc.

Final recommendations for fixed mobile network integration in 5G context will be drawn in deliverable D3.6, taking into account the main outcomes of 5G transport considerations in this deliverable D3.4 and COMBO architecture comparisons of D3.5, together with the main experimental achievements of D6.3.

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Table of Content

Glossary

2G	2nd Generation (mobile service)
3G	3rd Generation (mobile service)
3GPP	3rd Generation Partnership Project
5G	5th Generation (mobile service)
API	Application Programming Interface
AWG	Arrayed Waveguide Grating
BBU	Base Band Unit
BBUH	BBU Hotel
BFD	Bidirectional Forwarding Detection
BH	BackHaul
BNG	Broadband Network Gateway
BoM	Bill of Material
BRG	Bragg Reflector Gratings
BS	Base Station
CAPEX	Capital Expenditures
CO	Central Office
COMBO	COnvergence of fixed and Mobile BrOadband access/aggregation networks
COMP	Coordinated MultiPoint
CPRI	Common Public Radio Interface
C-RAN	Centralised, Co-operative, Cloud or Clean RAN
CRRP	Clustering, Routing and RCC Placement
CS	Coordinated Scheduling
CSG	Cell Site Gateway
CSI	Channel State Information
CU	Cost Units
CWDM	Coarse Wavelength Division Multiplexing
DAC/ADC	Digital-to-Analog/Analog-to-Digital Conversion
DBA	Dynamic Bandwidth Allocation
DL	Downlink
DMT	Discrete Multi-Tone
DSLAM	Digital Subscriber Line Access Multiplexer
DWDM-PON	Dense Wavelength Division Multiplexed PON
EDB	Electrical Duobinary
EFI	Expected Failure Impact
eNodeB	Evolved Node B
EPC	Evolved Packet Core
FEC	Forward error correction

FH	FrontHaul
FMC	Fixed Mobile Convergence
FP7	Seventh EU Framework Programme
FPC	Failure Penetration Count
FPP	Failure Penetration Probability
FTTB	Fibre To The Building or Fibre To The Basement
FTTC	Fibre To The Cabinet or Fibre To The Curb
FTTH	Fibre To The Home
FTTx	Fibre To The x
FWT	Fixed Wireless Terminal
HW	Hardware
IoT	Internet of Things
IP	Internet Protocol
JT	Joint Transmission
LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Media Access Control
MBS	Macro Base Station
MCA	Minimal Client Availability
MCO	Main CO
MFA	Maximal Failure Area
MIMO	Multiple-Input Multiple-Output
MLSE	Maximum-Likelihood Sequence Estimation
MPLS	Multiprotocol Label Switching
MTC	Machine Type Cellular
NFV	Network Function Virtualization
NGMN	Next Generation Mobile Networks
NG-PON2	Next Generation Passive Optical Network version 2
Node B	Base station (UMTS)
ODB	Optical Duobinary
ODF	Optical Distribution Frame
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency-Division Multiplexing
OLT	Optical Line Termination
ONU	Optical Network Unit
OPEX	Operational Expenditures
P2P	Peer to Peer
PAM4	Pulse-Amplitude Modulation with 4 intensity levels
PHY	Physical Layer Device (interface component)
PON	Passive Optical Network

PPP	Point-to-Point Protocol
PTP	Point-to-Point
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAA	RAN Access Area
RAN	Radio Access Network
RAT	Radio Access Technology
RAT	Radio Access Technology
RBD	Reliability Block Diagram
RCC	Radio Coordination Controller
RGW	Residential Gateway
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RRH	Remote Radio Head
RRU	Remote Radio Unit
RS	Rack Size
RUC	Rack Units occupied by Cell
RUPS	Rack Units Occupied by the Power Supply
SC	Small Cell
SDN	Software Defined Networking
SE	Spectral Efficiency
SFP	Small Form-factor Pluggable
SINR	Signal to Interference and Noise Ratio
SLA	Service Level Agreement
SW	Software
TCO	Total Cost of Ownership
TDM-PON	Time Division Multiplexed PON
TRX	Transmitter
TWDM	Time and Wavelength Division Multiplexing
TWDM PON	Time and wavelength division multiplexed PON
UAG	Universal Access Gateway
uAUT	Universal Authentication
uDPM	Universal Data Path Management
UE	User Equipment
UL	Uplink
ULLS	Ultra Low Latency Switch
UMTS	Universal Mobile Telecommunications System
VPLS	Virtual Private LAN Service
WDM	Wavelength Division Multiplexing
WDM-PON	Wave Division Multiplexing-Passive Optical Network
Wi-Fi	IEEE 802.11 Wireless Local Area Network
WLAN	Wireless Local Area Network
WP	Work Package
WR-DWDM	Wavelength Routing Dense Wavelength Division Multiplexing
WR-WDM-PON	Wavelength Routed Wavelength Division Multiplexing PON
WSS	Wavelength Selective Switch
WS-WDM-PON	Wavelength Selective Wavelength Division Multiplexing PON

1 Introduction

Fixed and mobile access networks have been developed and standardized almost independently from each other over the last decades and often managed by seperate organizations, and hence the degree of structural converence between fixed and mobile networks and pooling of resources between these have been limited.

The transition to All IP consituted one major step towards network convergence, where IP provides a convergence layer with common protocol and addressing on top of diverse access technologies and access-specific protocols. In the past decade, there has been a convergence in the fixed access, where triple-play services have been successfully rolled out on top of a common fixed access infrastructure. In mobile access, the past decade has been characterized by significant growth in mobile broadband, with packet-based services beyond traditional voice. Despite IP convergence, there has been a lack of convergence on a deeper structural level, where fixed and mobile access networks have continuted to evolve independently.

There are several major drivers and enablers for a deeper structural convergence between fixed and mobile networks:

- RAN densification: RAN densification, with an increasing density of mobile cell sites, will play an important role for enabling continued capacity growth in mobile networks. There are three main avenues to increasing the capacity over the RAN air interface, i.e., 1) more spectrum, 2) higher spectral efficiency and 3) RAN densification. For spectrum allocation, there are physical limitations to the amount of spectrum that can be allocated at low frequencies. At higher frequencies, wider bands are at disposal but due to poorer propagation conditions, exploitation will eventually rely on RAN densification (although beamforming technologies will help mitigate need for densification). For spectral efficiency, there is an upper bound dictated by physical limitations. Hence, eventually, RAN densification will remain as an important avenue for increasing capacity in mobile networks. This in turn presents a major challenge for mobile networks where large numbers of small cell sites need to be deployed, managed and connected at sufficienty low cost. This transition in the evolution of mobile networks will raise incentives for reusing available fixed access infrastructure for providing cell-site connectivity and is one major driver for structral convergence.
- Network Functions Virtualization (NFV): Beyond the transition to All IP, several operators are looking at the next steps in optimizing their networks and operations. NFV is a major trend in the industry where the separation of functions and HW brings several benefits. The separation allows for independent lifecycles of HW and SW. NFV is seen to enable faster service creation and deployment, and more efficient utilization of resouces. The long-term vision is a common infrastructure layer with distributed cloud (compute, storage and connectivity) resources that can be utilized both for fixed and mobile networks where parts of the network functions are virtualized and hosted in a common cloud environment.

- Site structure: One obstacle for convergence between fixed and mobile networks has been the structure of the networks and the logic behind how these are evolving. The evolution of fixed-access networks has been characterized by increasing fibre penetration to cater for increasing bandwidths with shorter copper loops and with the ultimite goal of FTTH. Beyond FTTH, several operators have seen node-consolidation as the next step in exploiting the evolution of optical technologies for reducing the number of central-office sites in FTTH networks and related operational costs. In contrast, mobile networks are increasingly characterized by densification. As a response to that, different ways of decomposing and deploying radio functions to enable centralization and pooling of functions have emerged. A key enabler for structural convergence is a common site structure for fixed and mobile networks where similar site locations are needed by the different technologies.
- Access systems: Optical access technologies that can enable relevant convergence scenarios are either mature or maturing. One example is NG-PON2, which has been designed to support various RAN transport deployment options.
- New eco-systems and business models: There is an ongoing transformation where different industry segments are looking at different ways of exploiting connectivity and in particular wireless connectivity. Whereas LTE brought mobile broadband, it is expected that 5G will be an enabler for the Networked Society, supporting improved mobile broadband but also completely new use cases such as massive machine-type communications (MTC) and mission-critical MTC. Not only will this bring a large range of applications with a vast span of requirements, it will also bring new actor cooperation models where the traditional role of the operator may change. This may impact the tradititional fixed/mobile organizations and new actors and roles may appear. Hence, new ecosystems for connectivity and infrastructure beyond the traditional operator-subscriber model will emerge, challenging today's structure with fixed and mobile operators.

The goal of COMBO Task 3.3 – Convergence of fixed / mobile equipment and infrastructure (structural convergence) – is to define and develop candidate architectures for structural convergence. Specifically, Task 3.3 focuses on converged transport in access and aggregation networks. As illustrated in Figure 1, the considered scope goes from the small cell (SC) / macro basestation (MBS) site or fixed-access client up to the Core Central Office (CCO), which is the boundary between the aggregation network and the core network.

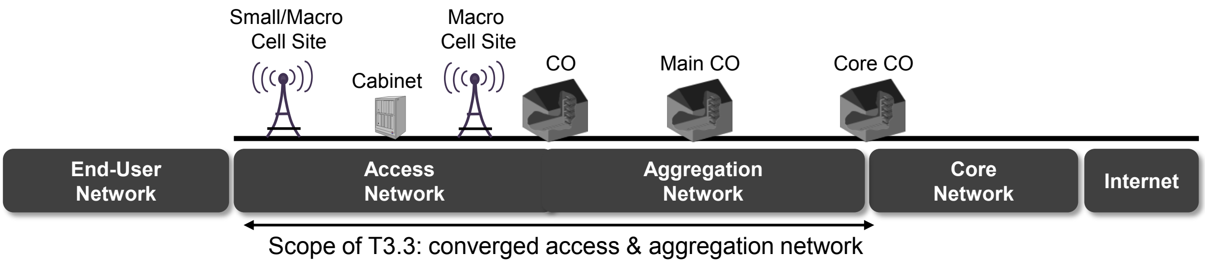


Figure 1: The scope of study of Task 3.3 – from cell sites up to the Core CO

The focus of the COMBO project has been on structural convergence of connectivity in the challenging access/aggregation segment. In this segment, there are increasing incentives for convergence and reuse of infrastructure as the RAN is densified. An important condition for convergence of connectivity resources is the convergence of locations or sites for hosting converged infrastructure. For this to be possible, the site distribution needs to be favorable for both fixed and mobile deployment. The consolidated fixed-access nodes should be compatible with latency requirements associated with the prefered mobile deployment. This is illustrated in Figure 2 where Figure 2a depicts a hypothetical non-converged network with dedicated systems for different purposes and site/node distribution dictated by individual requirements of each access. Figure 2b shows a converged scenario with a common access infrastructure and common sites between fixed and mobile access.

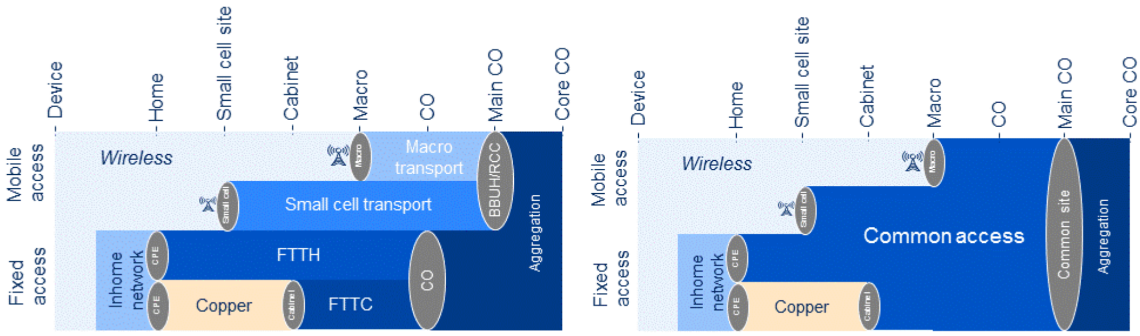


Figure 2: The left-hand figure shows a hypothetical non-converged scenario with multiple access systems/technologies and sites. The right-hand side shows structural convergence featuring convergence of sites structure and access systems/technologies.

Assuming a concentration of equipment at the main CO (MCO), the focus of structural convergence is on the access segment between the MCO and different client sites (Figure 3).

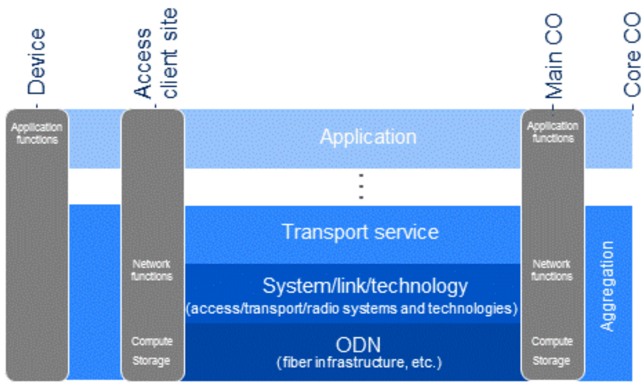


Figure 3: Focus area for structural convergence in COMBO and different convergence opportunities (ODN convergence, system level convergence, etc)

Hence, in the access segment, sharing of connectivity resources may range from sharing lower-layer fibre resources to sharing higher-level system resources (Figure 4). The main COMBO scenarios summarized here assume TWDM PON services for FTTH. Furthermore, they assume that PtP wavelength connectivity will be required for mobile transport as well as being favorable for cabinet backhaul in FTTC areas. The key question of structural convergence in COMBO concerns the convergence of

TWDM PON and PtP-wavelength services over the same access fibre infrastructure. Figure 4 depicts three key structural convergence scenarios. The scenario in Figure 4a, illustrating system convergence based on TWDM PON, is outside of the COMBO focus as it does not comply with stringent requirements associated with various mobile deployments. The scenario in Figure 4b illustrates convergence on the ODN level, whereas the scenario in Figure 4c illustrates dedicated infrastructure for TWDM PON services and PtP wavelength services.

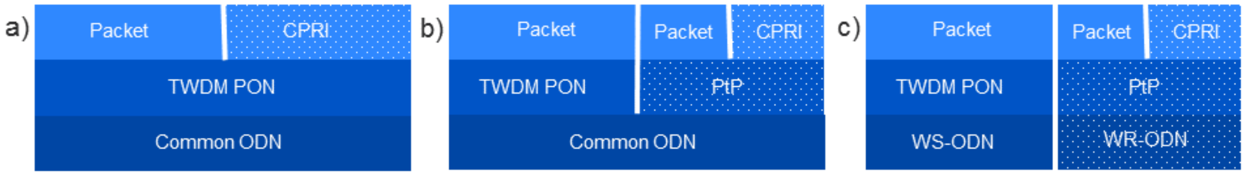


Figure 4: Different convergence scenarios in COMBO for connectivity between main CO and client sites featuring a) system level convergence, b) ODN convergence, c) dedicated infrastructure.

Given the convergence of sites, the next aspect is convergence of node resources. This includes system resources for the optical access systems and also potentially distributed cloud resources such as compute and storage resources for hosting various functions (fixed access, mobile access, applications, etc). This aspect of structural convergence is covered in Deliverable D6.1 [2] with the concept of the universal access gateway (UAG). The UAG provides converged node resources which may be used for both fixed and mobile access purposes.

Deliverable D3.4 extends the analysis of D3.3 [1] in several aspects:

- Decentralised RAN architectures: in the architectures considered in D3.3, it was assumed that the MCO is the main point for coordination, that is, either for placement of BBU hotels or for RAN coordination functions. An alternative location for this is the macro site. This involves distributed placement of BBUs or RAN-coordination functions at macro sites. Chapter 3 in this deliverable extends the analysis considering such distributed coordination architectures.
- 5G dimensioning: the work done in D3.3 considered mainly LTE-based RAN. During the past two-three years, there has been considerable work in defining 5G radio. 5G will bring increased radio capacity and to support that, advanced radio technologies and higher small-cell densities will be required. New antenna technologies will drive fronthaul bit rates towards the terabit-per-second region. New RAN splits have been proposed to mitigate the related transport requirements while still allowing for some degree of radio coordination and resource pooling. Chapter 4 in this deliverable extends the analysis by considering 5G traffic projections, 5G antenna configurations and new RAN splits.
- Flexibility, management & orchestration: the techno-economic results are extended to flexible system concepts, and different management and orchestration architectures are discussed.
- Protection: results in D3.3 omit protection requirements. With the general trend of increased dependency on connectivity and as the infrastructure converges, reliability will be an increasingly important requirement. Chapter 6

considers different protection schemes, how they affect reliability and how this impacts conclusions on structural convergence.

2 Methodology

This chapter describes the methodology used for the techno-economic analysis. Two main techno-economic studies are performed in this deliverable extending the results of D3.3 to:

- Decentralised SC aggregation architectures (Chapter 3)
- 5G RAN (Chapter 4)

Both cases start from the methodology described in D3.3 chapters 5 and 7, where the key elements for the evaluation of structural convergence were introduced. These elements include the access and aggregation technologies, the RAN architectures, the radio coordination schemes, the node consolidation approach, the HetNet model and the geotypes.

The extension of the analysis to decentralised coordination architectures involves consideration of additional RAN architectures not included in D3.3. Here, the scenarios for centralised aggregation (x-haul) of SCs and MBSs to the MCO are complemented by scenarios with decentralised aggregation (x-haul) of SCs to the MBS (Figure 5 left). The extension of the analysis to 5G RAN introduces a modified HetNet model, shifting the radio configuration and traffic volumes from LTE to 5G in centralised and decentralised scenarios (Figure 5 right).

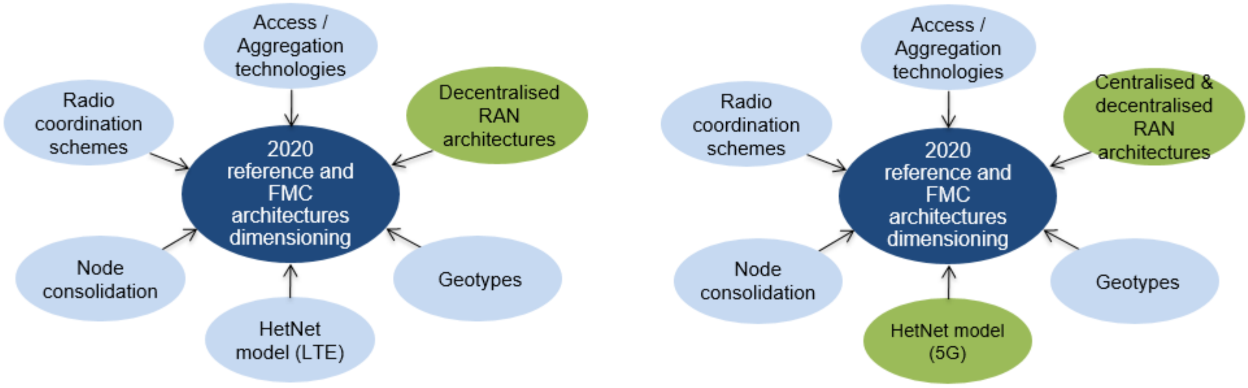


Figure 5: Scope of architectural evaluation with changes in D3.4 compared to D3.3 indicated in green. Left hand side shows scope of techno-economic studies in Chapter 3. Right hand side shows scope of techno-economic studies in Chapter 4.

Similar as for the techno-economic study in D3.3, the techno-economic studies in this deliverable are based on the same starting scenario, basic assumptions and methodology. The following list includes a summary of the most relevant points:

- A brownfield starting scenario with available fixed-access network infrastructure assets (like ducts, cables, fibres, and power) that can be reused depending on the degree of convergence.
- The brownfield scenario consisting of two main areas types: FTTC areas with active nodes at street cabinets that are connected via fibre to the CO, and FTTH areas based on a PON deployment with a split ratio of 1:128 (the fibre cost model

for FTTC and FTTH areas is described in Appendix 8.4). The study starts with a 30% FTTH mass-market deployment, which is sensitivity-analysed subsequently though variation from 0% up to 100% FTTH/FTTC penetration ratio.

- A basic SC deployment with an average of 10 SCs per MBS and assuming single-provider operation per small-cell location. In the 5G scenario, the SC density is increased to 50 SCs per MBS. The impact of this value is also sensitivity-analysed through variation from 3 to 150 SCs per MBS.
- An LTE radio configuration for both MBS and SCs with 40 MHz, 4x4 MIMO and 20 MHz, 2x2 MIMO, respectively. The MBS has three sectors and the SC is single-sectored. The MBS also hosts 3G and 2G equipment. For 5G, the radio configuration is increased to 125 MHz with 16x16 MIMO.
- Fronthaul and backhaul scenarios using 3-Gb/s and 10-Gb/s network interfaces for LTE and up to 100 Gb/s for 5G (see Appendix 8.4).
- Four different geotypes (ultra-dense urban, urban, sub-urban and rural) for a typical MCO area in Central Europe in 2020 (see Appendix 8.4.2 for geo-data details). Ultra-dense urban and urban areas continue to be of main interest, because of the expected earlier and higher demand for SC deployments. As in D3.3, for rural areas only MBS enhancements without additional SC deployments are considered.
- A reference network architecture for 2020 based on existing fixed mass-market access technology and PtP CWDM technology for mobile x-haul. This reference network architecture will be used for the comparison with converged x-haul solutions using NG-PON2, WR-WDM-PON and WS-WDM-PON technologies.
- The network architecture options are applied to the four geotypes to generate a Bill of Material (BoM). The BoM contains the amount of network elements needed (such as interfaces, splitters, amplifiers, fibres, etc.) to cover different areas for all kinds of geotypes and technologies.

Finally, a cost database is used together with the network dimensioning results to obtain the deployment cost. The cost database is based on the contributions from the industrial patners in the consortium and is provided as a separate document. Cost values are normalized using the cost of a standard ONU, which is equal to 100 cost units (CU). Chapter 3 details the study regarding the decentralisation of the RAN coordination to the MBS, whereas chapter 4 analyses the impact of 5G on FMC network architectures.

3 Decentralised RAN Architectures for LTE

COMBO deliverable D3.3 analyses different transport solutions for structural convergence for LTE. This chapter extends and complements these results. As illustrated in Figure 6, Chapter 3 extends the analysis to architectures where the radio coordination controller (RCC) is decentralised to the MBS. Section 3.1 presents the architectures for the decentralised RAN-coordination architectures. Section 3.2 provides a techno-economic analysis of the transport architectures for these additional scenarios. Section 3.3 provides an analysis of the RAN costs considering BBU and RCC components in relation to the different COMBO architectures and scenarios. Section 3.3 also complements the cost assessment with an analysis of coordination gain (i.e., improved RAN performance) associated with different RCC placement options.

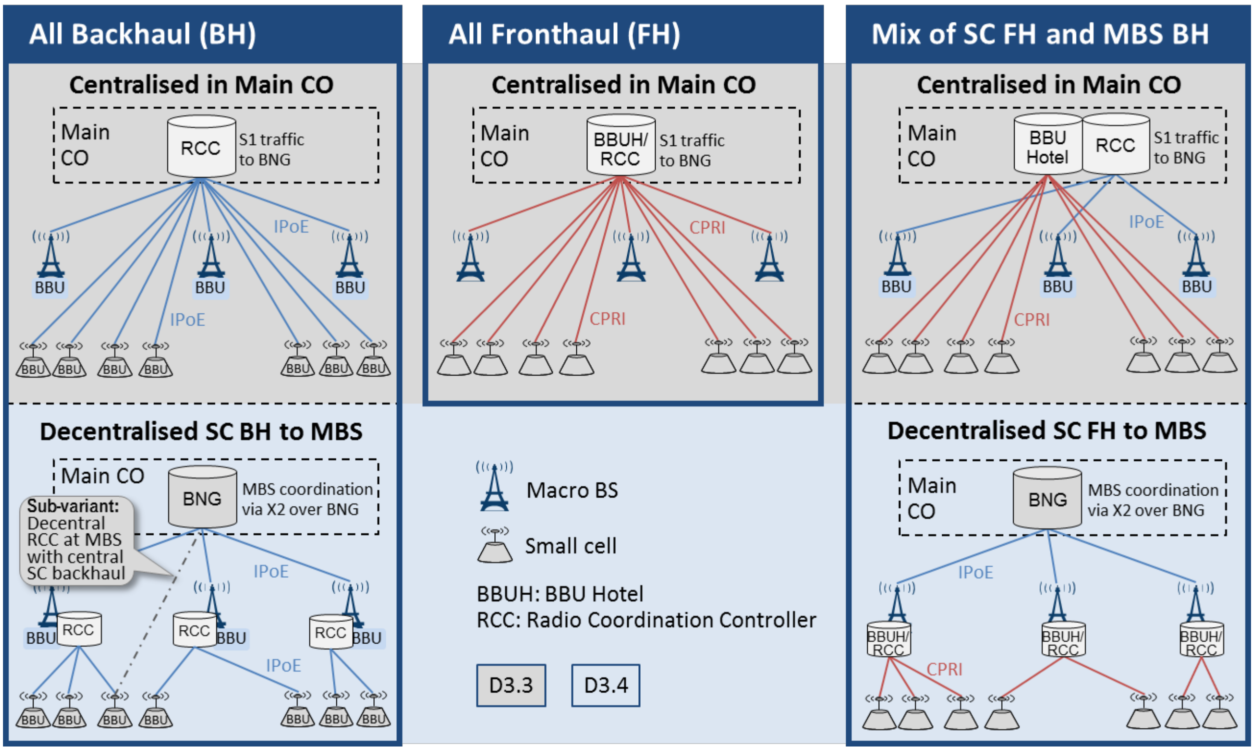


Figure 6: RAN architecture options in focus of COMBO

3.1 Decentral Coordination Architectures

D3.3 analyses the impact of different RAN deployment options, i.e., backhaul and fronthaul, coordination requirements and transport solutions, with special focus on converged transport solutions centralised at the MCO. One implication of decentralised RAN coordination (with RCC placement at the MBS) is that SCs are aggregated via the MBSs (as seen in Figure 6) instead of directly to the MCO. We refer to this as decentralised SC aggregation (backhaul/fronthaul). Decentralised SC backhaul aggregation follows the Midhaul definition of the Metro Ethernet Forum [3], where the mobile backhaul of SCs is done to the nearest MBS instead directly to the MCO. Another aspect of decentralised RAN coordination is that the BBU Hotel (BBUH) for the related SCs may also favorably be placed at the MBS.

Table 1 summarizes the different functions that may be centralised or distributed resulting in multiple architectural combinations of which some maybe more favorable than others. In deliverable D3.3, it was assumed that coordination (RCC) was centralised to the MCO and that SCs were aggregated directly to the MCO (row “D3.3” in Figure 6 and column “D3.3” in *Table 1*). With these assumptions, two options for BBU placement were considered ((1) and (2) in *Table 1*). This chapter considers architectures where the RCC is hosted at the MBS (row “D3.4” in Figure 6 and column “D3.4” in *Table 1*), which would also lead to decentralised aggregation (3) and BBUH at the MBS (4).

Table 1: Summary of different functions that can be centralised/distributed

	D3.3: Aggregation of SC at MCO	D3.4: Aggregation of SC at MBS
Integrated RBS	(1) RCC at MCO	(3) RCC at MBS
Centralised RAN	(2) BBUH and RCC at MCO	(4) BBUH and RCC at MBS

Given these combinations, two main scenarios are proposed:

- Decentralised SC backhaul to MBS (3): SCs are connected directly to a decentralised RCC at the MBS, terminating the X2 traffic of the SCs and handling the interference coordination from the MBS. SCs and MBS are commonly backhauled towards the MCO. Radio coordination between neighbouring MBSs is handled via the X2 interface interconnection through the MCO.
- Decentralised SC fronthaul to MBS (4): SCs are connected directly to a decentralised BBUH at the MBS, terminating the CPRI links of the SCs. The X2 traffic for the inter-BBU communication between the basebands of all connected SCs is handled by an RCC unit, which is located next to or integrated into the BBUH at the MBS. As in the decentralised SC backhaul variant above, the SCs and MBS are commonly backhauled towards the MCO and the radio coordination between neighbouring MBSs is done in the same way.

For both alternatives, it is assumed that the connection between the SCs and the MBS is enabled at an optical distribution frame (ODF) located at the CO. Typically, there is no direct duct/fibre connection between a SC and a neighboring MBS. Also, since FTTx infrastructure is not used for the MBS connection, as they have been deployed independently, the first common point in the infrastructure where connections between SCs and MBSs could be provided, is at the CO. The connection could also be realized at more centralised locations such as at the Main CO resulting in a third scenario 'Decentralised RCC with Central Backhaul'. This alternative is described in section 3.1.3 but not included in the techno-economic study, as it has similar cost structure as the "All Backhaul – Centralised in MCO" scenario analysed in D3.3.

For the decentralised SC aggregation architectures, backhaul and fronthaul have the same requirements in terms of link capacity, synchronization and delay as the centralised alternatives described in chapter 3 of D3.3 (including a round-trip time below 1 ms for very tight coordination). Three system solutions for FMC are analysed and compared against the 2020 reference network architecture, adapted for a decentralised SC aggregation approach. More details on these system solutions can be found in D3.3 Chapters 5 and 6:

- NG-PON2 with PtP WDM (using power-split ODN)
- Expanded-spectrum Wavelength-Selective (WS) WDM-PON ODN
- Expanded-spectrum Wavelength-Routed (WR) WDM-PON ODN

Decentralised aggregation architectures require new passive elements in the CO and new fibres to connect the SCs to their corresponding MBS; however, they require less equipment to be installed at the MCO due to the smaler number of x-haul links that are terminated at the MCO and less feeder fibres in the segment CO ↔ MCO. It also offers some degree of SC traffic aggregation at the MBS. The next sections, 3.1.1, 3.1.2, 3.1.3 introduce the decentralised aggregation architectures, whereas the detailed architectures are described in the Appendix 8.5. Sections 3.2 and 3.3 compare the different network architectures in terms of cost to quantify savings and expenses.

3.1.1 Decentralised Small cell Backhaul / RCC

The small cells are connected via passive fibre links through the ODF in the CO towards the MBS. An access technology is used between CO ↔ MBS because of the cumulative fibre demand for connecting several small cells per MBS. The higher fibre demand between CO ↔ MBS is to a certain degree compensated by fibre savings in the feeder part between CO ↔ MCO compared to centralised architectures. The RCC at the MBS handles, amongst others, the interference coordination between the MBS and the belonging SCs via the Xn interface. The SC backhaul access system at the MBS (OLT in case of PON or direct PtP interfaces in case of Bidi-CWDM) and the CSG of the MBS backhaul are connected to the RCC at MBS. Both, the MBS and SC traffic, is backhauled via a common backhaul link between the RCC at the MBS and the BNG at the MCO. Radio coordination between neighbouring MBSs is handled via the X2 interface between the RCCs at corresponding MBSs, which is connected through the BNG, supporting low-latency switching. The S1 traffic is forwarded from the BNG towards the Evolved Packet Core (EPC), see Figure 7.

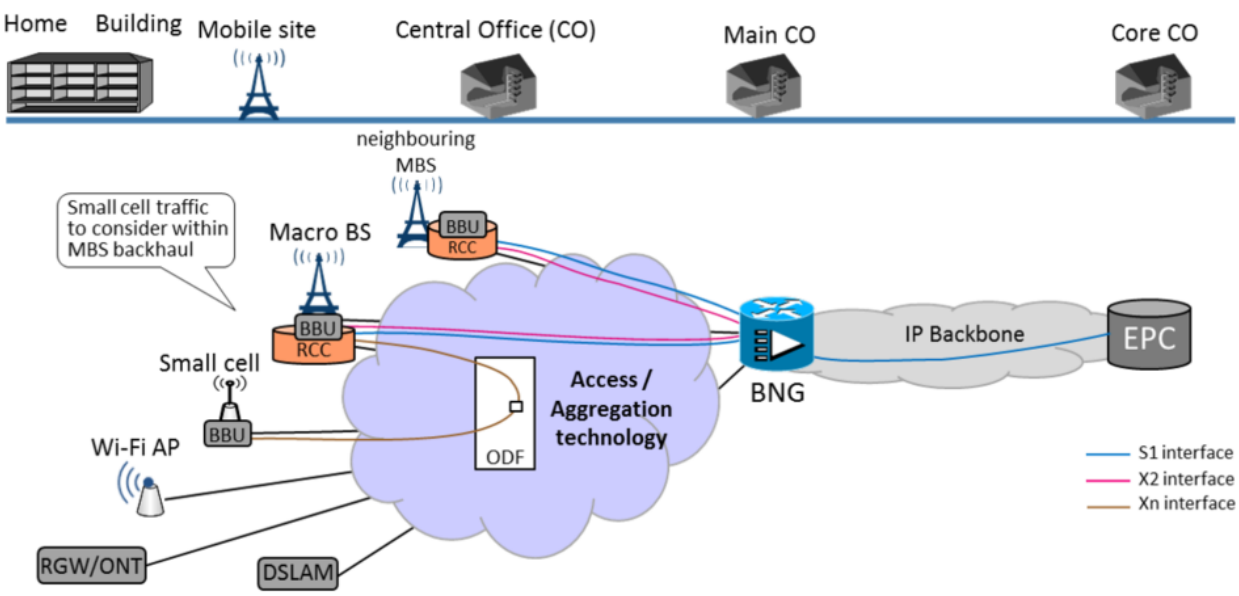


Figure 7: All-backhaul variant – Decentralised SC backhaul with RCC at MBS

3.1.2 Decentralised Small cell Fronthaul / BBUH

The structural architecture is identical with the decentralised SC backhaul case in the former section, with the exception that the SCs are connected via fronthaul links towards the MBS and a BBUH with an (integrated) RCC unit is placed at the MBS. The same access technologies as in the former chapter will be taken into account between CO ↔ MBS to overcome the cumulative fibre demand for connecting several SCs per MBS. A BBUH at the MBS handles the baseband processing and interference coordination of the MBS and the belonging SCs. The SC fronthaul access system at the MBS (OLT in case of PON or direct PtP interfaces in case of Bidi-CWDM) is connected to the BBUH at the MBS. The BBUH and the CSG of the MBS backhaul are commonly backhauled via PON or PtP towards the Main CO. The S1 traffic is forwarded from the BNG at MCO towards the EPC, see Figure 8. Radio coordination between neighbouring MBSs is handled via inter-BBU communication of the corresponding MBSs using the X2 interface, which is connected through, e.g., the BNG.

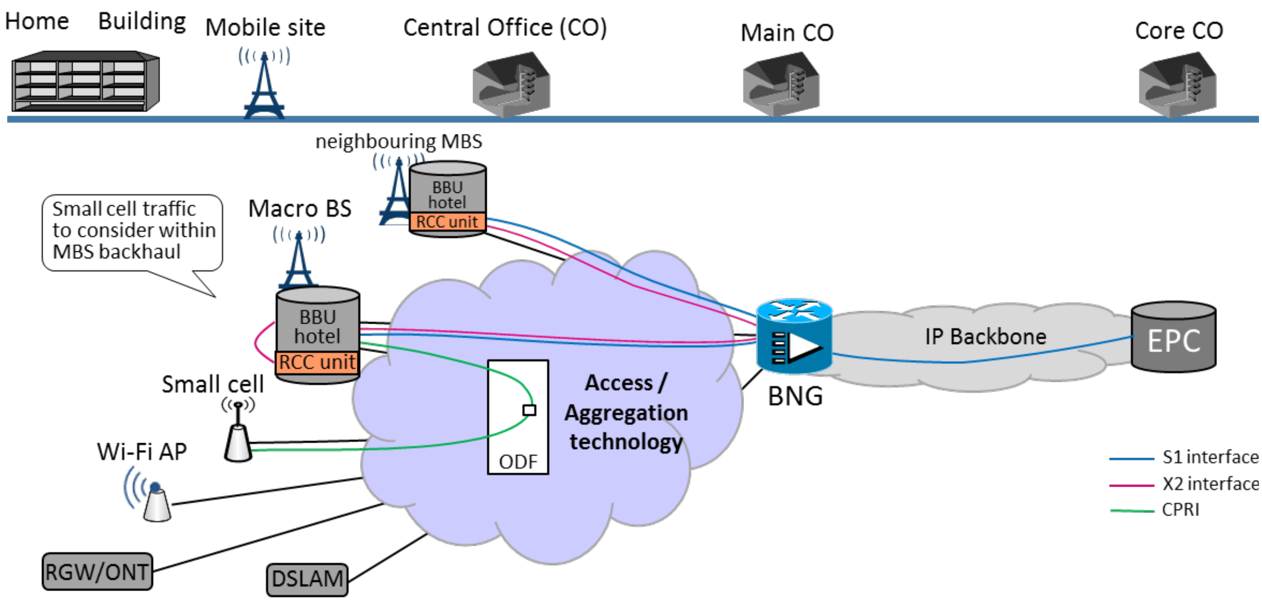


Figure 8: Mixed back-/fronthaul variant – Decentralised SC fronthaul with BBUH at MBS

3.1.3 Decentralised RCC with Central Backhaul

The motivation for this variant comes from the thought to place mobile equipment exclusively at the cell site and core edges of the network, while keeping all backhaul connections centralised. The difference to the D3.3 scenario lies in the decentralisation of the RCC functionality at the MBS, as shown in Figure 9. The decentralised RCC handles the interference coordination between the MBS and SCs via the Xn interface, which is connected through, e.g., the BNG in the MCO. The Xn traffic between the MBS and SCs includes control data as well as S1 user plane data. The structural backhaul architecture is identical with the centralised backhaul variant of D3.3, causing similar transport costs. Cost differences compared to the centralised D3.3 variant are therefore mainly expected for the mobile RCC equipment, which will be analysed in section 3.3.

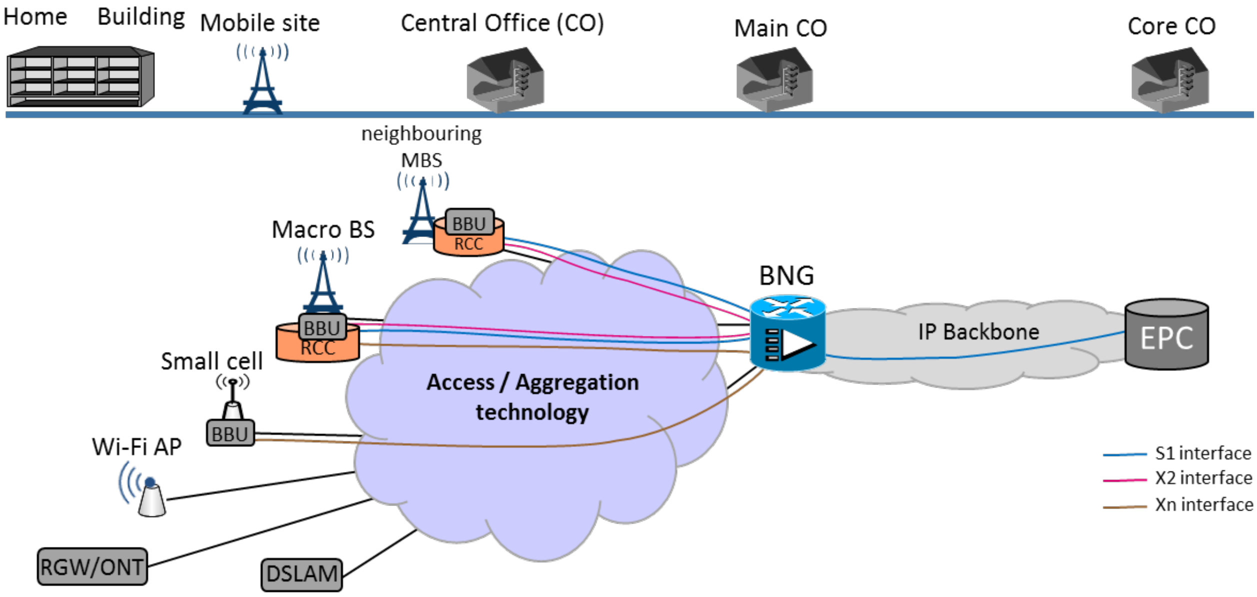


Figure 9: All-backhaul variant – Decentralised RCC at MBS with central backhaul

3.2 Comparison of Transport Cost

3.2.1 Cost Comparison of Decentral Architectures

This section presents the results for the cost assessment of the decentralised coordination architectures, comparing the different FMC solutions as well as the reference solution (PtP CWDM). In order to obtain comparable results to the centralised architectures (see section 3.2.2 for that comparison), the same "medium case" SC density as in D3.3 Chapter 5.1 is assumed, i.e., 10 SCs per MBS. Furthermore, we assume full FTTC coverage with an additional 30% FTTH coverage. Rural areas are not included in the assessment, as we do not assume SCs to be widely deployed there.

As for scenarios with centralised RAN coordination, the cost per connection (i.e., the cost divided by the number of cabinets, MBS and SC) increases as the population density decreases (see Figure 10). Considering the previous assumptions, cost differences among the 2020 reference architecture and FMC architectures are small (less than 10%); FMC solutions are not always the most favorable for all geotypes. The most cost efficient solutions are based on wavelength filtering.

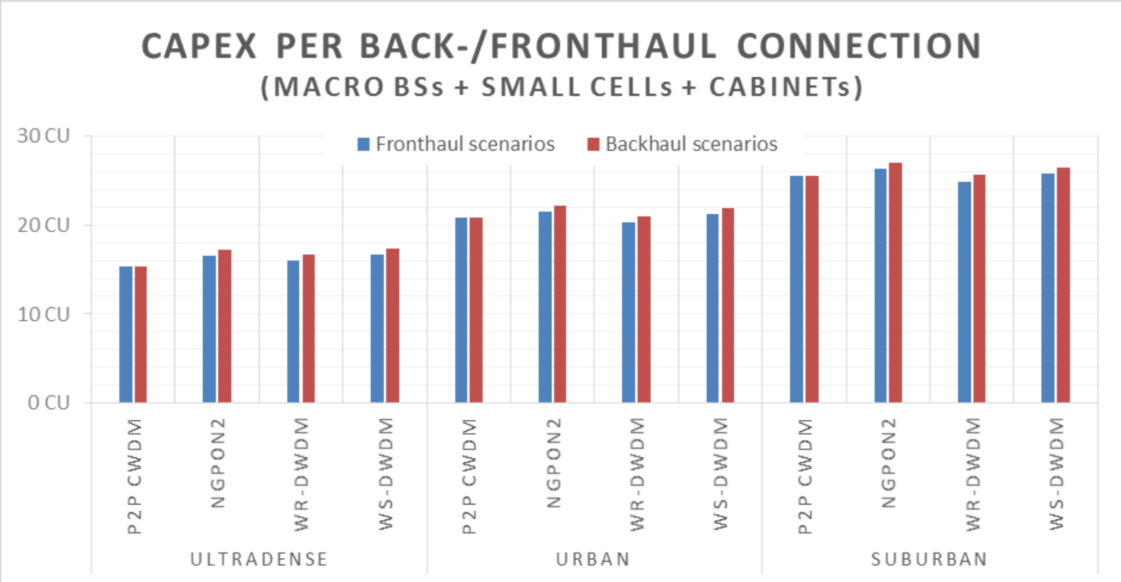


Figure 10: Total CapEx of backhaul and fronthaul architecture per geotype

Figure 11 depicts the cost difference between fronthaul and backhaul for each technology solution and for the analysed geotypes (100% is the cost of the backhaul case of the same technology). Note that in case of fronthaul the BBUH is here located at the MBS. The figure shows that the backhaul cost is the same as the fronthaul cost for P2P CWDM, as the same number of network resources is required in both cases. However, for FMC technology solutions, fronthaul is cheaper than backhaul, because fronthaul links are connected directly to the BBUH while backhaul requires an aggregation element for the interconnection to the RCC. Comparing the fronthaul cost of the four investigated technologies, Figure 12 shows that WR-WDM-PON has the lowest cost in urban and sub-urban geotypes, whereas P2P CWDM is the cheapest in the ultra-dense geotype.

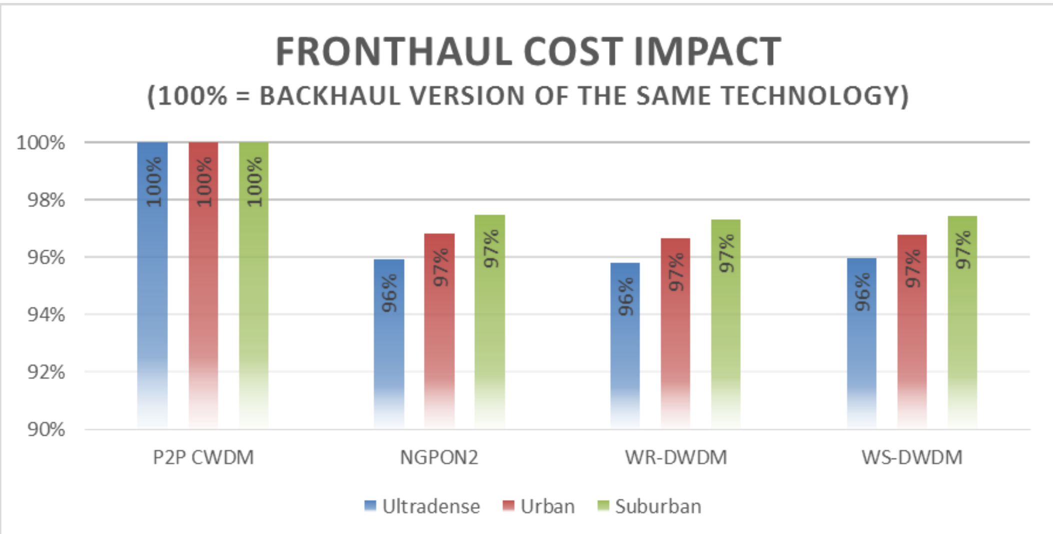


Figure 11: Decentralised SC Fronthaul vs. Backhaul costs I

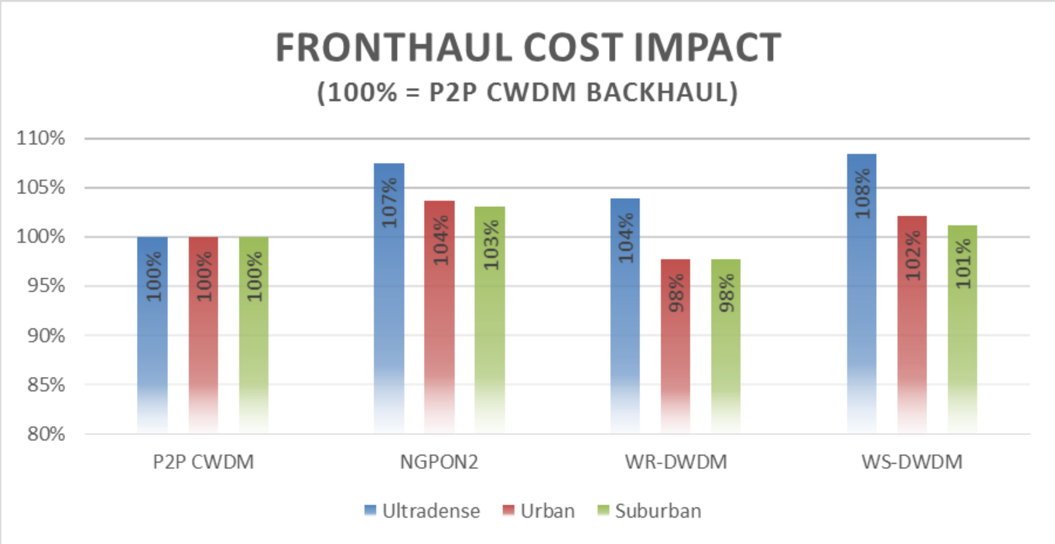


Figure 12: Decentralised SC Fronthaul vs. Backhaul costs II

Figure 13 details a cost breakdown of results for backhaul in the urban geotype (other geotypes show similar results) in order to understand the factors being responsible for the cost differences. Fibre cabling is responsible for a large percentage of the total CapEx. FMC solutions result in lower fibre cost due to the higher wavelength count for the WDM PON options and due to fibre reuse for the NG-PON2. Concerning Main CO and Macro sites, P2P CWDM and WR-WDM-PON have the lowest cost due to the reduced quantity of network elements of P2P CWDM and due to the higher number of channels supported by WR-WDM-PON (compared to WS-WDM-PON and NG-PON2) resulting in more efficient use or filters and amplifiers.

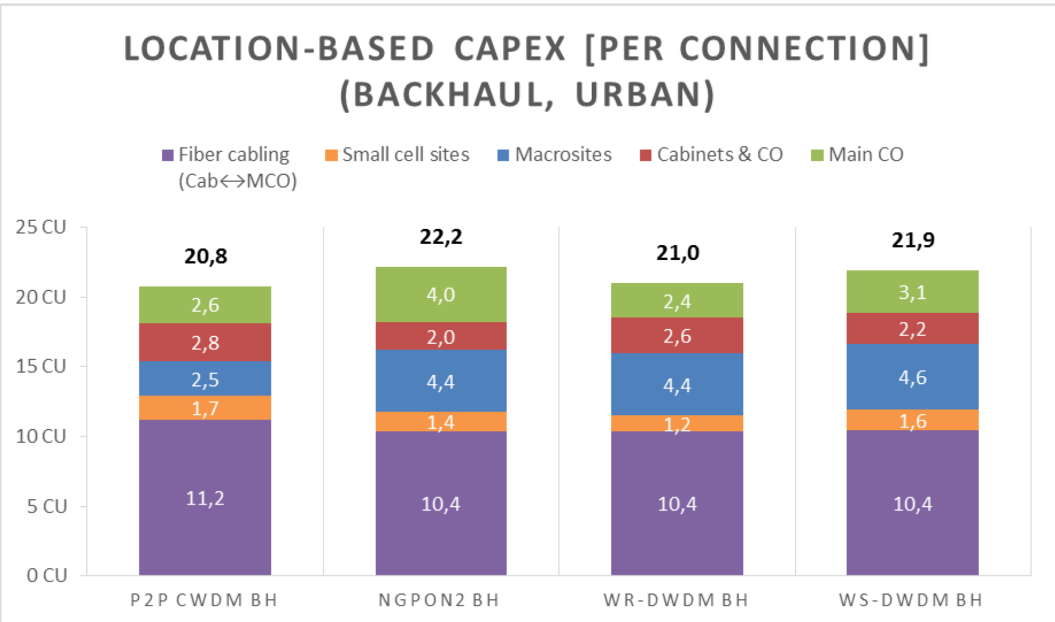


Figure 13: Location-based CapEx of decentralised urban backhaul architecture

A cost breakdown for fronthaul in an urban geotype is shown in Figure 14. The contribution of the different cost components to the total CapEx is similar as for backhaul. The cost of fibre cabling is the same as for backhaul since the same number of fibres are required for the SCs and for the MBSs. MCO costs are also the same, as the connection to the MBS is mobile backhaul in both cases. SC costs are also the same, as they require the same network resources for both fronthaul and backhaul in our model. The main difference is at the MBS location, where the FMC technology solutions use an OLT for backhaul (aggregating the SC traffic) and fronthaul (interconnecting the SCs to the BBUH without aggregation), with this second option being cheaper as switching capabilities and a high-capacity backplane in the OLT is not needed. This cost breakdown does not include the BBUH cost at the MBS location, which is analysed separately in section 3.3.

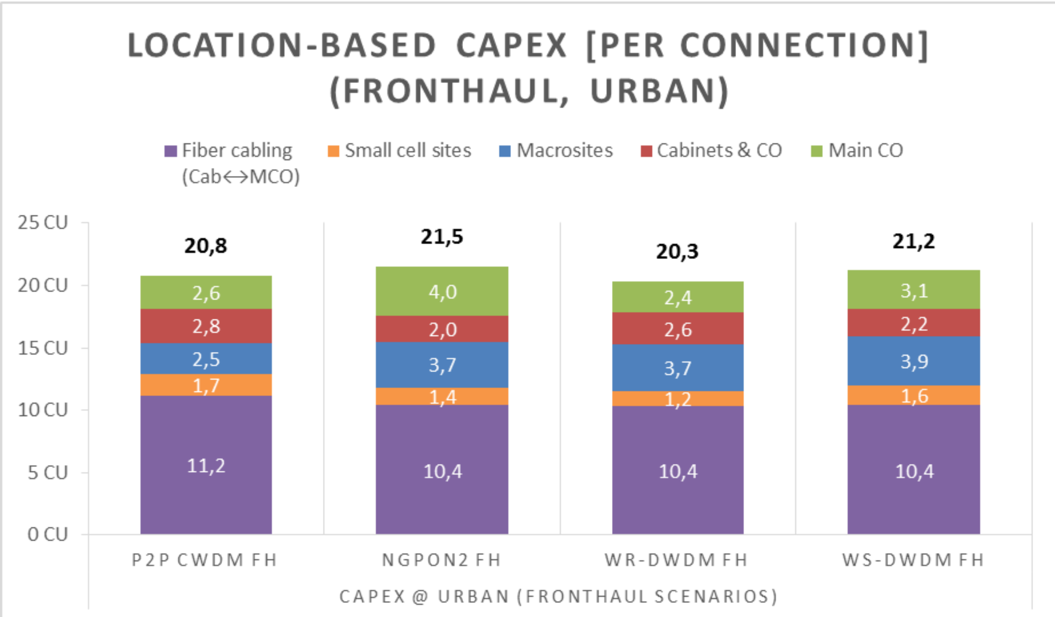


Figure 14: Location-based CapEx of decentralised urban fronthaul architecture

3.2.2 Cost Comparison of Decentral vs. Central Architectures

This section provides a CapEx comparison between the decentralised architectures presented in the previous sections with the centralised architectures of D3.3. Figure 15 shows the cost per connection for the different technology solutions per geotype and for either centralised or decentralised architectures. As can be seen, the overall cost per connection increases from ultra-dense towards less populated areas in both cases.

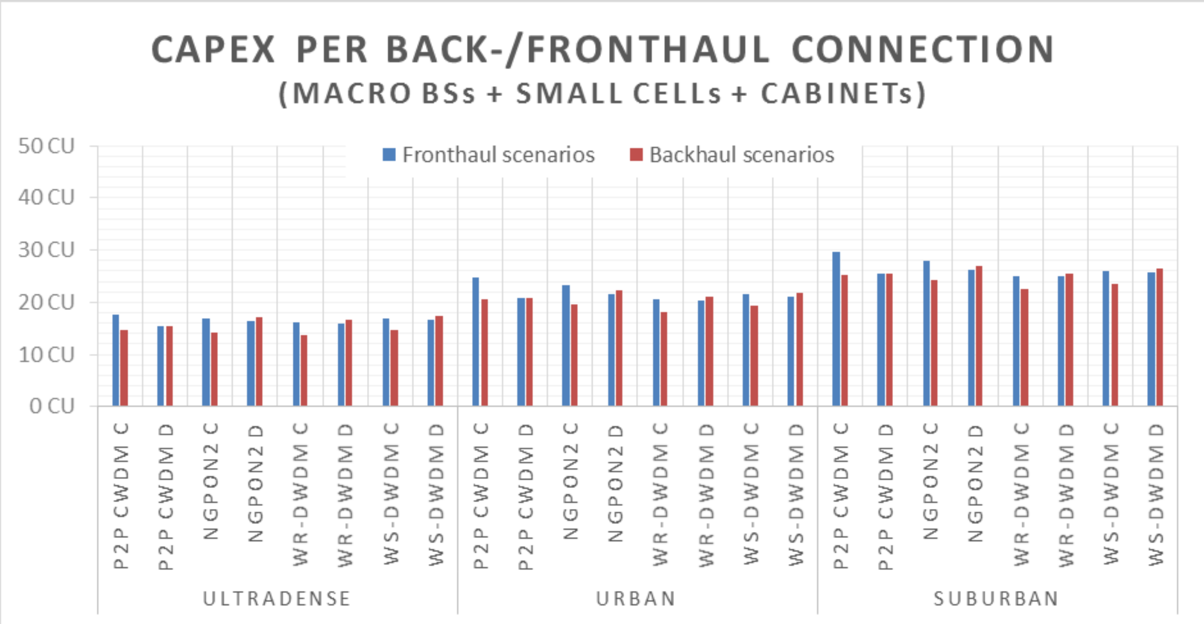


Figure 15: Total CapEx of backhaul and fronthaul architecture per geotype: Centralised vs Decentralised

For backhaul, the cost per connection is lower for the centralised case compared to the decentralised case. *Table 2* shows the cost ratio between centralised and decentralised architectures for backhaul. The largest differences (between centralised and decentralised) are seen for the FMC solutions in the ultra-dense geotype.

Table 2: Centralised vs decentralised backhaul CapEx ratio

CapEx	PtP CWDM BH	NG-PON2 BH	WR-WDM-PON BH	WS-WDM-PON BH
Ultra-dense	95%	83%	83%	85%
Urban	99%	89%	87%	88%
Sub-urban	99%	91%	89%	89%

Decentralised SC backhaul requires OLTs or network elements at the MBS, which are not needed for centralised SC backhaul. This additional cost at the MBS is not compensated by the cost reduction for decentralised scenarios in terms of less network interfaces at the MCO and fewer feeder fibres, as shown in Figure 16. PtP CWDM backhaul does not require an OLT at the MBS and for this reason, the cost differences are lower for this technology.

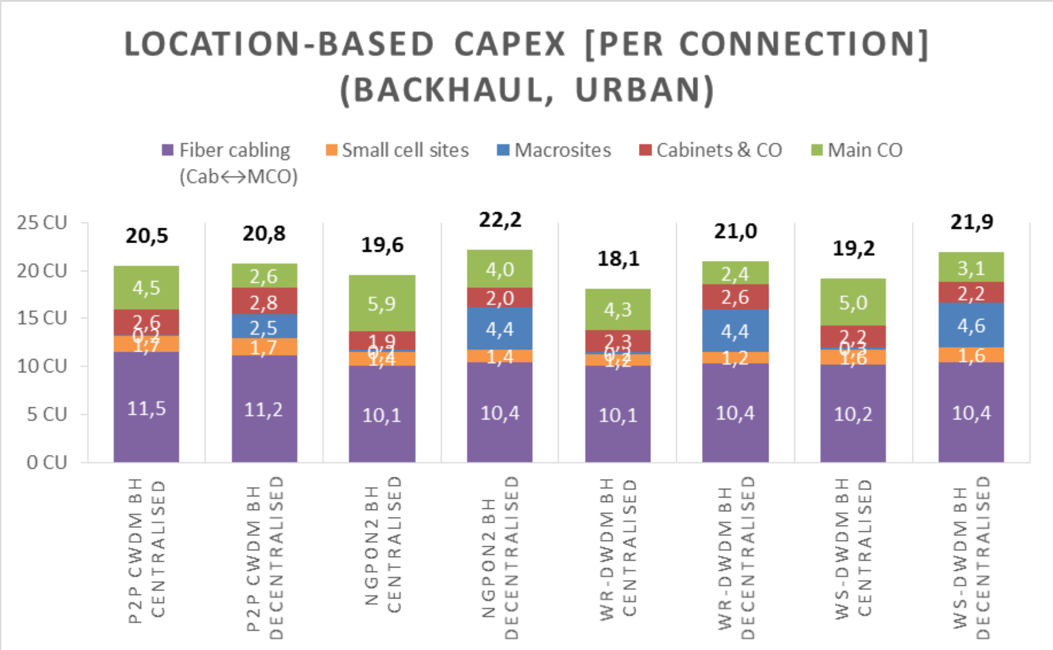


Figure 16: Location-based CapEx comparison for urban backhaul architectures

For fronthaul, the cost per connection is higher for the centralised case compared to the decentralised case. *Table 3* shows the centralised vs. decentralised cost ratio for fronthaul architectures. Note that for the centralised case, the BBUH is at the MCO while for the decentralised case, the BBUH is at the MBS. The largest difference is seen for the PtP CWDM solution. WR/WS-WDM-PON fronthaul have a slight cost increase up to 2 percent, while NG-PON2 fronthaul has an increase lower than 10 percent.

Table 3: Centralised vs. decentralised fronthaul CapEx ratio

CapEx	PtP CWDM FH	NG-PON2 FH	WR-WDM-PON FH	WS-WDM-PON FH
Ultra-dense	114%	102%	102%	101%
Urban	119%	108%	101%	102%
Sub-urban	116%	106%	100%	101%

Figure 17 shows the detailed comparison of the CapEx per fronthaul connection for the urban scenario, illustrating how the cost is split per each network location. Decentralised SC fronthaul is cheaper than centralised SC fronthaul because less network resources are needed:

- Only one network interface with a single channel required at the MBS to transport the aggregated traffic of all MBS and SCs

- New elements at the MBS and CO required but their cost is compensated by the lower number of network resources at the MCO
- Additional distribution and main fibres, but this cost is compensated by the reduction in the number of feeder fibres

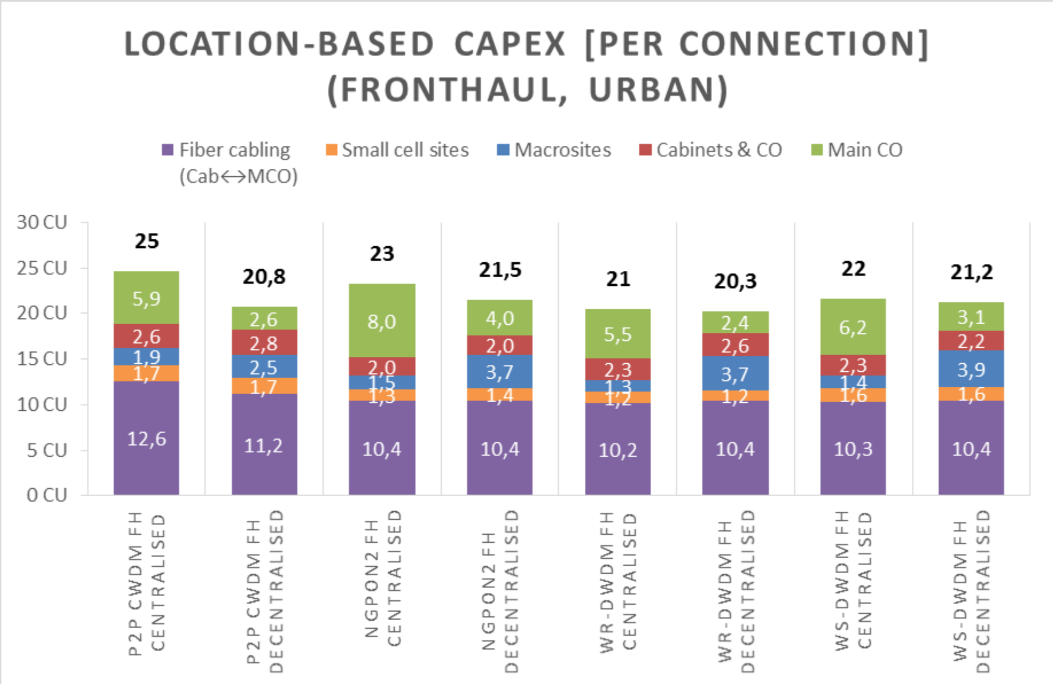


Figure 17: Location-based CapEx comparison for urban fronthaul architectures

Figure 18 presents the cost increase (above 100 percent) or reduction (below 100 percent) per location, for the urban geotype, comparing centralised and decentralised architectures (for both, backhaul and fronthaul). Although backhaul and fronthaul present different increase or reduction ratios, in general, for centralised architectures, the cost of the MCO is increased whereas the cost of the CO and MBS is reduced.

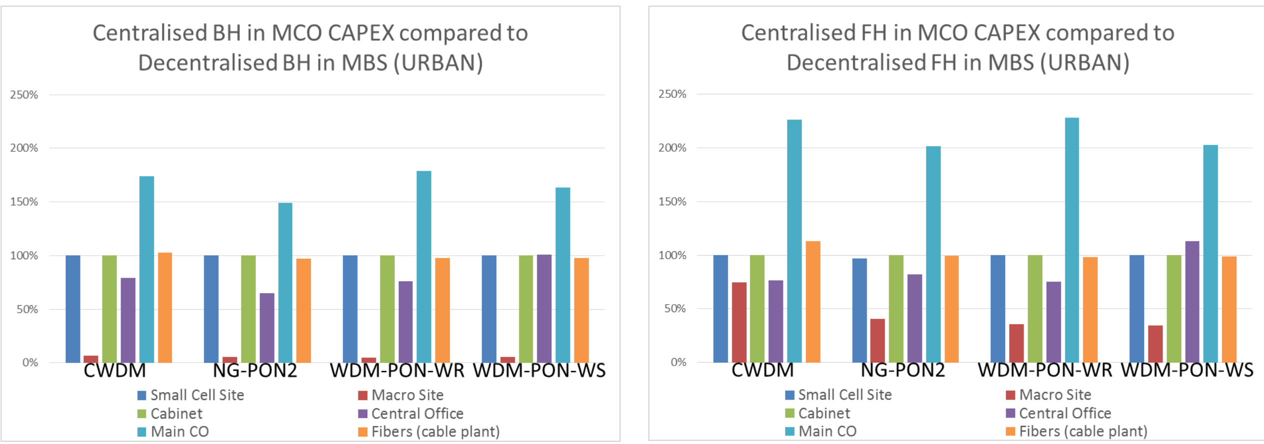


Figure 18: Increase or reduction ratio for centralised vs decentralised backhaul and fronthaul

3.2.3 Analysis of Convergence Potential

The previous sections have compared results for different technology options (CWDM 2020 reference network, NG-PON2 and WR/WS-WDM-PON) for a scenario with 30% FTTH area coverage and a SC density of 10 SCs per MBS. This section deals with a sensitivity analysis regarding variations of the SC density and the FTTH coverage.

For decentralised backhaul of SCs to MBS, results are similar to the fronthaul results due to the facts that fibres are aggregated in both cases between CO (where the SC are through-connected) and MBS, as well as the same amount of interfaces is required when considering one interface per SC. Therefore, only backhaul results are shown in this section in contrast to the centralised scenarios, where the MBS cause a significant difference between backhaul and fronthaul. The analysis is limited to the urban area as the cost relations between the different technologies are similar in the other geotypes. Figure 19 shows backhaul CapEx for all technologies relative to NG-PON2 for a pure FTTC area without mass-market FTTH rollout. All technologies are deployed as dedicated solutions. Furthermore, the graph shows results as a function of SC density. The variations in the trends of the curves are due to technology-specific characteristics.

Variation of SC density in <u>FTTC areas</u>

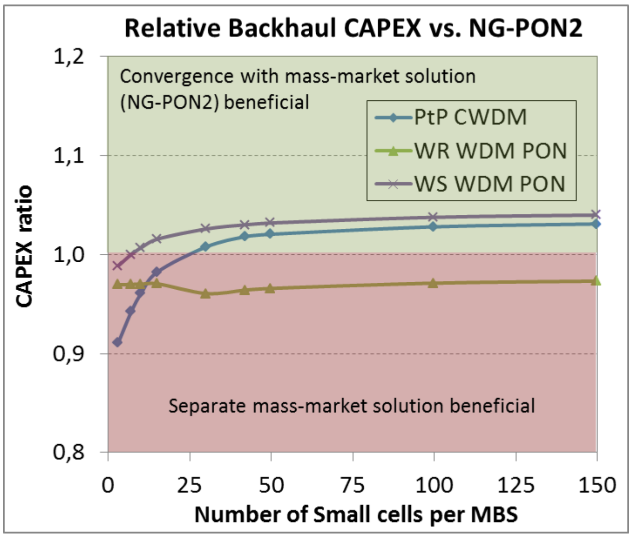


Figure 19: Decentralised backhaul CapEx: Variation of small cell density in FTTC areas

For decentralised architectures and FTTC areas, PtP CWDM has lowest cost for fewer than 12 SCs per MBS while WR-WDM-PON has lowest cost for higher SC densities. NG-PON2 suffers from the low wavelength count of the WDM overlay (16 channels) compared to WR-WDM-PON (20, 40 or even 80 channels). Furthermore, the NG-PON2 convergence potential with mass-market fibre rollout cannot be exploited in FTTC areas. WR-WDM-PON could be used in FTTC areas to allow potential convergence of future mass-market FTTH rollouts.

Figure 20 shows the equivalent results for an area with 100% FTTH coverage and for two fibre-availability cases. In the first case, an existing fibre-poor FTTH rollout is assumed requiring high add-on costs for new fibre cabling and connections, whereas in the second case, a fibre-rich FTTH rollout is assumed, requiring only low add-on costs for fibre through-connections.

For the decentralised architectures, there are no convergence benefits of NG-PON2 for the decentral links between the SCs and the MBS. However, NG-PON2 is still a fibre-efficient access solution for other acess links such as cabinet backhaul. That is the reason why NG-PON2 is most cost-efficient in fibre-poor areas when the SC density is low, compared to the number of cabinets. In fibre-rich areas, system-related costs dominate. For all technologies, different OLTs are located at the MBS and in the MCO. As the links between the SCs and MBS are not determined by the mass-market structure, the scaling behavior of the NG-PON2 OLT at the MBS is quite similar to the other technologies when using comparable splitting ratios. The utilization of the OLT in the MBS is low at low SC densities. This effect becomes visible in fibre-rich areas, shown in the left figure, where the fibre-convergence saving is low.

In conclusion, the FMC potential for decentralised backhaul architectures is limited and convergence brings only a significant benefit in FTTH/B areas with poor fibre availability and low SC density.

Variation of SC density in FTTH areas

Case 1: Fibre-rich FTTH
low fibre add-on costs
(fibre connecting only)

Case 2: Fibre-poor FTTH
high fibre add-on costs
(fibre cabling + connecting)*

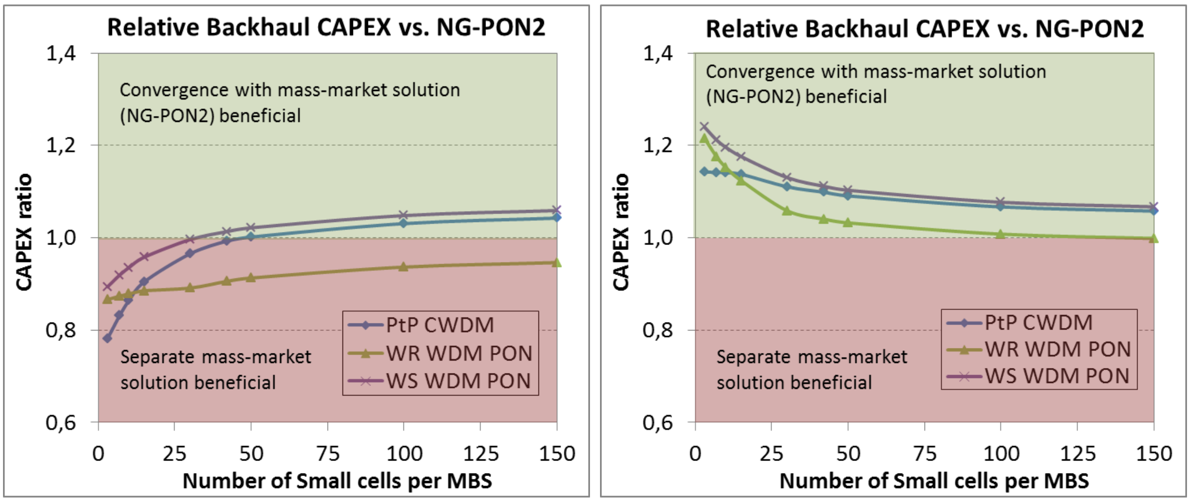


Figure 20: Decentralised backhaul CapEx: Variation of small cell density in FTTH areas

*) First mile Cab↔CO: fibre-rich = 3 CU per fibre and fibre-poor = 3.5 CU per fibre + 8.7 CU per km fibre; Feeder part CO↔MCO: no differentiation → fibre-poor assumed in Case 1 and Case 2

In addition to pure FTTC and FTTH areas, also areas with only partial FTTH coverage were considered. Figure 21 shows the relative backhaul CapEx relative to the NG-PON2 solution depending on FTTH coverage. In fibre-rich areas for decentralised architectures, the CWDM reference is the cheapest solution at low SC densities (<10 SC/MBS), and WR-WDM-PON is most cost-efficient at higher SC densities. These results are independent of FTTH coverage. WR-WDM-PON is more efficient at high SC densities due to the better system scaling compared to CWDM. The cost benefit compared to NG-PON2 increases with increasing FTTH coverage, because of the aforementioned bad utilization of the NG-PON2 convergence (w.r.t. the OLT in the MCO) with the mass-market in decentralised architectures. In fibre-poor areas, the NG-PON2 fibre infrastructure convergence benefits compensate for poor system scaling, which results in NG-PON2 convergence with the mass-market being beneficial at higher FTTH coverage (>25% FTTH coverage at 10 SC/MBS and >40% FTTH coverage at 30 SC/MBS). The benefits diminish with rising SC density due to better system scaling of WR-WDM-PON (w.r.t. the OLT in the MBS) for the decentralised architectures.

Variation of mass-market FTTH coverage

/ \

Case 1: Fibre-rich FTTH
low fibre add-on costs
(fibre connecting only)

Case 2: Fibre-poor FTTH
high fibre add-on costs
(fibre cabling + connecting)

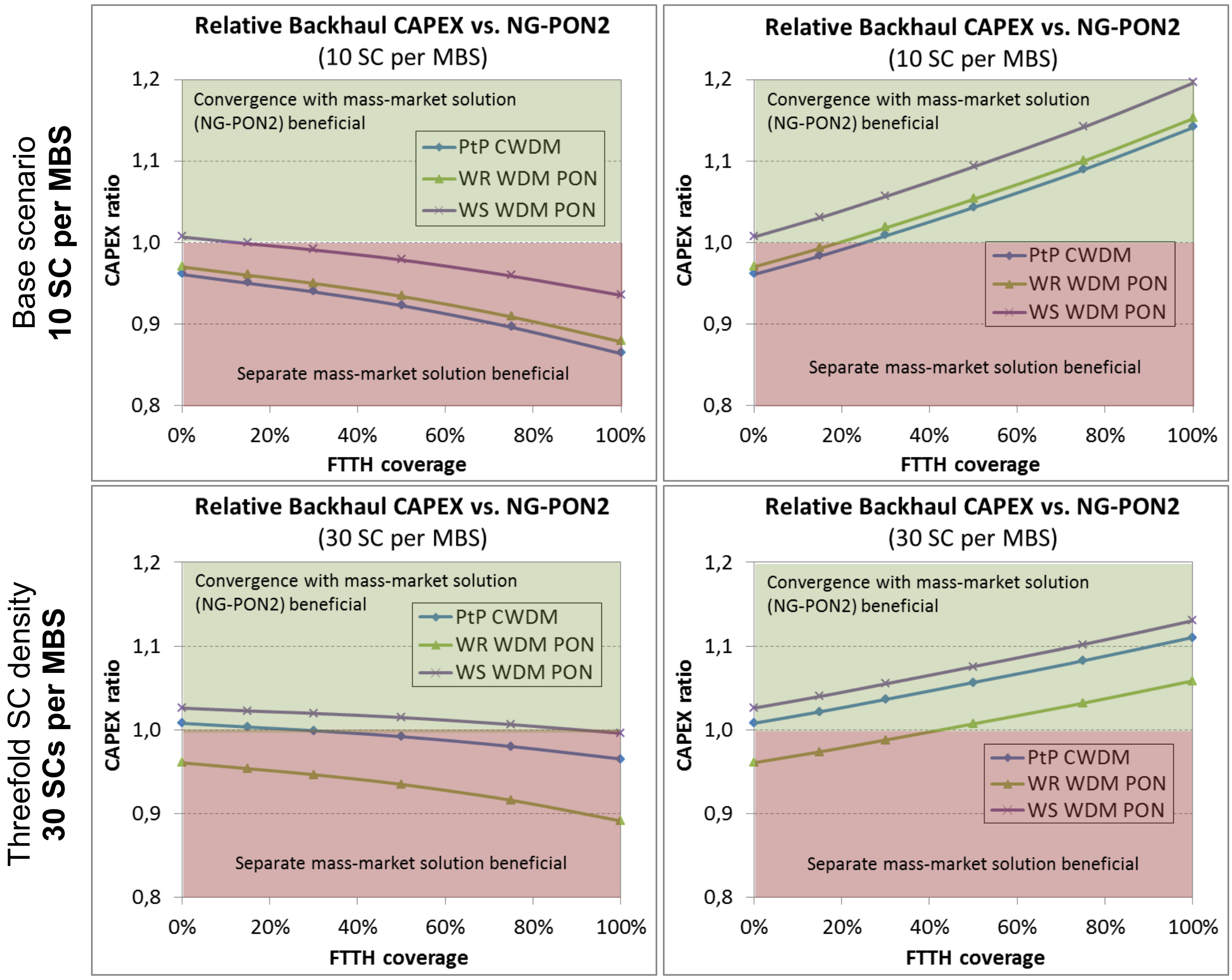


Figure 21: Decentralised backhaul CapEx: Variation of mass-market FTTH coverage

3.3 Cost impact of BBU and RCC placement

As already discussed in D3.3, a comprehensive cost assessment of the five RAN architecture options shown in Figure 6 requires to account not only for the transport cost as analysed in section 3.2, but also for the cost of BBUs, BBU hotels (BBUH) and radio coordination controllers (RCC), including the impact of placement and gains associated with pooling and sharing of resources.

As an example, compared to the traditional decentralised RAN architecture, the advantage of a centralised RAN architecture with BBUHs at the MCO presents a trade-off between the increased transport costs of fronthauling and the potentially decreased BBU costs associated with centralization and pooling. This trade-off requires an understanding of the cost drivers of the BBUH, which in turn depends on several design choices for the BBUH.

Three basic models for consolidation of BBUs into a BBUH are: (i) BBU stacking, (ii) BBU pooling, and (iii) Cloud BBU (please refer to D3.3 for a more detailed description of these three cases). The study in this section focuses on BBU stacking and BBU pooling as they are more relevant options in the 2020-time frame.

Another RAN function that can be broken out from the base station and subject to separate placement is the RCC, which handles radio coordination across multiple cells. The motivation for centralised placement of the RCC is that it facilitates realizing the required low-latency connectivity between cell sites that are part of a coordination cluster. A distributed RCC would require meshed low-latency connections between sites. In the five RAN architectures in Figure 6, the RCC is placed either at the MCO or at the macro site.

The following subsections present models for the BBU, BBUH and RCC as well as an analysis of different placement strategies of BBUs and RCCs, considering each of the five RAN architectures in Figure 6 and the four different geotypes.

3.3.1 BBU Hotel and RCC Modelling

This section presents the basic models for the BBU, BBUH and RCC (extending the models presented in D3.3).

3.3.1.1 Basic model for the BBU and RCC

Figure 22 shows the basic building blocks of a BBU. We can differentiate between baseline building blocks and system-specific building blocks. The units for control, alarms, cooling and power supply are considered as baseline blocks as discussed in D3.3. Interfaces for S1, X2, fronthaul (e.g. CPRI) and data exchange (I/O) as well as units for processing are considered as system-specific units.

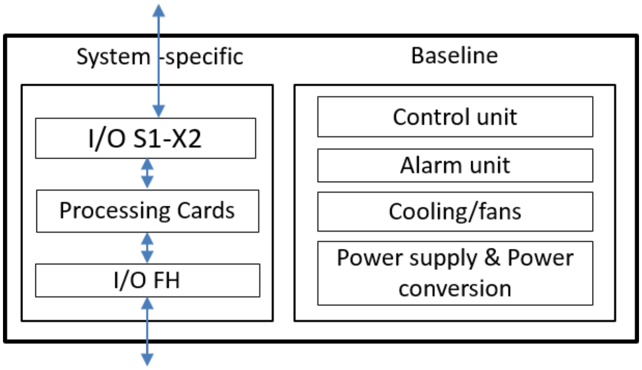


Figure 22: Basic BBU model architecture

The cost model consists in summing the costs of all blocks,

$$C_T = C_{control} + C_{Alarm} + C_{Cooling} + C_{PS} + rC_{FH} + C_{S1-X2} + C_{Proc.Card},$$

where C_T is the total cost, C_{S1-X2} is the cost of a S1-X2 interface, C_{FH} is the cost of the fronthaul interface, and r is the number of fronthaul interfaces. $C_{Proc.Card}$ is the cost of the processing unit which is composed of the general-purpose processing unit and the baseband processing unit. $C_{control}$ represents the cost of the processing unit, $C_{Alarm}$is the cost of the alarm unit, $C_{Cooling}$ is the cost of the cooling unit and C_{PS} is the cost of the power supply including power conversion.

Cost parameters for the small cell BBU are presented in Table 4. We assume that the small cell BBU occupies space corresponding to 1U rack space. As a macro site supports three sectors, compared to small cell sites which are single sector, we assume that the macro BBU costs three times that of a small cell and occupies 3U rack space [4].

Table 4: Cost of basic element for local small-cell BBU and RCC [in CU]

Item	FH I/O (10GSFP)	S1-X2 I/O (1GSFP)	Processing Unit	Baseline +Power Supply
Cost	0.5	0.2	6	4

Figure 23 shows the basic building blocks of a RCC. It consists of the baseline building blocks, the I/O S1-X2 interfaces, the L2 switch and the general-purpose processor. The cost model is presented in the following equation,

$$C_T = C_{control} + C_{Alarm} + C_{Cooling} + C_{PS} + C_{S1-X2} + C_{Proc.Card},$$

where $C_{Proc.Card}$ is the cost of the general-purpose processing unit.

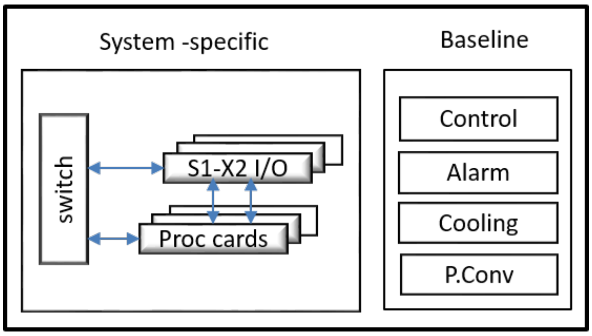


Figure 23: Basic RCC model architecture

The ratio of processing cards vs. S1-X2 interfaces is difficult to estimate. We assume 20 1Gbps S1-X2 interfaces (10 for input and 10 for the output) for each processing card as in [5]. We assume the same cost parameters for the RCC items as for the BBU (Table 4). Additionally, there is the cost parameter for the low-latency switch which is assumed to be 0.3CU per RCC.

3.3.1.2 BBUH model for BBU stacking

For BBU stacking, we assume that multiple BBU cards are stacked into shelves and that multiple shelves are stacked into racks forming the BBU hotel. Multiple units of the basic BBU card described in section 3.3.1.1 are thereby consolidated into a common shelf for sharing of power-conversion resources. Thus, only one power-conversion unit is required for every shelf (D3.3). Multiple shelves are consolidated into the same rack for sharing of power-supply and rack resources. An illustration of the stacking architecture is shown in Figure 24a where two BBU shelves are mounted in a rack sharing the same power supply. In contrast to the model for the local BBU, we here separate between power supply and power conversion and we model the cost of the shared power supply (Figure 24a) as 4CU and the cost of the baseline elements (containing control, alarm, cooling and power conversion) as 2.5CU. The cost of the other elements (e.g.,FH I/O, S1-X2 I/O etc.) remains unchanged.

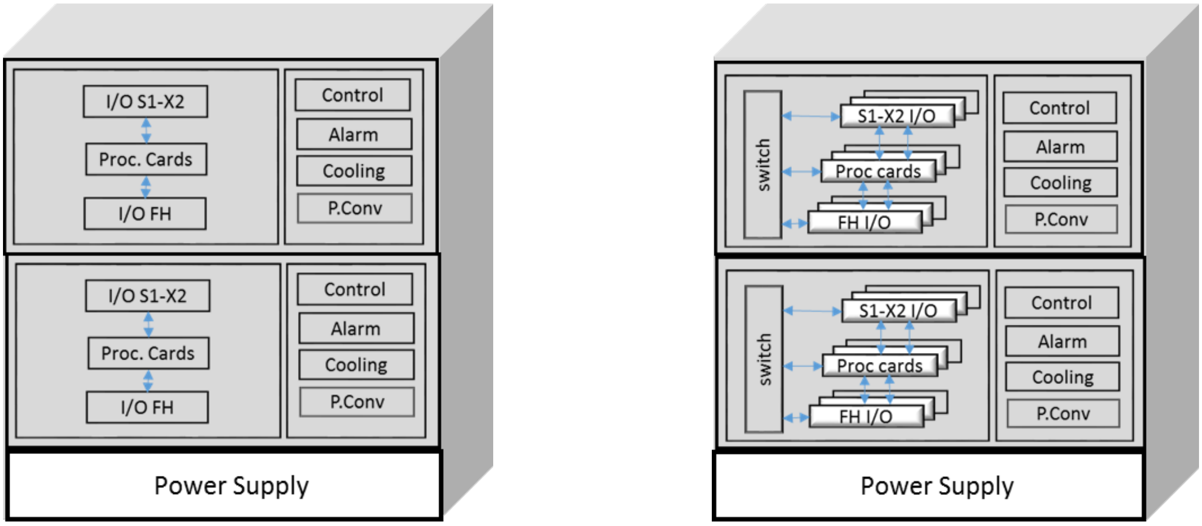
The total cost of a BBUH with stacking is the sum of the cost of the shelves, the power supplies and the racks, where the cost of each shelf is a sum of the cost of all the equipment housed in it. The number of racks is calculated according to the following equation,

$$\text{Number of racks} = \left\lceil CN \Big/ \frac{RS-RUPS}{RUC} \right\rceil,$$

where CN represents the number of cells, *RS* represents the rack size in terms of rack units, *RUPS* is the number of rack units occupied by the power supply and *RUC* is the number of racks units occupied by one cell:

Note that the cost of a rack changes according to its size x. We model the cost of a rack of size x as $4.42 - 0.04(42 - x)$. In the following analysis, we consider racks from 12U to 42U, always choosing the smallest rack capable of accommodating all cells.

With stacking, both energy and cost savings can be achieved. Gains are determined by the assumed costs of the BBU components but also by scaling in terms of the number of BBUs that can share the same power conversion resources (in a shelf) and of the number of BBUs that can share rack and power supply resources (in a rack).



(a) (b)

Figure 24: BBUH architecture with (a) BBU stacking and (b) BBU pooling

3.3.1.3 BBUH model for BBU pooling

For BBU pooling, the BBUH has a completely different design compared to stacking. The main feature is that multiple BBUs can share processing resources. Figure 24b shows the architecture of a BBUH for BBU pooling. Note that the processing cards can be dimensioned and scaled independently. An internal low-latency switch is required to properly allocate processing resources beween the processing resources and the interfaces. The following equation presents the total BBUH cost for BBU pooling:

$$\mathrm{C_T} = \text{Cost of all baseline and system specific items (i.e., FH and s1-X2 I/Os,} \\ \text{processing cards, control, etc.)} + \text{Cost of Power supplies} + \text{Cost of empty racks}$$

The number of items of a specific item type per serving area is $\lceil X \,\square\, n \rceil$, where X is the number of these items per shelf and n is the number of shelves. Moreover, with the pooling strategy, the number of fronthaul interfaces per shelf is equal to the number of cells served, divided by the number of shelves per area. The number of shelves is calculated as the minimum number of shelves to support a given number of cells, i.e.,

$$\text{Number of shelves} = \left\lceil {}^{CN}\!/_{\#\text{Cells per Shelf}} \right\rceil$$

The number of processing cards per shelf equals the number of fronthaul interfaces multiplied by a multiplexing gain (more discussion on this calculation is reported later), while the number of S1-X2 interfaces per shelf is calculated by dividing the number of processing cards per shelf by 6 as explained in D3.3 and [6].

The basic cost parameters are the same as for stacking except for the baseline cost per shelf which is 3 CU, and the power-supply cost per rack which is equal to 3.4 CU [6]. Moreover, as a basic assumption we assume that a shelf of size 2U supports 4 cells. A sensitivity analysis is performed for the dimensions of the shelf.

3.3.2 Decentral vs. central BBUH / RCC

This section presents cost calculations considering the proposed hotelling strategies. The hotelling strategies are applied to various fronthaul architectures for the four different geotype areas. The number of macro cells and small cells for the four geotypes are reported in Table 5.

Table 5: Number of macro cells and small cells per service area for each of the geotypes.

Geotype	Ultra-dense urban	Urban	Sub-urban	Rural
Macro cell	8	23	29	31
Small cell	80	230	290	0

3.3.2.1 Local BBU

Figure 25 presents total BBU and RCC cost per service area for the different geotypes. The local BBU scenarios are those associated with ‘Centralised All Backhaul’ and ‘Decentralised All Backhaul’. In both cases the BBUs are located at the cell sites and the BBU cost is the same for both cases. The RCC cost is significantly higher (around 75%) in the decentralised case for all the four geotypes.

3.3.2.2 Stacking strategy

As described in section 3.3.1.1, cost savings can be achieved by stacking several BBUs mainly due to sharing of power supply and racks. Three of the RAN architecture in Figure 25 have BBUH, i.e., ‘All Fronthaul’, ‘SC FH to MCO’ and ‘SC FH to MBS’. In Figure 25, the BBUHs are based on stacking. The minimum total BBU cost is always achieved by the ‘All Fronthaul’ architecture for all geotypes. This architecture guarantees the maximum degree of consolidation of the BBUs. Comparing the cost of ‘All Fronthaul’ with the cost of ‘Centralised All Backhaul’, the cost saving is around 25% in ultra-dense, urban and sub-urban areas and around 14% in rural areas. The lower savings in rural areas are due to the absense of small cells (all the other geotypes have both macro and small cells), hence the size of the BBUH at the main CO is smaller and this leads to reduced gain. Also, for ‘All Fronthaul’ saving are on average 6% compared to ‘SC FH to MBS’ in ultra-dense urban, urban and sub-urban geotype areas. Note that in the ‘SC FH to MCO’ and ‘SC FH to MBS’ RAN architectures, the MBSs are backhauled and since there are no SCs in the rural geotype area, the total cost in the ‘SC FH/MBS BH to MCO’ and ‘SC FH to MBS’ RAN architectures is equal to that of ‘All Backhaul’.

The total RCC cost also depends on the RCC placement as this determines the number of required interface ports and processing cards. For all RAN architectures where the RCC is at the main CO, costs will be the same ('Centralised All Backhaul', 'All Fronthaul' and 'SC FH to MCO'). RCC cost savings of on average 70% in ultra-dense urban, urban and sub-urban geotype areas are achieved by centralizing the RCC to the main CO, compared to having distributed RCCs each at macro site location ('SC to MBS' and 'Decentralised Backhaul'). This is due to multiplexing gain which allows saving more resources as more cells are consolidated.

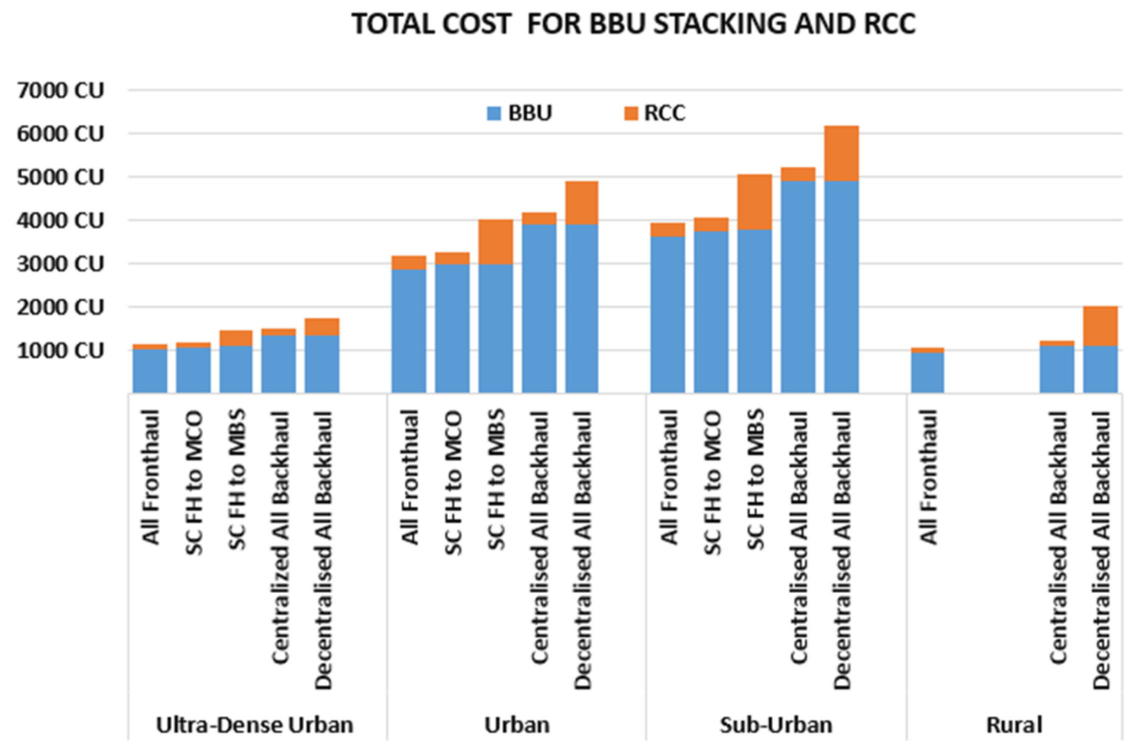


Figure 25: Total cost per service area of different RAN architectures for the BBU stacking strategy

3.3.2.3 Pooling strategy

With BBU pooling, multiple processing cards in the same shelf are interconnected by a low-latency switch and shared among multiple cells. In spite of added hardware complexity, considerable pooling gains are expected due to increased multiplexing gains as a larger number of cells are pooled. In the following numerical analysis, some values for "multiplexing gain" of processing resources in the BBUH are extrapolated from a study in [7], where savings are demonstrated by extensive simulations. These show that multiplexing gain with BBU pooling increases from about 5% for pools of 4 cells up to a steady saving of about 50% for pools of 80 cells and more.

Figure 26 shows total cost per serving area for different RAN architectures and geotypes considering BBUH based on pooling. Comparing the cost for BBUHs based on pooling with BBUH based on stacking strategy there is an average cost saving of 25% for 'All Fronthaul', 19% for 'SC FH/MBS BH to MCO' and 9% for 'SC FH to MBS'. Furthermore, 'All Fronthaul' on average saves 15% compared to 'SC FH to MBS' for ultra-dense urban, urban and sub-urban geotype areas. Note that for each geotype area, the cost increases as the number of the consolidated cells decreases.

As already seen in the results for stacking, the total cost of the 'SC FH to MCO' and 'SC FH to MBS' are equivalent for the rural geotype, as the rural geotype does not have small cells.

For the RCC we have the same models and costs in Figure 25 and Figure 26. Savings of the order of 85% for ultra-dense urban, urban and sub-urban geotypes are achieved by centralizing the RCC from the macro sites to the main CO location.

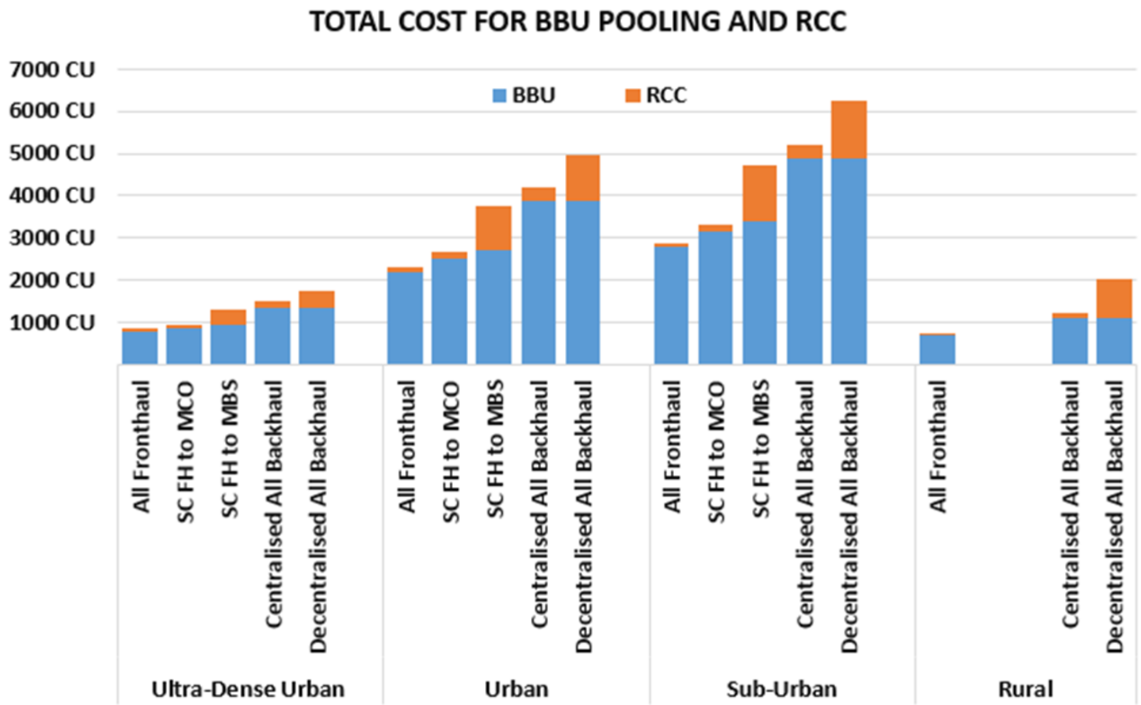


Figure 26: Total cost per service area for different RAN architectures for BBU pooling

Comparing stacking to pooling, it is clear that pooling reduces CapEx considerably because of sharing of processing resources. It can further be expected that hardware consolidation improves the computational performance and reduces the energy consumption.

Figure 27 shows a sensitivity analysis of the BBUH modeling where we consider the influence of the pool size (i.e., the number of cells sharing the same BBUH) on the BBU cost per cell. As expected, as the pool size increases the cost per cell decreases due to the increased sharing of computational resources, which allows for higher multiplexing gain. The basic stacking case (black line) is compared to two different scenarios: in the first scenario (the three continuous lines), processing cards are shared per shelf, i.e., each shelf acts as a separate pool even when shelves are placed in the same rack (shelves can serve 4 cells, 8 cells or 16 cells, occupying a size of 2U, 3U or 4U, respectively). In the second scenario, the shelves are interconnected through an additional switch and an optical backplane, such that all cells in the same rack belong to the same pool, leading to an even more efficient resources utilization. A gain of 20%-30% is achieved in the first scenario, and even larger gains in the order of 35-40% are achieved in the second scenario. Note that the oscillations that are seen in the cost curves are mainly due to the granularity of the rack model where deployment of new racks are needed to serve the increasing number of cells at certain sizes of the BBUHs. The analysis has been performed for small cells, but similar results are expected for macro cells.

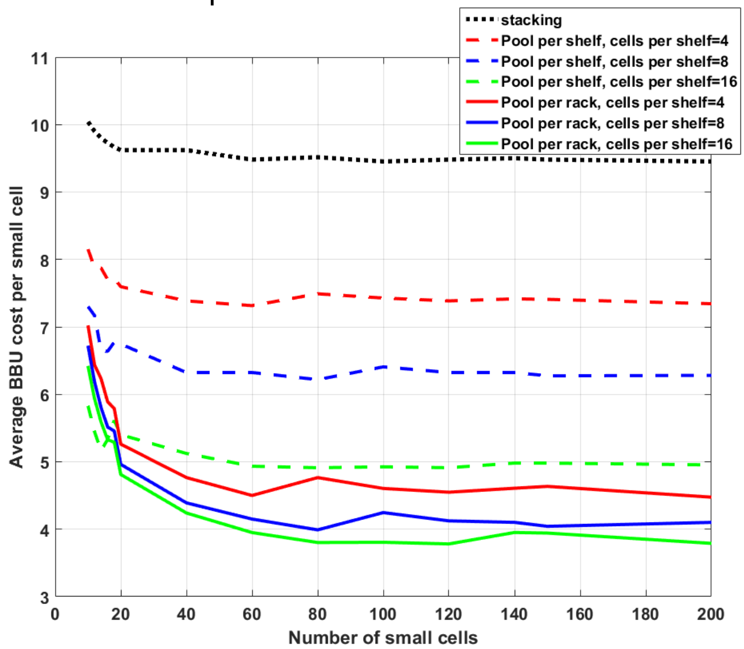


Figure 27:Average BBU cost per cell dependency on the pool size and the number of hotelled cells

In Figure 27, BBU costs per cell range between 4.5 and 10 CU depending on the hotel strategy and BBUH size. This can be compared to the transport cost per connection (section 3.2.2) which ranges between 15 and 30 CU depending on technology and geotype. As costs are of the same order of magnitude, both RAN and transport costs need to be considered for determining optimal RAN architectures.

3.3.3 Alternative options for controller placement

In all previous analyses, we assumed that the placement of RCC controllers is limited to two options: decentralised RCC placement in the macro BS, and centralised RCC in the main CO. In actual convergent access/aggregation networks, there could be more options to place the RCC as the metro network is characterized by a hierarchy of COs interconnected by a network based on interconnected rings and, in some parts, even based on a meshed topology.

We note here that a proper placement of RCCs within the network enables advantages in terms of throughput, that is, the bit rate experienced by end users (especially those located at cell edge) can be maximized if we place the RCC in the right location.

The optimal placement of RCCs depends on several conflicting factors, such as the number of cells coordinated by the same RCC (i.e., cells cluster size), the latency between RCC and coordinated cells, and the type of coordination scheme employed. In particular, the coordination gain, i.e., the throughput increase obtained by coordinating several cells, depends on cluster size and latency and its maximization derives from a trade-off between these two competing aspects. On one hand, the more cells are coordinated together, the higher is the coordination gain. On the other hand, given the hierarchical nature of access/aggregation networks, to coordinate more cells, it is necessary to place RCCs at higher layers of this hierarchy (e.g., in Access COs or Main COs). Therefore, this will increase the latency between the RCC and coordinated cells, thus negatively impacting the throughput gain. Another trade-off between coordination gain, latency and required bandwidth arises when selecting the coordination technique. We focus on two different Coordinated Multi-Point (CoMP) techniques, namely Coordinated Scheduling (CS) and Joint Transmission (JT), as their throughput gain is differently affected by cluster size and latency [8]. For more details on the effect of latency and cluster size on the CoMP throughput gain, please refer to section 8.2.

In the following, we quantitatively investigate the impact of different options for RCC placement, as well as of the selection of alternative coordination techniques, on the obtained throughput gain. In this study, we specifically focus on the different geotypes considered in the COMBO project, i.e., urban, sub-urban and rural. Note that a similar study has been performed in D3.3, but focusing on BBU placement, hence without accounting for the impact on throughput maximization enabled by CoMP coordination as we do here.

3.3.3.1 Aggregation network scenario

We consider a hierarchical ring-and-spur topology consisting of four stages, as shown in Figure 28. Four levels of aggregation nodes are considered, namely, Cell Sites, Access COs, Main COs and Core CO, interconnected via optical links. Note that each node in the network, including the COs, inserts (respectively, receives, in case of downlink stream) mobile-native traffic (e.g., UMTS, LTE or LTE-A), which is directed to (resp., originated by) the Core CO.

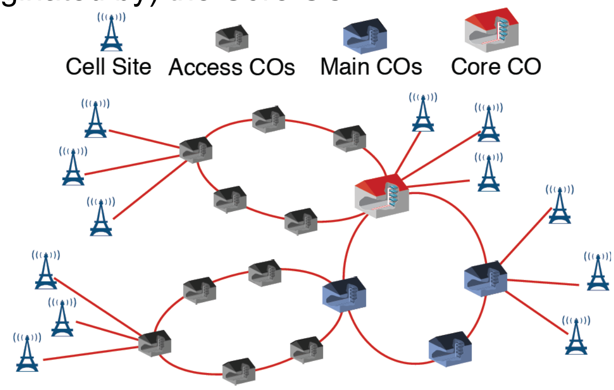


Figure 28: 4-stages aggregation network architecture.

3.3.3.2 Problem statement

The Clustering, Routing and RCC-Placement (CRRP) problem can be formally stated as follows.

Given a multi-stage metro network topology, represented by a graph G(N,E), where N is the set of nodes and E the set of fibre links, the set of backhaul (S1) traffic requests directed to the Core CO, the corresponding X2 traffic request, the set of possible CoMP techniques and their throughput gain as function of cluster size and X2 latency, ***decide*** the RCCs placement, the cells clustering, the coordination technique adopted for each cluster and the routing of S1 and X2 traffic, ***maximizing***

the overall throughput gain in the network, ***constrained by** i)* network links capacity, *ii)* latency between cell sites and RCCs, iii) routing of all the requests.

Due to problem complexity, we split the CRRP problem into two subproblems, i.e., 1) cluster assignment and 2) routing and RCC placement. Specifically, for every possible clustering option, we evaluate the optimal routing and RCC placement, and select the solution with highest throughput gain. Note that dividing the CRRP problem into two subproblems does not affect optimality, as the two subproblems are independent (for the details, please refer to [9]).

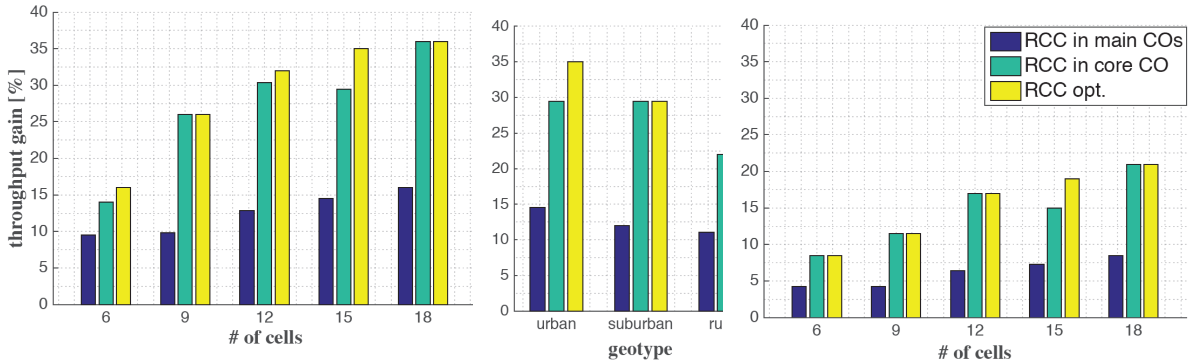
3.3.3.3 Illustrative numerical results

For our numerical results, we randomly generate several network topologies where nodes (we consider 6, 9, 12, 15 and 18 nodes) are uniformly distributed in a square area and then organized in hierarchical ring-and-spur topologies as in Figure 28. The size of the square area varies according to the geotype under consideration, namely, urban, sub-urban and rural, with a reference coverage area of 15, 142 and 615 km^2, respectively, as provided by D3.3 (see also section 8.4.2 for the details). Each node inserts an amount of S1 traffic randomly selected in the range 155-400 Mb/s, in line with an LTE site with 3 sectors, 20 MHz spectrum, 2x2 MIMO and 16 QAM modulation format. Our main performance metric is the throughput gain [%], i.e., the gain obtained with respect to a baseline case where CoMP is not used. It is calculated as the weighted sum of the throughput gains of all cells in the network.

We compare our optimized placement (“RCC opt.”) with two fixed-placement cases: 1) “RCC in main COs”, where each main CO is equipped with one RCC coordinating the cells connected to that main CO, and 2) “RCC in core CO”, where only one RCC is deployed at the core CO, and coordinates the largest possible cluster (limited by latency constraints). Initially, we assume that RCC processing time is negligible, i.e., tRCC = 0, so only propagation and switching delays are accounted for X2 latency (see section 8.2 for the details on X2 coordination traffic latency budget).

Before commenting the result, note that we do not account here the “intra-site” gain, i.e., the gain obtained by coordinating antennas of different sectors within a single cell-site. This gain is independent on RCC placement, and it can be obtained by placing intra-site RCCs in each cell site. For CS and JT, this gain is in the order of 5% and 11%, respectively [10].

In Figure 29, we plot instead the gain that can be obtained by coordinating several cells together (“inter-site” coordination). More specifically (see Figure 29a), in an urban scenario, inter-site gain can be almost 4 times higher than the intra-site gain, e.g., throughput can increase up to 36%. Moreover, in all cases, the coordination gain grows with increasing number of nodes, due to the fact that cell sites can be grouped in larger clusters. In all cases, *RCC opt.* provides much higher throughput (i.e., up to 20% higher) compared to *RCC in main COs*, proving the effectiveness of an optimized clustering and RCC placement. Further, in some cases (for 6, 12 and 15 nodes), *RCC opt* also outperforms the *RCC in core CO* case, i.e., it provides up to 5% higher throughput. As we consider an urban scenario, JT is selected for all clusters, as for this geotype latency is not stringent and JT is preferable due to its higher gain.



(a) urban scenario, t_{RCC}=0; (b) 15-nodes network, t_{RCC}=0; (c) urban scenario, t_{RCC}=250µs;

Figure 29: Numerical results obtained for different RCC placement options ("RCC in main COs", "RCC in core CO" and "RCC opt.").

To observe the effect of the X2 latency on the coordination gain, Figure 29b shows the comparison between the 3 geotypes, in the case of a 15-node network. As the considered area increases, the coordination gain decreases, confirming that for larger X2 latency, throughput gain decreases.

Finally, we show results for a larger value of RCC processing latency (tRCC = 250 µs), used to capture the case of an RCC incurring longer processing delay due to high load. As expected (see Figure 29c), lower gain is obtained compared to the case with tRCC = 0, however optimized RCC placement still provides significant gains with respect to the RCC in main COs.

3.4 Conclusions

This section summarises the key findings of the cost assessment and the convergence potential of FMC architectures where RAN coordination is decentralised to the MBS location, and where SCs are backhauled or fronthauled from the MBS location.

From a technology point of view, PtP CWDM has lowest CapEx in fibre-rich deployment situations with less than 12 SCs per MBS. However, the cost difference with respect to other technologies is small and CapEx per connection is just slightly lower than for WS-WDM-PON. Decentralised RAN coordination architectures are less convergent in general, as SCs are served from the MBS sites and the SC infrastructure is not shared with fixed customers.

WR-WDM-PON is the technology with the lowest CapEx in fibre-rich situation; however, NG-PON2 has a lower cost if fibre deployment is required, especially when the FTTH ratio is high. The number of channels per fibre is also important to delimit the technology with the lowest CapEx, especially when the number of SC per MBS is higher than the number of channels per Mux/Demux.

The total cost of backhaul in a decentralised scenario is similar to the fronthaul version of the same technology (the difference is less than 4%), because the network resources required for the backhaul and fronthaul of the SCs to the MBS are also similar.

Compared to centralised architectures, decentralised SC backhaul and fronthaul architectures need additional elements in the MBS and in the CO; however less equipment is required in the MCO because of the aggregation of the SC traffic in the MBS. These architectural changes have a different impact on backhaul and fronthaul:

- In backhaul, the cost per connection is higher in decentralised than in centralised scenarios (e.g.: 13% more in NG-PON2 urban) due to the cost of the additional network elements required in the MBS, which is not compensated by the reduction in feeder fibres and the number of interfaces in the MCO.
- In fronthaul, the cost per connection is lower in decentralised than in centralised scenarios (e.g.: 7% less in NG-PON2 urban) because the cost reduction in feeder fibres and network elements in the MCO is higher, as the MBS are only connected using a single optical channel (backhaul from MBS to MCO).

Decentralised architectures do not benefit from convergence in the same way as centralised FMC architectures. This is independent of small cell density, FTTH ratio and fibre rich-poor assumptions.
Figure 30 shows an example comparing centralised (right) and decentralised (left), where the relative total CapEx of NG-PON2 against other technologies is reduced in decentralised architectures.

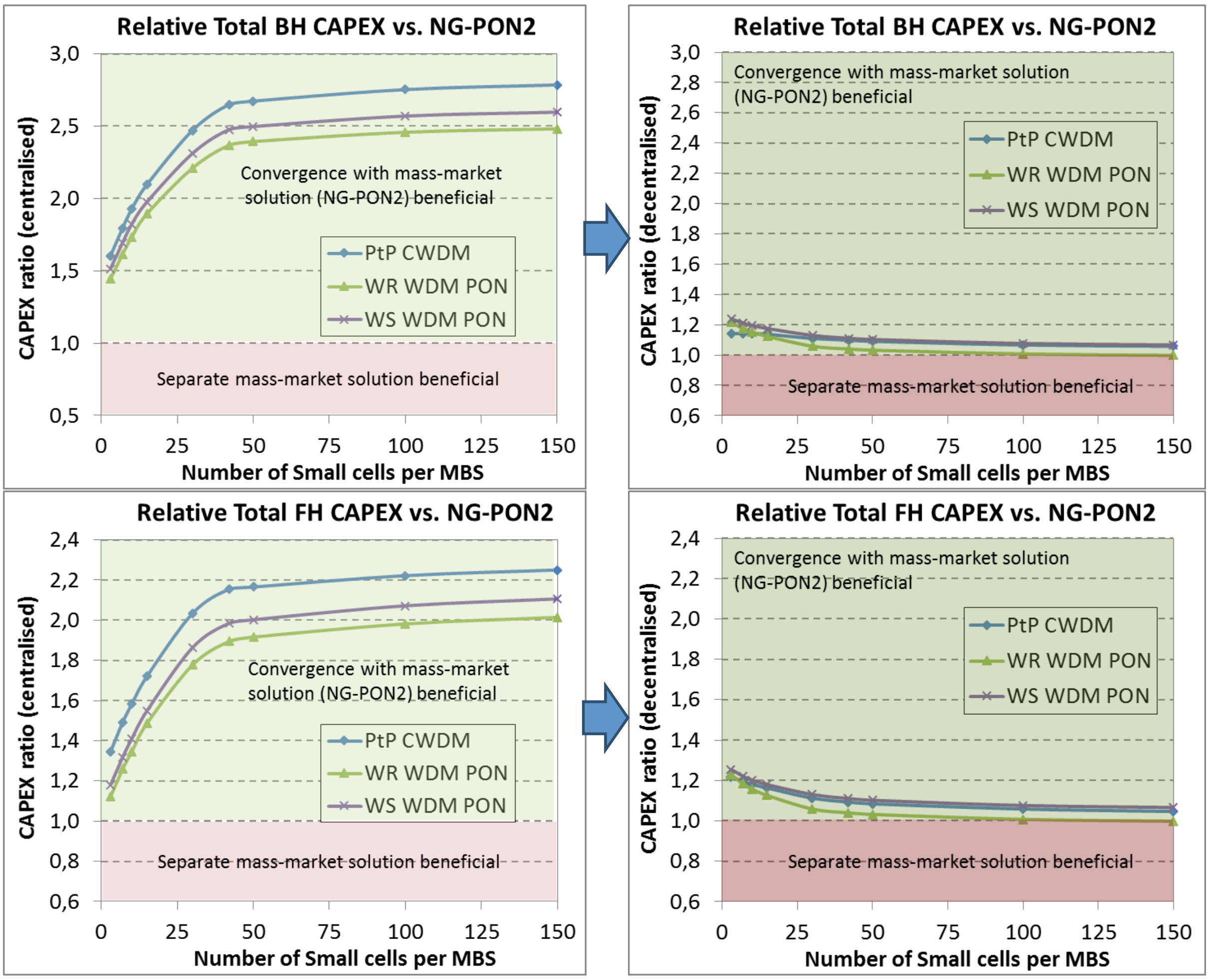


Figure 30: BH and FH CapEx: Variation of SC density in fibre-poor FTTH with high fibre add-on costs (urban)

Comparing the cost of BBU hotelling at MCO and BBU hotelling at MBS, the results show that a BBUH stacking strategy at MCO saves around 6% (BBU cost) for ultra-dense, urban and sub-urban geotype areas, while a BBUH pooling strategy at MCO saves about 15% (BBU cost). RCC hotelling at the MCO has larger relative effect as it saves around 70% (RCC cost) with the stacking strategy and 85% with the pooling strategy. Comparing BBU costs to transport costs we see that possible savings of BBU stacking/pooling are of the same order of magnitude as differences in transport costs for these scenarios. As costs are of the same order of magnitude, both RAN and transport costs need to be considered for determining optimal RAN architectures. Finally, considering additional benefites of RCC placement related to optimizing radio performance, we demonstrated that, in comparison to traditional RCC placement, network throughput can be substantially enhanced (up to 20% higher) with an optimized placement of RCCs at different nodes in the metro network.

4 Transport solutions for 5G

The 5th generation of mobile networks (5G) is the next major phase of mobile telecommunications. The vision of 5G is commonly presented as part of the network vision for 2020 and beyond, which in turn embodies a number of services for the future information society in which everything that can connect to this society indeed will do so. The typical services identified span across areas such as enhanced mobile broadband, massive machine-type communications, and ultra-reliable and low-latency (critical) machine-type communications. In addition, there is an increasing attention paid to potentially special requirements from media distribution applications of various kinds, not least inherent media distribution scalability inside the network, e.g., for multicasting. Besides new services and applications, 5G will also need to support a wide range of ecosystems and cooperation models supporting digitalization of industry and trends of business horizontalization.

There are several ways 5G could be deployed, resulting in different requirements on the transport networks. Hence, 5G transport is not necessarily a single system concept but rather a set of systems and solutions that can meet the requirements of different 5G deployment scenarios. 5G itself is a term with several interpretations and there are at least three perspectives on 5G that have implications on the design of transport/access networks:

- 5G radio: in a narrow sense, 5G refers to the set of radio interfaces that will be defined as part of 5G radio, as well as the internal 5G radio system architecture. Given suitable radio configurations, system splits, etc., these interfaces result in performance requirements (connectivity, capacity, latency, etc.) that the transport networks must satisfy.
- 5G performance: in a broader sense, 5G is defined by the expected performance parameters (traffic densities, peak rates, latency, etc) which to large extent is expected to be enabled by 5G radio. In particular, increased capacity through densification of access sites brings clear challenges to the transport in terms of connecting large numbers of sites.
- Connected society: beyond the previous bullets, 5G is also associated with changes in society and trends in network infrastructure, i.e., IoT and the digitalization of industry as well as cloud and NFV. This is of broader scope, but brings important additional requirements to the transport solutions for 5G including support for new ecosystems with new actor networks and cooperation models, etc. A variety of business and cooperation models will evolve in different segements of industry and society. This adds additional requirements on flexibility, security, operations, etc. and providing relevant interfaces to support evolving ecosystems, which may also impact the transport segment.

In summary, there are at least three perspectives to 5G which all bring complementing requirements on the supporting transport network. This chapter considers implications on all of these perspectives but with focus on the first two. In sections 4.1 to 4.3, we review projections of 5G traffic and 5G radio configurations. In section 4.4, we model how different traffic densities could be supported by different

RAN densities. In section 4.5, we review different RAN split options that have been proposed and establish the capacity requirements associated with each split. Section 4.6 provides models for new technology components such as high-speed optical interfaces required in the transport segment in order to meet the requirements of various 5G deployment models. Section 4.7 provides the techno-economic analysis of the different deployment options.

4.1 5G radio

Many key telecoms industry players tend to agree on a vision beyond 2020 that assigns a considerable role for LTE and its evolution in various directions. Whilst LTE is considered and has proven to be a robust technology, and is thus often positioned as a foundation layer for 5G, some of its fundamental numerology may need adaptation in order to cater for new requirements on latency, energy efficiency, etc.

5G requirements are challenging. The following list referred to by many is presented in the FP7 METIS project:

- 1000 times higher mobile data volume per area
- 10 to 100 times higher number of connected devices
- 10 to 100 times higher typical user data rate
- 5 times reduced end-to-end latency

Figure 31 presents a view of 5G wireless access from one radio network vendor [11]. What could be expected for 5G is an evolution of mobile technology along the LTE track, primarily in existing spectrum, paralleled by new RATs at, e.g., higher frequencies, or variations of existing ones to meet specific demands of tomorrow, e.g., extremely energy-efficient machine-type applications. The different RATs may be tightly coordinated for supporting offloading. Higher bandwidths will be supported by use of wider spectrum available at higher frequencies. These will primarily be adressed by new RATs. Reduced propagation conditions at higher frequencies will call for a need for advanced multi-antenna technologies, e.g., beamforming, to mitigate the increasing radio propagation challenges. On the other hand, multi-antenna technologies will also become more feasible due to the smaller required antenna dimensions at higher frequencies.

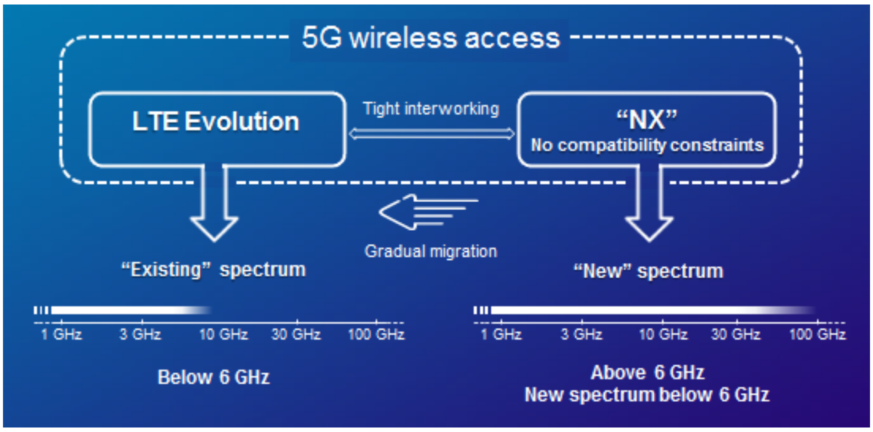


Figure 31: 5G wireless access as proposed by Ericsson [11]

Besides advances in radio interface technology and use of new spectrum, particularly the placement of new antennas, e.g., small cells, will lead to a significant densification of radio sites that need to be interconnected flexibly and with low cost in a short time frame. A potentially major structural impact from 5G heterogeneous networks results from the combination of 5G technology enablers (beamforming, new bands above 6 GHz, multi-RAT connectivity etc.) with Fixed Wireless Terminal (FWT) technologies. FWTs are currently gaining momentum as a complement to fixed broadband access, and as a consequence from the convergence of radio access and wireless backhauling. With the very high bandwidths expected on new bands for 5G radio, e.g., 100 MHz on a carrier with possible aggregation of several of such carriers, optical fronthaul solutions and technology will need to keep very high pace in order to meet capacity challenges into the 2020's. Projects such as METIS, 5G-Crosshaul, iCirrus, 5G-XHaul etc., predict that other types of RAN splits will dominate. If LTE is to become the foundation layer for 5G, any structural impact from LTE such as those implied by fronthauling need to factor in 5G from the outset. Great flexibility in mixing front- and backhauling will be required according to NGMN.

4.2 Radio configurations

In this section, we provide details on the antenna configurations which have been identified by COMBO as promising for 5G and which will be used in the analysis and techno-economic modelling in section 4.7.

As a result of discussions among the partners, including experts from a radio network vendor, two radio network configurations were identified as "reference" antenna types: antenna configuration #1 as an extension of LTE-Advanced operating below 6 GHz, and antenna configuration #2 using novel radio technologies, operating above 6 GHz. The configurations are summaried in *Table 6*. We assume that each macro site is equipped with three sectors whereas small cells are single-sectored. Dimensioning the RAN with respect to configuration #2 brings many uncertanties, as the high frequency, massive MIMO and/or beamforming techniques will impact the network throughput and capacity, making it difficult to quantitatively assess performance without extensive radio network simulations which are outside the scope of COMBO. Hence, as a first step, we use configuration #1 in the analysis of the required RAN density, and based on these results, we discuss implications for configuration #2.

Table 6: 5G compliant antenna configurations

Antenna configuration		#1 (LTE-A+)	#2 (new 5G)
Frequency band		3.5 GHz	15 or 30 GHz
Macro sites	Sectors	3	3
	Bandwidth	125 MHz	500 MHz
	MIMO	16 x 4	16 x 16 or Massive MIMO / Beamforming
	Modulation	256-QAM	256-QAM
	Peak rate	**3 x 10 Gb/s**	**3 x 40 Gb/s**
	Transmission power	60 W	60 W
Small Cells	Sectors	1	1
	Bandwidth	125 MHz	500 MHz
	MIMO	16 x 4	16 x 16 or Massive MIMO
	Modulation	256-QAM	256-QAM
	Peak rate	**10 Gb/s**	**40 Gb/s**
	Transmission power	30 W	30 W

Given the proposed antenna configurations, various radio performance parameters can be estimated. The peak rate per MBS sector or SC is calculated as:

Peak Rate *= [Spectral Efficiency$_{max}$] * [Bandwidth] * [MIMO gain]*

The 16x4 MIMO configuration means 16 antennas at the MBS/SC, and 4 antennas at the UE, i.e., a multi-user MIMO implementation. Therefore, the theoretic maximum MIMO gain at the UE is 4, and at the MBS or SC, it is 16:

Peak Rate of **MBS sector or SC**= 5.0 b/s/Hz * 125 MHz * 16 = 10 Gb/s

Peak Rate of **UE**= 5.0 b/s/Hz * 125 MHz * 4 = 2.5 Gb/s

Obviously, the mean throughput of a base station or small cell is never the peak rate: depending on the distribution of UEs, the achieved spectral efficiency is lower than its maximum. The MBS is configured as a 125 MHz – 256 QAM – 16x4 MIMO site, which is able to provide a radio peak rate of 10 Gb/s per sector, hence 30 Gb/s per MBS. As for MBS coverage, we assume that the current spectral efficiency is equal to 2.6 b/s/Hz, provided as ITU requirement for LTE-A in urban scenarios (full-buffer) [12], will increase by a factor 3 thanks to future 5G technology (e.g., exploiting advanced techniques such as beamforming, MIMO etc.), thus leading to an overall throughput as in the following:

Thr$_{MBS}$ *= 125 [MHz] *2.6 [b/s/Hz] * 3 [5G spectral efficiency increase]* 3 [sectors per MBS] =* ***2.9 Gb/s per MBS***

For small cells, we assume a reference antenna configuration of 125 MHz – 256 QAM – 16x16 MIMO, consisting of only one sector, which is able to provide a radio peak rate of 10 Gb/s. For small-cells spectral efficiency, we consider, besides the spectral-efficiency increase due to 5G technology, an increase factor of 1.25, taking into account that channel interference experienced by small cells is reduced in comparison to MBS. Therefore, for a small cell with 125 MHz – 256 QAM – 16x16 MIMO antenna configuration the overall throughput is given by:

Thr_{SC} *= 125 [MHz] *2.6 [b/s/Hz] * 1.25 [increased spectral efficiency for SC only] * 3 [5G spectral efficiency increase] =* ***1.2 Gb/s per SC***

4.3 5G radio performance & requirements

In this section, we review models for 5G traffic and define two traffic density scenarios (one low and one high) as a basis for the network dimensioning. In the NGMN 5G White Paper [13], a number of 5G use cases are presented. One use case, relevant for the ultra dense geotype, is “broadband access in dense areas” which dictates a user experienced data rate requirement of 300 Mb/s (even at the cell edge), and a connection density between 200-2500 active connections/km^2 (10% of the 2.000-25.000 devices/km^2 assumed to be active simultaneously). Based on this, the NGMN white paper calculates a maximum traffic density of 750 Gb/s/km^2, i.e. 2500 connection x 300 Mb/s per km^2. One could argue that the actual traffic density would be lower, using sustained data rate instead of user experienced data rate, but still, the NGMN white paper is the most referenced source in this field, so we have decided to use this value as Traffic Alternative 1 (“high”). We have defined Traffic Alternative 2 as the “lower end” of the NGMN parameters, i.e., 200 connections/km^2 x 300 Mb/s = 60 Gb/s/km^2. In fact, this value is closer to the traffic forecasts and estimations of some major vendors, e.g. Ericsson [14]. Using these two traffic densities, we have an upper and lower bound to the traffic density in ultra-dense urban areas, both with strong references.

These traffic density figures, however, reflect the total mobile traffic of the area, shared among all operators. Following the assumptions of our previous deliverable [1], we divide the traffic among three operators, all of which having 33.3% market share – therefore, the traffic to be served by a single operators network is 20-250 Gb/s/km^2.

Table 7: Trafic alternatives for 5G radio

Traffic density for Ultra-dense geotype	Traffic Alternative 1 (High)	Traffic Alternative 2 (Conservative)
User experienced data rate	300 Mb/s	300 Mb/s
Connection Density	2500 / km^2	200 / km^2
per operator	833 / km^2	67 / km^2
Traffic density	750 Gb/s / km^2	60 Gb/s / km^2
per operator	**250 Gb/s / km^2**	**20 Gb/s / km^2**

Even though the most challenging traffic requirements are foreseen for the ultra-dense geotype, also the urban, sub-urban and rural scenarios were considered. For the urban geotype, we have assumed a “medium” dense case of the traffic forecast for the ultra-dense geotype, while for the sub-urban and rural scenarios, the NGMN's "50+ Mbps everywhere" use case was used to define the traffic density.

Table 8: Trafic assumptions for geotypes

Scenario:	Urban	Sub-urban	Rural
User experienced data rate	300 Mb/s	50 Mb/s	50 Mb/s
Connection Density	800 / km^2	400 / km^2	100 / km^2
per operator	267 / km^2	133 / km^2	33 / km^2
Traffic density	240 Gb/s / km^2	20 Gb/s / km^2	5 Gb/s / km^2
per operator	**80 Gb/s / km^2**	**6.7 Gb/s / km^2**	**1.67 Gb/s / km^2**

4.4 RAN dimensioning

According to the envisioned 5G traffic requirements described in Section 4.3, we perform a RAN dimensioning to provide an estimation of the small-cell density needed to cope with traffic forecasts. Once calculating the small cell density, we assume an ultra-dense scenario with a macro-site coverage area of 0.25 km^2 (i.e., a macro-site density of 4 MBS per km^2), as discussed in COMBO deliverable D3.3 [1]. Two different methodologies were used for the RAN dimensioning, and they are described in the following subsections.

4.4.1 Geometrical dimensioning model

In this model, we assume that small-cell capacity is exploited to enhance the MBS coverage, especially at the macro cell edge, where users experience lower channel quality in comparison to those closer to the MBS. Therefore, given the required 5G traffic density (i.e., Gb/s/km^2/operator), the MBS and small-cells antenna configurations (and so their radio throughput), we use the model to calculate small-cell density as well as the small-cell radius[1]. As the objective of this dimensioning is to enhance the radio coverage especially at the macro cell edge, our deployment approach is to first deploy small cells at the cell edge. Then, the remaining small cells are placed in the macro center area for providing increased capacity.

In the algorithm for the geometrical dimensioning, we use the following notation:

- D_{MBS}: density of MBS, i.e., number of macro sites per km^2 [1/km^2];
- T: total required 5G traffic [Mbps/km^2/operator];
- THR_{MBS}: throughput for a MBS [Mbps], according to the antenna configuration;
- THR_{SC}: throughput for a small cell [Mbps], according to the antenna configuration;
- A: total area [km^2];
- A_{MBS}: coverage area of a MBS [km^2];
- R: radius of the macro site area [m];

[1] We assume that both macro sites and small cells coverage areas are circular.

- A_{SC}: coverage area of a small cell [km^2];
- r: small cell radius [m]
- N: density of small cells, i.e., number of small cells per km^2 [$1/km^2$].

4.4.1.1 Algorithm for the geometrical RAN dimensioning

The algorithm adopted for the RAN dimensioning in the geometric model is reported below.

Inputs: D_{MBS}, T, THR_{MBS}, THR_{SC}, A.

Outputs: N, r.

1. area of a MBS:

   $$A_{MBS} = 1/D_{MBS}$$

2. radius of a MBS area:

   $$R = \sqrt{\frac{A_{MBS}}{\pi}}$$

3. number of small cells per km^2:

   $$N = \frac{T - D_{MBS} * THR_{MBS}}{THR_{SC}}$$

4. area of a small cell:

   $$A_{SC} = 1/N$$

5. radius of a MBS area:

   $$r = \sqrt{\frac{A_{SC}}{\pi}}$$

4.4.1.2 Case studies and numerical results

We perform the RAN dimensioning considering both 5G traffic alternatives described in Section 4.3, namely, 250 Gb/s/km^2/operator (“traffic alternative 1”) and 20 Gb/s/km^2/operator (“traffic alternative 2”). In both cases, we assume a MBS density of 4 MBS per km^2, as in COMBO deliverable D3.3, and consider the MBS antenna configuration as a 125 Mhz – 256 QAM – 16x16 MIMO, providing a peak rate of 30 Gb/s and a radio throughput THR_{MBS} = 2.9 Gb/s. Though we assume a fixed antenna configuration for each MBS, we carry out a sensitivity analysis by varying the small-cells antenna configuration (and therefore the value of THR_{SC}). Thus, for each of the considered antenna configurations we provide the number of required small cells and their radius. The different options for the small-cell configuration are shown in Table 9. Note that for antenna configurations exploiting higher bandwidth values (e.g., above 100-125 MHz), it can be assumed that they are deployed at frequency bands above 6 GHz (e.g., around 30 GHz). Keeping the 125 MHz – 256 QAM – 16x16 MIMO case as a reference configuration, for every change in the utilized spectrum, modulation format and MIMO, we scale the radio throughput and peak-rate values accordingly. As an example, changing the modulation format from 256 QAM to 64

QAM provides a reduction of a factor 8/6 ($= log_2 256/log_2 64$) in both radio throughput and peak rate in comparison to the base case. Similarly, changing the MIMO configuration from 16X16 to 4x4 MIMO will provide a reduction factor 4 (=16/4), whereas changing the utilized spectrum from 125 MHz to 50 MHz will provide a reduction factor of 2.5 (=125/50) with respect to the base case.

Table 9: Possible small cells antenna configurations and corresponding throughput and radio peak rates.

Option n.	Antenna configuration	Radio Throughput [Mbps]	Peak rate [Mbps]
1	20 MHz - 64QAM - 4x4 MIMO	37	300
2	20 MHz - 128QAM - 8x8 MIMO	85	700
3	50 MHz - 128QAM - 4x4 MIMO	107	875
4	50 MHz - 256QAM - 4x4 MIMO	122	1000
5	20 MHz - 256QAM - 16x16 MIMO	195	1600
6	50 MHz - 256QAM - 8x8 MIMO	244	2000
7	125 MHz - 256QAM - 4x4 MIMO	305	2500
8	100 MHz - 256QAM - 8x8 MIMO	488	4000
9	125 MHz - 256QAM - 8x8 MIMO	610	5000
10	175 MHz - 256QAM - 8x8 MIMO	853	7000
11	100 MHz - 256QAM - 16x16 MIMO	975	8000
12	125 MHz - 256QAM - 16x16 MIMO	1219	10000
13	150 MHz - 256QAM - 16x16 MIMO	1463	12000
14	225 MHz - 256QAM - 16x16 MIMO	2194	18000
15	250 MHz - 256QAM - 16x16 MIMO	2438	20000
16	300 MHz - 256QAM - 16x16 MIMO	2926	24000
17	500 MHz - 128QAM - 16x16 MIMO	4267	35000
18	500 MHz - 256QAM - 16x16 MIMO	4876	40000
19	500 MHz - 256QAM - 32x32 MIMO	9752	80000

For the considered antenna configurations, we show the results of the RAN dimensioning in Figure 32 and Figure 33, for the cases of traffic alternative 1 (250 Gb/s/km^2/operator) and 2 (20 Gb/s/km^2/operator), respectively.

We observe from these figures how the required number of SCs decreases for more advanced antenna configurations, and how their radius decreases accordingly. In some cases, unpratical SC deployment would be required, especially for traffic alternative 1, in terms of both number of required SCs and their radius. In particular, LTE-like antenna configurations (such as configuration 1 of Table 9) would require several thousands of SCs per km^2, with reduced coverage (i.e., with radius below 10 meters).

We envision that, given the aforementioned 5G traffic requirements, advances in antenna configurations will be mandatory and will lead to the adoption of cell sites able to provide around 10 Gb/s peak rate, such as antenna configuration 12 in Table 9, which we will consider as a reference configuration in our techno-economic evaluation in Section 4.7. With this assumption, even considering high traffic scenarios (i.e., traffic alternative 1), around 200 SCs per km^2 would be required, corresponding to about 50 SCs per MBS.

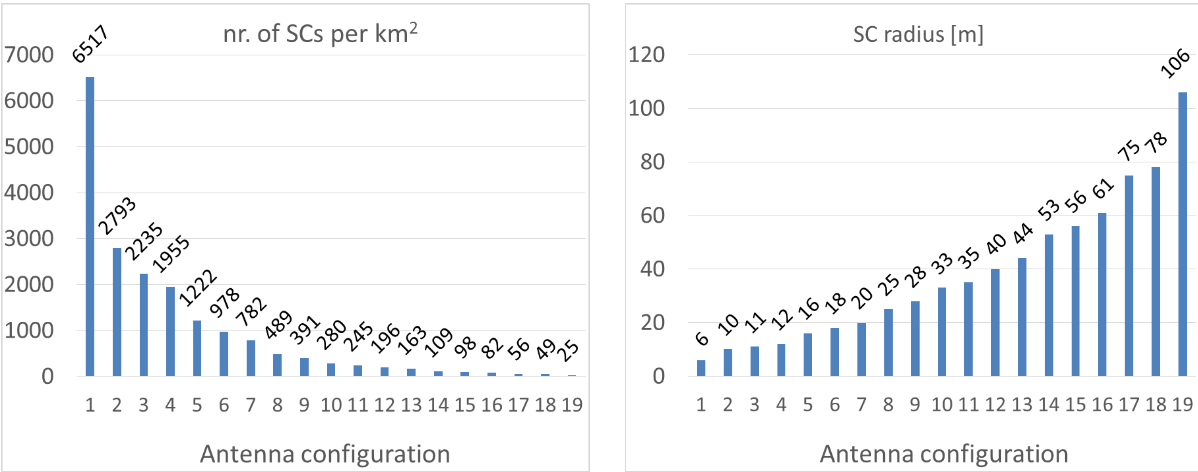


Figure 32: RAN dimensioning for traffic alternative 1 (250 Gb/s/km²/operator)

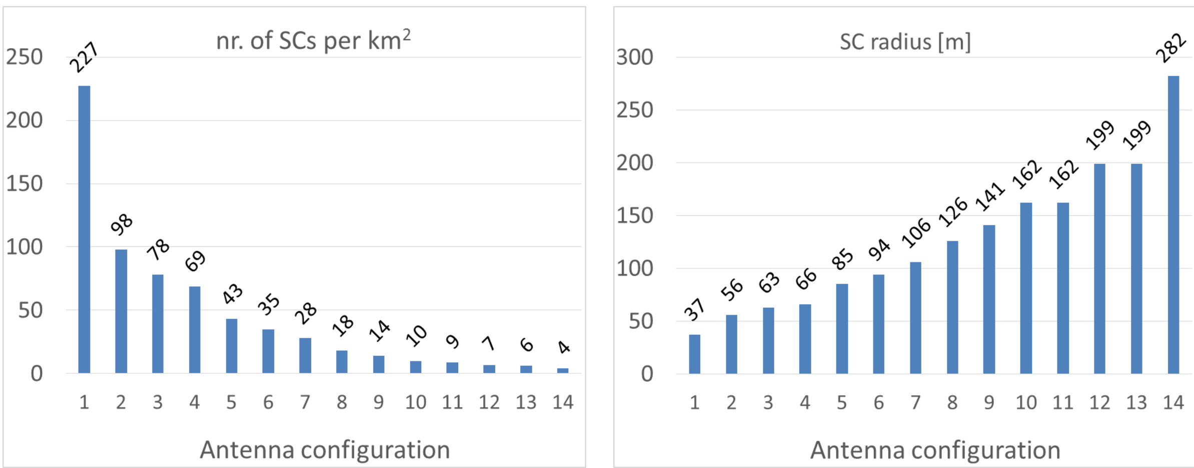


Figure 33: RAN dimensioning for traffic alternative 2 (20 Gb/s/km²/operator)

4.4.2 RAN dimensioning and throughput simulations

For the RAN dimensioning and throughput simulation, dimensioning of the radio access network (RAN) was done with the goal to determine the number (density) of Macro Base Stations and Small Cells with respect to the expected mobile traffic requirements (described in section 4.3).

The simplified estimation described in the previous section was based on, and validated by, a more complex radio-network simulation that was able to consider various technical and physical parameters of the RAN. The antenna configurations were discussed in section 4.2. There were numerous aspects in which these configurations are different from the currently deployed radio access networks, therefore simulations were carried out to understand the capacity of the network.

We have carried out MATLAB simulations for dimensioning the network. Specifically, randomized Monte-Carlo simulations were applied: terminals (UEs) were generated according to density and bit rate derived from the traffic assumptions, and MBSs and SCs installed with respect to a predefined MBS and SC density, and these were configured according to the “reference” RAN configuration. Finally, the UEs were assigned to the MBSs and SCs as follows:

- the Signal-to-Interferer/Noise-Ratio (SINR) was calculated for every UE based on:
  - the received signal power from the antenna it is assigned to
  - the suffered intereference from the surrounding MBSs and SCs (i.e., the MBSs and SCs are operating in the same frequency range)
  - the thermal noise
  - the COST231 signal propagation model was used to calculate the path loss between the UE and the assigned / interfering MBSs and SCs
  - the SCs were simulated as omnidirectional antennas, the MBSs as sectorized antennas with 120° angle, using the 3GPP antenna characteristic
- based on the SINR, the spectral efficiency (SE) was calculated using a modified version of Shannons formula, having a peak of 7.5 for 256QAM, and 5.0 for 64QAM (according to LTE-Advanced adaptive modulation and coding schemes), plus we were also considering MIMO gain
- knowing the bit rate and SE, the radio bandwidth needed to serve the UE at the MBS/SC was calculated (since the dimensioning was made for peak load, we assume full load both in time and frequency domain)
- the assignment of UEs to BSs and SCs was done maximizing the spectral efficiency of the system, i.e., every UE was assigned to the first MBS or SC with enough capacity that provides the highest SINR
- iteratively, if at least 95% of the UEs was served by its required bit rate, the antenna density was accepted, otherwise the MBS and/or SC density was increased

In the calculations carried out for COMBO D3.4, the MBS density was fixed to the present densities for ultra-dense, urban, sub-urban and rural cases, respectively. Then, the density of SCs was adapted so that the heterogeneous network has enough capacity to serve the traffic demand.

Such process is obviously more time consuming than the geometric estimations, but more precisely handles the impact of different antenna densities on interference, or the various radio network parameters, such as modulation or MIMO configuration.

4.4.2.1 Base Station and Small Cell density

Primary results are presented in *Table 10* (note that these figures are per operator values):

Table 10: 5G dimensioning simulation results

Geotype	Ultra-dense	Urban	Sub-urban	Rural
Traffic Density [Gb/s/km^2]	250	80	6.7	1.67
UE density [UE/km^2]	833	267	133	33
Bit rate per UE [Mbps]	300	300	50	50
MBS density [MBS/km^2]	4	1.5	0.2	0.05
SC density [SC/km^2]	42.6	17.1	1.9	-
SC per MBS	10.6	11.4	9.5	-

The bit rate per UE, UE density, and the derived traffic density figures are input parameters, based on NGMN's 5G White paper [13]. The MBS density was fixed to the values described in COMBO D3.3 [1], and the small cell density was calculated, according to the traffic. It is worth to note that even though cell size in the macro layer is increasing between urban, sub-urban and rural scenarios, the average number of small cells per macro base stations remains close to 10.

4.4.2.2 Throughput

Figure 34 shows the related between the achieved mean throughput per SC and the SC density. The simulations were made for the Ultra-dense scenario, scaling the traffic between the two traffic alternatives in four steps: 20, 50, 125, 250 Gb/s/km^2. The higher traffic density requires more SCs, and the smaller cells lead to higher spectral efficiency – it is clear that UEs closer to the SC have better signal quality. Besides the trend, the range of the throughput values is of interest: with the given RAN configuration, the throughput was between 1.5 – 4.3 Gb/s per SC or MBS sector.

We have to point out that these throughput figures consider the spectral-efficiency gain due to using MIMO. Calculating the MIMO gain brings some uncertainties; first because of the size of UEs and therefore the applicable antenna arrays; secondly due to the unknown correlation of MIMO channels. The figures here assume to have 16x4 MIMO configuration and 4 uncorrelated channel between the MBS/SC and the UE, and using multi-user MIMO from the antenna side (4 UEs in parallel).

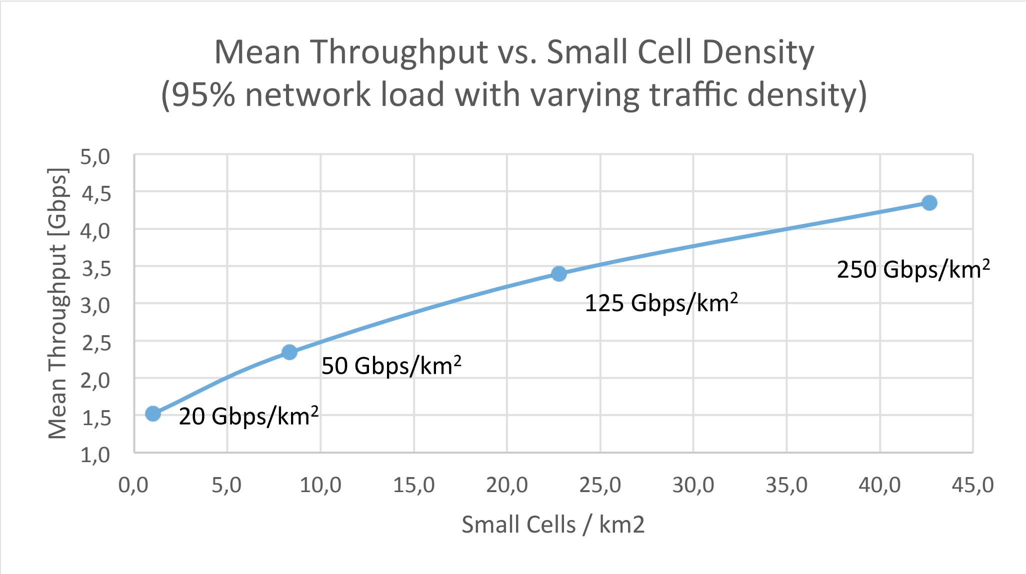


Figure 34: Througput vs. small cell density

4.5 RAN splits

In traditional CRAN implementations, the BBU hoteling principle consists of geographically separating each BBU from its RRU (which remains at the antennas site), and consolidating BBUs into a common BBU hotel. Thus, relevant benefits can be obtained in terms of costs, due to the possibility of performing centralised computing, eventually exploiting network functions virtualization (NFV), and improved performance, by facilitating advanced radio coordination techniques such as CoMP. However, RRUs interfacing with antennas front/back-ends only perform basic layer 1 functions, i.e., Digital-to-Analog/Analog-to-Digital Conversion (DAC/ADC) of the baseband signals, frequency up/down-conversion, power amplification and signal measurements. Therefore, high data rates, i.e., the fronthaul, must be exchanged between BBUs and RRUs. So, instead of the traditional CPRI interface [15] defined to transport such information, more efficient solutions are needed to cope with capacity shortage. This is especially true if we consider future 5G scenarios, where a large number of deployed small cells are expected to support huge amounts of traffic, as commented in Section 4.3. Therefore, different RAN protocol stack splits (in the following, simply *RAN splits*), i.e., different functional separations between L1 and L2/L3 cell processing, have been identified and evaluated, in terms of potential cost/performance benefits and required capacity. These new radio protocol split points aims to go beyond the existing full radio stack radio base stations separation in BBU-RRU, and permit the flexibility of different deployments combinations, i.e., the centralization and/or virtualization of higher radio protocol layers in CO-like sites, and the placement of lower radio protocol layers in the remote sites. In contraposition to traditional fronthaul, the traffic transported between the two separate locations (i.e., the antenna site and remote BBU-like site) is also known as *x-haul*.

In this section, we investigate the capacity needed to transport x-haul traffic for the different RAN split options. As the (x-haul) transport capacity directly depends on the radio bit rate supported by the specific cell configuration (in terms of utilized spectrum, modulation format and MIMO transmission/reception), we carry out a sensitivity analysis by considering several antenna configurations representing the potential candidates for 5G network deployment.

4.5.1 Overview of RAN split options

According to the considered RAN split options, several network functions can be implemented in the remote site, as a physical network function, or in the central cell, as a virtualized network function. In this study, we refer to the RAN split options considered in [16], derived from the mobile network function virtualization adopted in [17]. In Figure 35, we show the considered RAN split options[2].

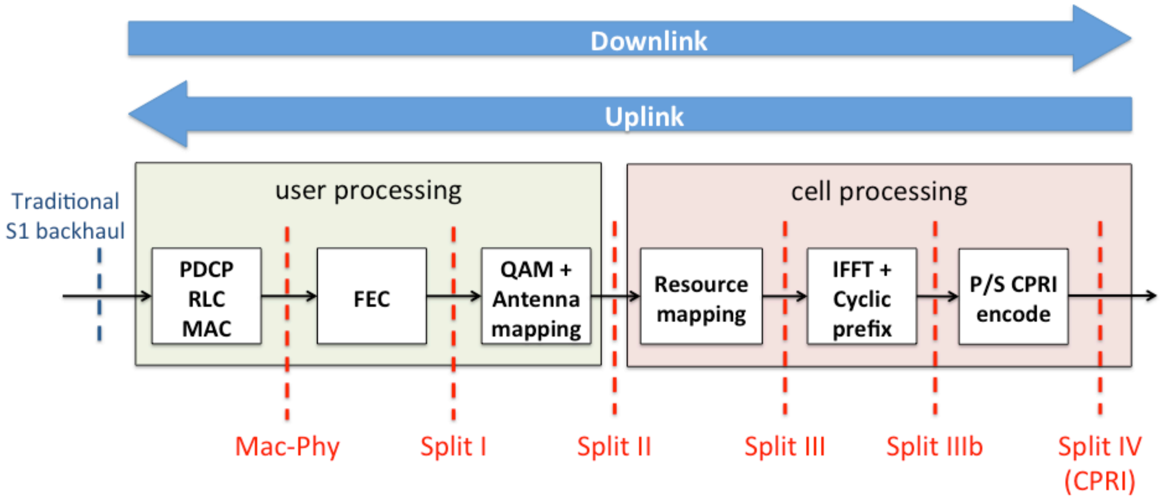


Figure 35: Cell site RAN splits (figure adapted from [16]).

The choice of RAN split is determined, among other things like site aspects, power, resources sharing, etc, by the trade-off between the benefit of functional centralization, the required transport capacity and the chosen radio configuration. Though several models can be found in literature (see, e.g., [18]), for the required bit-rate values we refer to the model in [16], where the evaluation is performed for a basic configuration, i.e., a cell site with an antenna configuration exploiting 20 MHz spectrum, 64 QAM modulation format and 2x2 MIMO. According to the considered split options and given the above mentioned antenna configuration, the required bit rates in downlink and uplink are shown in Table 11. Note that we here consider both downlink and uplink since the direction which needs higher data-rate transport depends on the considered split option (see Table 11). Therefore, the network capacity to be deployed is dimensioned according to the maximum data-rate to be supported in the downlink and uplink directions.

[2] Note that other RAN splits are also considered in [16], mainly concentrating on L2/L3 functional splits. However, we do not consider these further splits as the required bandwidths do not differ substantially from the MAC-PHY split bandwidth values.

Table 11: Downlink/uplink required bandwidth for antenna configuration with 20 MHz - 64 QAM - 2x2 MIMO.

	Mac-Phy	Split I	Split II	Split III	Split IIIb	Split IV (CPRI)
Downlink [Mbps]	152	173	933	1075	1966	2457.6
Uplink [Mbps]	49	452	903	922	1966	2457.6

4.5.2 Scaling analysis for different antenna configurations

To understand the impact of different antenna configurations on the required x-haul capacity, we consider the antenna configurations used in Section 4.4. Starting from the base configuration with 20 MHz - 64 QAM - 2x2 MIMO, and considering the model in [16], we evaluate the required transport capacity for the considered C-RAN splits and for the different antenna configurations. The obtained numerical results are shown in Figure 36. More details on the x-haul capacity calculation are provided in Section 8.2.

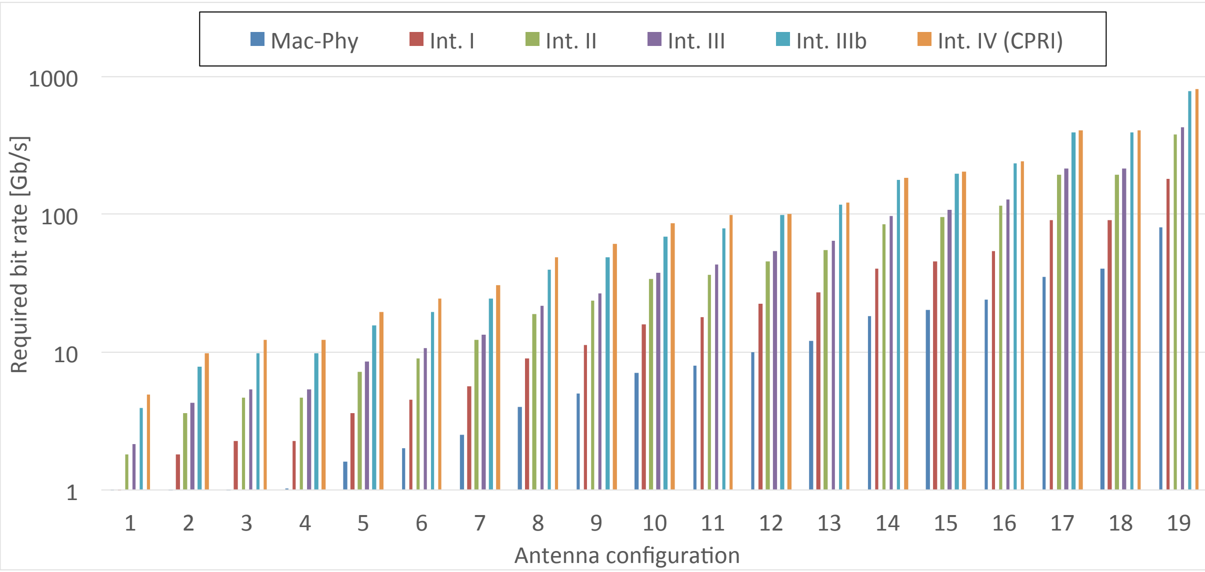


Figure 36: Required transport capacity for different RAN splits and antenna configurations.

From the obtained results we can identify, for each C-RAN split, the antenna configurations which require x-haul transport capacity "optimally fitting"[3] into 1 Gb/s, 10 Gb/s, 25 Gb/s, 40 Gb/s and 100 Gb/s optical interfaces. The selected antenna configurations are shown in Table 12. To assess the required x-haul bit rate values, we select the maximum between required downlink and uplink capacity for every antenna configuration.

[3] For each C-RAN split, among the antenna configurations with x-haul bit rate below x Gb/s (x=1/10/25/40/100), we select as "optimal" configuration the one which provides the highest radio peak rate.

Table 12: Optimal antenna configurations for each RAN split and for different optical interfaces.

Option n.	Antenna configuration	Radio peak rate [Mbps]	RAN split	Reqired x-haul [Mbps]	Required interface
3	50 MHz - 128QAM - 4x4 MIMO	875	Mac-Phy	881	1G
11	100 MHz - 256QAM - 16x16 MIMO	8000		8042	10G
16	300 MHz - 256QAM - 16x16 MIMO	24000		24122	25G
17	500 MHz - 128QAM - 16x16 MIMO	35000		35177	40G
19	500 MHz - 256QAM - 32x32 MIMO	80000		80403	100G
1	20 MHz - 64QAM - 4x4 MIMO	300	Split I	903	1G
8	100 MHz - 256QAM - 8x8 MIMO	4000		9032	10G
12	125 MHz - 256QAM - 16x16 MIMO	10000		22579	25G
13	150 MHz - 256QAM - 16x16 MIMO	12000		27095	40G
18	500 MHz - 256QAM - 16x16 MIMO	40000		90317	100G
6	50 MHz - 256QAM - 8x8 MIMO	2000	Split II	9032	10G
9	125 MHz - 256QAM - 8x8 MIMO	5000		23775	25G
11	100 MHz - 256QAM - 16x16 MIMO	8000		36127	40G
15	250 MHz - 256QAM - 16x16 MIMO	20000		95013	100G
5	20 MHz - 256QAM - 16x16 MIMO	1600	Split III	8602	10G
8	100 MHz - 256QAM - 8x8 MIMO	4000		21504	25G
10	175 MHz - 256QAM - 8x8 MIMO	7000		37632	40G
14	225 MHz - 256QAM - 16x16 MIMO	18000		96768	100G
4	50 MHz - 256QAM - 4x4 MIMO	1000	Split IIIb	9830	10G
7	125 MHz - 256QAM - 4x4 MIMO	2500		24576	25G
8	100 MHz - 256QAM - 8x8 MIMO	4000		39322	40G
12	125 MHz - 256QAM - 16x16 MIMO	10000		98304	100G
2	20 MHz - 128QAM - 8x8 MIMO	700	CPRI	9830	10G
6	50 MHz - 256QAM - 8x8 MIMO	2000		24576	25G
7	125 MHz - 256QAM - 4x4 MIMO	2500		30720	40G
12	125 MHz - 256QAM - 16x16 MIMO	10000		101376	100G

Moreover, in Table 13 we show the values for the reference antenna configuration, used in Section 4.4 for the C-RAN dimensioning and in Section 4.7 for our techno-economic evaluation.

Table 13: Required midhaul capacity for the reference antenna configuration and for different each RAN splits.

Option n.	Antenna configuration	Radio peak rate [Mbps]	RAN split	Reqired x-haul [Mbps]	Required interface
12	125 MHZ 256 QAM 16x16 MIMO	10000	Mac-Phy	10052	25G
			Split I	22579	25G
			Split II	45158	100G
			Split III	53760	100G
			Split IIIb	98304	100G
			CPRI	101376	100G

4.6 High speed optical interfaces

Since any infrastructure poses significant invest, it must be ensured that it can scale to future bandwidth requirements. Hence, the converged-infrastructure proposals derived in COMBO Deliverable D3.3 [1] must be checked, regarding technical feasibility and resulting cost, against increased bandwidth demand that is extrapolated into the future.

In general, bandwidth increase will occur for both, wireline and wireless or mobile access. However, the most aggressive bandwidth-growth numbers currently known refer to 5G [4]. Therefore, we check the COMBO infrastructure proposals especially regarding potential 5G fronthaul (or next-generation fronthaul, or midhaul) bit rates.

Possible alternatives to (CPRI) fronthaul have briefly been discussed in COMBO D3.3, Ch.3.2.3, and in the previous sections of the document at hand, (sections 4.5.1, 4.5.2). If CPRI-like fronthaul (i.e., *without* significant changes that lead to bit-rate reductions) is extrapolated to 5G bandwidth requirements, per-radio-head bit rates can easily scale to, or exceed, 100 Gb/s. For examples, one can extrapolate the bit rates from Figure 8 in Ch.3.2.2 of D3.3 to extended radio bandwidth and MIMO, or refer to Table 13 in the previous section. Therefore, it is likely that bit rates in next-generation fronthaul will be reduced by whatever means, for example different functional splits of base stations as discussed in D3.3, Ch.3.3.3. Such approaches are followed in various research projects, most notably EU H2020 project iCIRRUS [19], 5G-PPP 5G-Crosshaul [20], and 5G-PPP 5G-XHaul [21].

Since the resulting bit rates are not known at the time of writing this deliverable, the *analysis regarding future bandwidth scaling must cover pessimistic (worst-case) scenarios*. Therefore, next to smaller bit rates, we investigate infrastructure scaling also with CPRI bit rates extrapolated to reasonable 5G scenarios. Then, it is highly likely that next-generation fronthaul or midhaul bit-rate scaling will not lead to even more demanding requirements.

Fronthaul in 4G / LTE-A can reach bit rates of 10 Gb/s *per sector* for 20 MHz radio bandwidth and MIMO degree of 8. Theoretically, up to 100 MHz radio bandwidth can be used in LTE-A, leading to 50 Gb/s fronthaul bit rate per sector. However, this can be regarded an unlikely broad-scale scenario due to bandwidth scarcity.

These bit rates still assume 8B/10B line coding as has been used in early CPRI variants (line bit-rate options 1 to 7) [15]. With the newer 64B/66B coding, 50 Gb/s can be reduced to ~41 Gb/s. CPRI 64B/66B has been introduced with line rate option 8.

5G intends to use even higher bandwidth compared to 4G, and possibly higher MIMO degrees. For infrastructure-scaling calculations, we used a maximum 5G scenario with 125 MHz radio bandwidth, 16x16 MIMO, and CPRI-like fronthaul. These data are sufficient to provide the intended 5G peak bit rate toward the user equipment of 10 Gb/s. 125 MHz may not even be the maximum bandwidth possible in any 5G scenario, on the other hand it is more than unlikely that CPRI-like fronthaul will be used. More likely, different functional split of the base stations will be used which potentially can reduce next-generation fronthaul bit rates by up to a factor of 10. Therefore, we regard the resulting fronthaul bit rate as mid-term worst-case upper bound for bandwidth scaling. Without any further bit-rate reduction over CPRI (again, the related techniques are not yet agreed upon), the maximum fronthaul bit rate per sector is then given by:

$$200 \cdot 66/64 \cdot 491.52 \text{ Mb/s} \approx 101.4 \text{ Gb/s}$$

For smaller radio bandwidth or smaller MIMO degree, smaller bit rates will result, and v.v. Other examples for CPRI-like fronthaul (that is, without bit-rate reduced fronthaul/midhaul) include ~41 Gb/s for 100 MHz radio bandwidth and 8x8 MIMO (the example mentioned above), or ~25 Gb/s for 60 MHz bandwidth and again 8x8 MIMO.

For these extended bit rates, investigations regarding technical and commercial (low-cost) feasibility and potentially achievable cost are required to ensure that the recommended COMBO infrastructure solutions can even scale to worst-case 5G bandwidths. In reality, bit rates most likely will be lower due to newer fronthaul technologies. On the other hand, we “only” consider 5G bandwidth scaling and nothing that may come beyond.

For simplicity, and because these bit-rate ranges are well-known already, we restrict the analysis to the three following classes:

- “25G”, payload up to 25.78 Gb/s (25GbE), framed bit rate ~28 Gb/s
- “40G”, payload up to 41.25 Gb/s (40GbE), framed bit rate ~43…44 Gb/s
- “100G”, payload up to 103.125 Gb/s (100GbE), framed rate ~108…112 Gb/s

From today’s perspective, and for reasons of cost suitable for access infrastructure, *direct-detection methods* must be considered even for these extended bit rates. The rationale behind is that these methods can benefit from grey, short-reach interfaces which are under development for 100GbE and 400GbE intra-data-centre applications, and which will be *based on multiple carriers and direct detection* (for reasons of cost, energy consumption, and form factor). As known from all other intra-data-centre interfaces, the related technology will go into mass production and will achieve low cost. Consequently, for our consideration, we can consider *single-carrier variants* of these technologies. If adaptation toward access-scale (up to 50…60 km reach) WDM transport can be achieved, the respective methods very likely are cheaper than scaled-down coherent variants at the respective bit rates.

Recently, a set of direct-detection modulation schemes has been discussed for both, grey short-reach interfaces and also for WDM transport up to typical inter-data-centre distances (i.e., up to 80…100 km). These schemes comprise Electrical Duobinary (EDB, mainly as possible contender for 25G WDM), Optical Duobinary (ODB, also with focus on 25G WDM), PAM4 (Pulse-Amplitude Modulation with 4 intensity levels, can be used for any of the bit rates considered here), and DMT (Discrete Multi-Tone, the real-valued, direct-detect variant of OFDM; so far main focus was on 100G).

Today, the decisions for 100GbE and 400GbE grey interfaces with reduced lane-number are not yet fully stable. There is consensus to use PAM4 for 400GbE [22], but that is not yet true for 100GbE. This also means that, *should a decision in favour of PAM4 be made also for 100GbE, then DMT is likely no commercial low-cost contender for COMBO infrastructure applications anymore* (because the related chip sets would not go into mass production and DMT would end up being too expensive).

For this reason, we focus on PAM4 for the higher bit rates here, complemented by variants of Duobinary (i.e., Partial Response) for the lower bit rates (25G, also 40G). Background here is that Duobinary was one of the few commercially successful technologies that were used approximately 10 years ago for 40-Gb/s WDM systems. Likewise, Optical Duobinary with 28 Gb/s lane rate is used for direct-detect variants of WDM 100-Gb/s super-channel WDM transport for distances up to ~600 km. Consequently, and unlike PAM4, we must consider Duobinary an established technology for 25G and 40G.

For comparison, block diagrams of the high-speed, direct-detect schemes are shown in Figure 37. WDM filters (according to WR-ODN) are shown for all cases.

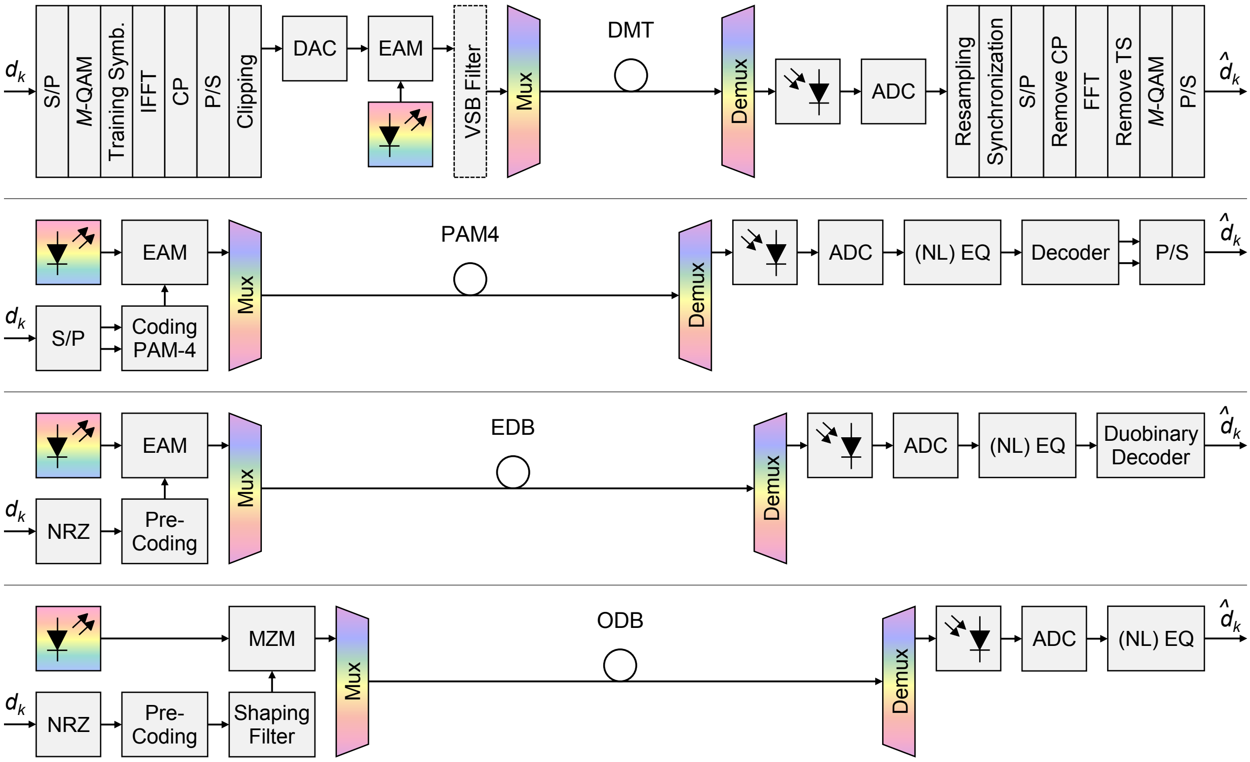


Figure 37: Block diagrams of DMT, PAM4, EDB, and ODB (top to bottom). ADC: Analogue-Digital Converter. CP: Cyclic Prefix. DAC: Digital-Analogue Converter. EAM: Electro-Absorption Modulator. (I)FFT: (Inverse) Fast Fourier Transform. MZM: Mach-Zehnder Modulator. (NL) EQ: Nonlinear Equalizer. NRZ: Non-Return-to-Zero. P/S: Parallel-Serial Converter. S/P: Serial-Parallel Converter. TS: Training Symbols. VSB: (optional) Vestigial Sideband (filter).

Direct-detection PAM4 and optical and electrical Duobinary have been analysed in [23]-[28]. Both, low-cost potential and reach capability suitable for the site-consolidated access scenario described before have been investigated. In addition, a basic maximum-reach and cost comparison is made here that also includes DMT.

Cost mark-up of the resulting 25G and 40G transceivers, *measured against low-cost 10-Gb/s WDM pluggable transceivers*, was estimated under the *assumption of fully ramped-up mass production*. This means that the cost mark-up considered production numbers *similar to those intended for tunable-laser WDM-PON*.

Such cost figures will likely not be reached within the next couple of years.

Both, cost and reach analysis have been performed for 25G and 40G, considering transceivers of different analogue bandwidths, respectively. This was done to identify the lowest possible bandwidth each in order to enable cheapest-possible components. The analysis was based on simulation and confirmed by experiment. Results of the cost analysis are shown in Figure 38 for Electrical Duobinary (EDB) and PAM4.

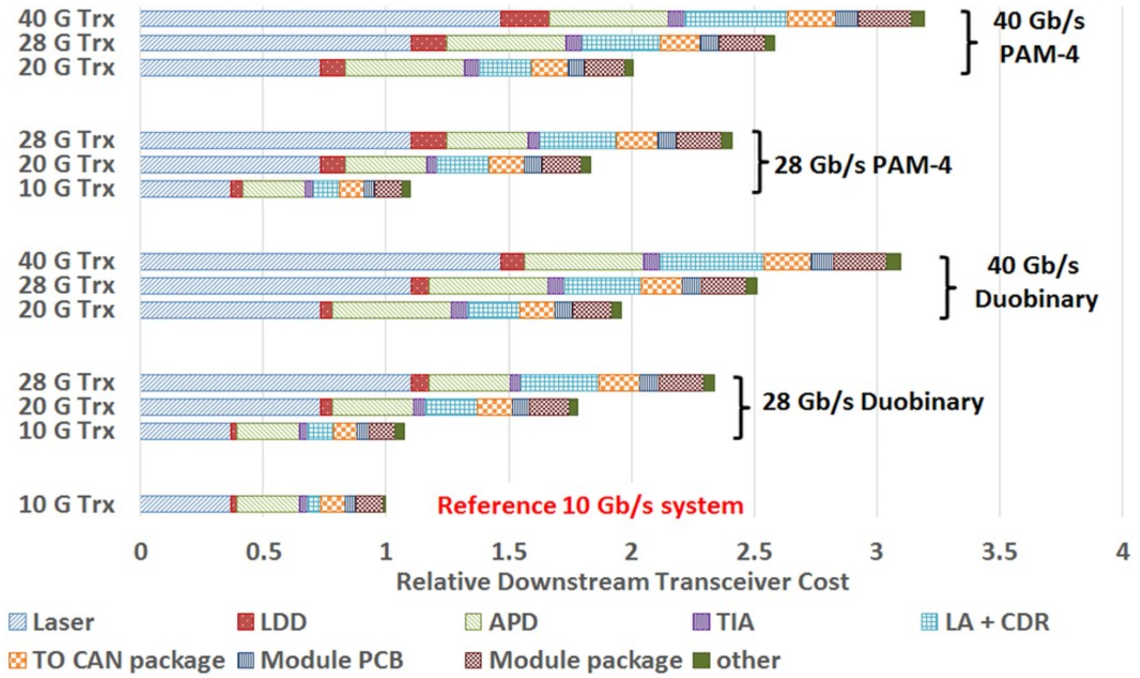


Figure 38: Cost, relative to 10-Gb/s transceivers (Trx), for 28 Gb/s and 40 Gb/s (Electrical Duobinary and PAM4, for transceivers with bandwidth of 10 GHz, 20 GHz, and 40 GHz, respectively [23].

Obviously, the transceiver cost decreases with decreasing bandwidth (per bit rate). On the other hand, if bandwidth is limited too strongly (e.g., to allow 10G components to be re-used for 40G Duobinary), then performance will decrease in an unacceptable way due to severe signal distortions. This effect can partially be compensated by (nonlinear) digital equalizers (Digital Signal Processing, DSP).

As a first result, it has been shown in [23] and [24] that transceivers with somewhat reduced bandwidth can be used to achieve almost maximum performance (i.e., further bandwidth increase does not lead to reach-performance increase anymore). For 28 Gb/s, components bandwidth of 20 GHz or slightly above is sufficient. For 43 Gb/s, components with 28 GHz bandwidth can be used. This in particular holds for the transmitters. Receivers can tolerate even smaller bandwidth for both, Duobinary and PAM4. This is due to the fact that PAM4 obviously reduces the Baud rate, and Duobinary reduces the bandwidth via Partial-Response coding. Then, from Figure 38, one can derive that for 25G transceivers, a cost mark-up over 10G components in the range of a factor of 2 results. For 40G, this factor is 2.5…3.

For our dimensioning studies, we used factors of 2.1 for 25G, and 2.7 for 40G.

Again, these numbers assume mass production. They hold for the transceiver modules only. Since 25G and 40G always require the use of FEC (Forward Error Correction, otherwise the reach performance would clearly be insufficient), the added

FEC cost contribution must be considered. The same holds for any additional digital equalizers (e.g., receive-end MLSE, Maximum-Likelihood Sequence Estimation). On the other hand, other components (e.g., housing, controllers, diplexers, filters, isolators, connectors) are not affected regarding cost by bit-rate increase. Therefore, mark-up factors of 2…3 for transceivers will *not* lead to the same increase for complete links

Figure 39 complements the cost analysis of Figure 38 by also considering Optical Duobinary for 40G transceivers. Here, optimized analogue bandwidth has already been considered. One can derive that ODB is slightly more costly compared to EDB. This is attributed in particular to somewhat higher complexity of the transmit modulator.

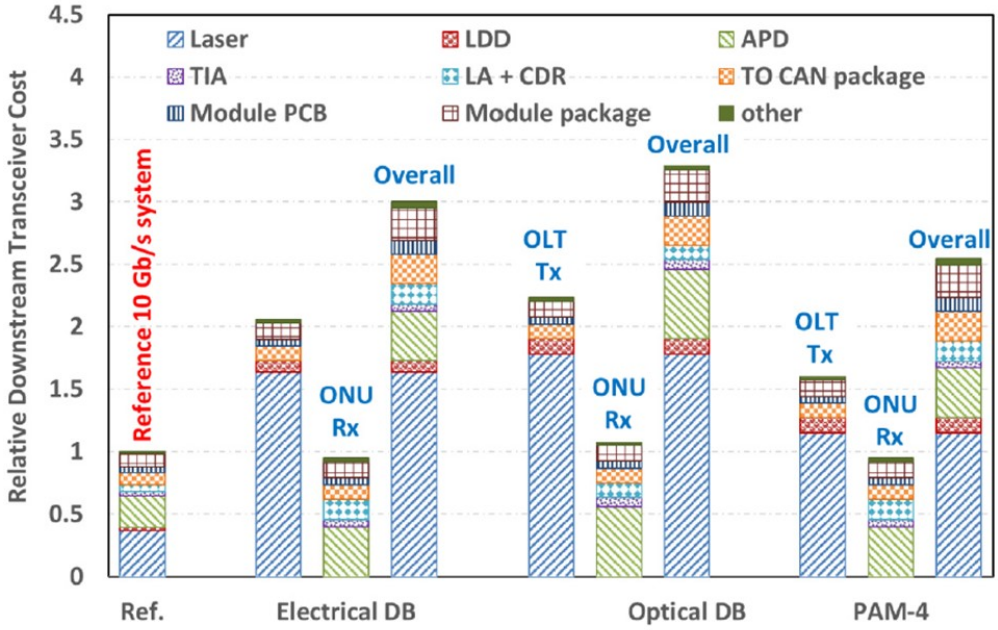


Figure 39: Cost, relative to 10-Gb/s transceivers, for 40 Gb/s Electrical Duobinary (DB), Optical Duobinary and PAM4, for transceivers with optimized bandwidth, respectively [24].

The cost mark-up for higher bit rates can be regarded as moderate given that other components of the systems (as stated above) and the infrastructure itself will not necessarily get more expensive with bit-rate increase.

Also, no *significant* cost differences between EDB, ODB and PAM4 can be derived.

So far, cost estimations regarding DMT (Discrete Multi-Tone) are missing. To first approximation, transceiver cost (per bit rate) are similar to the ones for PAM4. DMT, as a multi-carrier technology, requires higher linearity in particular of the transmitter. It may also require more signal processing for the mult-carrier modulation, compared to the MLSE required for PAM4. On the other hand, it can allow *significantly* less effort for dispersion compensation. Therefore, *to first approximation, DMT cost is the same as for PAM4*, and differences relate to specific configurations which cannot be discriminated with reasonable effort here since the cost mark-up factor estimations include uncertainty anyway.

Then, reach performance of the modulation schemes must be considered next.

Figure 40 shows the reach comparison for EDB, ODB and PAM4 for 40G systems [24]. The reach shown here is *dispersion-limited* for all modulation schemes. It does *not* (yet) consider dedicated dispersion compensation. Likewise, digital equalizers (linear ones, which mainly compensate dispersion effects, or nonlinear ones, which can also compensate components nonlinearities) have not been considered. In particular, nonlinear equalizers have some potential for reach increase since they can compensate some negative effects of bandwidth-limited components. On the other hand, nonlinear equalizers typically are much more complicated than linear ones.

In Figure 40, no additional amplifiers (booster, pre-amplifier) have been considered.

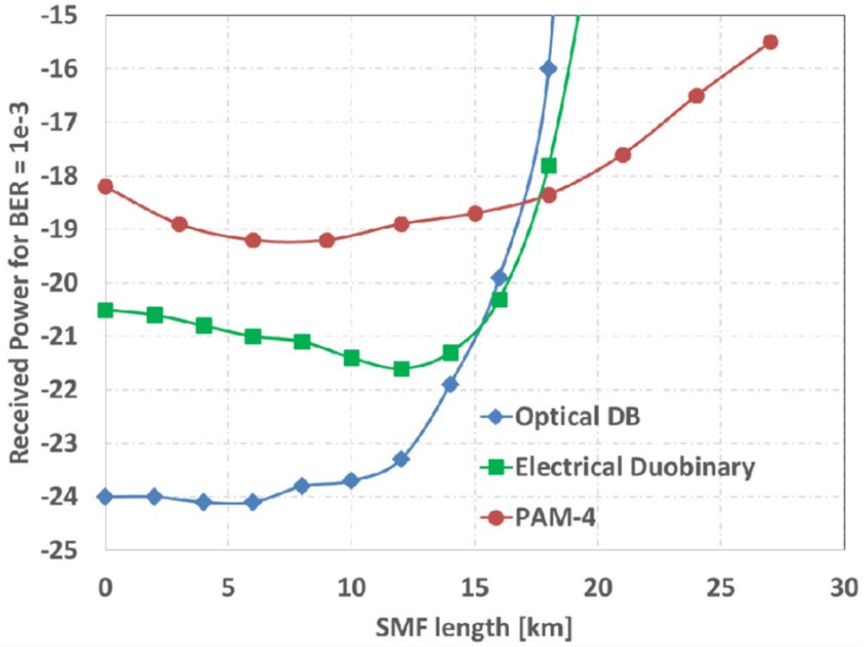


Figure 40: Reach for 40 Gb/s Optical Duobinary (DB), Electrical Duobinary and PAM4, without additional amplification or dispersion compensation [24].

From Figure 40, a heterogeneous result regarding reach, sensitivity and modulation must be derived. ODB achieves the best sensitivity (-24 dBm, i.e., allowing relatively simple receivers and thus compensating for part of the higher transmitter effort), but above 12 km, it shows the strongest reach penalty. PAM4, on the other hand, starts with the weakest sensitivity (-18 dBm, mandating pre-amplifiers in almost all cases), but reach penalty only moderately increases above 20 km.

Similar results are obtained, at generally higher reach and better sensitivity, for 25G. Here, PAM4 (with FEC, as before) achieves sensitivity of -25 dBm, leading to maximum reach without dispersion equalization of 60 km. EDB achieves sensitivity of -28 dBm and dispersion-limited reach of 20 km (without added equalization).

At least for PAM4, analysis has also been confirmed by first test results [25], [26].

For DMT, reach is again comparable to the one obtained for PAM4, with clear advantages for DMT for cases where dispersion compensation is to be avoided.

For 100G, so far only a rough extrapolation of cost and reach-performance figures has been done. Resulting numbers are therefore subject to potential deviation.

For 100G cost dimensioning, we use a cost mark-up factor over 10G transceivers of 4.0. This factor is only higher by a factor of ~2, compared to the mark-up factor between interfaces at 1 Gb/s and 10 Gb/s. This is reasonable given that the required effort increase between 10G and 100G is significantly higher compared to the one between 1G and 10G. (One now needs multi-carrier or multi-level and in addition DSP).

Unamplified 100G sensitivity is in a range where unamplified configurations do not make sense anymore (sensitivity with FEC is in the range of, or weaker than, -15 dBm). Non-equalized reach is in the range of 8 km. Above this value, dispersion compensation must be provided. This can be done with (static or tunable) optical dispersion compensation (e.g., based on Bragg Reflector Gratings, BRG) or with digital equalizers. Here, it must be considered that digital equalization for direct-detection schemes is limited in efficiency and for significant improvement requires nonlinear equalizers or MLSE.

If compensation (or significant part of it) is provided optically for the WDM multiplex section (i.e., it is applicable to all channels simultaneously), it also poses a *limitation for the differential reach* of the related links. Then, differential reach between the individual links is limited to ±8 km. Otherwise, per-channel compensation must be provided. (The same effect occurs at 25G and 40G as well, respectively.)

Table 14 gives a summary of the high-speed transceiver analysis.

Table 14: Summary of high-speed transceiver analysis.

		ODB	EDB	PAM4	DMT
Cost Factor over 10G	25G	2.1			
	40G	2.7			
	100G	4.0			
Reach [km] without added Compensation	25G	(20)	20	60	(60)
	40G	10	15	25	(25)
	100G	-	-	8	(>8)

Numbers for ODB in brackets are derived from EDB performance, numbers in brackets for DMT are derived from PAM4 performance.

The results from Table 14 will change in particular with the addition of (digital) nonlinear equalization or MLSE. First, *reach is substantially increased by adding this equalization*. This is particularly relevant for 25G (except for PAM4) and 40G since it can avoid added optical dispersion compensation. When adding equalization, EDB becomes more advantageous [26]. For 40G, it can then be used for up to 40 km, thus even slightly outperforming PAM4. For 40G and reach above 40 km, however, effort for digital equalization becomes very high and may lead to prohibitive cost.

In general, 25G to 100G can be done at reasonable cost over meaningful converged-access distances. Some more investigation is required to identify the optimum modulation scheme, in particular when (nonlinear) equalization is added and considered in the cost. This is difficult today because the potentially required tap numbers of the equalizers cannot be simulated with reasonable effort for distances

>40 km today. For this reason, we also consider optical dispersion compensation (by means of BRGs) in our high-speed dimensioning studies.

Also, it seems that for the higher bit rates, in particular for 25G and 40G, *two different, reach-dependent implementations make sense to optimise resulting cost*. In both cases, for short reach (below 20 km or even below 10 km), Duobinary may be used, without added equalization or amplification. For higher reach, PAM4 with amplification (and equalization in case of 40G) may be used.

For 100G, it seems that dispersion-compensated PAM4 is the choice for all reach domains. For significant distances (somewhere above 10 km), optical compensation must be used due to prohibitive effort for digital equalizers.

4.7 Techno economic results

This section completes the techno-economic study started in D3.3 with the analysis of 5G in FMC network architectures. The techno-economic study is based on the same methodology as previous studies included in D3.3 and D3.4, see Chapter 2, the main change being a heterogeneous network model more oriented to 5G.

The heterogeneous network model, initially based on LTE, now considers a radio configuration with extended bandwidth (125 MHz) and higher-order constellation (256 QAM) and MIMO (16x16). As an initial 5G scenario, we assume a SC density of on average 50 SCs per MBS. Based on modeling in section 4.4.1.1, this is the estimated number of SC per km^2, required to support an estimated 5G traffic density of 250 Gb/s/km^2/operator. Other SC densities were also analysed at the end of this section. In the 5G scenarios, we assume that the MBS sites will be based on 5G, LTE and 2G radio technologies (but not 3G, as it can be replaced by 4G), whereas SCs only will be based on 5G. *Table 15* shows a summary of the assumed radio:

Table 15: Radio configuration for MBSs and small cells

Heterogeneous Network Radio Configuration	Macro Base Station	Small Cell
Radio technologies	2G / 4G / 5G	5G only
Sectors per technology	3	1
Bandwidth	40 MHz for 4G 125 MHz for 5G	125 MHz
HO-MIMO	4 x 4 for 4G 16 x 16 for 5G	16 x 16

The 5G radio scenarios have an impact on the dimensioning of the transport for both backhaul and fronthaul to the MBS and SC sites. Additional RAN interface points for new fronthaul interfaces have also been included in the analysis (see section 4.5 about RAN splits).

Table 16 summarizes the considered RAN splits and the capacity required for a single sector with the selected radio configuration. The typical backhaul scenario is not included in the table but has similar requirements as the Mac-Phy RAN split in terms of capacity and latency. The new optical interfaces used for next-generation fronthaul are 25G, 40G and 100G. These were analysed in section 4.6, and the impact on reach (adding amplification and compensation for long distances and higher bit rates) and cost has been included into the techno-economic model. The data rate required for RAN Split I can be supported by an interface of 25 Gb/s, however, as it is close to that limit, we have used 40 Gb/s in the model to support potential traffic increase in the S1 or X2 interfaces due, for example, to additional interference coordination traffic or IPsec overhead.

Comparing the connectivity requirements from the different RAN splits and for the different RAN site types (MBS and SC), we note that for the MBS there will be a difference both in required interface speed as well as number of wavelengths to each site depending on split. For the SC the difference is in the interface speed and we note that several of the splits (Split II – Split IV) have the same requirements.

Table 16: Required network interfaces for different RAN splits

RAN split	Macro Base Station	Small Cell
Mac-Phy	1 wavelength – 25 Gb/s (2G, 4G and 5G)	1 wavelength – 25 Gb/s (5G)
Split I	1 wavelength – 40 Gb/s (2G, 4G and 5G)	1 wavelength – 40 Gb/s (5G)
Split II	1 wavelength – 100 Gb/s (2G, 4G and 5G)	1 wavelength – 100 Gb/s (5G)
Split III	1 wavelength/sector – 100 Gb/s (4G and 5G) 1 wavelenth – 3 Gb/s (2G)	1 wavelength – 100 Gb/s (5G)
Split IV / CPRI	1 wavelength/sector – 100 Gb/s (5G) 1 wavelength/sector – 10 Gb/s (4G) 1 wavelength – 3 Gb/s (2G)	1 wavelength – 100 Gb/s (5G)

The network architectures analysed in D3.3 were updated with the 5G radio scenario. The main changes compared to the network architectures described in D3.3 Chapters 5 and 6 are higher bit-rate network interfaces at the MBS, SC and Main CO sites as well as additional elements for amplification and dispersion compensation for long distances. It is important to remark that the 2020 reference network based on CWDM does not scale well to the 5G scenario because of the shorter reach of high-speed interfaces and since CWDM channels require individual amplification (compared to DWDM where channels can be amplified by a common amplifier). Hence, although it is possible to increase the bit rate of CWDM transceivers, those will require per-channel amplification when the bit rate or the distances increase, which in turn will require a large number of amplifiers. For CWDM scenarios and cases that would require CWDM amplification, we instead opt for PtP connections over dark fibres. This avoids the high cost of a large number of amplifiers at the expense of more fibre. Appendix 8.6 describes the results of the amplification studies for high bit rates, and Appendix 8.7 contains a summary of the dimensioning calculations, including the different RAN split points for each technology.

4.7.1 Comparison of transport dimensioning

This section introduces the results for the initial 5G scenario where a SC density of 50 SCs per MBS is assumed (except for rural areas where no SCs are assumed) and where complete coverage of FTTC is assumed with an additional 30% FTTH coverage (except for rural areas where no FTTH is assumed). Section 4.7.2 investigates the impact as these parameters are changed.

Figure 41 depicts the cost per connection of the different network architecture options for all geotypes and RAN split points. As can be seen, the cost per connection increases from ultra-dense areas to rural areas. It can also be seen that in most cases, costs increase going from Mac-Phy split to Split IV. For all geotypes, NG-PON2, WR-WDM-PON and WS-WDM-PON have similar cost, with WR-WDM-PON being the transport technology with the slightly lower CapEx among these. The small cost difference between the architectures is due to the dominating contribution of high-speed interfaces, which is a common cost for all architectures. For splits where interfaces costs dominate, the difference between different architectures diminish. The different connectivity requirements between MBS and SC for different splits (*Table 16*) are visible in the results where costs in ultra-dense urban, urban and sub-urban areas are driven by the SC connectivity, whereas costs in rural areas are driven by the MBS connectivity. This is seen in Split II, where SCs have the same connectivity requirements as Split III and IV, whereas the MBS requires a higher number of wavelengths. In Figure 41, the cost for Split II is significantly lower than Split III and Split IV for rural areas due to the absence of SC and because only a single wavelength is needed per site.

For urban, sub-urban and rural geotypes, PtP CWDM has a higher cost per connection than the other architectures. This is particularly pronounced for RAN splits II, III and IV, the reason being that the required 100 Gb/s wavelengths to large extent need to be amplified in a CWDM deployment. Hence, to avoid large amplifier costs, we have assumed that the all 100 Gb/s wavelengths that would need amplification instead are carried over PtP dark fibre rather than CWDM. This drives fibre costs which seen as main contributors to the high costs in Figure 41, but is still less costly than a full CWDM deployment. For the dense-urban geotype, costs of the CWDM deployment are particularly low for Splits II-IV. Here we also assumed 100 Gb/s over PtP dark fibre rather than CWDM when it is more cost efficient to use 100 Gb/s grey transceivers for RAN splits II, III and IV, rather than coloured BiDi CWDM transceivers, because distances are shorter and the possibility to share fibres to different sites in ultra-dense areas is lower.

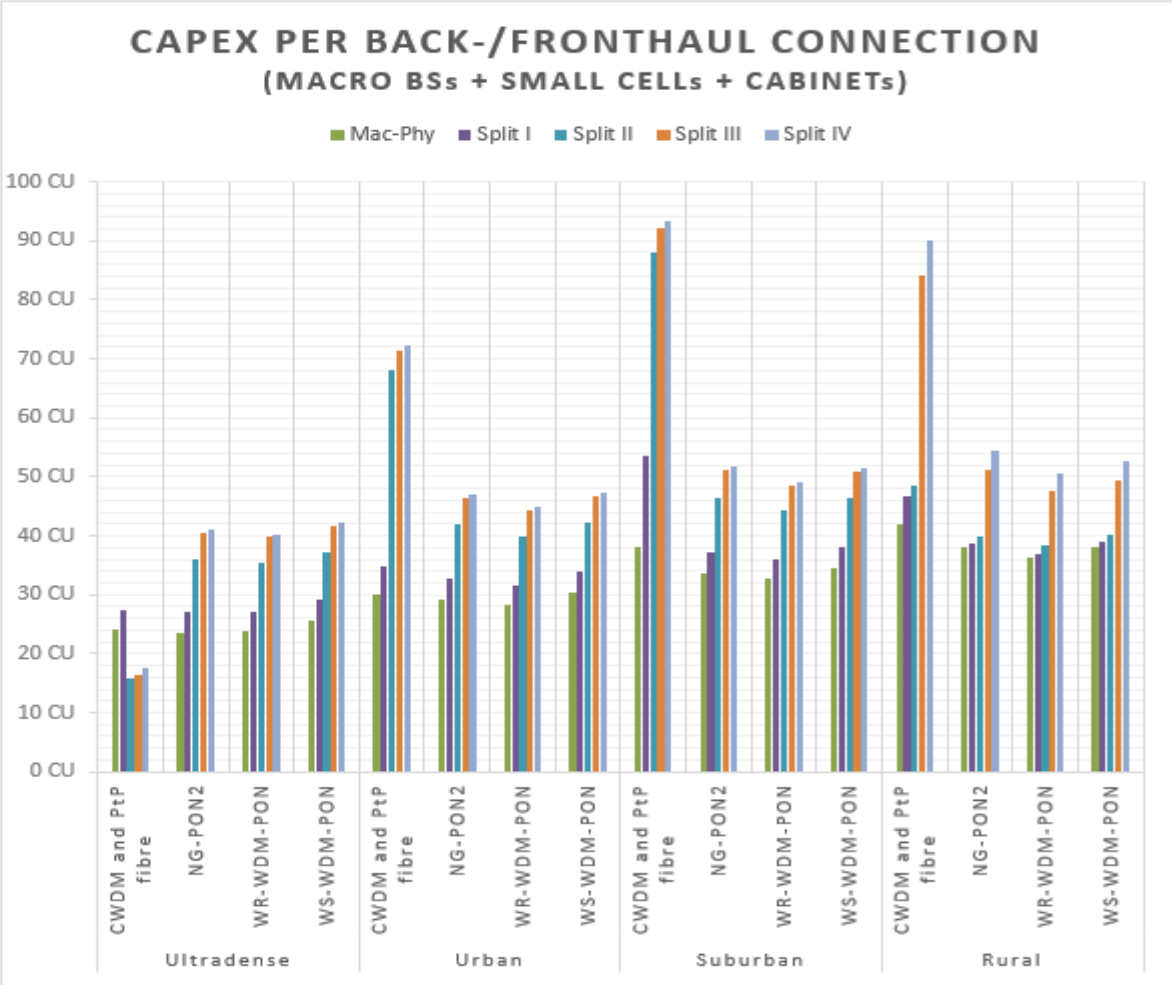


Figure 41: Total CapEx of RAN split points per geotype

Relative cost differences for a single technology are similar for NG-PON2, WR-WDM-PON and WS-WDM-PON, even varying RAN splits. Three main groups are identified: Mac-Phy and Split I as the most cost efficient, Split III and Split IV as the most expensive ones and Split II in an intermediate position. *Table 17* illustrates the cost increase for the different RAN splits for NG-PON2 in an urban scenario.

Table 17: Cost per connection increase in urban areas with NG-PON2

Mac-Phy	Split I	Split II	Split III	Split IV
100%	112%	144%	160%	162%

Focusing on the three main technology options, i.e., NG-PON2, WR-WDM-PON and WS-WDM-PON, Figure 42 shows the CapEx difference among the RAN split points of each technology for all geotypes, where normalized to the cost of the Mac-Phy split point case of NG-PON2.

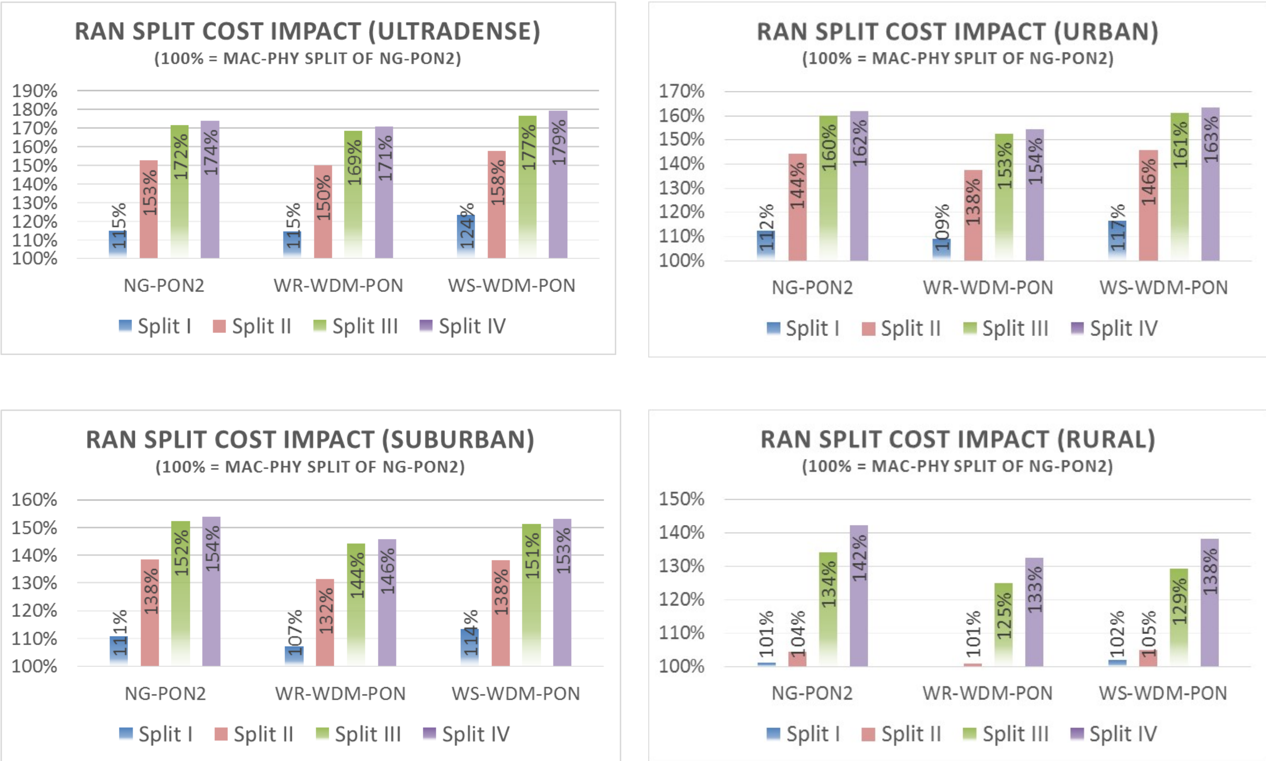


Figure 42: Relative cost per connection of RAN split points (normalized to the Mac-Phy split of NG-PON2)

The figure indicates that:

- The cost difference for all RAN splits decreases from ultra-dense to rural geotypes, as the weight in the total cost of the transmission technology is lower and fibre cabling is higher.
- All technology solutions have a similar cost increase when moving from a lower RAN split to a higher; however, WR-WDM-PON has the lowest increase for all RAN splits and all geotypes, followed by NG-PON2 and WS-WDM-PON.
- The cost increase of RAN Split II is lower in the rural geotype as only the MBS connectivity requirements determine the scaling for rural areas and only a single wavelength is required per site compared to multiple wavelengths for Split III and Split IV.

Figure 43 shows a summary of the percentages in Figure 42 including all geotypes in a single graph. It can be seen that the cost increase for the considered RAN splits has a similar slope for all geotypes, with small differences, with WR-WDM-PON being the most cost efficient solution under the assumptions of 50 SC/MBS and 30% FTTH coverage.

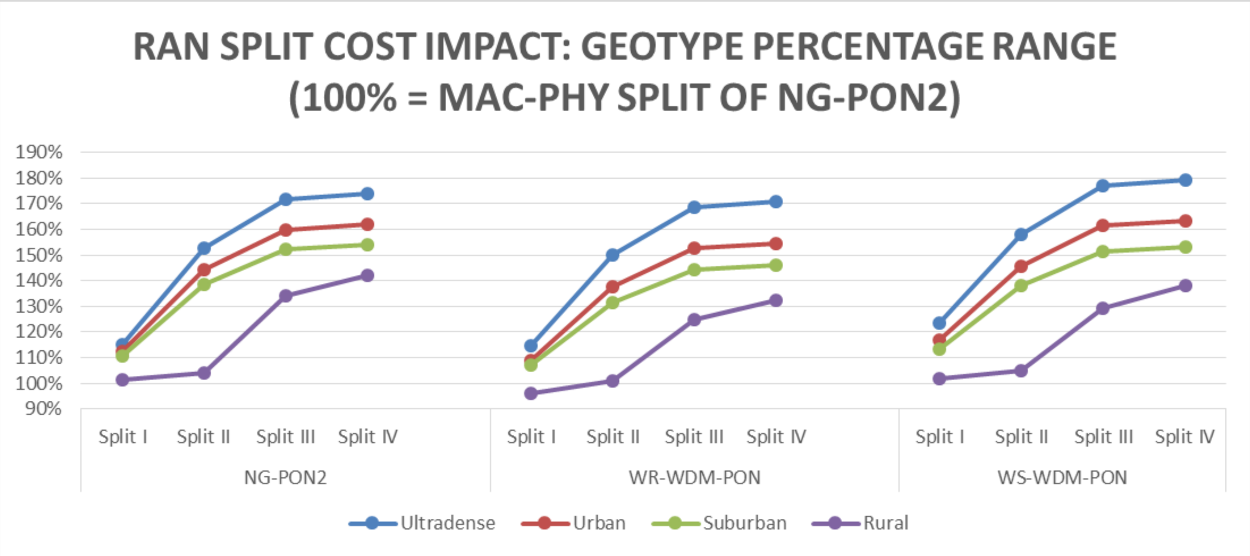


Figure 43: Summary of the relative cost per connection of RAN split points

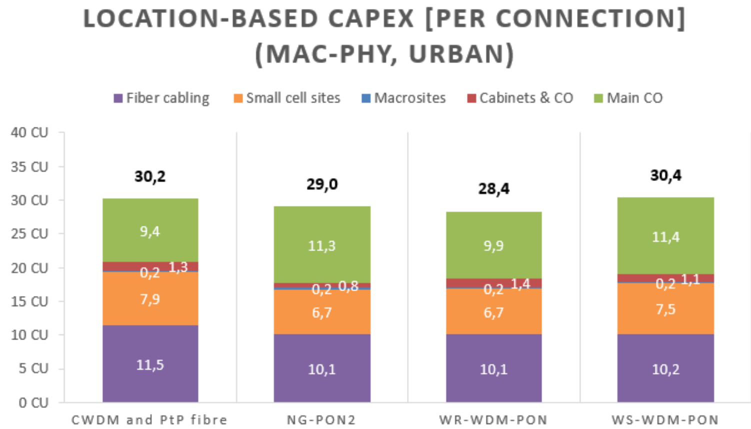
To further understand the cost drivers, we present a cost breakdown per each network location. Figure 44 presents the total cost and the cost per location type for each RAN split point in the urban scenario.

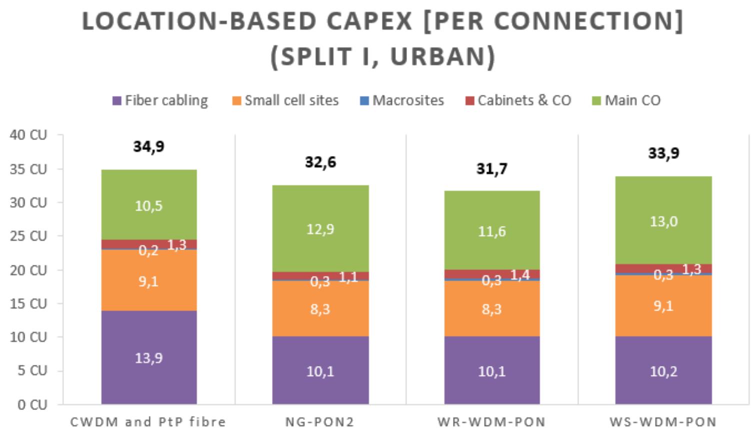
Starting with fibre costs, we note that costs are similar for all architectures (except CWDM and PtP) and for the different splits. CWDM and PtP fibre requires high fibre cabling costs, in particular for higher RAN splits (Split II-IV). The fibre cabling costs eliminate the advantages of lower interface costs.

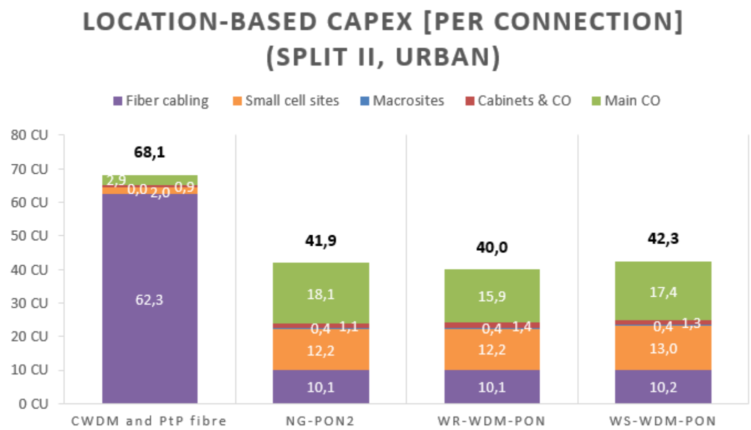
For the RAN cell sites, we see that cost of SC sites dominate over MBS sites. This is because of the large number of SCs assumed in the urban scenario. We also see that costs are the same for Split II to Split IV as they have the same SC connectivity requirements (100 Gb/s). For the Mac-Phy split and Split I, costs are lower due to 25 Gb/s and 40 Gb/s connectivity requirements, respectively. Comparing the different technologies, we see that for the SC sites, cost if higher for WS-WDM-PON due to more complex transceivers with tuneable receivers. When CWDM BiDi transceivers are used, the cost of the Main CO is reduced (no OLT is needed), however this cost is not compensated by the higher cost of SC sites and the cost of the fibre cabling.

For Main CO costs, trends are similar to those of the SC costs. This is due to the large number of SCs and the fact that there is a corresponding interface for each SC at the Main CO. For the Main CO, the higher cost of WS-WDM-PON is due to increased need for amplification compared to the other architectures.

Considering the total cost and comparing the different architectures for the urban scenario, we see that CWDM is only an alternative for the first two RAN split points where 25 Gb/s and 40 Gb/s CWDM transceivers can be used without amplification. The cost per connection of NG-PON2 and WR-WDM-PON are similar, however, WR-WDM-PON has a slightly lower total cost because of reduced CapEx in the Main CO (thanks to its higher wavelength split ratio and lower dependency to optical power amplification). WS-WDM-PON is more expensive than NG-PON2 and WR-WDM-PON, with a higher cost at Main CO and SC sites locations.


LOCATION-BASED CAPEX [PER CONNECTION] (MAC-PHY, URBAN)
Fiber cabling
Small cell sites
Macrosites
Cabinets & CO
Main CO
40 CU
35 CU
30 CU
25 CU
20 CU
15 CU
10 CU
5 CU
0 CU
30,2
9,4
0,2
1,3
7,9
11,5
29,0
11,3
0,2
0,8
6,7
10,1
28,4
9,9
0,2
1,4
6,7
10,1
30,4
11,4
0,2
1,1
7,5
10,2
CWDM and PtP fibre
NG-PON2
WR-WDM-PON
WS-WDM-PON


LOCATION-BASED CAPEX [PER CONNECTION] (SPLIT I, URBAN)
Fiber cabling
Small cell sites
Macrosites
Cabinets & CO
Main CO
40 CU
35 CU
30 CU
25 CU
20 CU
15 CU
10 CU
5 CU
0 CU
34,9
10,5
0,2
1,3
9,1
13,9
32,6
12,9
0,3
1,1
8,3
10,1
31,7
11,6
0,3
1,4
8,3
10,1
33,9
13,0
0,3
1,3
9,1
10,2
CWDM and PtP fibre
NG-PON2
WR-WDM-PON
WS-WDM-PON


LOCATION-BASED CAPEX [PER CONNECTION] (SPLIT II, URBAN)
Fiber cabling
Small cell sites
Macrosites
Cabinets & CO
Main CO
80 CU
70 CU
60 CU
50 CU
40 CU
30 CU
20 CU
10 CU
0 CU
68,1
2,9
0,0
2,0
0,9
62,3
41,9
18,1
0,4
1,1
12,2
10,1
40,0
15,9
0,4
1,4
12,2
10,1
42,3
17,4
0,4
1,3
13,0
10,2
CWDM and PtP fibre
NG-PON2
WR-WDM-PON
WS-WDM-PON

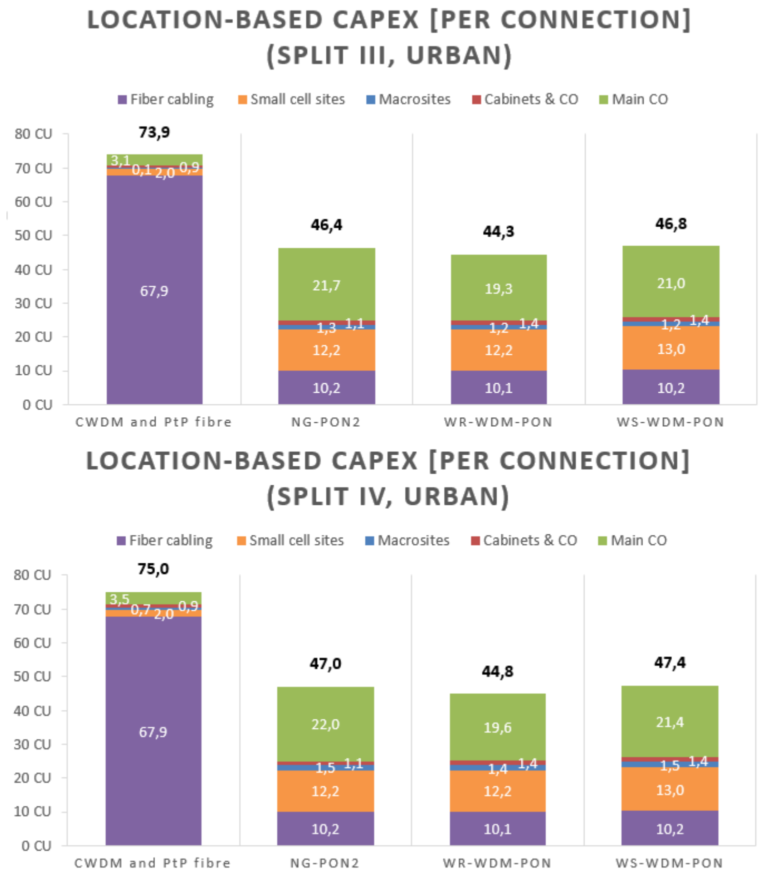


Figure 44: Location-based CapEx in urban geotype

Comparing the different RAN splits, we find that the Mac-Phy split and Split I have a lower total cost as backhaul traffic can be carried over a single wavelength of 25 Gb/s and 40 Gb/s interface, respectively. Split II has an increased cost as an interface of 100 Gb/s is needed (in addition to a more expensive module, 100 Gb/s optical transmission requires amplification and dispersion compensation for the same distance compared to 25 Gb/s and 40 Gb/s). Split III and IV have the highest cost because multiple 100 Gb/s channels (one per MBS sector) are needed for the transmission of their corresponding data. The main difference in cost between Split III and IV corresponds to the additional 10-Gb/s wavelengths needed for the transmission of 4G traffic to MBS, which is a relatively small portion of the over all cost.

The CapEx results for sub-urban and rural geotypes are characterised by a higher cost in the fibre cabling section; however the cost differences among RAN splits and technologies are similar to the urban geotype analysed in this section.

4.7.2 Analysis of convergence potential

The results presented so far are valid for the initial 5G scenario with 50 SCs per MBS (except for rural areas) and 30% FTTH coverage (except for rural areas). They show the comparison of the CWDM network reference and variants of NG-PON2 and WR/WS-WDM-PON for different RAN split variants under the initial 5G scenario conditions. For different scenario conditions, the comparison will change as different costs scale differently with different parameters. In order to show how the transport solutions behave under conditions of significantly deviating cell density and fibre availability, variations of the SC density from 0-150 SCs per MBS as well as the mass-market FTTH/B rollout coverage from 0%-100% have been investigated for two fibre availability cases.

In the first case, an existing fibre-poor FTTH roll-out is assumed, requiring high add-on costs for new fibre cablings and connections, whereas in the second case, the focus is on a fibre-rich FTTH rollout, requiring only low add-on costs for fibre through-connections. This analysis concentrates on the comparison of the NG-PON2 and WR-WDM-PON technologies in urban areas for different RAN splits, as the cost of the WS-WDM-PON is quite similar, and the CWDM reference is the most expensive solution in general in all geotype areas. The RAN site and 5G antenna configuration (125 MHz, 256 QAM, 16x16 MIMO) are the same as for the initial 5G scenario.

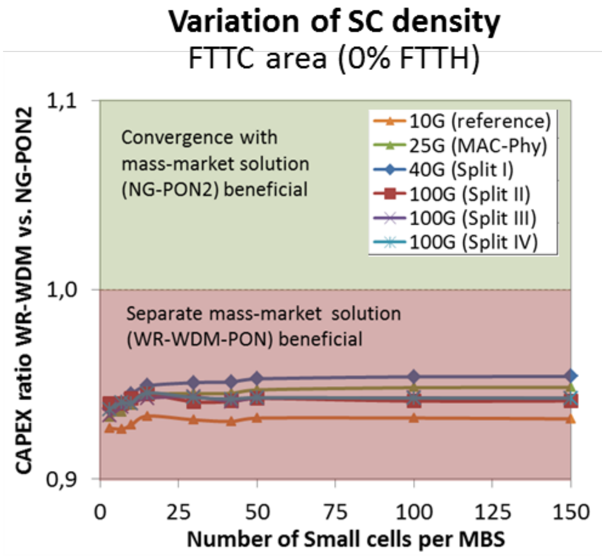


Figure 45: CapEx ratio WR-WDM-PON vs NG-PON2: Variation of small cell density in FTTC areas

Firstly, we look at SC density variations in pure FTTC areas. Figure 45 shows the relative CapEx per technology compared to the NG-PON2 solution for FTTC areas without any mass-market FTTH rollout, in which the WR-WDM-PON as well as the NG-PON2 are deployed as solutions to connect SC, MBS and cabinets. That means that NG-PON2 has the same convergence degree as WR-WDM-PON, which is limited to a joint use of cable and duct resources, but not of fibre and system level resources. This results in WR-WDM-PON being most cost-effective in FTTC areas independent of the regarded SC density and the RAN split.

The relative transport CapEx of the WR-WDM-PON versus NG-PON2 solution for a variation of the SC density in an area with 100% FTTH coverage is shown in Figure 46. A convergence with the mass-market NG-PON2 technology is economically beneficial for all RAN splits in fibre-poor FTTH areas (relative cost value > 1), due to the high fibre-infrastructure sharing degree of the NG-PON2 and high fibre add-on cost for WR-WDM-PON. In fibre-rich FTTH areas, the infrastructure convergence potential of NG-PON2 declines as the system-related CapEx becomes more dominant. This leads to the result that in those areas a dedicated WR-WDM-PON, separate from the mass-market NG-PON2, is economically beneficial in case of low

SC densities (< 12 SC/MBS), caused by the initially low NG-PON2 system utilisation determined by the mass-market structure. It is also economically beneficial at higher SC densities in case of 100G interfaces (RAN splits II – IV), due to the additional number of required amplifiers and Bragg Reflector Gratings (BRG) for dispersion compensation in the NG-PON2. The highest NG-PON2 convergence benefit arises for 10G interfaces, mainly caused by the lower amount of amplifiers compared to 25G, 40G, or 100G interfaces.

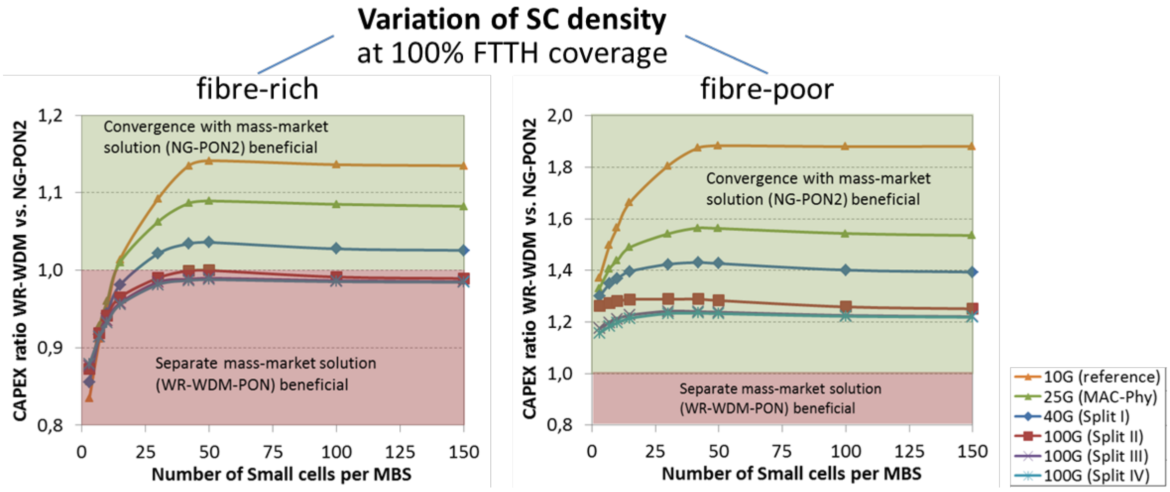


Figure 46: CapEx ratio WR-WDM-PON vs NG-PON2: Variation of small cell density in FTTH areas

In addition to the pure FTTH area, also areas with only partial FTTH coverage have been evaluated. Figure 47 shows the relative CapEx of the WR-WDM-PON versus NG-PON2 full-convergence solution per RAN split for a variation of the FTTH coverage at a SC density of 50 SC/MBS. Variations of the FTTH coverage cause changes in the dimensioning numbers of NG-PON2, because of the changed fibre convergence degree with mass-market FTTH deployments. For WR-WDM-PON, the total system and fibre count stay constant when varying the FTTH coverage. Nonetheless, also WR-WDM-PON benefits from the higher fibre availability in fibre-rich areas due to the resulting lower fibre add-on cost.

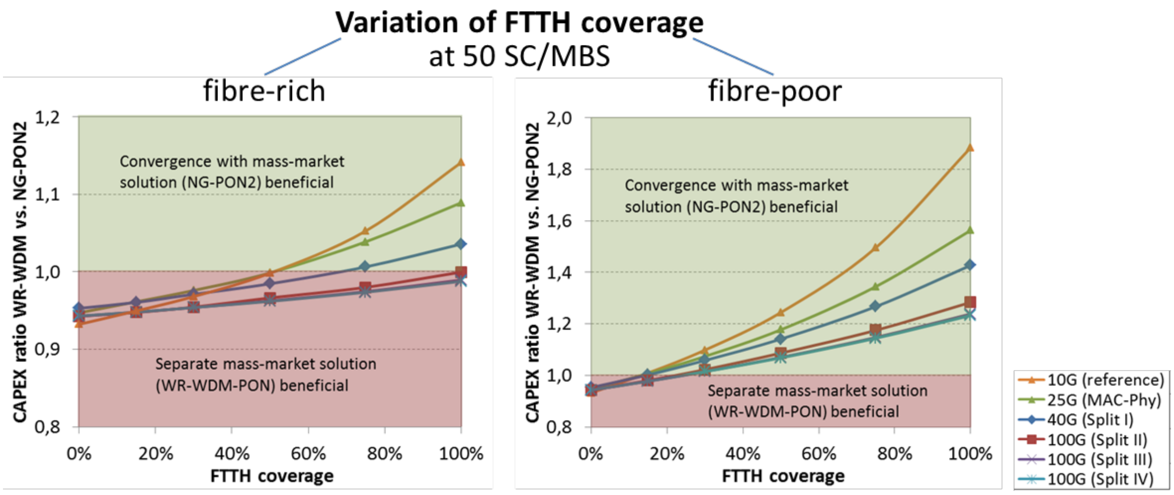


Figure 47: CapEx ratio WR-WDM-PON vs NG-PON2: Variation of mass-market FTTH coverage

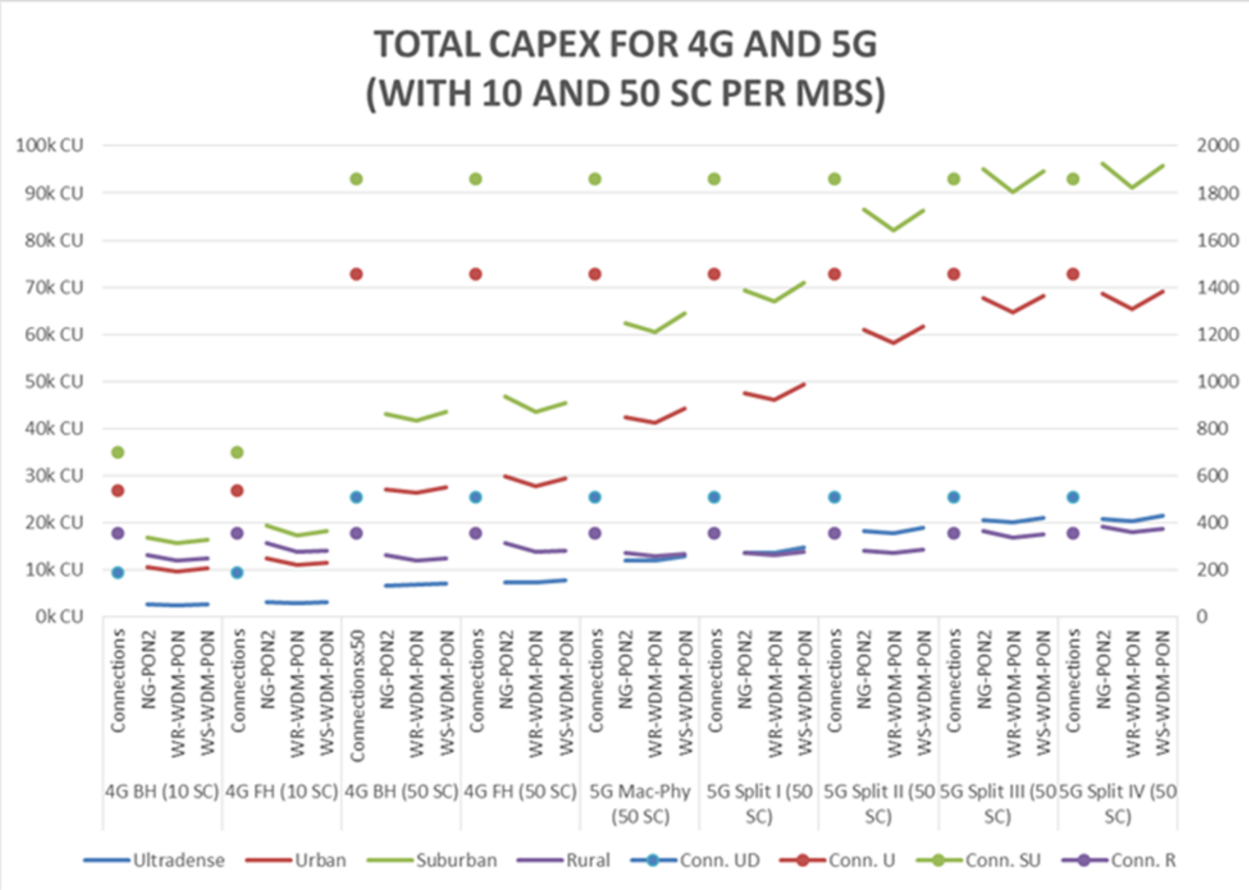
Figure 47 shows that the economical convergence benefit of NG-PON2 increases with higher mass-market FTTH coverage, reaching the highest benefit in areas with 100% FTTH. This is driven by increased fibre infrastructure sharing with the mass-market fixed-access solution. The highest NG-PON2 convergence potential arises in fibre-poor areas. In non-FTTH areas and in areas with a low FTTH deployment ratio (<15% FTTH fibre-rich, <50% FTTH fibre-poor), a dedicated WDM-PON solution is most cost-efficient for all RAN splits. The differences between the RAN splits are caused by additional amplifiers at higher interface capacities, by additional BRGs for dispersion compensation in case of 100G, and multiple wavelengths for constant bit rate RAN split points in multi-sector antenna configurations for the MBS.

For a given radio capacity, different RAN splits may lead to significantly increased transport data rates, different costs, and different architectures being favourable. The techno-economical assessment of 5G transport reveals that the benefit of re-using mass market infrastructure in an FTTH area decreases significantly if high-bit-rate interfaces (>10 Gb/s) need to be deployed. In a fibre-rich infrastructure, WR-WDM-PON, separated from the mass-market, offers lower cost if 100G transport is required, independent from the established FTTH coverage.

As described in section 4.4.1.1, a scenario with 50 SCs per MBS with an antenna configuration of 125 MHz, 256 QAM, 16x16 MIMO can support a traffic demand of 250 Gb/s/km^2/operator. The results for the double or triple number of SC per MBS (100 or 150 SCs per MBS) can be used as a rough estimation for the double or triple traffic demand. These results show that in case of higher traffic demands, the same conclusions regarding the best FMC choice in different scenarios is still valid.

4.7.3 Cost Comparison with LTE transport

D3.3 analysed a heterogeneous network based on LTE (referred to as 4G for simplicity) with an initial deployment scenario of 10 SCs per MBS for a reduced traffic density. Figure 48 shows the total transport cost of deployment comparing 4G (backhaul and fronthaul) and 5G scenarios (5 RAN splits) for each geotype. Additionally, an intermediate scenario is included for comparison purposes based on 4G with 50 SCs per MBS. As the number of connections (number of MBS, SCs and cabinets to connect) depends on the number of SCs per MBS, this number is included in the graph represented as small circles. Two set of values are represented corresponding to the two situations analysed: 10 and 50 SCs per MBS.



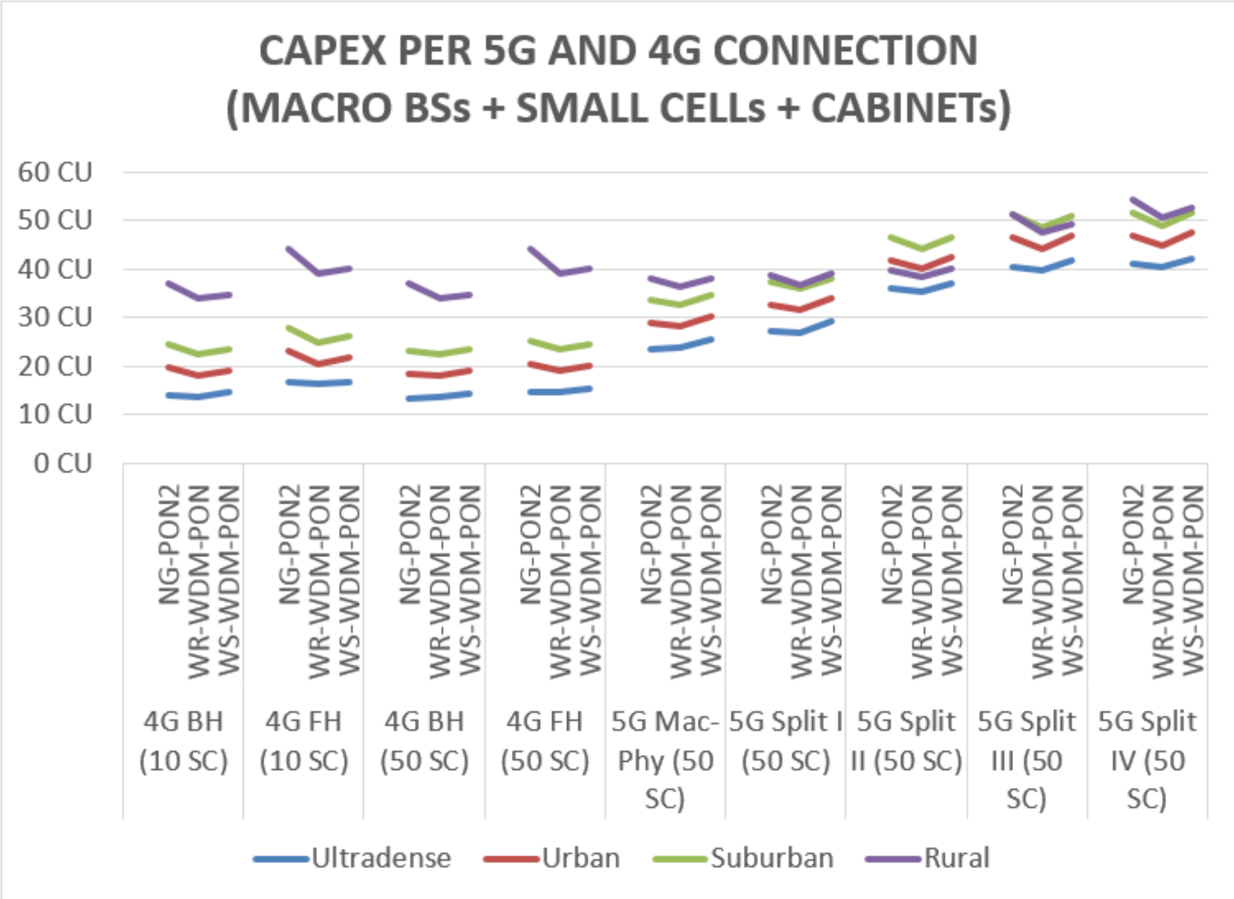
* Small cells are not deployed in rural areas

Figure 48: Total CapEx: 4G and 5G scenarios

For 4G, the total cost increases around 2.6 times as the SC density is increased from 10 to 50 SCs per MBS for ultra-dense, urban and sub-urban scenarios (both BH and FH). If simultaneously going to 5G, the increase depends on the starting situation but is always higher. For example in urban areas, the increase from 4G BH to 5G RAN Mac-Phy Split is 4.2 times and from 4G FH to 5G RAN Split IV is 5.9 times. A reduced increase of 3.7 times is obtained from 4G FH to 5G RAN Mac-Phy Split. The total cost is higher as the population density decreases when SCs are deployed. The diagram also shows that WR-WDM-PON is also the cheaper solution compared to NG-PON2 and WS-WDM-PON, the difference being higher as the total cost increases.

The impact of 5G in rural areas is more limited (from 1.07 to 1.3 times more, compared to 4G for different splits) as there are no SCs in these areas. Hence, the cost per connection in rural areas is not affected by the cost of the connection of SCs. As can be seen in Figure 48, the increase in cost for 5G in rural areas is low (across the different RAN splits) as SCs are not deployed.

Figure 49 displays the results in Figure 48 as cost per connection. The cost per connection decreases slightly in 4G scenarios when the number of SCs per MBS is increased from 10 to 50 (1% in BH and 7% in FH for the urban geotype), resulting in a cost per connection closer to the cost of the SC connection, which is lower than the cost of a MBS connection. The cost per connection increases 1.56 times from 4G BH to 5G RAN Mac-Phy Split and 2.18 times from 4G FH to 5G RAN Split IV. Comparing the 4G BH and FH cost per connection with the RAN split points in 5G, shows that 5G has a higher cost but also a wider cost range; these RAN split points will allow for reducing the cost and capacity requirements of traditional CPRI fronthaul in 5G.



* Small cells are not deployed in rural areas

Figure 49: CapEx per connection: 4G and 5G scenarios

Finally, we compare 4G and 5G scenarios considering a mass-market FTTH/B rollout coverage from 0%-100%. We showed already in D3.3 chapter 7 that the relative total CapEx of WR-WDM-PON versus NG-PON2 is 0.9 in FTTC areas for both 4G backhaul and fronthaul. In a 5G scenario with a similar FTTC ratio, although higher bit rates are needed, the ratio is 0.95, resulting in a reduced cost difference.

For FTTH areas, a comparison between 4G and 5G is found in Figure 46 and Figure 47, where 4G is represented by the 10 Gb/s reference line. These figures reveal that with 5G, the convergence benefits of reusing the mass market fixed access infrastructure in FTTH areas decreases when high-bit-rate interfaces are needed. In fibre-poor scenarios, NG-PON2 continues to be most beneficial while in fibre-rich scenarios WR-WDM-PON, continues to be more beneficial for a lower density of SCs.

4.7.4 Analysis of decentralised coordination architectures for 5G

Chapter 3.1 analyses different transport solutions for LTE backhaul and fronthaul where the RCC is decentralised to the MBS sites instead of the Main CO sites. This section extends this study to 5G RAN.

Figure 50 and Figure 51 show the CapEx per connection for centralised and decentralised RCC in urban areas. Three deployment situations have been identified as the most representative: an FTTC area without mass-market FTTH rollout, a fibre-rich FTTH area with low fibre add-on costs and a fibre-poor FTTH area with high fibre add-on costs. Two SC densities are displayed for comparison: 10 SC per MBS (reference density for LTE RAN study) and 50 SC per MBS (reference density for 5G RAN study).

Figure 50 presents the CapEx per connection for the 5G RAN Mac-Phy Split. For low SC densities (10 SCs per MBS), decentralised scenarios have a higher cost per connection than centralised scenarios for all technologies. These results are similar as for LTE RAN backhaul, and depend on the low sharing of the additional network elements at the MBS. For high SC densities (50 SCs per MBS), and for NG-PON2 deployments in FTTH areas, the decentralised backhaul scenario is even more expensive than the centralised due to absence of convergence for SC backhaul. In case of WR-/WS-WDM-PON, the cost difference between centralised versus decentralised architecture diminishes with increasing SC density, due to the more efficient use of higher splitting ratios to interconnect SC to the MBS, reducing the number of passive elements and feeder fibres.

NG-PON2 backhaul is in general cheapest in fibre-poor FTTH areas in centralised as well as decentralised architectures; however, the cost-benefit diminishes with increasing SC density in a decentralised architecture. WR-WDM-PON backhaul is in general cheapest in FTTC and fibre-rich FTTH areas, except for centralised RAN architectures with high SC density in fibre-rich FTTH areas, because of the higher feeder fibre convergence degree of the NG-PON2.

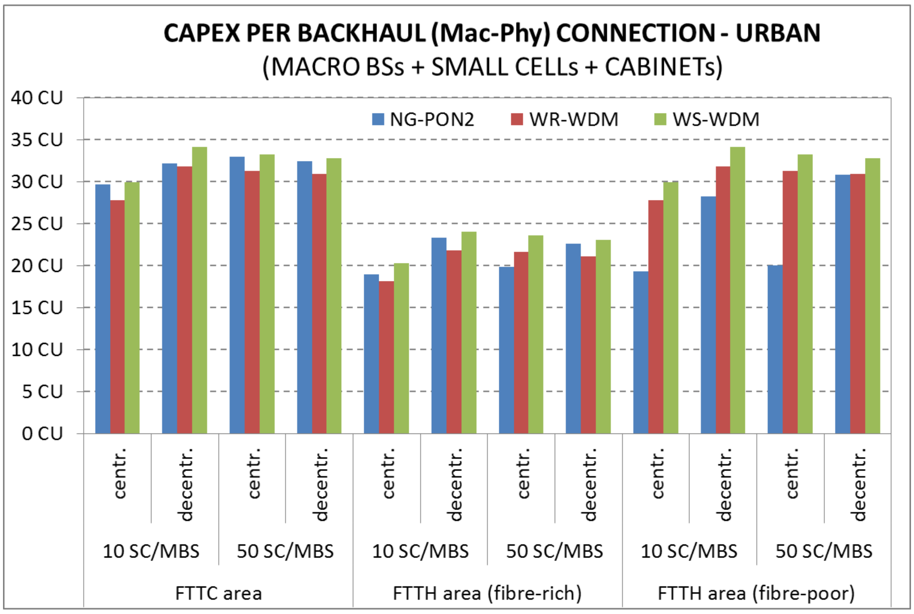


Figure 50: CapEx per backhaul connection for 5G RAN with central and decentralised architectures

Figure 51 shows the CapEx per connection for the 5G RAN Split IV (i.e., CPRI). Similar to LTE RAN fronthaul, the cost per connection in decentralised scenarios is in general lower, because the SCs are fronthauled to the MBS and the MBS is backhauled to the MCO using a single optical channel in contrast to the centralised fronthaul architecture, where all cells are fronthauled to the MCO.

As in the backhaul scenario, NG-PON2 fronthaul is in general cheapest in fibre-poor FTTH areas in centralised as well as decentralised architectures; however, the cost-benefit diminishes as well with increasing SC density in a decentralised architecture. WR-WDM-PON fronthaul is always cheapest in FTTC and fibre-rich FTTH areas, as the NG-PON2 cannot exploit the fibre convergence potential in these areas.

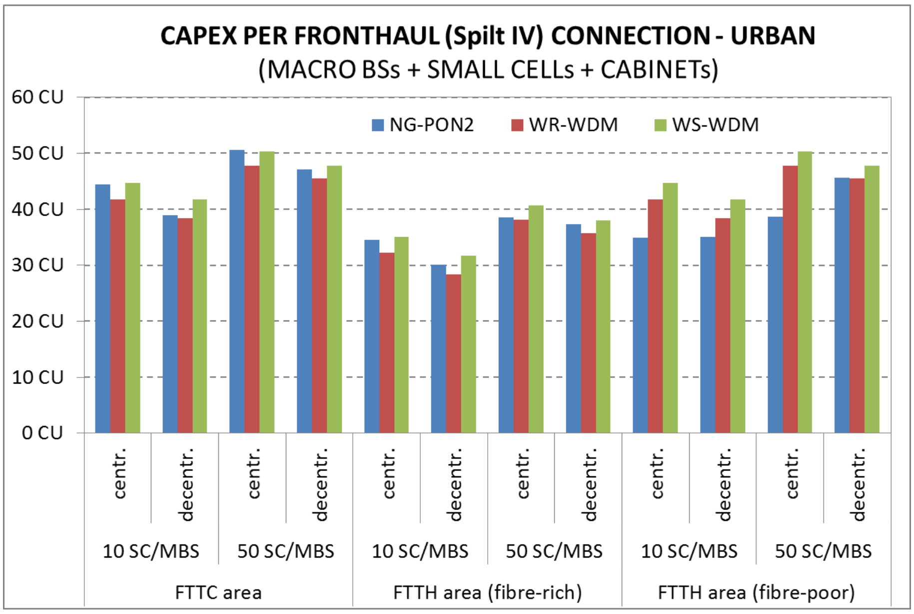


Figure 51: CapEx per fronthaul connection for 5G RAN with central and decentralised architectures

Fronthaul requires with 30-50 CU per connection significantly higher cost compared to backhaul with 18-33 CU per connection, which is mainly caused by the higher fronthaul interface capacity and in the centralised scenario by the additional fronthauling of the MBS.

4.8 Conclusions

5G will enable new services, including enhanced mobile broadband, massive IoT, ultra-reliable and low-latency communications, among others. The fixed part of the 5G network will need to deal with the requirements of future 5G radio, which is expected to increase the utilized spectrum and network capillarity.

Studies detailed in this chapter consider several 5G reference radio configurations (e.g., 125 MHz – 256 QAM – 16x16 MIMO), traffic demand scenarios from NGMN (250 Gb/km^2/operator) and 5G UE peak data rates (10 Gb/s). They conclude that the number of SCs needed per km^2 can vary from several tens to several thousands depending on the radio configuration resulting in very different requirements on the transport network. For the selected reference 5G radio configuration, around 200 SCs per km^2 would be needed in an ultra-dense area.

The 5G radio configurations present new challenges, especially with respect to mobile fronthaul, because of the high traffic volume exchanged between the BBU and RRH.

Different functional split points between L1 and L2/L3 cell processing have been considered and capacity requirements calculated. The different RAN splits have also been included in the performance assessment of different FMC architectures for 5G. For the selected 5G radio configuration, the transport capacity required could vary from 10,052 Mb/s to 101,376 Mb/s per sector.

In terms of transport technologies, we have extended the analysis to include 25G, 40G and 100G optical transceivers based on EDB, ODB, PAM4 and DMT. Table 18 shows a summary of the estimated cost and reach using PAM4 without amplification. An extended reach will require amplification and dispersion compensation. Such combinations are also included into the deployment models and techno-economic assessments.

Table 18: Summary of cost and reach for high-speed transceiver analysis

Cost factor over 10G			Reach [km] without added compensation		
25G	40G	100G	25G	40G	100G
2.1	2.7	4.0	60	25	8

The cost assessment extends the results of D3.3 with the analysis of a 5G scenario on FMC network architectures with different RAN splits and transceiver capacities.

Figure 52 (left) shows that a convergence with the mass-market NG-PON2 technology is beneficial for all RAN splits in fibre-poor areas (driven by the high fibre-infrastructure sharing degree and high fibre add-on cost) compared to WR-WDM-PON, declining in fibre-rich areas as the system-related CapEx gets more dominant, especially for low SC densities (< 12 SC/MBS). The NG-PON2 convergence benefit is highest for 10G interfaces, because of the lower amount of amplifiers compared to 25G, 40G, or 100G interfaces.

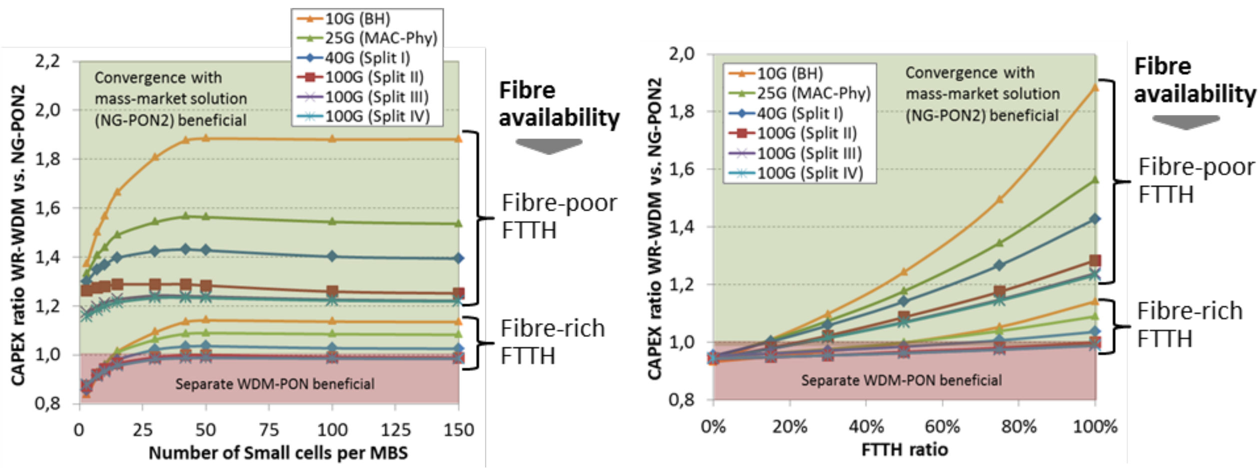


Figure 52: Variation SC-density 0-150 SC/MBS (100% FTTH; left) - Variation FTTH ratio 0%-100% (50 SC/MBS; right)

Figure 52 (right) shows that the economic convergence benefit of NG-PON2 increases the higher the mass-market FTTH ratio is, with the highest benefit in areas with 100% FTTH deployment, which is the target for operators in many European countries. In non-FTTH areas and in areas with a low FTTH deployment ratio (<15% fibre-rich; <50% fibre-poor), a dedicated WDM-PON solution is most cost-efficient for all RAN splits.

The differences between the RAN splits are caused by additional amplifiers and BRGs for high-bit-rate interfaces and additional wavelengths for constant bit rate RAN split points in multi-sector configurations for MBS.

The techno-economical assessment of 5G transport reveals that the benefit of re-using mass-market infrastructure in an FTTH area decreases significantly if high-bit-rate interfaces (>10 Gb/s) need to be deployed. In a fibre-rich infrastructure, WR-WDM-PON, separated from the mass-market, offers lower cost if 100G transport is required, independent from the established FTTH coverage.

5 Flexibility, management and orchestration

Structural convergence and sharing of resources assumes some degree of flexibility. There needs to be flexibility to support the wider range of services in a resource-efficient manner and there needs to be network flexibility to facilitate provisioning of services for different purposes. This section examines the drivers and boundaries for flexibility in the access segment given the main convergence scenarios defined in COMBO. It also outlines the management and orchestration architecture to support the dynamic provisioning of connectivity services as well as coordination with other network resources.

5.1 Flexible architectures

The type and degree of flexibility that will be available in future networks will depend on a trade-off between benefits and costs of adding flexiblity. Flexible switching and generic hardware may bring benefites in terms of scaling and adapting to changing needs but may also lead to costs in terms of additional hardware (active nodes, optical switching) or reduced performance (generic vs. specialised hardware).

5.1.1 Flexibilty in COMBO scenarios

COMBO is focused on nation-wide roll-out of fixed and mobile services and minimization of total costs. Here, the number of nodes represents a major cost, and node consolidation presents a major enabler for savings of operational costs. Hence, in an optimized deployment scenario, the number of central offices will be few and access areas large. The remaining bottleneck is then the connectivity between the main central office locations and the cell/client sites, and the focus of COMBO is to exploit convergence of connectivity resources in this segement. This also means that for the COMBO project, the question on need for flexibility is a question on need for flexible connectivity (Figure 53a). For other scenarios that are less cost-sensitive to distributed node and cloud resources, other forms of flexibility beyond connectivity will be relevant (Figure 53b).

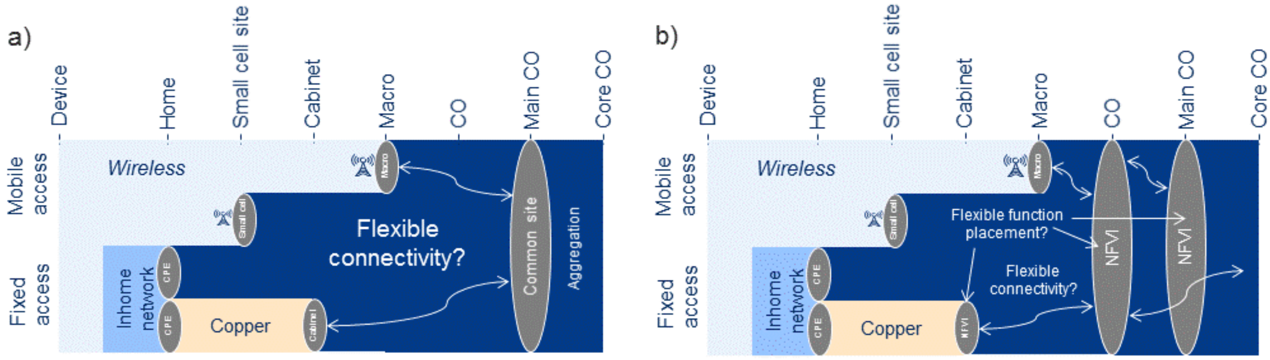


Figure 53: a) shows the COMBO scenario with node consolidation and flexible connectivity resources. b) shows an alternative scenario with distributed node/cloud resources and need for flexible provisioning of connectivity as well as processing and storage.

5.1.2 Flexible connectivity

Depending on the convergence scenario, there are several options for how to realize flexible connectivity. Here, we consider the three scenarios depicted in Figure 4. Figure 54 details these scenarios including relevant resources. For example, for system-level convergence (Figure 54a), there is a direct association between TWDM system resources and an ODN. Hence, TWDM system resources are tied to an ODN, and the ODN is tied to particular system resources. Furthermore, the TWDM system in this scenario is assumed to be capable of catering for all transport services. For ODN convergence (Figure 54b), the ODN is a shared resource between the TWDM system and PtP WDM links where different clients may require PtP wavelength services or services from TWDM. In the scenario with dedicated infrastructure (Figure 54c), the ODN resources are directly associated with either the TWDM system or PtP WDM.

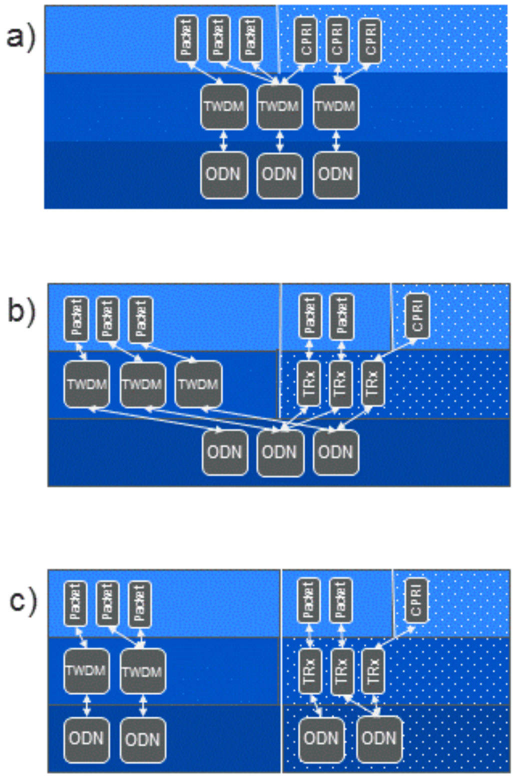


Figure 54: Relation between the ODN, systems resources, and different transport services for the three scenarios: a) system convergence, b) ODN convergence, and c) dedicated systems.

For each of these three convergence scenarios, there are different types of flexiblity that could be desirable as illustrated in Figure 55 and described below:

- System convergence: for RAN deployment without stringent requirements on latency or capacity, optical access systems used for fixed access may be reused for mobile transport. Existing resource allocation mechanisms in fixed-access systems (e.g., DBA for TDM PON) may be reused or enhanced for converged deployments to provide flexibility for provisioning of different services as well as for sharing of system resources between clients within an ODN. Flexible connectivity between client (service) ports and different TWDM PONs is handled by a packet switch or backplane. For deployments that put more stringent requirements on transport, there are ongoing research efforts in extending TWDM PON support. Likely, existing TWDM PON systems could be enhanced to support some of the proposed RAN deployment splits. One challenge for efficient resource allocation of connectivity is that it would require tight coordination with the RAN. Alternatively, resource allocation could be performed statically and manually reconfigured based on demand or semi-statically providing at least some degree of flexibility to cater for varying traffic demand.
- ODN convergence: the COMBO focus is on examining ODN convergence where fixed-access systems and dedicated wavelengths share the same ODN, with the ODN being one of the main cost drivers in the network. In addition to the flexibility mentioned for system convergence, there are additional aspects that need to be considered in this scenario. One aspect is

the flexibility to connect between different service ports (i.e., BBU ports, etc) and different PtP TRx resources. This could be handled by manual patching if limited dynamicity is expected. Alternatively, it could be supported by a switch if large degree of dynamicity is extected. Likely, this would need to be a low-latency switch as clients requiring PtP wavelength services typically are latency-sensitive. Another aspect of flexibility in this scenario is the flexible allocation of TWDM system and PtP TRx resources across different ODNs. This could be beneficial if system and TRx resources are costly and are favorably pooled and/or if large dynamicity is expected in the service needs between different ODNs. This type of flexibility requires additional support in the system design and will be analysed in section 5.1.5. Finally, another aspect of flexibility in this scenario is the flexible allocation of PtP TRx resources to different clients in an ODN. This requires a power-spitter-based ODN or an ODN that supports wavlength switching. This is beneficial if large degrees of dynamicity or large pooling gains can be expected within each ODN.

- Dedicated infrastructure: with dedicated infrastructure for different client groups, need for flexibilty is limited to the individual domains covered by the dedicated infrastructure.

Four categories of flexibility are summarized in Figure 55. The first category, i.e., “flexible provisioning of services in access systems” is out of scope in COMBO. The second category, i.e., “flexible connectivity between service ports and access/transport system/TRx resources”, is addressed in appendix 8.8.1 on the COMBO OLT model. The two last categories, i.e., “flexible allocation of system/TRx resources between ODNs” and “…within ODNs”, impact the structure of the ODN and are addressed in the remaining part of this section.

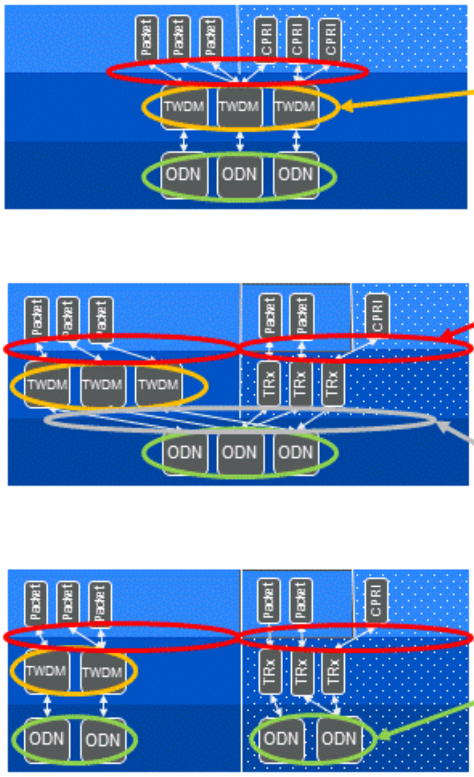


Figure 55: Different types of flexibility and relation to the different convergence scenarios

5.1.3 Benefits of flexibility

There are two main benefits of flexibility:

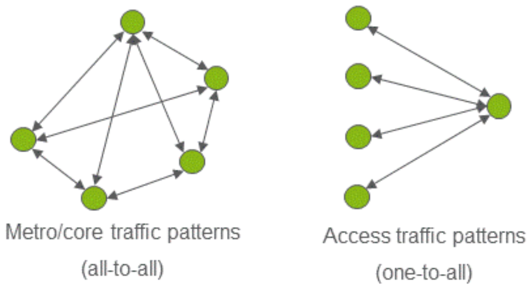
- Simplified provisioning/scaling of services
- Efficient resource utilization

These two factors are related in the sense that if there is no flexible provisioning of resources, this will either lead to a need for manual reconfiguration of resources or alternatively static overprovisioning of resources. The latter provides inefficient resource utilization. These drivers are general for different kinds of resources such as connectivity, compute and storage.

Efficient resource utilization

One main driver for flexibility is efficient resource utilization. In optical networks, the scarce or costly resources are primarily fibres and transceivers. Wavelengths can be seen as a scarce resource but in the end, they generate costs in the form of additional fibre or transceivers.

In metro/core networks, flexible optical technologies – wavelength switching (ROADMs and WSSs) and flex-grid – are more widely spread compared to the access segment. One reason for this is that the technology is costly and that costs in central parts of the network can be split over a large number of clients. Another reason for the presence of flexiblity in metro/core networks is related to traffic patterns between nodes. In the metro/core segment, these traffic patterns are “many-to-many” whereas they are “one-to-many” in the access segment. For networks where traffic patterns among nodes are “many-to-many”, the number of possible connections between nodes grows quatratically with the number of nodes (Figure 56). As the number of nodes grow, overprovisioning of all possible connection possibilities becomes unfeasible (in terms of fibres and transceivers) and flexibility is required to dynamically provision required connectivity based on need. For a network with “one-to-many” traffic patterns, the number of possible connections grows linearly with the number of nodes. Hence, overprovisioning of number of connections is of less effort.



# Nodes	# Connections ("all-to-all")	# Connections ("one-to-all")
5	10	4
10	45	9
50	1225	49
100	4950	99
N	N*(N-1)/2	N-1

Figure 56: Traffic patterns between nodes and impact on number of connections as the number of nodes grow

On the other hand, the access segment is generally characterized by low average utilization (Figure 57). Hence, each of the possible connections have fairly low utilization. If such fluctuations in utilization can be exploited, shared resources such as feeder fibre and OLT transceivers can be saved at the host site. This is the basic idea behind TDM-PON systems.

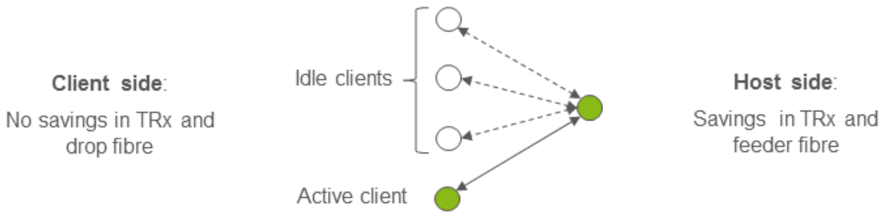


Figure 57: Low utilization of connections in the access and potential savings.

Achievable savings depend on the number of clients that can be attached to the same shared resources (host TRx and feeder fibre) and if resources can be dynamically shifted between clients sufficiently quickly. The first point is limited by the number clients that can be attached to an ODN which in turn is limited by power budget.

5.1.4 Service provisioning

A major benefit of flexibility is simplified service provisioning. A wider variety of actors and services utilizing transport services will drive dynamicity of service provisioning, both in terms of how frequently services are provisioned as well as in the variety of transport services. With the densification of mobile networks through increasing numbers of small cells, simplified introduction of new radio cell sites is expected to become an increasingly important requirement. Traditionally, this process requires significant planning and configuration of both radio and transport hardware and software resources. The complete process may take weeks or even months. For macro sites, the dynamicity of adding and removing sites is relatively limited, but this dynamicity is expected to increase for small cells and with higher RAN densities.

Simplified processes for configuring both radio and transport resources will be increasingly important. For packet-based backhaul, this could involve provisioning connectivity with the correct QoS characteristics together with relevant radio resources (e.g. BBU, RRU, RCC). For fronthaul/backhaul, deployment based on point-to-point (PtP) WDM, this involves provisioning of wavelength resources to connect between relevant radio resources. Automatic provisioning of such transport resources over a filtered ODN as used for WR-WDM-PON requires pre-installation of host transceivers for each potential client. For low take rates, with few clients (small cells) per ODN, this presents a significant penalty in terms of over-dimensioning of the number of optical transceivers. An alternative approach is to add host transceivers based on demand, which requires manual installation of host transceivers each time a new cell site is deployed. The case of adding a new small cell in a statically wavelength-routed ODN is illustrated in Figure 58a where the installation of a small cell not only requires manual installation at the new cell site but also installation of required host transceiver resources. Figure 58b illustrates the case where host transceivers instead are pre-installed for each ODN attachment point. In a flexible ODN (Figure 58c) based on power splitters and/or reconfigurable elements, host transceivers can be pre-installed based on estimated ODN take rates and flexibly provisioned together with radio resources based on demand. However, in optical transport, flexibility often comes at a cost, either in terms of performance (i.e., decreased system reach and cross talk) for a power splitter based ODN which must be compensated by additional amplifiers and/or lower splitting ratios in the ODN, or in terms of more costly reconfigurable components (WSSs, ROADMs, etc). However, within a few years' time (<2020) the cost ratio between a WSS and a tunable transceiver is expected to be around 5-10 which indicates the minimum reduction in number of host transceivers per WSS required for this type of flexible transport solution. The concept of simplified service provisioning is not limited to optical transport resources but can be expanded to other types of network resources such as BBUs. Here, flexibility, either in the optical transport itself or in the connection between the BBU and the optical transport system, can simplify service provisioning of new remote radio units without manual configuration at the host site. This in turn requires coordinated control between radio and transport resources.

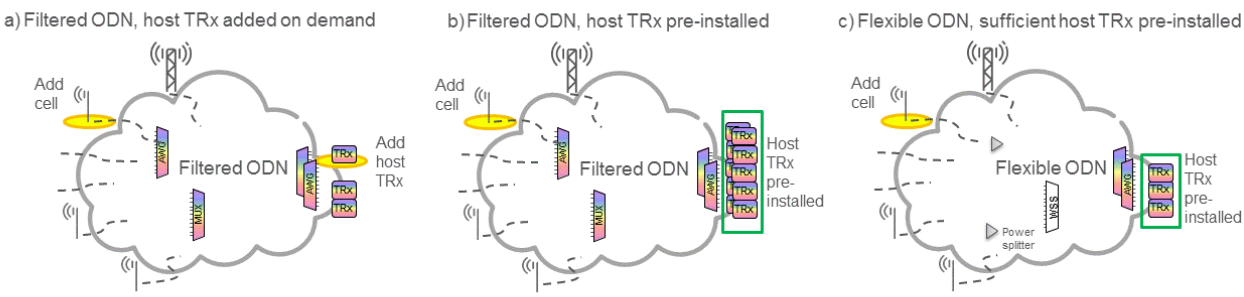


Figure 58: Service provisioning of transport resources for a new small cell for: a) filtered ODN with manual installation of host resources b) filtered ODN with pre-installation of host resources and c) flexible ODN with pre-installation of host resources (based on expected take rate) and flexible allocation of host resources.

5.1.5 Flexible system design

Flexibility can be realized by introducing intermediate elements in the system/network that provide different degrees of flexibility. Such elements could be active nodes for switching on packet (Ethernet, IP), TDM (OTN), or wavelength (WSS, ROADM) level. Alternatively, passive elements such as power splitters could be exploited for flexibility in a broadcast-select fashion. Given the COMBO focus on node consolidation, here we primarily consider architectures with a flexible ODN including power-splitter-based infrastructures and wavelength switching. Flexible architectures where already proposed in D3.3. Here we consider two of these architectures which can be seen as flexible variants of the main two COMBO options, i.e., NG-PON2 with WDM overlay and WR-WDM-PON. The added flexibility comes at an additional cost in terms of more costly components (such as WSSs) and increased insertion loss that may need to be compensated for by reach extenders.

Flexible WDM overlay

Figure 59 shows a solution for flexible PtP-WDM overlay in NG-PON2. The advantage of this architecture compared to static variants is that PtP-WDM wavelengths can be flexibly re-allocated between different ODNs. For example, if the distribution of small cells is changed, the network can be flexibly reconfigured to support the new connectivity requirements. In *Figure 59*, multiple ODNs are attached to a WSS that provides flexible wavelength allocation between the ODNs. A challenge with shared-spectrum NG-PON2 is that there are only 16 wavelengths available for PtP-WDM. This limits the number of ODNs that can be attached to the same WSS since these ODNs will be sharing the same pool of 16 wavelengths. As a consequence of the small cell density, the WSSs are of low fan-out leading to a large number of required WSSs. The number of WSSs is therefore driven by the total number of PtP-WDM wavelengths in the deployment rather than the number of ODNs that require PtP-WDM services. If the spectrum for PtP-WDM services could be extended resulting in more PtP-WDM connections per ODN, the number of WSSs could be decreased correspondingly, possibly combined with using higher fan-out WSSs.

Due to the additional insertion loss of the WSSs, amplifiers are typically required in the ODN. This means that the number of amplifiers scale with the number of ODNs. In principle, the amplifiers could be placed at the OLT or between the OLT and the WSSs. This would reduce the number of required amplifiers with a factor corresponding to the fan-out of the WSS. However, based on power-budget calculations made in the project considering laser safety class 1M, no such configuration with sufficient reach was identified. Another challenge with the configuration in *Figure 59* is the operational range of the WSS, which should support both the C and the L bands simultaneously. An alternative configuration is obtained by changing the order of the OLT diplexers and the WSSs. This doubles the number of WSSs but half of them will be C-band WSSs and half of them L-band WSSs.

Hence, one of the critical limitations is the limited size of the wavelength pool. The pool is determined by the spectrum allocation for overlay wavelengths in NG-PON2 and is limited to 16 wavelengths. The pool size puts an upper bound to the number of client attachment points and ODNs that can be connected to the pool. Assuming each ODN has 128 attachment points (1:128 split ODN) and that dimensioning should accomodate 5 guaranteed wavelength channels per ODN, then each wavelength resource pool could be attached to maximum three ODNs.

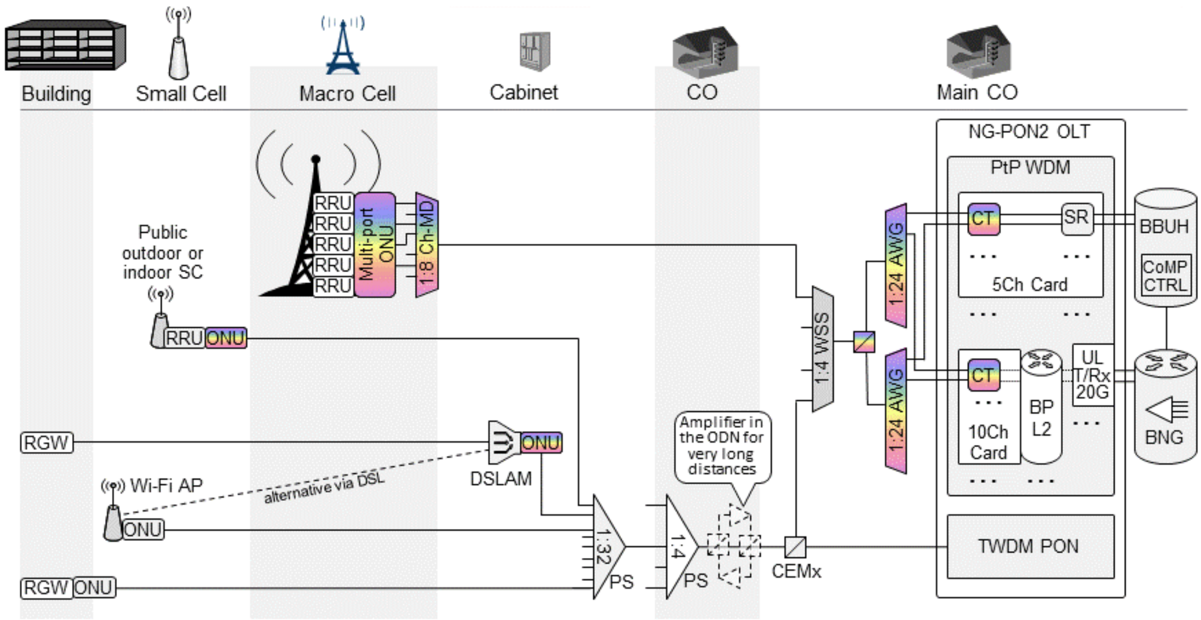


Figure 59: NG-PON2 (shared spectrum) with flexible PtP-WDM wavelength allocation

Flexible DWDM

Figure 60 show a variant of a flexible WDM-PON in a scenario with a separate TWDM PON-based fixed-access network. Compared to the shared-spectrum scenario, we here assume an expanded spectrum for WDM supporting up to 80 channels in each direction. *Figure 60* shows a variant where one of the power splitter stages in a WS-ODN has been replaced by a large-fan-out WSS. This improves reach at the expense of a more costly WSS-based ODN. Thanks to a larger wavelength pool, statistical multiplexing gains can be exploited to larger extent. A drawback with this architecture is that although it may provide some benefites in terms of improved resource utilization, the service provisioning gains are limited as the wavelength services are provided over a dedicated ODN. This means that manual patching most likely will be required for attaching new clients as the drop fibre associated with the clients needs to be connected to the correct ODN. A possibility not shown in the figure is to replace the 1:8 power splitters by filters (e.g., AWG) in *Figure 60* for clients with more static connectivity needs. This improves reach and reduces cost (no tunable Tx/Rx filters) for static clients.

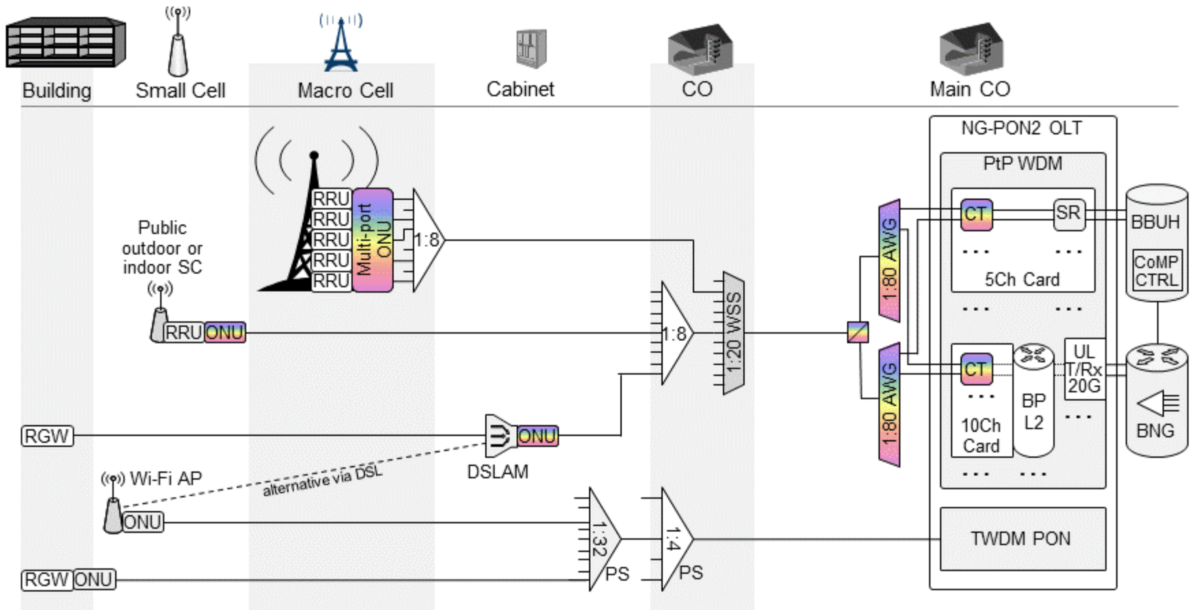


Figure 60: Flexible DWDM-centric access network based on WSSs

5.1.6 Cost and performance impact

One effect of introducing WSSs in the flexible system design is the added insertion loss of the WSSs as well as the tunable Rx filters at the client receivers which reduces system reach compared to the non flexible variants.

shows a summary of maximum reach for the two different systems at different interface speeds as well as amplification options. Flexible DWDM is compatible with reach requirements of rural areas for lower interfaces speeds but requires in-field amplification (ODN). Hence, in practice it is favorable mainly for ultradense and urban areas. For flexible WDM overlay in NG-PON2, power-budget limitations are even more severe. Reach requirements of ultradense and urban geotypes can be met but require amplification.

Table 19: System reach for the two flexible system variants for different interface speeds and amplification options

System	Config.	Interface speed (Gbit/s)	Amplification	Reach (km)
Flex. DWDM	1:20 WSS, 1:8 PS	3	No	5
Flex. DWDM	1:20 WSS, 1:8 PS	3	at OLT	25
Flex. DWDM	1:20 WSS, 1:8 PS	3	at ODN	57
Flex. DWDM	1:20 WSS, 1:8 PS	10	at OLT	16
Flex. DWDM	1:20 WSS, 1:8 PS	10	at ODN	53
Flex. DWDM	1:20 WSS, 1:8 PS	25	at OLT	10
Flex. DWDM	1:20 WSS, 1:8 PS	25	at ODN	23
Flex. DWDM	1:20 WSS, 1:8 PS	25	at ODN and OLT	55
Flex. DWDM	1:20 WSS, 1:8 PS	40	at ODN and OLT	38
Flex. DWDM	1:20 WSS, 1:8 PS	100	at ODN and OLT	10
Flex. WDM overlay	1:4 WSS, NG-PON2(1:128)	3	at OLT	6
Flex. WDM overlay	1:4 WSS, NG-PON2(1:128)	3	at ODN	38
Flex. WDM overlay	1:4 WSS, NG-PON2(1:128)	10	at ODN	27
Flex. WDM overlay	1:4 WSS, NG-PON2(1:128)	25	at ODN and OLT	39
Flex. WDM overlay	1:4 WSS, NG-PON2(1:128)	40	at ODN and OLT	23
Flex. WDM overlay	1:4 WSS, NG-PON2(1:128)	100	at ODN and OLT	10

One benefit of the flexible systems is that the WSSs enable more efficient use of filters compared of the static variants. Hence, in some cases there is a reduction in filter cost associated with fewer fixed filters. For example, for the flexible WDM overlay in NG-PON2, the 1:4 fan-out of the WSS reduces the number of required fixed filters for a group of four NG-PON2 systems from eight to two. Hence, the cost impact of introducing flexibility in the wavelength level can be summarized as:

- Additional cost: WSSs, amplifiers, tunable filters at clients
- Reduced costs: reduced filter count (some cases)

Disregarding any pooling savings of optical resources enabled by flexibility, the system cost is generally higher. However, potential benefites of flexibility must also be included in the comparison. For example, the cost of one WSS corresponds to ~10 DWDM transceivers. This means that (unless there are large savings in filter costs) at least 10 transceivers need to be saved with the flexible system variants to break even.

In *Figure 61* and Figure 62, we model the relative cost of adding flexible WDM for the two considered architectures and for geotypes where the flexible systems are viable.

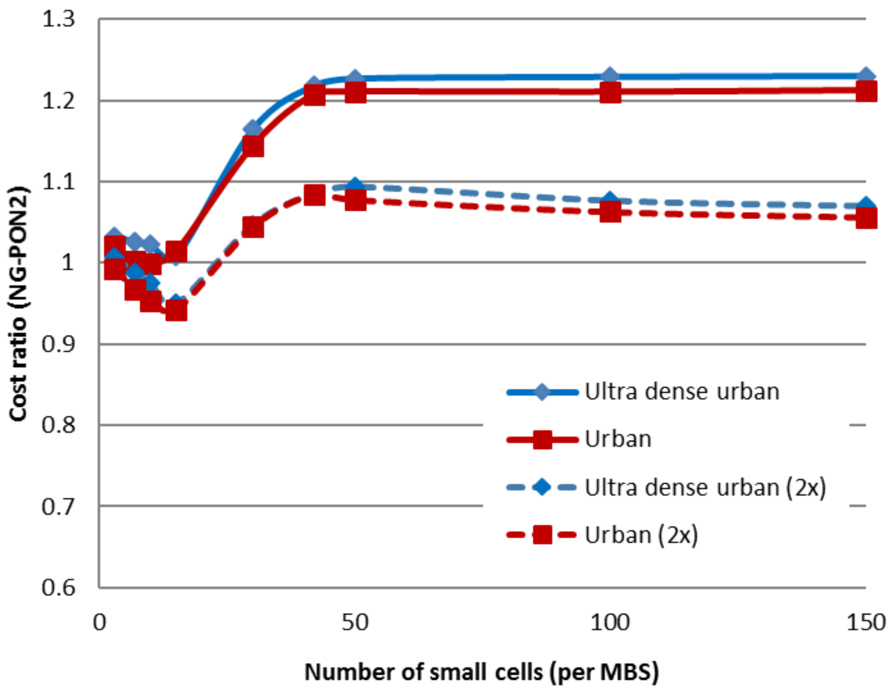


Figure 61: Cost comparison of the flexible WDM overlay in NG-PON2 compared to NG-PON2 for 100% FTTH and centralised backhaul of small cells to the MCO. The dashed curves show results for a factor 2x sharing of interfaces.

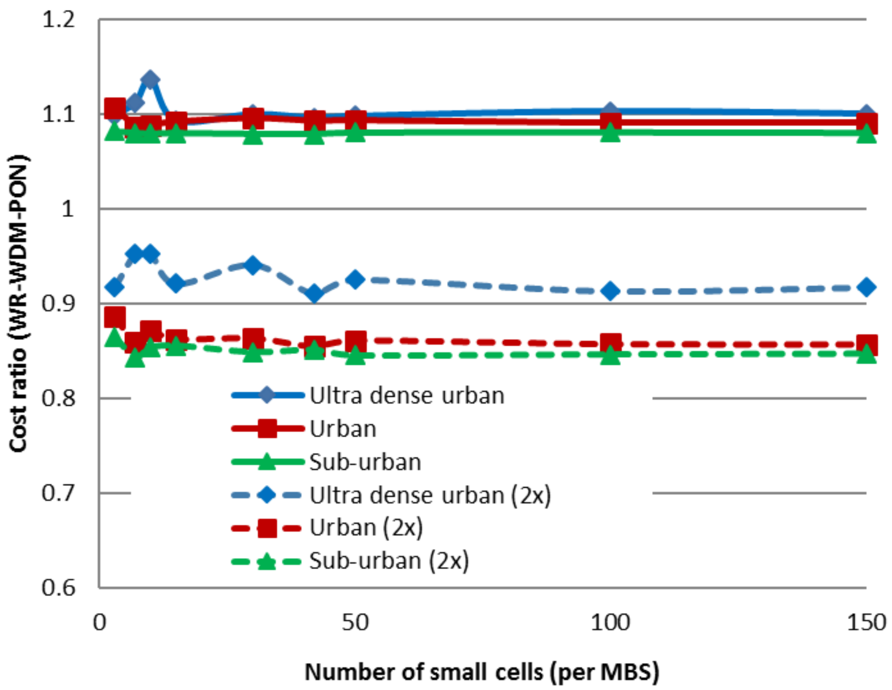


Figure 62: Cost comparison of the flexible DWDM to WR-WDM-PON for 100% FTTH and centralised backhaul of small cells to the MCO. Upper curves show cost without sharing of MCO interfaces. The bottom curves show results for a factor 2x sharing of interfaces.

The comparison considers relative cost of flexible variants compared to the ridged variants. The calculations are performed for backhaul scenarios with centralised aggregation of SCs to the MCOs considering 100% FTTH and fibre-rich scenarios. We find that without any modeled gain there is a 10% cost increase of the flexible variants due to WSSs and additional amplifiers. If we model a pooling gain of a factor 2x on interfaces resources at the MCO, we find that cost savings of 10-15% can be made. Main conclusions for the two flexible systems designs are summarized below:

Flexible WDM overlay in NG-PON2

- Pooling gain limited by the maximum 16 overlay wavelengths available in the wavelength the pool
- The limited wavelength pool limits the number of ODNs that are reasonable to connect to a single wavelength pool. This number is estimated here, based on the considered SC densities, to three ODNs per wavelength pool.
- With three ODNs per wavelength pool, there are maximum 384 (=3x128) ODN attachment points per wavelength pool
- The cost of one WSS is shared over 16 wavelengths, alternatively over 384 ODN attachment points
    - High system cost per wavelength
    - Low system cost per ODN attachment point
- Given the high system cost per wavelength, there are limited benefits for the system in terms of efficient resource utilization
- Given the low cost per ODN attachment point, the system brings benefits in terms of simplified service provisioning

Flexible DWDM:

- Pooling gain is limited by the maximum 80 DWDM wavelengths available in the wavelength the pool
- Dedicated ODN for wavelength pool (not shared with fixed access) and hence less useful to connect large numbers of attachment points to the same ODN. Number of attachment points per system should optimimally resemble expected savings from efficient resource utilzation.
- The cost of one WSS is shared over 80 wavelengths, alternatively over ~160 ODN attachment points (depending on dimensioning and expected pooling gains, i.e., here 50% in resources)
    - Low system cost per wavelength
    - High system cost per ODN attachment point
- Given the low system cost per wavelength, there are expected benefits for system in terms of efficient resource utilization
- Given the high cost per ODN attachment point, the system brings limited benefits in terms of simplified service provisioning

5.2 Management and orchestration

Sharing of resources, e.g., between fixed and mobile networks, requires that resources are managed across domains. In some cases, resources can be statically configured and split between the domains. In other cases, where resources are dynamically allocated to different domains based on demand, cross-domain orchestration of resources may be required. For the scenarios described in chapters 3 and 4, the assumption is that resources are configured manually through the patching of fibres, filters, transceivers, etc. For the flexible scenarios described in chapter 5, coordination of resources across the domains (radio, transport and fixed access) is required. For scenarios involving cloud resources such as the virtualized BBUs (section 3.3.1 or UAGs (section 8.8.1), also the cloud domain needs to be covered.

Section 5.2.1 describes management and orchestration architecture options focusing on the COMBO scenarios. Primary focus is the joint orchestration of RAN, transport and fixed access. We also consider the joint orchestration with the cloud domain which is relevant for virtualized deployment scenarios. Section 5.2.2 discusses abstraction models and interfaces between different management and orchestration entities and applicability to the COMBO scenarios. This section does not develop interfaces and abstraction models (which is outside the scope of COMBO) but describes how available models can be used in a COMBO context.

5.2.1 Management and orchestration architecture

The COMBO focus on structural convergence is primarily on connectivity between the MCO and client sites (MBS, SC, CPE, etc). We recap the main structural convergence scenarios as presented in chapter 1 (Figure 63), where structural convergence may range from common systems to common ODN or dedicated systems. In addition to the structural convergence, there is also a convergence in the transport service layer where the same transport service may be provided over different systems/technogies (e.g., packet, CPRI).

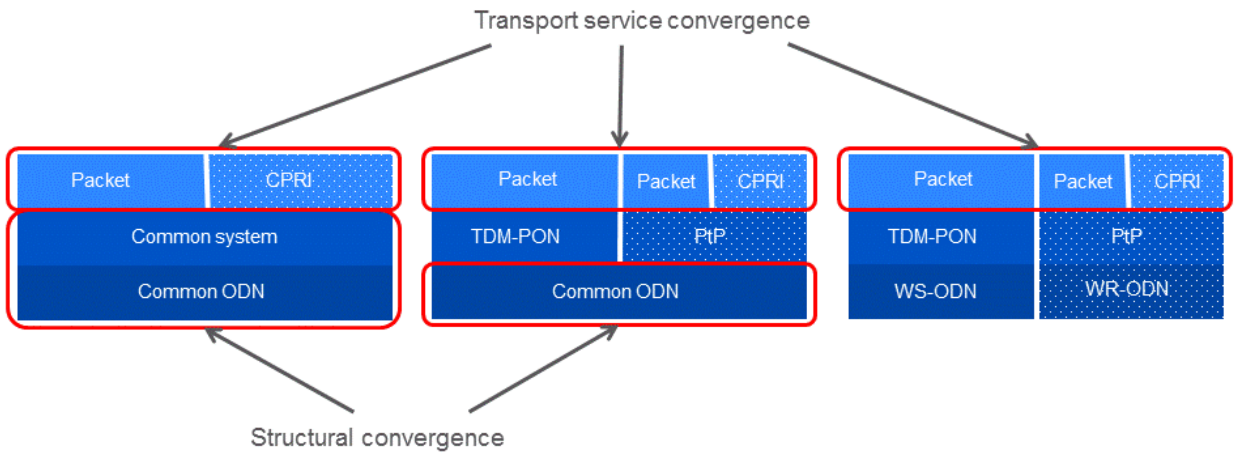


Figure 63: COMBO scenarios for structural convergence

Based on these three scenarios a number of architectures for cross-domain management and orchestration of resources are possible.

First consider the scenario with dedicated systems for shared wavelengths (TWDM PON) and dedicated wavelengths (PtP WDM) as illustrated in the top lefthand part of Figure 64. In this case, system resources are not shared. A related scenario is illustrated in the lower lefthand side of Figure 64 where the ODN is shared but resources are statically configured to each system. In both scenarios, it is assumed that the system resources are managed independently by individual domain managers (DM). However, despite lack of system convergence in these two scenarios, both the fixed-access and mobile-access domains will be clients to the transport domain for cabinet backhaul and RAN x-haul transport services. In the first simplest management architecture illustrated in Figure 64, there is no cross-domain orchestration of resources. Instead, these services are statically configured. This is reasonable if limited dynamicity is expected in the transport connections serving the fixed- and mobile-access domains.

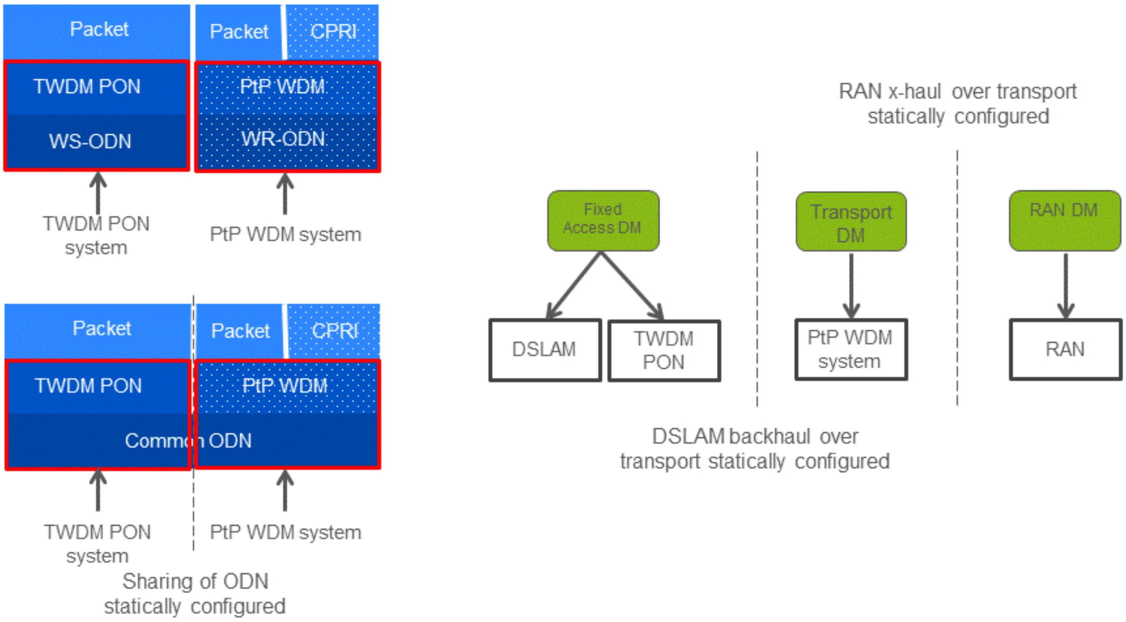


Figure 64: Scenarios with two independent systems for TWDM PON and PtP-WDM, where the bottom left figure shows the case with a shared ODN. The right hand side shows independent management of the different domains by individual domain managers (DM).

In case there are benefits from coordination of resources between the RAN and transport, two alternative management architectures are shown in Figure 65. In the first topmost alternative, the RAN DM is a client to the transport DM. The transport DM may present a more or less detailed view of resources available to the RAN DM. Note that the transport resources could be sliced by the transport DM and presented to several different clients (e.g., multi-operator cooperation scenarios). Based on an abstract view of the transport resources, the RAN DM can perform various optimizations by requesting and releasing transport services. A second alternative for the cross-domain orchestration is presented at the bottom of Figure 65 where the global optimization of resources is performed by an orchestrator. In this architecture, the RAN DM needs to present a more or less detailed abstraction of its resources to the orchestrator such that the orchestrator has sufficient information for the intended optimization use cases (resource pooling, service provisioning, etc). This option with the orchestrator would facilitate optimization of resources.

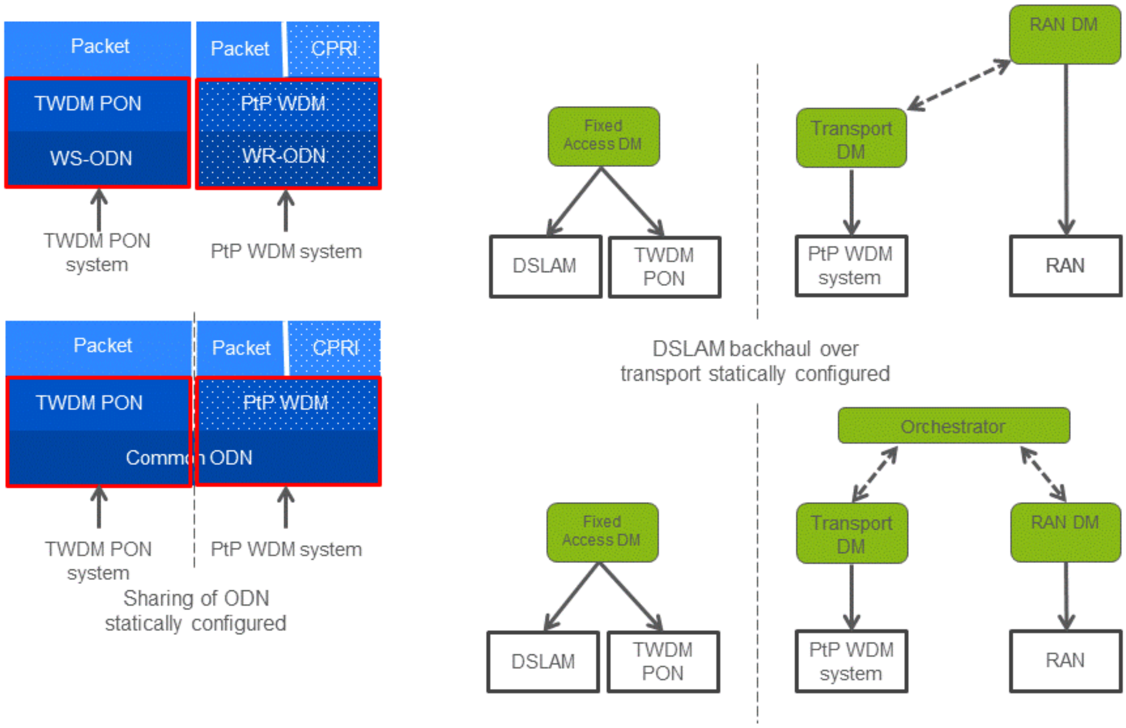


Figure 65: Scenarios with independent systems for TDM-PON and PtP-WDM, where there is cross-domain coordination of resources between the RAN and the transport (PtP WDM).

Figure 66 shows the scenario where the TWDM PON and PtP WDM systems are managed as one optical system. This leads to either a common system able to provide both, packet and CPRI transport services, or a transport orchestrator managing the combined resources from different optical systems and being able to provision both dedicated and shared wavelength services. Also for this case, several different management architectures are possible. Two alternatives are shown in Figure 66. The top-most figure shows an alternative where the fixed access DM and RAN DM are clients to the transport DM. These client domain managers may request and release resources from the transport DM. In a second alternative, the optimization performed by an orchestrator, where all the individual domain managers now need to present a relevant view of resources to the orchestrator such that the orchestrator can do the cross-domain optimization.

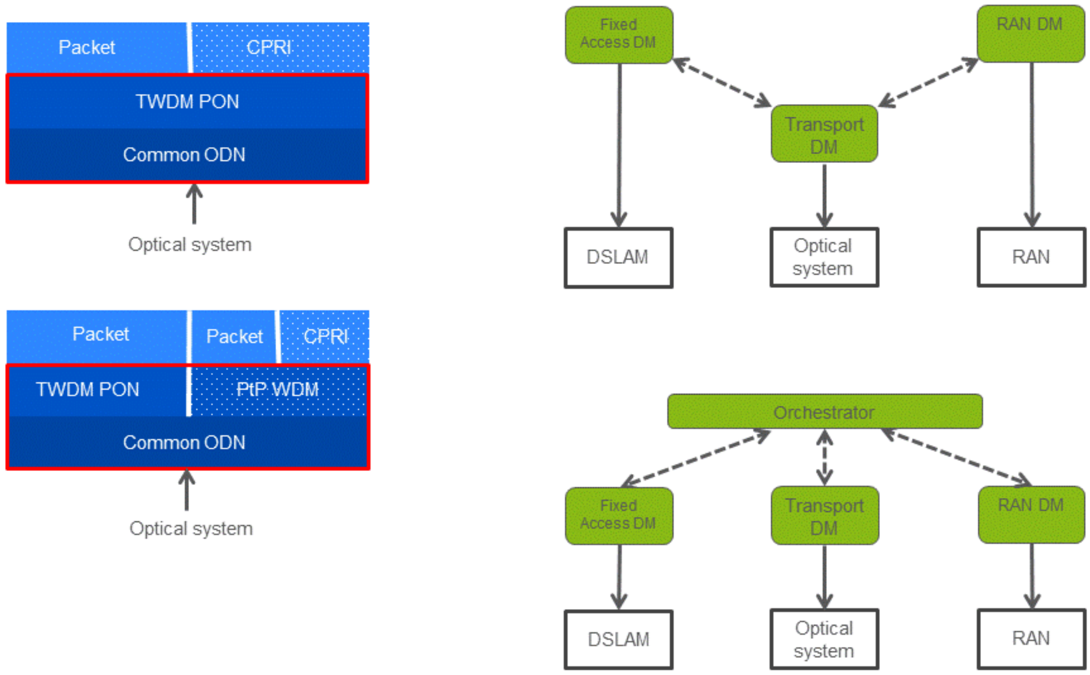


Figure 66: Scenarios with a common system or common control of TWDM PON and PtP WDM and with cross-domain coordination of resources among the RAN, transport (PtP WDM) and fixed access.

Finally, Figure 67 shows the scenario assuming a flexible ODN and for the case where there is a dedicated controller managing the shared resources of the ODN. Here, the ODN may either be serving the transport DM and TDM-PON DM with ODN resources or it could be placed directly under an orchestrator that would be doing detailed orchestration of resources.

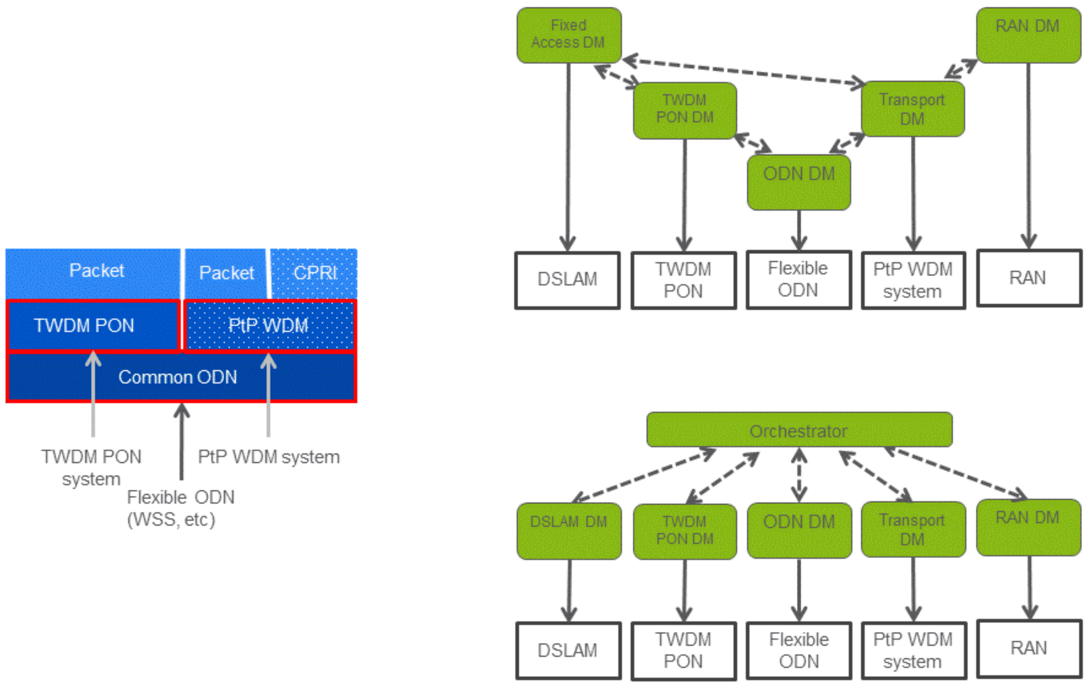


Figure 67: Scenario with independent systems for TDM-PON and PtP-WDM as well as independent control of the flexible ODN. The right-hand side shows different management and orchestration architectures for cross-domain coordination of resources.

The architectures in this section have so far only considered orchestration of connectivity resources. Next step is the inclusion of cloud resources into the management and orchestration architecture. A common reference model for the cloud domain is the ETSI MANO architecture [29] as illustrated in Figure 68.

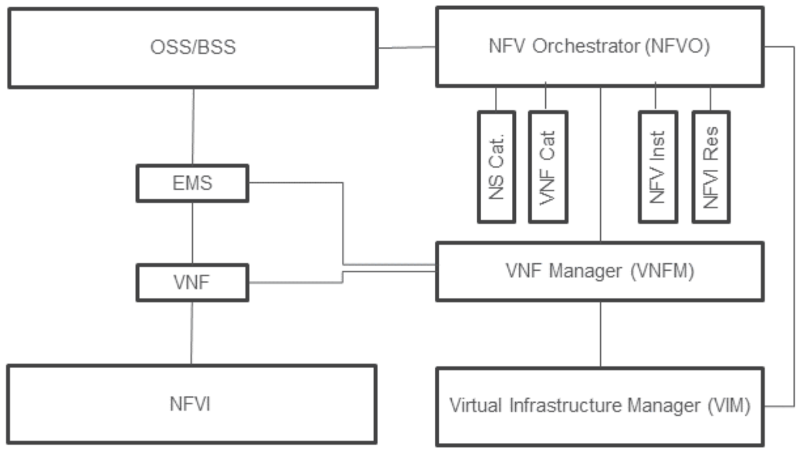


Figure 68: ETSI MANO architecture [29]

In the COMBO scenarios, although not part of the techno-economic assessments, it was assumed that there could be cloud resources at the Main CO in the form of the UAG. Furthermore, we considered scenarios where part of the RAN functions could be virtualized and hosted in a cloud environment. Also, the fixed access is subject to trends of virtualization. *Figure 69* shows one avenue for integrating the management of RAN, transport and cloud into one framework where the RAN DM and fixed-access DM are clients to the cloud DM and transport DM. The latter in turn are interconnected with an east-west interface as the transport may involve virtualized functions hosted by the cloud domain and the cloud domain may rely on the transport for interconnecting cloud resources that are distributed.

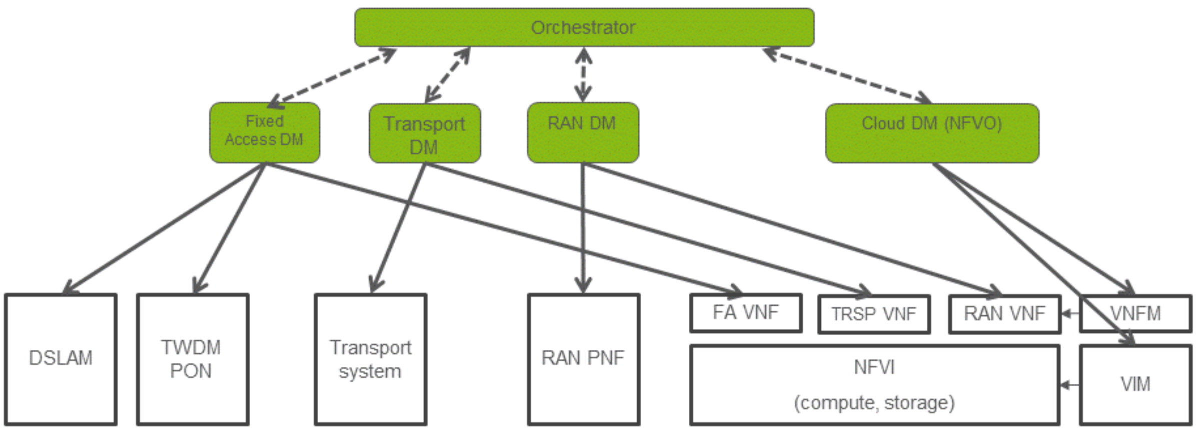


Figure 69: Management architecture for coordination between fixed access (FA), RAN, transport (TRSP) and cloud, with both physical network resources (PNF) and virtualized network resources (VNF) for different domains.

Figure 70 shows a second avenue for integrating the management of RAN, transport and cloud into one framework, allowing for cross-domain optimization. Here, RAN, fixed access, transport and cloud are seen as a common pool of resources that is available to an orchestrator to dynamically setup or scale a large variety of services that could be composed based on these resources.

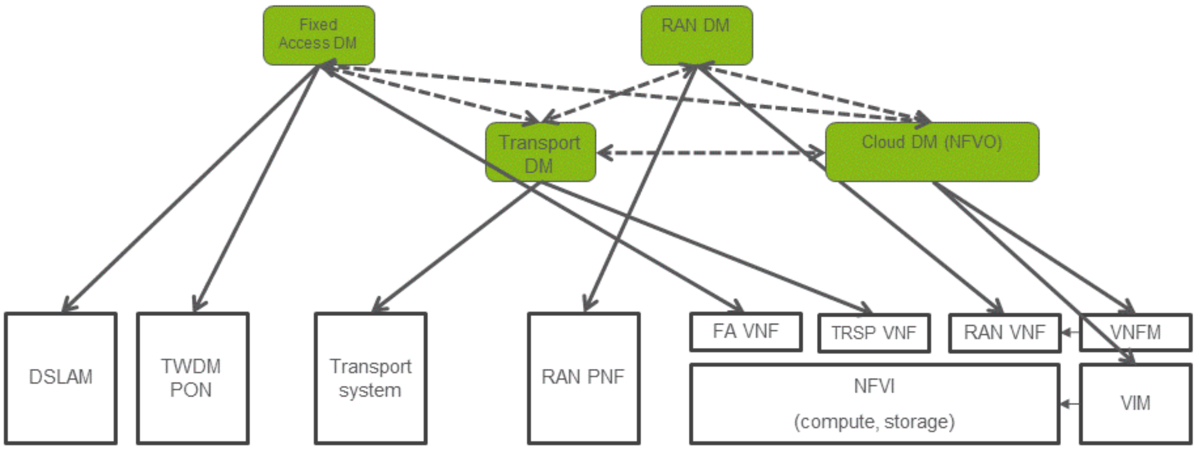


Figure 70: Management architecture for orchestration between fixed access, RAN, transport and cloud.

5.2.2 Abstration and interfaces

One of the key elements for detailing the architectures presented in section 5.2.1 is to define the roles and responsibilities of different management entities as well as detailing the interfaces between these given the use cases that need to be supported. An important aspect of the interfaces between different management entities concerns the representation and abstraction of resources from a domain, which in turn is presented to another management entity or orchestrator higher up in the hierarchy. The level of detail in the abstraction models presents a balance between simplicity and scalability of the architecture on one hand and on the other hand providing sufficient information to enable the desired optimizations efficiently. Also, a model is needed that can cope with a diverse set of resources including compute, storage, connectivity as well as functional resources. Another important aspect concerns the structure of the service request going from one management entity or orchestrator higher up in the hierarchy to another management entity below it. This service request also needs to be able to handle and formulate diverse service requests based on the diverse set of resources in the framework.

For connectivity, different abstraction models have been described such as the big-switch and virtual-link model. More challenging is the unified description of connectivity, processing, storage and functional resources. Here, we utilize a powerful abstraction model developed in the FP7 project UNIFY. The abstraction is called Big Switch – Big Software (BiS-BiS), and the service request is called Network function forwarding graph (NFFG). Details can be found in UNIFY deliverable [30]. BiS-BiS is a joint presentation of networking and compute/storage resources, which are characterized by various parameters (processing capacity, storage, etc). *Figure 71* illustrates two different levels of abstractions of the same resources where the second alternative is more detailed. The external connection points to the resources are called service access points (SAP).

Figure 71: Illustration of the resource abstraction model BiS-BiS from the UNIFY project [30] and two levels of abstraction.

Hence, various management entities may present their resources to higher-level management entities with some level of granularity, where BiS-BiS could be one frame work for this. Based on this view of the resources, service graphs consisting of chains of functions may be mapped to the resources taking into account the capabilities and constrictions associated with the resources as well as considering some overall optimization objectives. *Figure 72* shows an example of the resulting NFFG which is the mapping of functions and forwarding rules to the resource description.

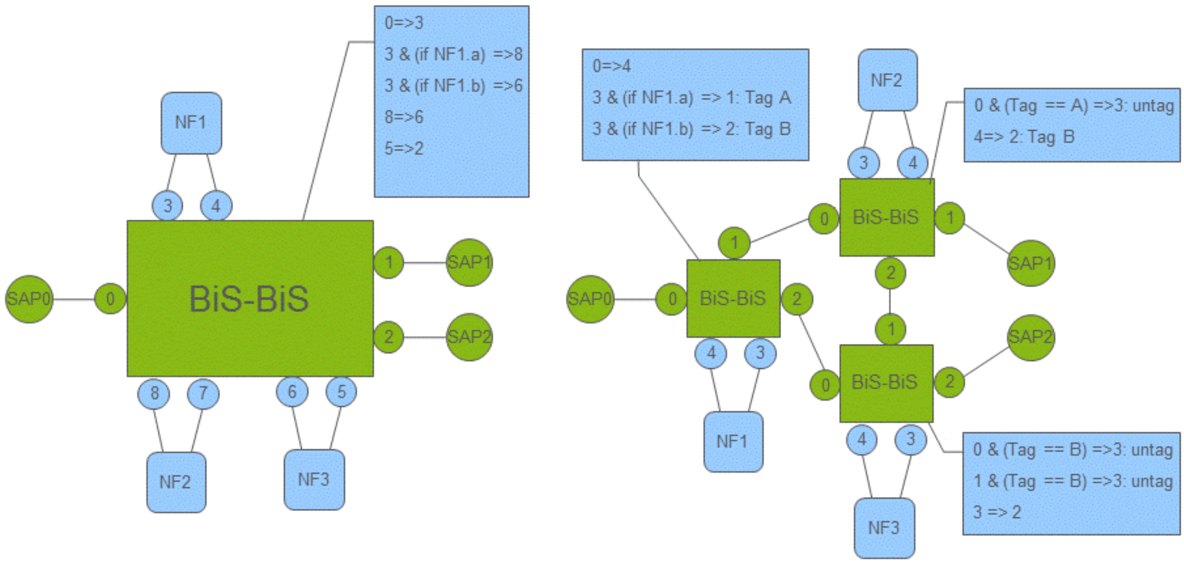


Figure 72: Illustration of the service request format NFFG from the UNIFY project [30] on two abstractions.

Hence, BiS-BiS and NFFG together provide one way of implementing the interfaces between different management entities in the architectures descriped in section 5.2.1. Finally, in *Figure 73*, we also show an example of how BBU and transport resources could be modelled within this framework. The example illustrates a scenario where a larger number of RRUs are sharing a limited number of BBU resources through flexible connectivity. This flexibility could be implemented through a flexible optical layer (section 5.1.5) or electrically through a low-latency switch (8.8.1). Though, this does not necessarily need to be revealed by the resource abstraction. As part of this example, the BBU and RRU resources are represented as physical network resources. An implementation and demonstration of this scenario using the UNIFY framework applied to the COMBO structural convergence scenario is provided in D6.3 [31].

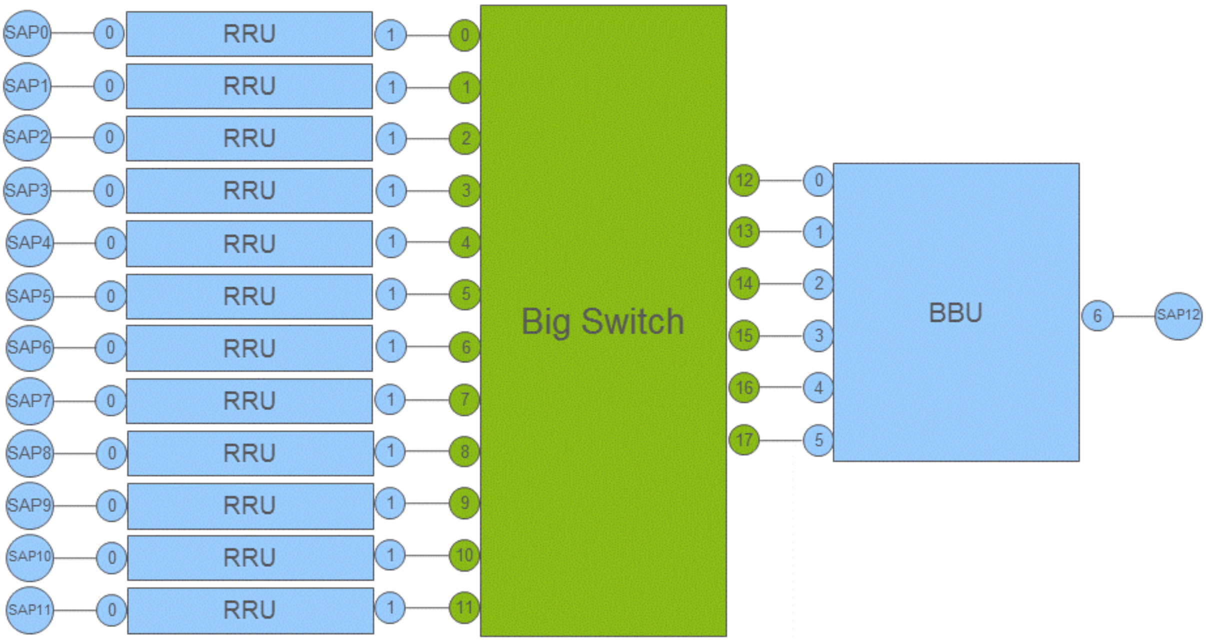


Figure 73: Transport and RAN resources modelled in the BiS-BiS framework.

6 Protection

In evolving FMC networks, fixed and mobile customer services will be carried over a joint access infrastructure in which all services would become unavailable in case of failure. New protection mechanisms are required, assuring a basic set of services as for instance emergency services. Different general concepts are thinkable such as path doubling of jointly used network segments, inband wireless backhaul protection, switchover to neighbouring MBSs or even to small cells if the MBS fails or vice versa. The focus of this study lies on protection concepts for fixed backhaul connections, which use the same access technology and infrastructure as FTTx fixed lines. Since MBSs provide a widespread coverage of the entire mobile service portfolio, covering smallband as well as broadband services, the main requirement for protection arises for MBSs. Still, small cell protection may be of interest in particular areas, for instance at business parks or hotspots with poor MBS coverage, in order to also ensure a certain degree of mobile broadband coverage during a network outage.

Hence, while on the one hand, mutualization of fixed and mobile infrastructure increases the risk of having failures of high penetration and impact, on the other hand, the convergence of the originally independent network segments opens new possibilities in providing redundant / protected connection to the end users, exploiting the substitution possibilities of the overlapping networks. When discussing availability of FMC access networks, strict cost constraints of access networks have to be respected, i.e., the use of redundancy and protection resources is very limited. This altogether suggests that availability and protection aspects of FMC access networks should strongly focus on a more efficient use of the already available resources.

6.1 Survivability in an FMC context

In the following, we attempt to review the specific aspects of potential failures in FMC networks. We present metrics for the classification of failures, review the various applications and services in FMC networks from the viewpoint of availability aspects, and discuss respective survivability strategies.

6.1.1 Classification of failure events

The most harmful potential failure events should be identified, and the “risk” needs to be quantified, as a protection strategy should be able to focus on the most critical points of the network. In this section, we propose a few metrics to evaluate certain failure events, and these metrics then help to identify the critical failures. In addition to defining metrics for failures themselves, we also propose related network-level metrics for evaluating the survivability of the access network (against the critical failures identified by the discussed metric).

Before the formal definitions, some commonly used variables and notions are defined. As a collective term, all possible endpoints of the FMC access network (macro base stations, mobile small cells, fixed residential and business customers) will be called clients. Let F and C denote the set of individual failure events and the set of clients, respectively:

$$F = \{f_1, f_2, \dots\}, C = \{c_1, c_2, \dots\}$$

A failure event occurs in the physical network infrastructure, e.g., a cable cut affects network links that share the same duct, even if they are logically independent links. A failure event f_i “affects” the subset of clients that become disconnected if the failure occurs:

$$A(f_1) = \{c_{i1}, c_{i2}, \dots\} \subseteq C$$

6.1.1.1 Failure penetration

Failure penetration is the amount of clients affected by a single failure event. Critical f_i failures are those which affect more clients then a predefined limit N: $|A(f_i)| > N$. The related network availability metric is the number or total probability of critical failures, Failure Penetration Count (FPC) or Failure Penetration Probability (FPP):

$$FPC = |\{f \in F: |A(f_i)| > N\}|$$
$$FPP = \sum P(f): f \in F \wedge |A(f_i)| > N$$

6.1.1.2 Failure impact

Let us define the expected impact E_i of a failure event f_i as the product of the failure probability and the affected clients. E_i stands for the expected value of clients suffering service disruption due to failuref_i: $E = P(f_i) \cdot |A(f_i)|$. Obviously, the most critical failures are the ones with high expected failure impact.

Network level availability metric is the sum of the expected impact of all failure events, i.e., a weighted sum of failure penetrations, using the respective failure probabilities as weights. This gives the expected value of clients being disconnected due to any of the failures in the network (Expected Failure Impact, EFI):

$$EFI = \sum E_i = \sum P(f_i) \cdot |A(f_i)|$$

6.1.1.3 Individual client availability

The individual availability of every client can be calculated separately, using the well-known Reliability Block Diagram (RBD) model: the connection of each client (base station) is a combination of series and (if redundancy is deployed) parallel connected links. Knowing the probabilities of failure events affecting these links, availability of the client (A_c) can be calculated using the RBD model.

The network operator may be interested in meeting certain availability requirements for each of the clients individually. Critical clients are those that do not meet the availability requirement. The network availability is the minimum of all client availability values (Minimal Client Availability, MCA):

$$MCA = \min_{c \in C} A_c$$

6.1.1.4 Failure area

The last failure criticality metric evaluates a failure event by the area it affects. More specifically: the largest enclosed area it affects, i.e., the set of neighboring cells with the largest connected area, without the inclusion of any unaffected clients (small cells). If there are multiple enclosed areas affected by the failure event f_i, the largest enclosed area is denoted by $Area(f_i)$. With this definition of the failure criticality, failure events that affect a “scattered” set of clients have low criticality, even if a large amount of clients are affected, since the largest enclosed area will be small. The network level availability metric will be the the largest enclosed area that can be disconnected from the network due to a failure event (Maximal Failure Area, MFA):

$$MFA = \max_{f_i \in F} Area(f_i)$$

6.1.1.5 Most relevant metric

The selection of one or another metric for identifying critical failures and evaluating the access network clearly depends on the service/application itself. Without exploiting FMC, and treating the fixed access, small cell backhaul/fronthaul, and macrosite backhaul/fronthaul network individually, the most appropriate metrics could be:

- minimal client reliability for mobile macrosites (if the operator needs to keep all of them alive)
- failure area for small cells
- failure penetration/impact for fixed access

6.1.2 FMC services/applications

An FMC network provides various services and applications, similar to fixed or mobile access networks. Services and applications may have specific requirements for the underlying network infrastructure, among others, also for availability. It is always somewhat more difficult, and requires a level of abstraction to translate these requirements to specific networks elements, but “network-wide” requirements for the distinct services and applications can be defined in a more intuitive manner.

Table 20 lists a set of such requirements. We try to address the most typical and characteristic services, however the list can be extended with new elements based on the profile of the service provider, and hence, making a “complete” list is clearly impossible. The table is based on the bitrate and availability requirements for a set of reference applications defined in COMBO D2.4 [32].

Table 20: Reference services and their availability requirements

Service/application with approx. bitrate requirement	**Availability requirement for fixed/mobile end-user**
Emergency calls (<64 kbps)	**“Mission impossible”: “always on”**
Voice calls (<64 kbps)	**99.99%**
Low bitrate data traffic (e.g., mails and news) (100-500 kbps)	**99%**
High speed internet / data (e.g., videostreams) (~ 10 Mbps)	**99% availability for a minimum of 10 Mbps**

6.1.3 Necessary infrastructure and substitute roles

The operators can set up (internal) goals for availability of their services; and they can guarantee some requirements in contracts / SLAs. Cleary, violating the “internal goals” and the “external” guarantees has significantly different consequences – the networks will be planned to meet the internal goals, and typically over-performing the guarantees. Due to the complexity of networks, and the circumstances not under control of the network operator, making end-to-end services guarantees is difficult, and typically such guarantees are relatively low/loose, at least for residential services. Therefore, here we focus on the “internal goals”, being reasonable requirements for the network operators themselves.

In this section, we review how these generic services can be provided in a failure-proof manner, i.e., what availability metrics could be used to evaluate network availabity, and what subset of the network infrastructure should remain alive in case of a failure in order to keep the desired service availability.

6.1.3.1 Emergency & voice calls

FMC access networks may be treated as critical infrastructure, most prominently for at least making emergency calls possible. Access to the network is desirable anycase, anytime, and almost anywhere (even in inhabitated areas). On the other hand, emergency call services only need coverage with negligible network capacity demand. Therefore, a minor subset of the FMC network infrastructure, typically the “macro layer” (or even parts of it) is enough. In addition, emergency calls may be initiated in any operator's network by any user, therefore only "cumulated coverage" of all operators is required.

Hence, for **emergency calls**, the minimal network infrastructure is a subset of MBSs of all network operators, which provides pure coverage. In urban environments, it needs typically less then a single operator's MBSs, while in rural environments it means all MBSs of a single operator's network (or an equivalent mix from all network operators). In a multi-technology radio access network, typically the network operated at the lowest frequency provides survivable emergency call service.

The case of **voice calls** is similar to emergency calls, with one significant difference being the absence of domestic roaming (at least in several Europen countries), i.e., the MBS coverage should be provided by every operator's own network.

Among the availability metrics presented in the previous section, both for emergency and voice calls, typically the individual availability of (all or designated) MBSs is the right metric – the minimal subset of MBSs that keeps the service alive.

In order to give a rough estimation, let us to have a quick look at current LTE networks: the "noise floor" (below which voice calls are not possible) is at the range of -120 dBm signal power. Assuming a Base Station with 60 W transmission power, and using the COST231/Hata Path Loss model, it allows very long distances between the UE and an antenna placed 10-20 m high (Path Loss approx. 160 dB). In rural scenarios, the UE can be up to 10 – 20 km away from the MBS, at 800 or 1800 MHz, respectively. In urban scenarios, a voice call could be possible still 3-5 km away from the antenna (considering 1800/2600 MHz). Considering 1-4 MBS/km2 in urban, and 0.05 MBS/km2 in rural scenarios, it leads to the estimation that **approx. 10% of a single operators MBSs could be enough to provide only voice call services, and even less for emergency calls** (in case roaming to another operator provides backup).

6.1.3.2 Low bitrate data

Low-bitrate data services allow the end-users to access their e-mails, read news, etc. but do not necessarily support bandwidth-hungry applications, such as streaming traffic. The "always connected" life of the "Networked Society" necessitates such services to be almost always available. Therefore, a high availability is desired – at least with short experienced downtimes (as these services are typically not real-time services). Since we are not addressing streaming or real-time traffic here, a limited set of SCs and/or MBSs could meet the requirements, serving the end-users within their reach in successive timeslots.

According to our simulations (section 4.4.2), a low-bitrate data service of up to 1 Mbps per UE can be provided solely by the MBS "layer". In sub-urban and rural scenarios, having all base stations is necessary to keep this low-bitrate service alive (otherwise, coverage could be lost). In urban and ultradense scenarios, even a subset (approx. 25% evenly distributed) of MBSs may be enough to provide low bitrate data: having smaller cells in urban environments leads to "spare" coverage.

Regarding availability metrics, the individual availability of the MBS is desired, especially for sub-urban and rural scenarios. Addressing the urban and ultradense scenarios, having a guarantee that 1 out of every 4 MBS is available (i.e., uniformly distributed 25%) could be an option, which tends to be a Failure Area metric, i.e., the largest area where network connectivity is lost should not exceed the area of 4 MBSs (1 km^2 for ultradense and 6 km^2 for urban).

6.1.3.3 High-bitrate data

High-bitrate data is the most demanding service that the FMC network provides to its customers with respect to capacity. Still, it is clearly not possible to guarantee survivability of the network as a whole. Specifying a guaranteed bitrate at a certain availability can be translated to a (typically major) subset of the network having to be available in case of a failure, and if the guaranteed bitrate is too high, availability requirements cannot be met in a cost-efficient way. Therefore, guaranteed high bitrate is not expected in the foreseeable future; and instead of adding protection and redundancy for almost the whole access network (including fixed residential access), smart network planning strategies are recommended to minimize impact of possible failures.

The network operator can take reasonable actions to minimize the deterioration of user experience, following one of the long-term goals of 5G networks identified as “zero perceived downtime”. The perception of a network failure for the end-user clearly depends on the service/application used, and in several cases, availability of a moderate bitrate keeps customer satisfaction, until it supports applications with lower bandwidth demand. In other cases, minimizing failure penetration and impact, or maximizing the “survivable” network capacity in case of failures is recommended.

We have carried out a set of simulations (see Chapter 4.4.2 for the methodology), identifying the set of resources that should be available in the physical infrastructure to support a limited, but still relatively high bitrate service. The overview of the results are concluded in Table 21 below. Our assumption was that failures in the fixed residential access will not be protected; hence we focus on the (5G compliant) mobile network’s ability to backup the fixed access. Our initial assumption was that the macro BSs are protected and hence, operating – and we have investigated how the loss of SCs decrease the bitrate. The density of SCs necessary to meet the high 5G traffic requirements (see Chapter 4.3) were calculated. The respective traffic density, bitrate per UE and UE density is in the first row of the table. We have then investigated what an evenly distributed loss of SCs brings. Since the powerful, 3-sector MBS provides a certain traffic capacity, the loss of throughput is not linear with the loss of SCs, and approx. 10 Mbps bitrate per endpoint is provided only by the macros.

Since the amount of fixed access endpoints is comparable to the UE densities listed here (or even lower), the mobile network is able to backup in terms of “endpoint quantity”, and not only in terms of bitrate or throughput.

Table 21: SC survivability vs. High bitrate service

SC survivability %	Throughput (bitrate per UE x UE density)		
	Ultradense	Urban	Suburban
100%	750 Gbps/km^2 300 Mbps per UE 2500 UE per km^2	240 Gbps/km^2, 300 Mbps per UE 800 UE per km^2	20 Gbps/km^2, 50 Mbps per UE 400 UE per km^2
50%	80% ~240 Mbps per UE	50% ~150 Mbps per UE	60% ~30 Mbps per UE
25%	60% ~180 Mbps per UE	33% ~100 Mbps per UE	45% ~22 Mbps per UE
10%	40% ~120 Mbps per UE	22% ~65 Mbps per UE	40% ~20 Mbps per UE
0%	11.6% ~30 Mbps per UE	13.3% ~40 Mbps per UE	34% ~17 Mbps per UE

6.1.3.4 Conclusions

Based on reviewing the minimal necessary infrastructure for reference services/applications, having only the MBSs alive in the network in case of failures could guarantee even a (limited, but) high bitrate data service of up to 10 Mbps, and voice / emergency calls can be served even by a smaller fraction of MBSs.

Among all the defined representative applications of Deliverable D2.4, only the Digital Home / content delivery (up to 50 Mbps bitrate) necessitates (partial) survivability of the Small Cells. Hence, in the following, our study will focus primarily on protecting the MBSs, and minimizing the losses due to single failures in other network elements (preferably without added protection).

Table 22 Mobile infrastructure survivability vs. Reference services

Service/application	Mobile infrastructure survivability required			
	Ultradense	Urban	Suburban	Rural
Emergency calls (<64 kbps)	10% of MBSs (of any operator)			
Voice calls (<64 kbps)	10% of MBSs (for every operator)			
Low bitrate data traffic (e.g., mails and news) (100-500 kbps)	25% of MBSs		100% of MBSs	
High speed internet / data (e.g., videostreams) (~ 10 Mbps)	100% of MBSs			
Digital Home / Content delivery (~ 50 Mbps)	+ 10% of SCs	+10% of SCs	+100% SCs	-

6.2 Protection strategies

The fundamental principle is to restrict the deployment of backup resources to the very minimum, but still meet the availability requirements (discussed in chapter 6.1.2). Besides the possibility of using the converged network elements for mutual backup, the deployed protection can also be minimized using different concepts.

6.2.1 Impact of the physical network layout

One consequence of FMC among others is a closer relation of the fixed and mobile networks: the customer is connected to a converged network, and it helps to substitute segments of one network with another one. The most plausible example is the fixed residential (and business) access being backed up by the mobile network to some extent (with possible bandwidth degradation). Similar substitutionary relationship exists between Wi-Fi networks and mobile, at least for data traffic. The efforts to further converge these two network, like the functional convergence work of COMBO (uAUT and uDPM), help to streamline such substiutions, staying hidden from the end-user.

In addition, there are elements of the FMC network infrastructure that may be used as each others backup: the macro BSs and SCs could also be used to protect each other's capabilities, even if it may lead to a somewhat capacity-limited scenario.

However, if one part of the converged network is intended to protect another part of the network, the respective infrastructure elements must be independent (disjunct). In case of using the mobile networks MBS layer to protect the (low-bitrate) fixed access, the MBS backhaul and the cabinet backhaul links must not share the same fibres or ducts. Such independence may be contradictory with the efforts for fibre convergence, and leads to additional considerations for network design.

Among the availability metrics defined earlier, Failure Impact will be an important measure. The network infrastructure should minimize the risk of concurrently losing connectivity for a large set of customers or affecting parts of the network intended to protect each other. Hence, failures of low penetration and low probability are affordable, but (1) either the probability of high penetration failures need to be reduced (protection), and/or (2) penetration of higher-probability failures need to be reduced (diversification).

Such network planning and protection strategies will be discussed in the following.

6.2.2 Diversification

Smart network planning strategies help to keep failure penetration under control. In case we avoid single point of failures affecting too many clients, certain network availability metrics can be kept "over the bar", even without adding protection. It works mostly for fixed access and small cells (where not only the number of affected SCs, but also their geographical distribution plays an important role).

In this case, the critical failures are identified by high failure penetration rates. Instead of applying protection to avoid the occurrence of critical failure events, the effect of these critical failures should be reduced – preferably, in the network planning phase. **Failure penetration** may be **lowered** by **diversification**, i.e., not allowing cable ducts to accommodate more connections than the failure penetration limit *N*, and routing the rest of the connections on alternative paths – and so, the critical failures are eliminated, without the costly addition of redundancy.

To have a sense of the associated cost, let us assume the n^{th} shortest paths being 10% longer than the $(n-1)^{th}$, splitting the connection of M clients over a path of length L into K parallel paths increases the total fibre length from $M \cdot L$ to:

$$\sum_{i=0}^{K} (M/K) \cdot L \cdot 1.1^{i}$$

Splitting to 2,3 or 4 parallel paths leads to 5%, 10.3% or 16.0% increase in fibre lengths, respectively. In contrary, end-to-end protection increases fibre lengths by 110% (length of the 2nd shortest path).

In case we intend to **minimize failure impact**, instead of failure penetration, we can apply **weighted diversification**. In this case, the connections should be distributed over the the parallel paths $P_1, P_2, \dots, P_n$ inversely proportional to the respective path failure probability, i.e. the failure impact of the parallel paths will be balanced.

Cost and availability implications of the weighted diversification are similar to the equally split case, but the fibre lengths reflect the weighted balance over parallel paths. Total fibre length is increased from $M \cdot L$ to:

$$\sum_{i=0}^{K} \frac{M}{K} \cdot \frac{P(P_i)}{\sum_j P(P_j)} \cdot L \cdot 1.1^{i}$$

6.2.3 Spatial diversification

In case of small-cell networks, the most critical failure events have a large Maximal **Failure Area**, i.e., failures when all SC connectivity is lost over a large area. Transforming these kind of failures into “scattered” loss of clients may be achieved even without adding redundancy to the network, but diversifying the backhaul links of neighboring small cells.

Figure 74 gives schematic examples for diversifying clients originally connected via 2 or 4 separate cabinets. In the original configuration, a cable cut may disconnect all four clients of a cluster. After diversifying the connections, at least part of the clients in each cluster area remains available, and at most two neighboring cells will be affected by a failure. As an expense, failure penetration is increased: in the original case, the expected value of clients being cut by a single failure was (1+2+3+4)/4 = 2.5. In the diversified case, any cable cut will affect 4.5 clients. In general, having N (separated) clusters and C clients in each cluster, a cable cut may affect all C clients of a cluster area. With diversified connections, $C \cdot (N-1)/N$ clients remain connected in each cluster in case of any cable cut, and the Maximal Failure Area reduces from C to 2 – which was the critical failure metric in this case. As an expense, the expected value of failure penetration increases from $(1+C)/2$ to $C + 1/2$.

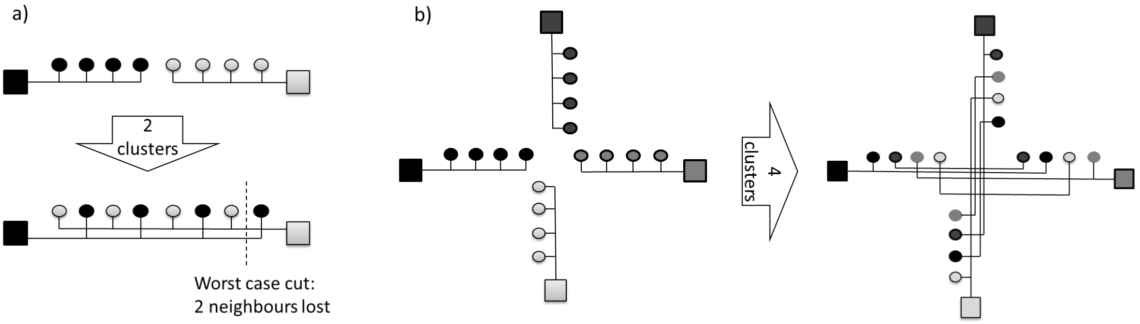


Figure 74: Diversification of small cell connections

6.2.4 Selective protection

Depending on the service/application, and the availability requirements, there is typically no need to implement the same protection strategy (e.g., end-to-end dedicated protection) for all endpoints (e.g., macrosites). Some of them having a connection with high failure probability may need protection, while others may have the desired availability even without added protection.

Selective protection means the pre-filtering of endpoints already having at least the predefined availability, i.e., not needing any kind of protection. It could mean either endpoints being relatively close to the CO, with a low failure probability connection; or endpoints with lower availability requirements (e.g., differentiating between high and low priority MBSs or SCs).

6.2.5 Partial protection

Even if protection should be added to the network to meet survivability requirements, it does not necessarily mean that end-to-end protection is a definite need. In some cases, adding end-to-end protection is impossible (not having two completely independent paths), or imposes unreasonably high costs. Still, protecting a certain part (segment) of the backhaul connection increases availability, and if that is enough to meet the requirements, such partial protection helps to keep costs in bay.

Partial protection is a strategy to reduce costs of protection for endpoints that require some redundancy, but not necessarily need an end-to-end disjoint protection path to have the predefined availability. Partial protection could also mean to protect certain network segments (e.g., between CO and Main CO), but not protecting the CO-MBS segment, as it is more cost-sensitive.

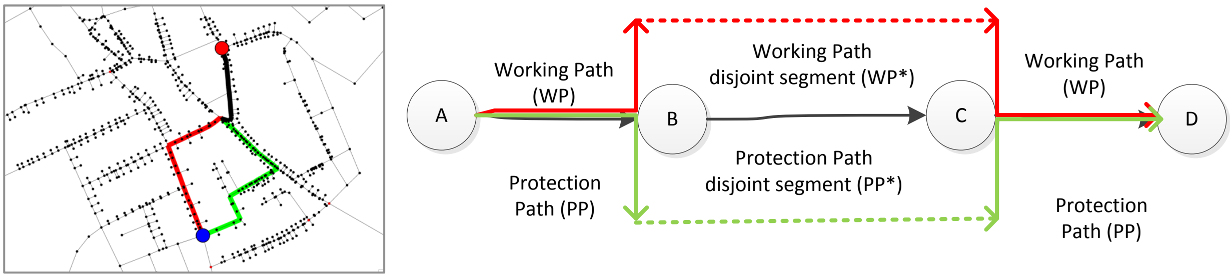


Figure 75 Partial protection

We made an in-depth investigation of these approaches in some case studies, using real maps and our network planning software, in order to evaluate how selective and partial protection performs for fixed access networks [33]. The results have shown that added redundancy with surprisingly low cost implications (+1-10%) could help to increase availability of all critical clients to meet the pre-defined availability requirements.

6.3 Mobile backhaul protection of macro sites in FMC networks

A high level of structural convergence between fixed and mobile network comes with the risk of a total telecommunication black out in large service areas by losing all types of connectivity in the case of a disruption of central network elements or network sections. In order to prevent such a scenario, the COMBO project studies concepts to guarantee **a minimum level of connectivity by back/fronthauling of macro cells** with appropriate network protection mechanisms.

Providing protection to the macro sites concerns a relatively limited part of the network. On the one hand, macro site backhaul/fronthaul connections are significantly fewer than the small-cell backhaul/fronthaul connections, not to mention the fixed access network endpoints – therefore, ensuring connectivity of macro sites means less protected endpoints than for other approaches. On the other hand, the "macro layer alone" is in typical scenarios able to maintain the most critical services: emergency calls and voice calls – and, depending on the scenario, even a limited amount of data traffic as well. Therefore, protecting the macro layer is the primary and most straightforward choice for the network operator to provide a survivable FMC access network.

Figure 76 shows the the current practice in state of the art mobile backhaul networks. Link protection is typically implemented between the Main CO and RAN Access Areas (RAA), for example, using MPLS Virtual Private LAN Service (VPLS). The selection of the active path between NodeB/eNB and RAA is managed by the mobile carrier using appropriate Layer-3 protocols (e.g., BFD and VRRP). However, there is typically no link protection between the Macro site and Main CO. This part of the network is therefore, the focus of the following work.

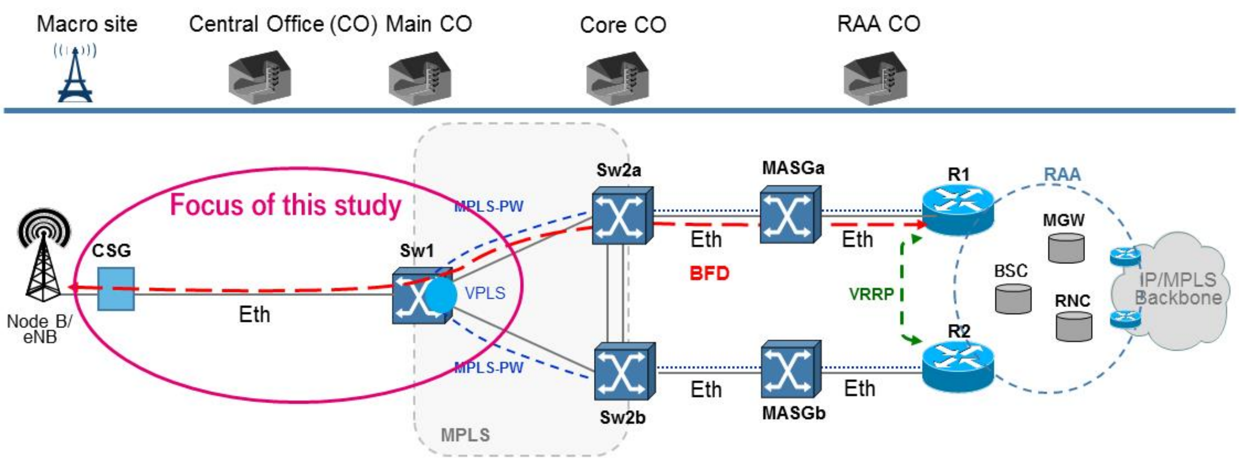


Figure 76: Mobile backhaul protection - status quo

6.3.1 Protection architectures

If the FMC network operator decides to protect the macro layer only, the most appropriate availability metric is typically the individual availability of all macro sites (see section 6.1.1.3). The requirement for the backhaul/fronthaul network is simple: each and every macro site should meet a predefined minimum availability, in order to maintain connectivity to all endpoints.

In such a scenario, among the earlier discussed protection strategies, diversification is not an option, as it ensures connectivity only for a subset of clients. Similarly, selective protection is rarely a choice in this case, even though the macro sites may be investigated one-by-one, and for those which already meet the availability requirement, no protection is needed (although this is rare).

Hence, all endpoints (i.e., macro sites) should be protected – but there is still some potential to reduce the cost of protection. Instead of blindly deploying *full path* protection to all macro sites, **partial** protection may be applied, i.e., instead of full path protection, adding redundancy only to a part/segment of the backhaul/fronthaul link.

Figure 77 gives a generic overview of the protection architecture alternatives which are elaborated in the following sections. Two full path protection scenarios have been defined which are characterized by a continuous doubling of the backhaul/fronthaul links between the mobile site and Main CO. The two full path protection scenarios differ in the location of the link termination of the working path and the backup path at the Main CO site. In the scenario “single homing with full path protection” both links (working path as well as backup path) are terminated at the same Main CO whereas in the scenario “dual homing with full path protection” the links are terminated at different Main COs. In addition, two partial protection scenarios have been defined with a doubling of the backhaul/fronthaul link only between the CO and Main CO. This means there is no link protection between the mobile site and the CO. The two partial protection scenarios also differ in the location of the link termination of both paths at the Main CO site. In the scenario “single homing with partial path protection” both links are terminated at the same Main CO whereas in the scenario “dual homing with partial path protection” the links are terminated at different Main COs.

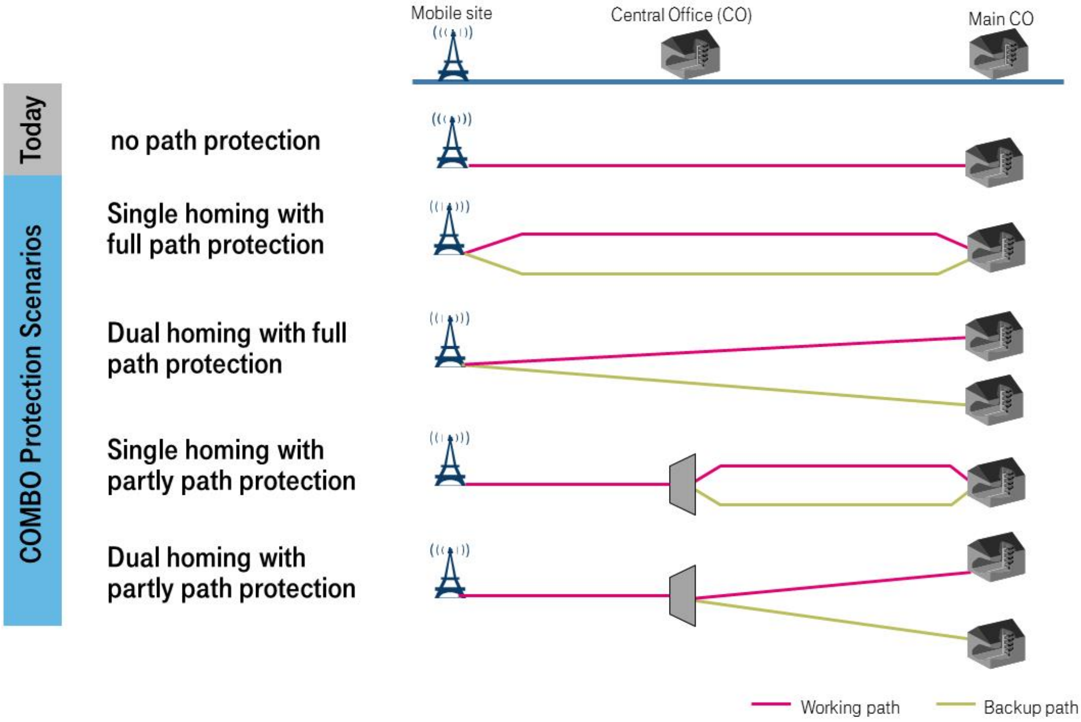


Figure 77: Protection architecture options (generic)

6.3.1.1 Full path protection

This section discusses three full-path-protection implementation alternatives including a pro and contra analysis.

Alternative 1: fully disjunct fibre routes

The first full-path-protection alternative is perhaps the most intuitive scheme with completely disjunct cable routes. Figure 78 depicts the implementation of the single homing approach with fully disjunct cable routes whereas the dual homing architecture is shown in Figure 79. Working path and backup path run on different cable routes/ ducts within the first-mile and feeder-fibre sections and pass different COs. In addition, both paths run on separate cable routes within the in-house section of the macro site location and enter the location via different house lead-ins.

This full path protection would clearly allow the highest availability. However, a network structure passing different COs does not match very well with current fixed access networks which have been constructed with a star/tree topology and one CO in the center. This means that the full-path-protection alternative would require cost-intensive civil works in the first mile in order to establish a second path passing a CO of a neighbouring service area.

Pro:

- Allows the highest availability with fully disjunct fibre routes between the macro site and the Main CO

Contra:

- Backup path to second CO does not match with current network structure
- Civil works needed in the first mile
  - Main cable civil works in order to route the backup path via a CO of a neighbouring service area
  - Distribution cable civil works in order to connect the macro site to a desjunct main cable section
- Second house lead-in and disjunct in-house links needed

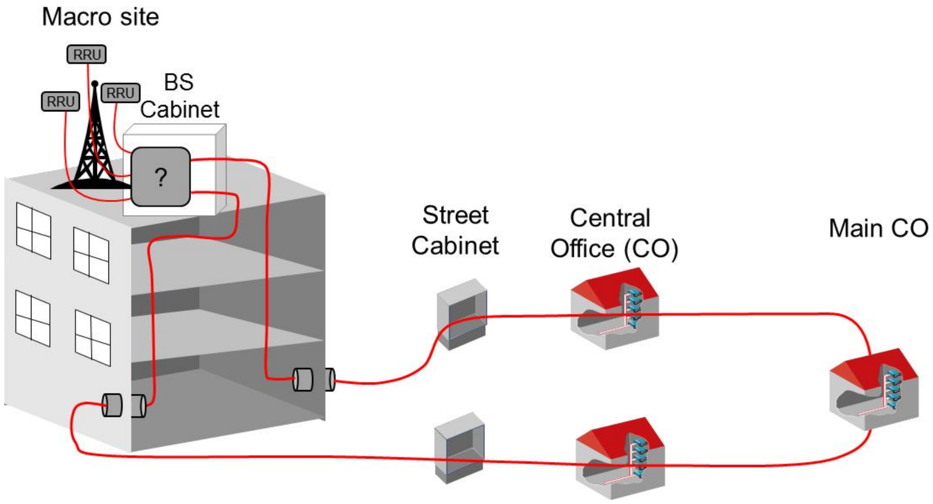


Figure 78: Single homing with fully disjunct fibre routes

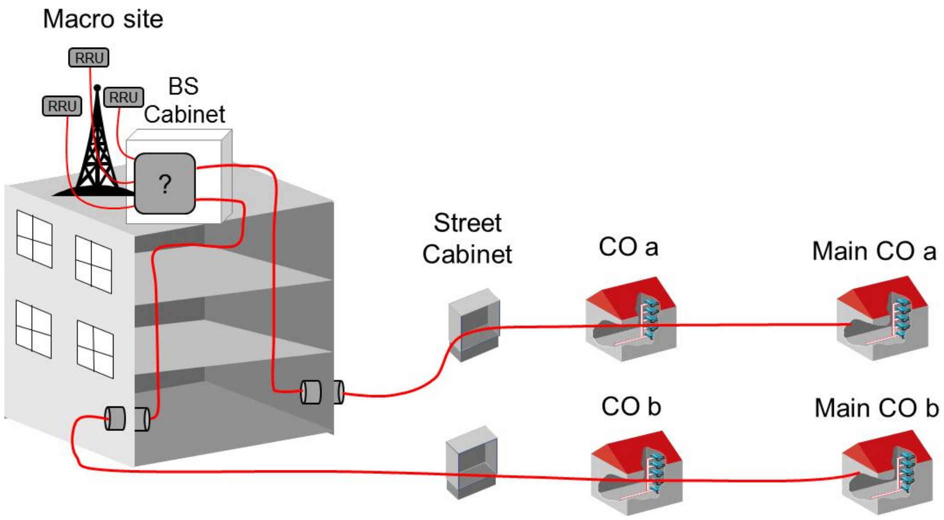


Figure 79: Dual homing with fully disjunct fibre routes

Alternative 2: one CO with disjunct links

The second full-path-protection alternative has been defined in order to overcome the major obstacle of Alternative 1. In contrast to Alternative 1, the working path and backup path pass the same CO in the full-path-protection Alternative 2. Apart from that, Alternative 2 also provides disjunct cable routes in the feeder fibre, first mile and In-house network sections as depicted in Figure 80 and Figure 81 for the single-homing and the dual-homing approach.

In general, a routing of the working path and backup path via the same central office is not a major weak point in the design since all considered backhaul/fronthaul technologies and systems use passive network components at the central office location. On the one hand, passive equipment has per se a high availability and on the other hand, both paths can be routed via different fire zones within the central office which reduces the probability of a simultaneous disruption of the working and backup path.

Pro:

- Mostly disjunct fibre routes which better matches with current access network structure (one CO only)

Contra:

- Civil works needed in the distribution cable section in order to connect the macro site to a desjunct main cable section
- Second house lead-in and disjunct in-house links needed

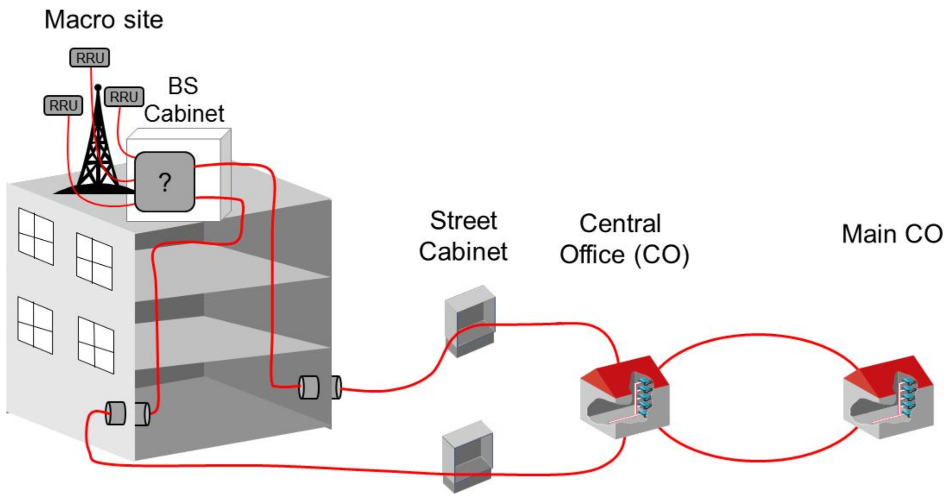


Figure 80: Single homing with only one CO and disjunct links

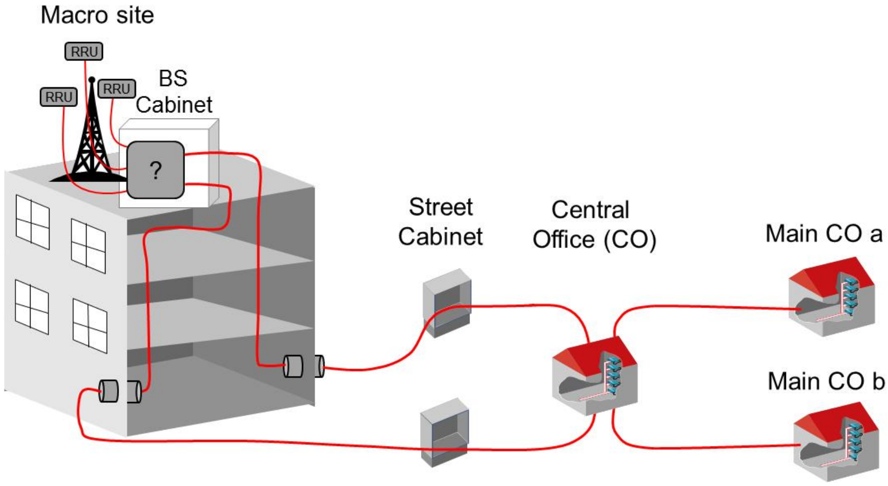


Figure 81: Dual homing with only one CO and disjunct links

Alternative 3: partly non-disjunct links

The third full-path-protection alternative has been defined in order to overcome a further obstacle of the first two alternatives. In practice, the implementation of disjunct in-house links with a second house lead-in is very complex from a planning point of view since the network operator is often not the owner of the building. The full-path-protection alternative 3 has therefore been designed with a non-disjunct cable route between the MBS and the street cabinet as shown in Figure 82 and Figure 83 for single homing and dual homing respectively. Non-disjunct links are, of course, not ideal from a methodological point of view but the network section between the macro site and the street cabinet is relatively short and, therefore, the statistical probability of a failure event is correspondingly low.

Pro:

- Architecture with one central office only
- One house lead-in only; easy in-house implementation
- No cost intensive civil works in the distribution cable section

Contra:

- Civil works needed in the main cable section in order to connect the backup link to a disjunct cable route
- No disjunct fibre routes between the macro site and the cabinet

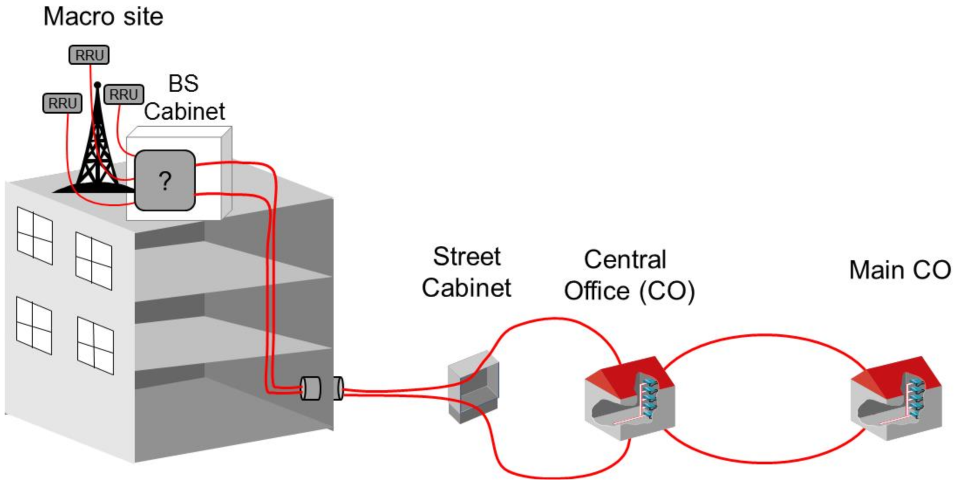


Figure 82: Single homing full path protection with only one CO and partly non-disjunct links

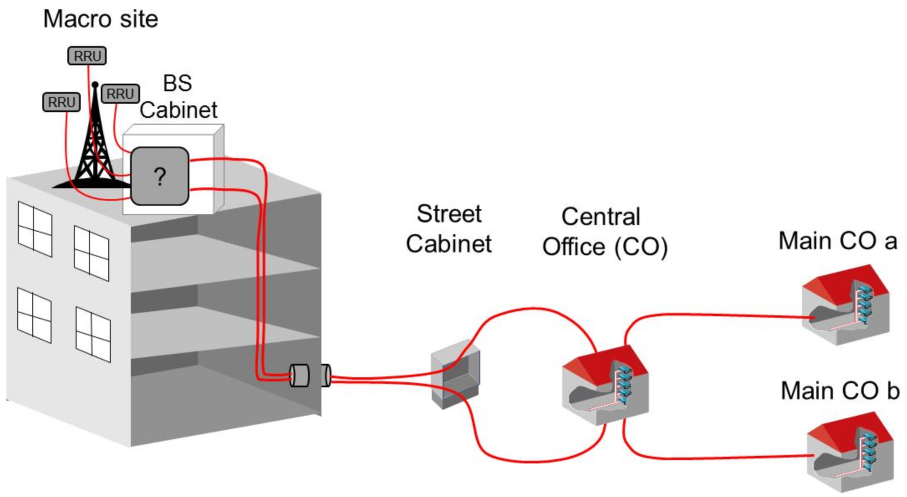


Figure 83: Dual homing full path protection with only one CO and partly non-disjunct links

6.3.1.2 Partial path protection

In contrast to full path protection, the implementation of partial path protection is fairly straight forward. Figure 84 and Figure 85 show the implementation of partial path protection for single homing and dual homing, respectively. In general, partial path protection is characterized by a doubling of the backhaul/fronthaul link only between the central office and Main CO. There is no link protection between the mobile site and the central office.

Pro:

- No civil works needed
- Architecture with one central office only
- One house lead-in only; easy in-house implementation

Contra:

- No disjunct fibre routes between the macro site and the CO

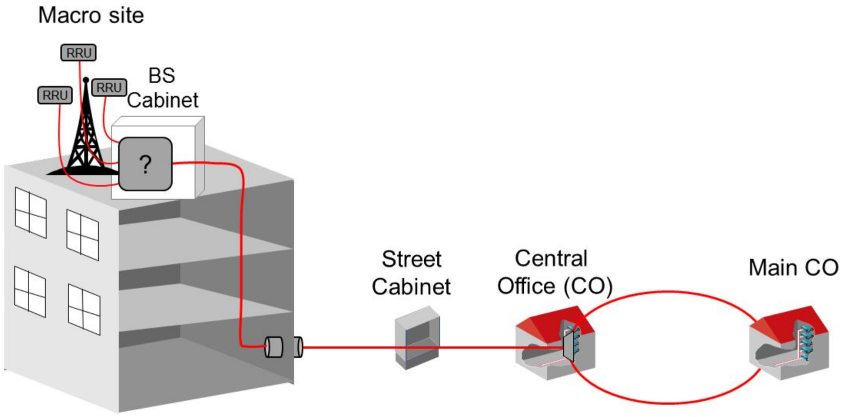


Figure 84: Single homing with partial path protection

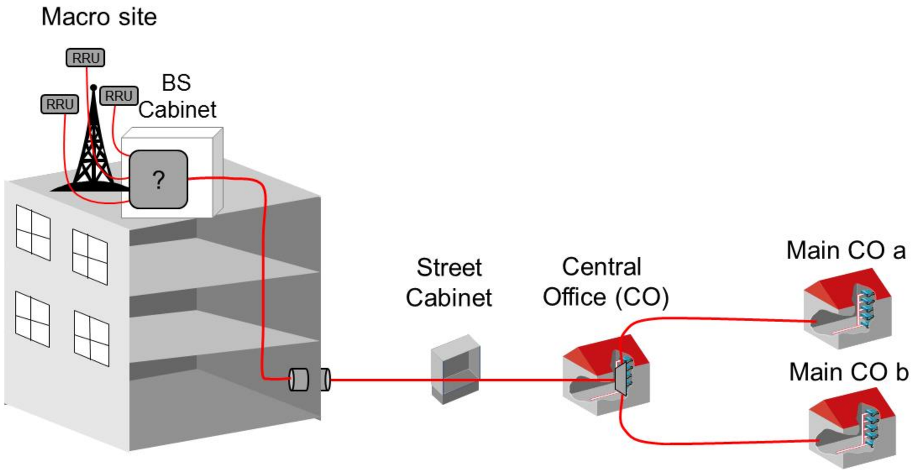


Figure 85: Dual homing with partial path protection

6.4 Evaluation

This section analyses the availability improvement and cost impact of different MBS protection variants. As the focus of COMBO lies on convergent transport networks, radio base station equipment as well as RCC and BBUH will not be part of this protection study. It is assumed that the difference between backhaul and fronthaul is negligible w.r.t. transport-network protection. Fronthaul and backhaul use a similar physical network infrastructure.

6.4.1 Modelling approach

The modelling approach is shown in Figure 86. The protection architectures described in section 6.3 are the basis of the following evaluation with focus on partial-path-protection and full-path-protection alternatives 2 and 3. The study includes a modelling of the considered technologies on a component level per network location. The evaluation also considers the geometric model defined in COMBO with the different service area types (e.g., ultra-dense urban, urban, sub-urban, rural). Additional input parameters are the availability values and the cost information of the network elements/ components. The compilation of these data enables conclusions on the availability and CAPEX per protection architecture and transmission technology.

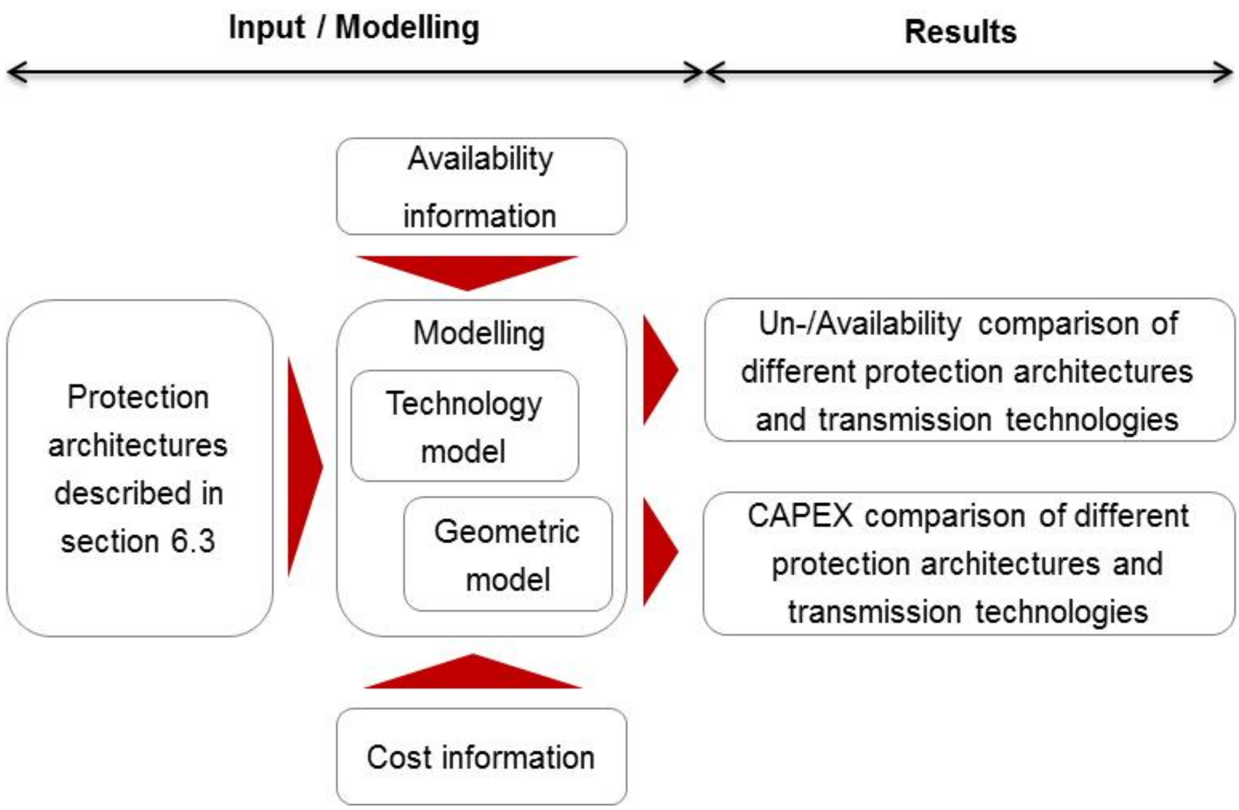


Figure 86: Modelling approach

The geometric model and the technology cost information used for this analysis are described in D3.3.

6.4.1.1 Technologies

This section gives a short overview of the considered transmission technologies. It is assumed that the MBS site is provided with one 10 Gbit/s link for mobile backhauling.

WR-WDM-PON

Figure 87 shows the WR-WDM PON implementation using the example of the protection architecture “single homing with full path protection”. The WR-WDM-PON system includes PIN based 10G ONUs at the BS site, two ONUs in case of full path protection and only one ONU in case of partial path protection. Each ONU is connected to an 80-channel AWG at the central office site passing the first-mile network sections distribution cable and main cable. The working-path link and backup-path link are connected to dedicated OLT devices with downlink line cards providing 80 x 10G channels, baseline card (switch, CPU, control and management plane) and power supply. In case of single homing, both OLTs are located at the same Main CO whereas in a dual homing scenario, the OLTs are located at different Main COs.

The radio equipment (RRU, BBU, RCC) and the cell site gateway (CSG) are not in the scope of this analysis as depicted in Figure 87.

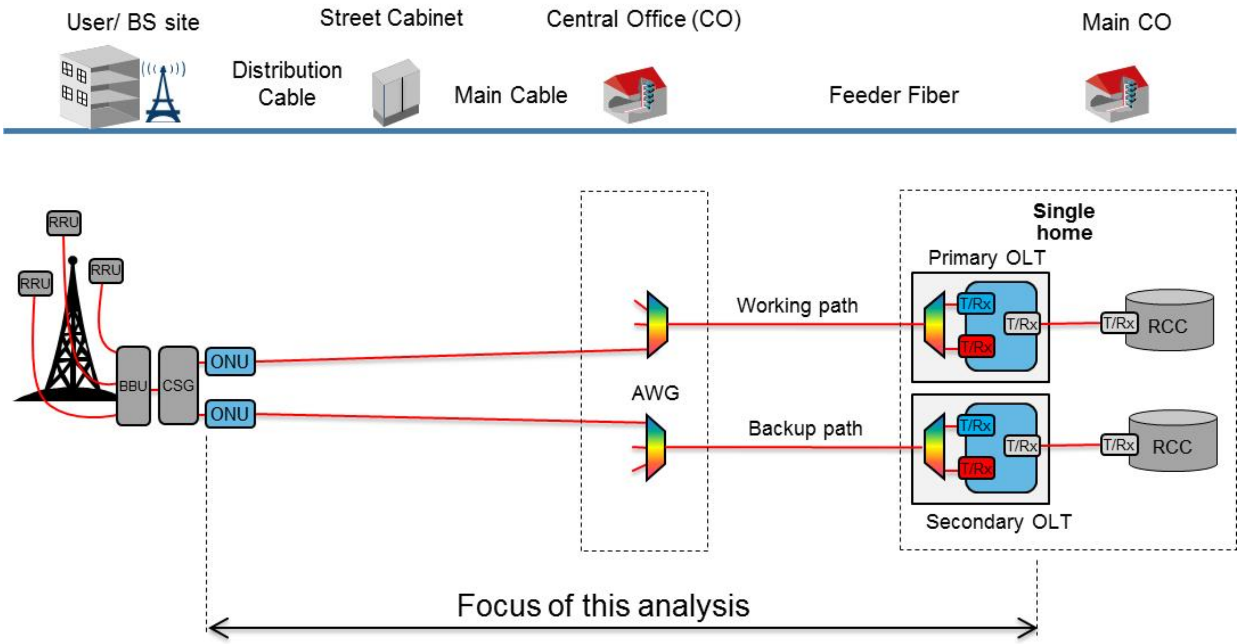


Figure 87: WR-WDM-PON backhaul with single homing and full path protection (Example)

WS-WDM PON / NG-PON2 (WDM overlay)

The WS-WDM-PON system includes APD based 10G ONUs at the BS site, two ONUs in case of full path protection and only one ONU in case of partial path protection. Each ONU is connected to a power splitter (1:64) at the central office site passing the first-mile network sections distribution cable and main cable. The working-path link and backup-path link are connected to dedicated OLT devices with downlink line cards providing 64 x 10G channels, baseline card (switch, CPU, control and management plane) and power supply.

In principle, WS-WDM-PON and NG-PON2 with PtP WDM overlay are similar from the system design view-point. Both systems work on a power-splitter-based optical distribution network (ODN). In contrast to the WS-WDM PON, the NG-PON2 standard offers the option of a system coexistence with other TDM/TDMA based PON standards (e.g., GPON, XG-PON1) using an additional filter for system coupling. However, system coexistence is not in the scope of this analysis.

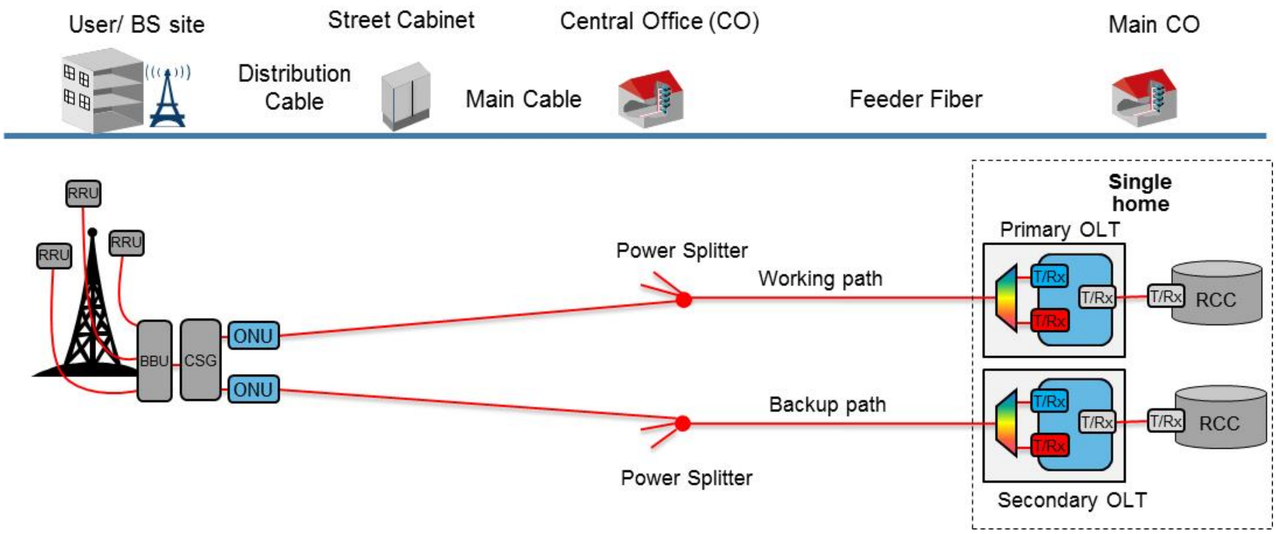


Figure 88: WS-WDM-PON / NG-PON2 (PtP WDM overlay) Backhaul with single homing and full path protection (Example)

CWDM

The CWDM system consists of bidirectional Tx/Rx 10G transponders (SFP+, LR) and 1:20 CWDM filters. The pluggable transponders are directly plugged in the cell site gateway (CSG) at the BS site and the RCC at the Main CO site, as depicted in Figure 89 using the example of the protection architecture "single homing with full path protection". The CWDM filters are used at the CO and the Main CO sites.

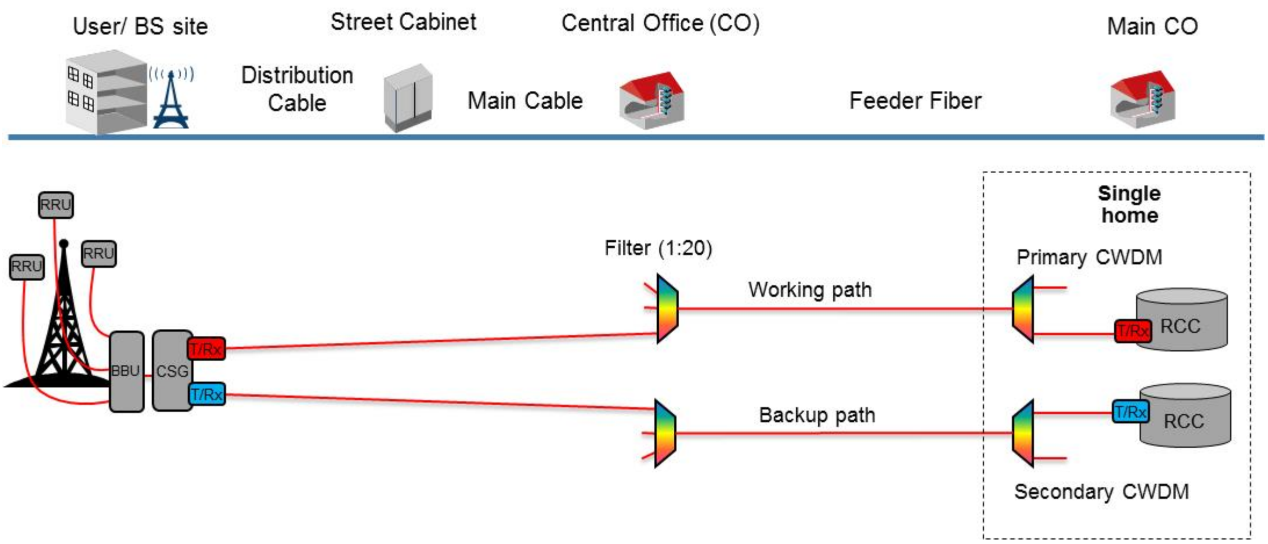


Figure 89: CWDM backhaul with single homing and full path protection (Example)

6.4.1.2 Availability assumptions

The availability analysis is based on the following formulas and assumptions:

$$A = \frac{MTBF}{MTBF + MDT}$$

$$MDT = MTTR + MLDT$$

$$MLDT = TW + TT + TK + TA$$

Definition:
A - Availability
MDT - Mean Down Time
MLDT - Mean Logistic Delay Time
MTBF - Mean Time Between Failures
MTTR - Mean Time To Repair
TA - Administrative lost time
TK - Waiting time due to maintenance capacity constraints
TT - Transport time
TW - Waiting for spare parts

Assumption:

TW = 0 hour (spare parts always available)
TK = 0 hour (no maintenance capacity constraints)
TA = 2 hour

$$A = \frac{MTBF}{MTBF + MTTR + TA + TT}$$

A country-wide network is typically subdivided into several maintenance districts (MDs). The number of central access nodes with active equipment is at least one order of magnitude higher that the number of MDs. For a German wide network this means that the number of MDs should be assumed to be equal to, or less than, about 100. The number and the dimensions of the MDs depend on the number and density of the end users. Each MD covers multiple service areas and includes one maintenance office (MO) where the technicians are located. The Transport time (TT) depends on the traveling distance between the MO and failure location. Table 23 shows the average traveling distance between the maintenance office and different failure locations. These values are based on the traveling distance model developed in the EU project OASE. The average traveling distance have been derived from the parameters of next generation optical access (NGOA) service area categories described in the OASE deliverable D5.1.

Table 23: Traveling distance according to the OASE Traveling distance model

Average traveling distance between maintenance office and …	NGOA service area		
	Dense Urban [km]	Urban [km]	Rural [km]
Main Central Office	5.00	20.00	35.00
Central Office	6.00	23.00	40.00
Street Cabinet	7.20	25.10	42.90
Macro Site	7.50	25.50	43.50
Feeder fibre failure	5.50	21.50	37.50
Main cable failure	6.60	24.05	41.45
Distribution cable failure	7.35	25.30	43.20
Inhouse cable failure	7.50	25.50	43.50

Table *24* shows the average transport time (TT) between the maintenance office and different failure locations. These values have been derived from the average traveling distance shown in Table 23 assuming the following average travel speed per service area type:

- Dense urban: 20 km/h
- Urban: 40 km/h
- Rural: 70 km/h

Table 24: Transport time (TT) according to the OASE Traveling distance model

Average transport time (TT) between maintenance office and …	NGOA service area		
	Dense Urban [h]	Urban [h]	Rural [h]
Main Central Office	0,25	0,50	0,50
Central Office	0,30	0,58	0,57
Street Cabinet	-	-	-
Macro Site	0,38	0,64	0,62
Feeder fibre failure	0,28	0,54	0,54
Main cable failure	0,33	0,60	0,59
Distribution cable failure	0,37	0,63	0,62
Inhouse cable failure	0,38	0,64	0,62

Table 25 shows the MTBF and MTTR values of the system technology and the link levels. These values are based on the availability study of the EU project OASE with an update regarding the 10G optics and CWDM technology.

Table 25: MTBF and MTTR values

Components	**MTBF (hour)**	**MTTR (hour)**
WR WDM-PON solution		
ONT (PIN)	299.094	0,5
Shelf / Backplane	1.500.000	4,0
Baseline card (Switch, CPU, Control and Management Plane) (~500G)	420.000	1,0
Power Supply	500.000	1,0
OLT Downlink line card DWDM-PON port card 80 channels (for use in 80ch config) (incl 80x10G Laser/Rx Array C-band, 1 diplexer)	180.000	1,0
Remote Node AWG 80 channels + Diplexer+Interleaver	4.000.000	3,0
WS WDM-PON / NG-PON2 (PtP overlay) solution		
ONT (APD)	281.250	0,5
Shelf / Backplane	1.500.000	4,0
Baseline card (Switch, CPU, Control and Management Plane) (~500G)	420.000	1,0

Power Supply	500.000	1,0
OLT Basic Downlink line card DWDM-PON port card 64 channels (for use in 64 config) (incl 64x10G Laser/Rx Array C-band, 1 diplexer) incl EDFA preamp	166.667	1,5
Optical power splitter (1:64)	6.000.000	2,0
CWDM solution		
LT bidi Transponder (CWDM SFP+ 10G, LR)	2.000.000	0,5
NT bidi Transponder (CWDM SFP+ 10G, LR)	2.000.000	0,5
Filter TFF (1:20)	6.000.000	1,0
Link Level		
Feeder Fibre 192 fibres	1.350.000	16,5
Main Cable	1.400.000	13,7
Distribution Cable	1.500.000	5,9
Inhouse Cable	525.000	2,0

This analysis also considers the availability of the BS, CO and Main CO locations. The location availability typically covers a range of potential failure events, e.g., faulty connection, power failure, climate failure, fire, vandalism, etc.

The BS location can be assumed as the most critical site. There is often no battery backup at the BS location which means that the availability of the public power supply must be considered. Figure 90 shows the electrical power un/availability of different European contries. The electrical power availability is between 99.997% (Germany) and 99.974% (Spain).

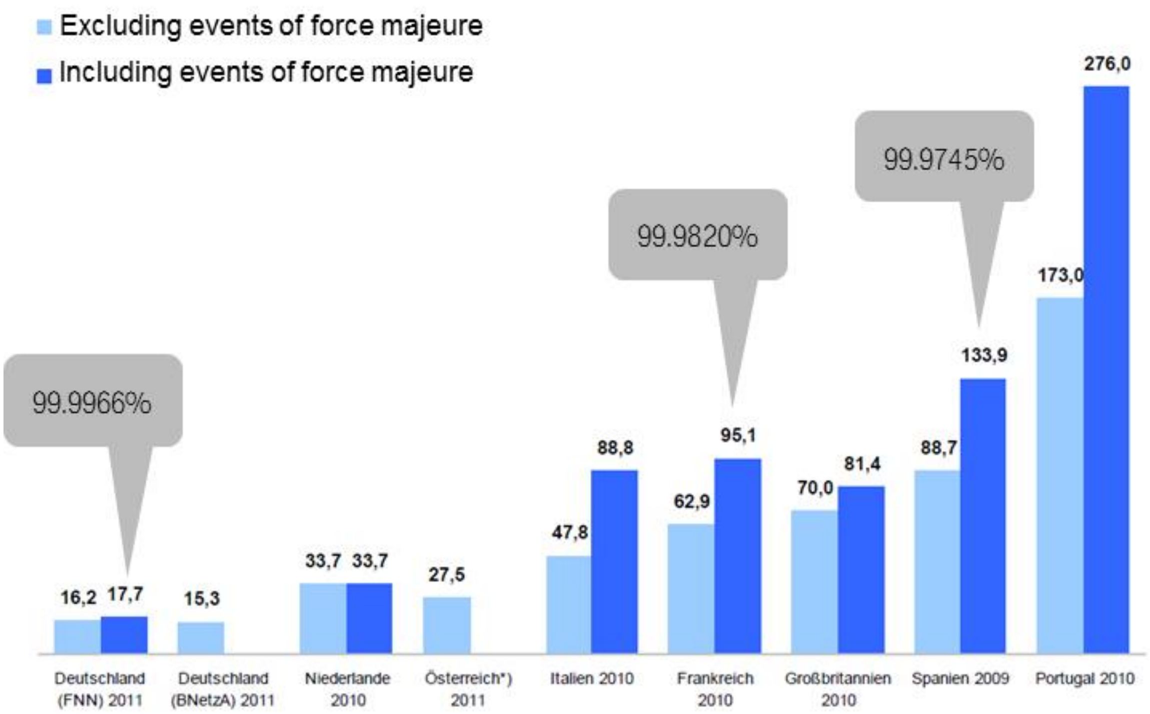


Figure 90: Overview of the electrical power unavailability in the European comparison (09/2012) [34]

The central office location can be assumed as the most uncritical site since all considered system technologies use passive network components at the CO site and, therefore, we only consider the availability of inhouse cabling in addition to the passive system elements.

We assume a high power-supply availability for the Main CO location that is typically equipped with battery backup.

Table 26 shows the assumptions regarding the location availability and annual downtime.

Table 26: Location availability and Annual Downtime assumptions

Locations	Availability	Annual Downtime
BS location (AC Power)	99.99 %	52.6 min
CO location (passive equipment only)	99.9999 %	0.5 min
Main CO location (DC Power)	99.999 %	5.3 min

6.4.2 Results

The following two sections present the results of the availability and cost analysis.

6.4.2.1 Availability results

Figure 91 shows the unavailability breakdown for different protection architectures with WR-WDM-PON as an example. The unavailability is presented for the geotypes dense urban (DU), urban and rural.

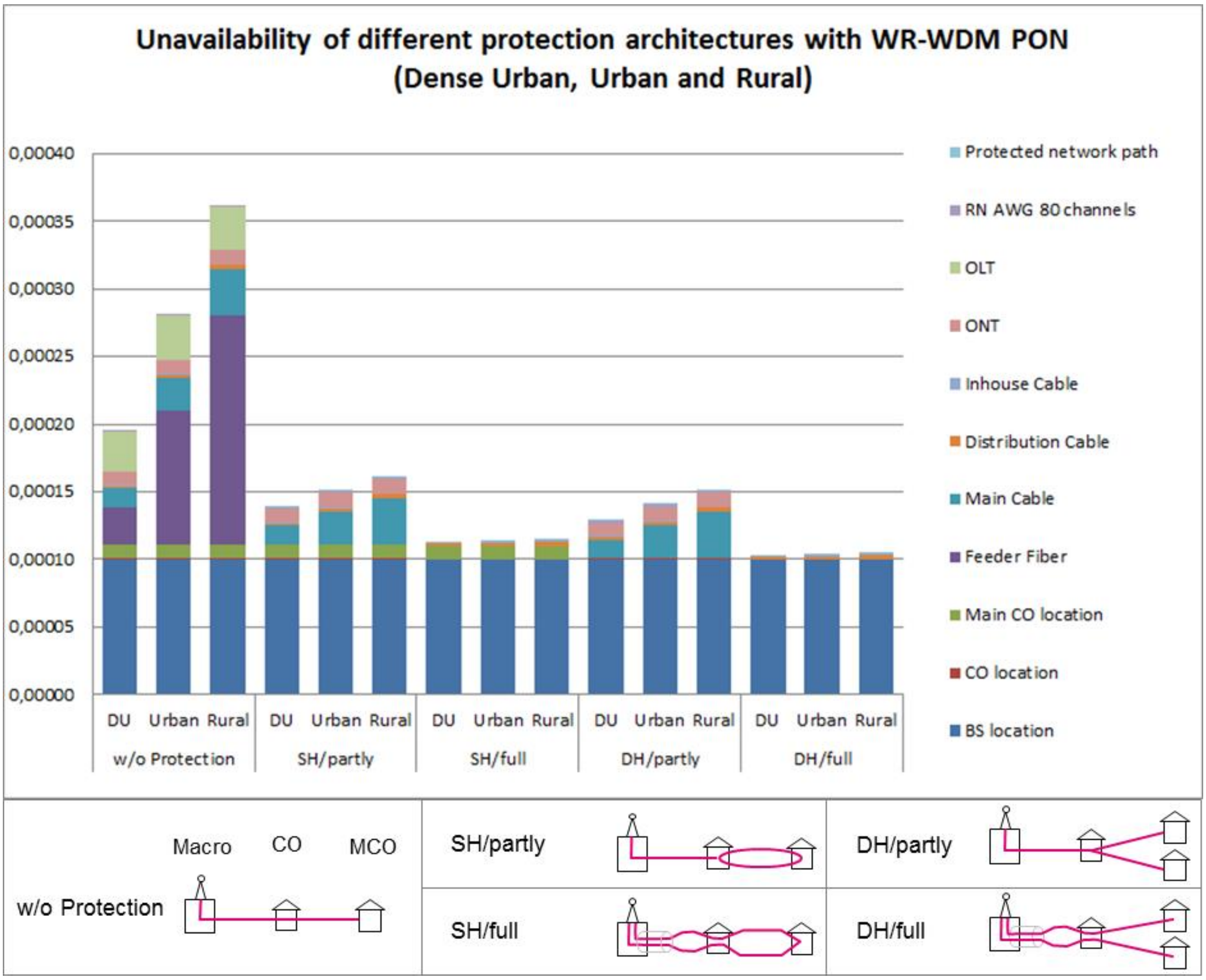


Figure 91: Unavailability breakdown of different protection architectures with WR-WDM-PON

Figure 91 shows that all protection architectures allow a significant reduction of the backhaul link unavailability. The protection architecture “dual homing with full path protection (DH/full)” enables the lowest annual downtime followed by “single homing with full path protection (SH/full)”, “dual homing with partial path protection (DH/partly)” and “single homing with partial path protection (SH/partly)”. In general, the impact of WR-WDM-PON technology on the total backhaul link unavailability is small. The total backhaul link unavailability for the different protection architectures is dominated by the unavailability of the BS location powering. It is therefore highly recommended to consider a battery backup at the macro basestation site. Figure 91 also shows that the difference between single homing and dual homing is small due to the relatively high availability of the power supply at the MCO location. However, dual homing should be considered in the case of a low MCO location availability, for example, caused by frequent power failures, climate failures, faulty connections, fire, vandalism, etc.

The annual downtime and the availability for the different protection architectures and transmission technologies (WS-WDM-PON, WR-WDM-PON and CWDM) are shown in Figure 92 and Figure 93 (urban geotype). Both figures show that the impact of the transmission technologies on the annual downtime and the availability is small.

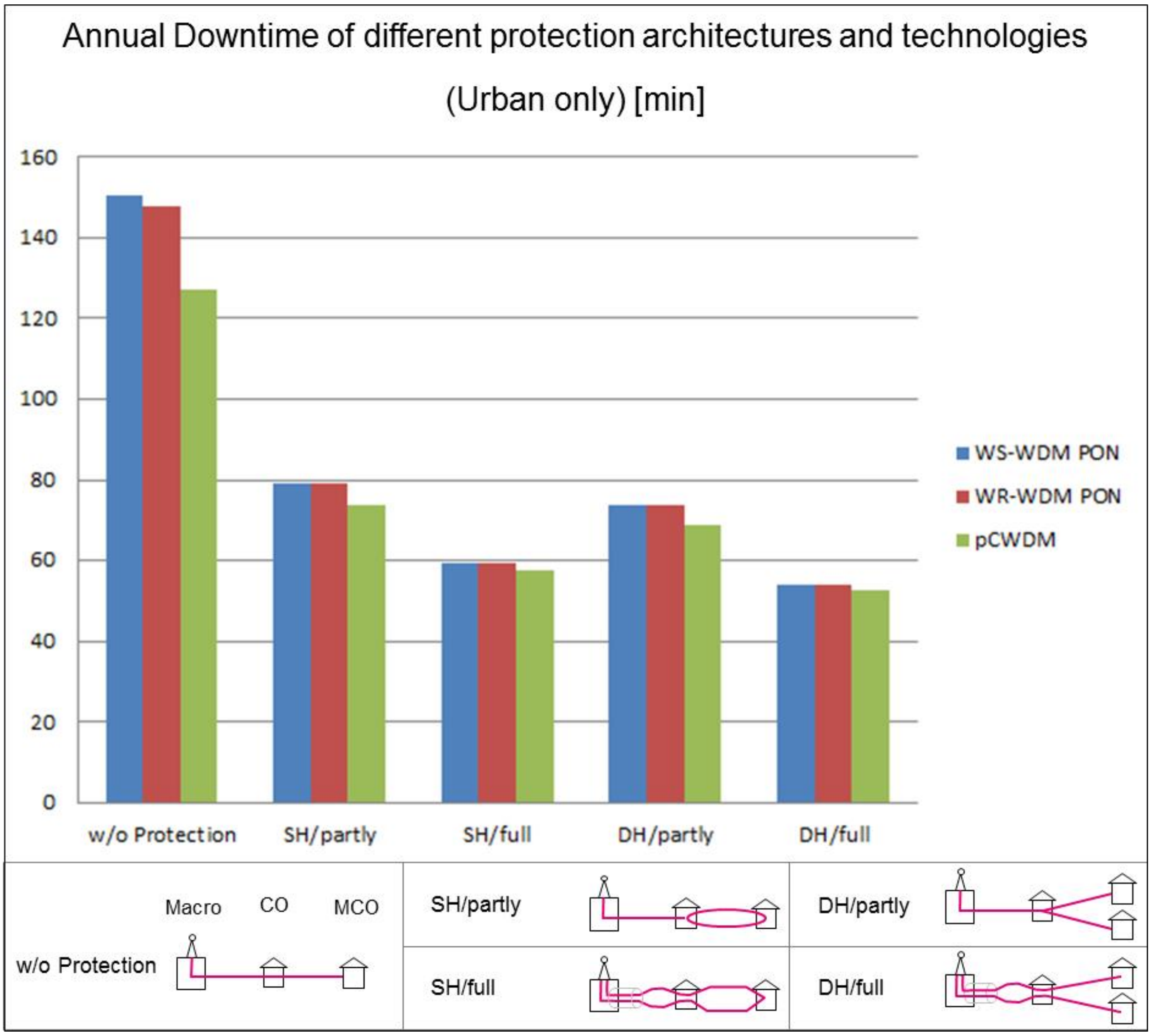


Figure 92: Annual downtime for different protection architectures and technologies (urban only)

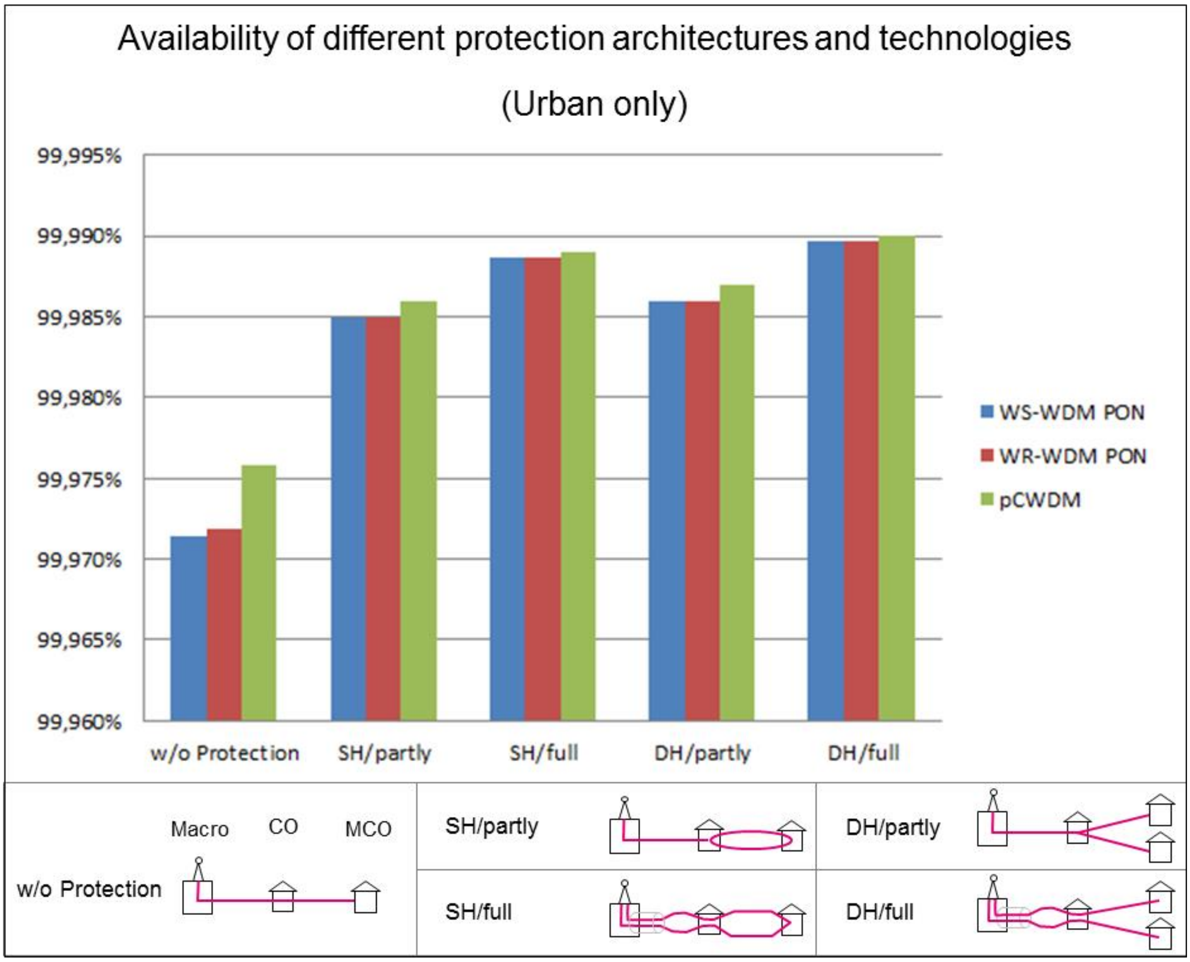


Figure 93: Availability for different protection architectures and technologies (urban only)

The previously shown results of the full-path-protection architectures (SH/full and DH/full) are based on the alternative 3 (partly non-disjunct links) as described in section 6.3.1.1. Figure 94 shows a comparison of the alternatives 2 (one CO with disjunct links) and 3 using the example of the annual downtime of the WR-WDM-PON for the urban geotype. The difference between the alternatives 2 and 3 is negligible regarding the annual downtime and the availability. This means that a non-disjunct cable route between the MBS and street cabinet is not a major weak point in the design from the availability point of view.

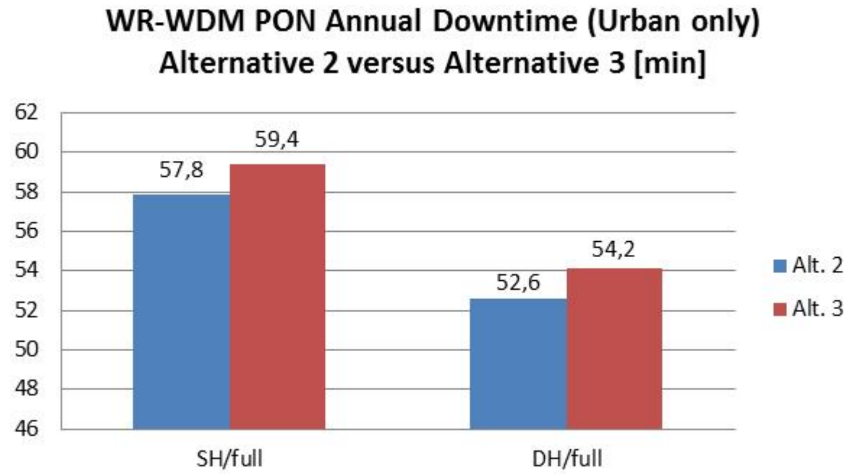


Figure 94: Annual Downtime of WR-WDM-PON: alternative 2 versus alternative 3

6.4.2.2 CAPEX results

Figure 95 shows the CapEx breakdown of the different macro BS protection architctures for the example of an urban FTTC Main CO area with WR-WDM-PON deployment. It does not include the CapEx of the SC and DSLAM backhaul links.

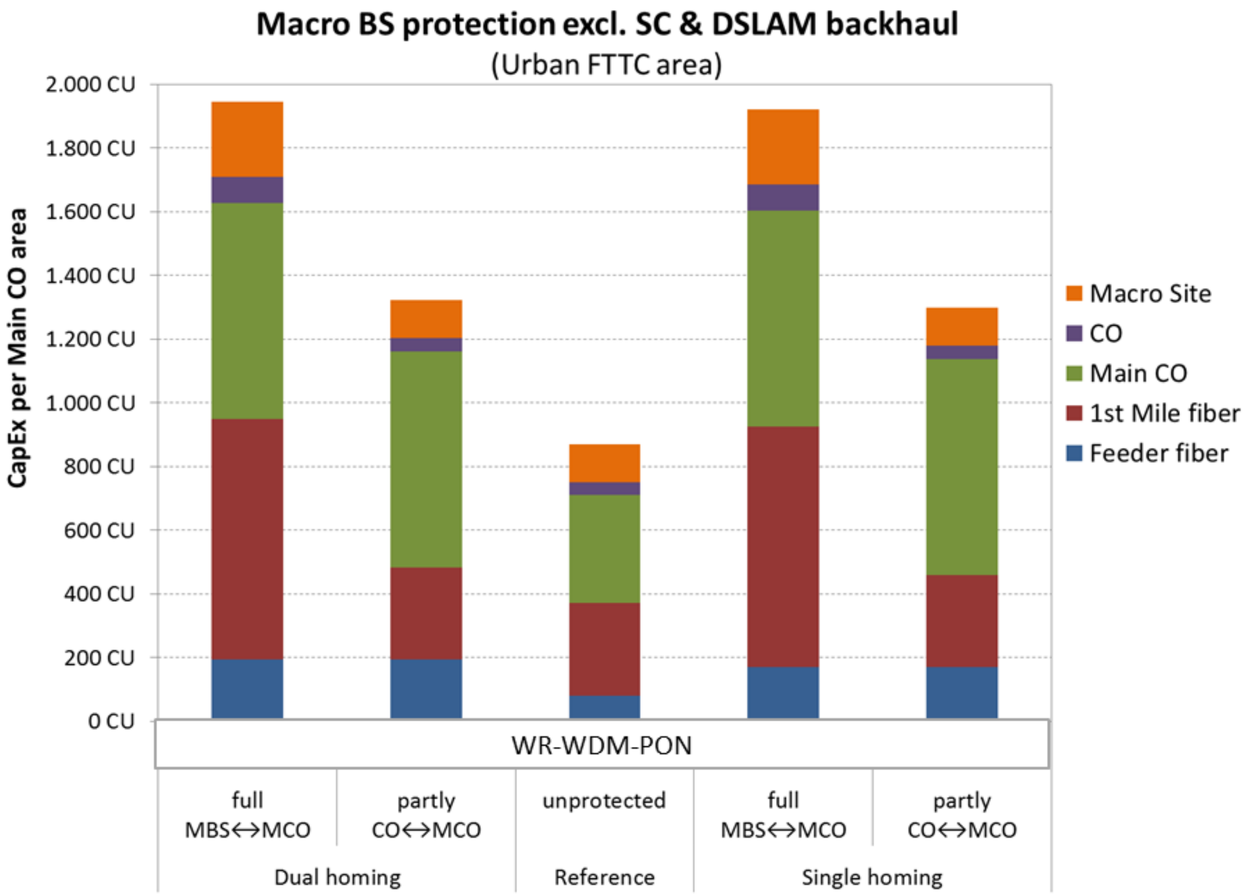


Figure 95: CapEx – Macro BS protection only, excl. SC & DSLAM backhaul costs (Urban FTTC area)

Figure 95 shows that partial protection results in a significant cost increase by 50% compared to the case of an unprotected backhaul link, if considering only the MBS backhaul cost, caused by:

- Additional feeder fibres
- Equipment doubling in the MCO

It also shows that full protection results in the highest cost increase of 125% compared to the case of an unprotected backhaul link, driven by:

- Additional 1st mile and feeder fibres
- Equipment doubling at the MBS, CO and MCO

Dual homing causes only a marginal cost increase compared to single homing, because of:

- High WR-WDM-PON splitting ratio → only 1 additional feeder fibre with a longer length required (high feeder fix cost, less length dependent)
- Same equipment numbers, except for RE

As an extension of the results presented in the previous chart, Figure 96 shows the CapEx breakdown, including the CapEx of the SC and DSLAM backhaul links.

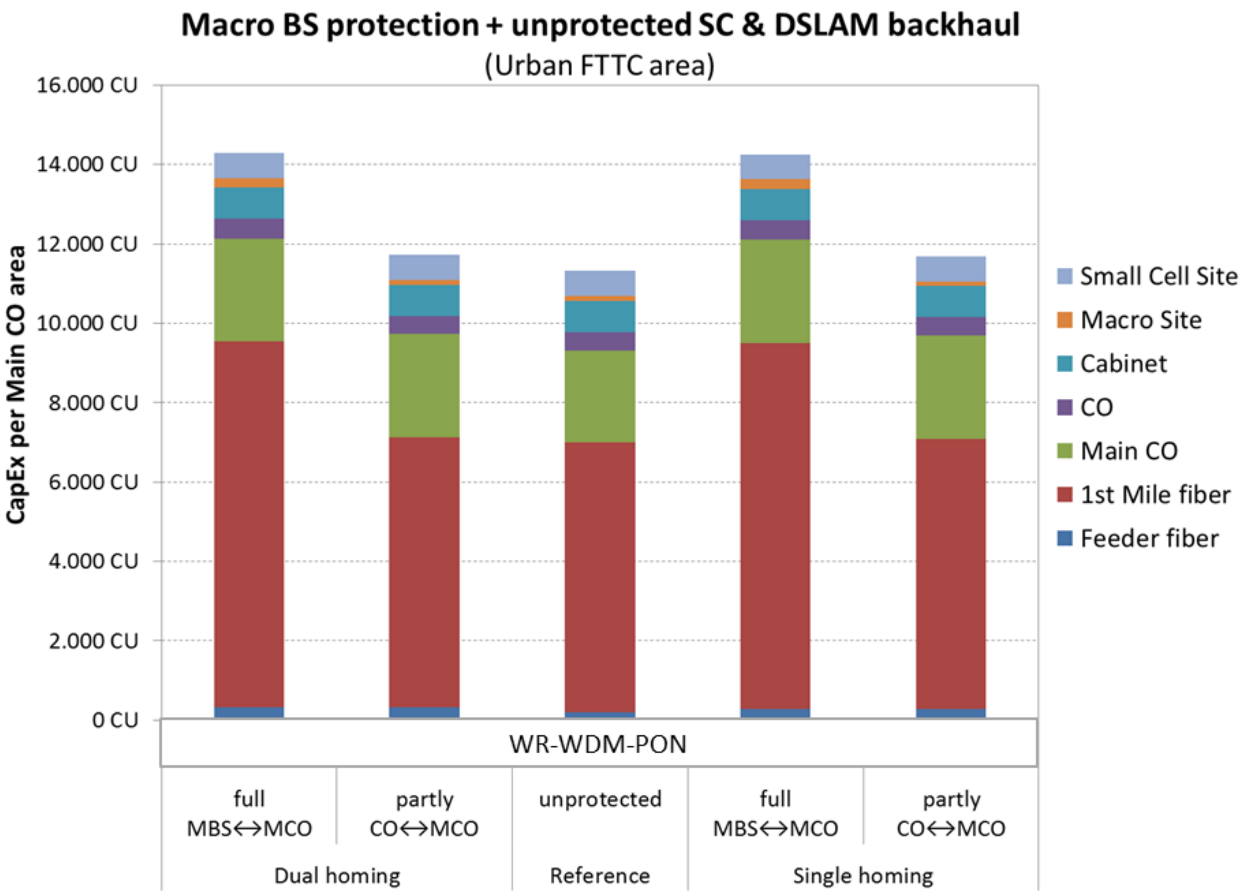


Figure 96: CapEx – Macro BS protection and unprotected SC & DSLAM backhaul (Urban FTTC area)

Figure 96 shows that partial protection results in only a marginal cost increase compared to an unprotected backhaul link, if considering also SC and cabinet backhaul costs, because of:

- Low number of MBS compared to numbers of SCs and cabinets → only 1 additional WR-WDM-PON and feeder fibre for all MBSs
- MBS BH equipment doubling only in MCO

It also shows that full protection results in the highest cost increase of 25% compared to the case of an unprotected backhaul link, driven by:

- Additional fibre costs in the 1st mile
- MBS BH doubling at MBS, CO, MCO

Dual homing causes only a marginal cost increase compared to single homing, because of:

- High WR-WDM-PON splitting ratio → only 1 additional feeder fibre with a longer length required (high feeder fix cost, less length dependent)
- Same equipment numbers, except for RE

Partial protection of the MBS with dual homing in an integrated deployment with additional unprotected backhaul of e.g. SCs and cabinets seems to be the best compromise between availability improvement and cost.

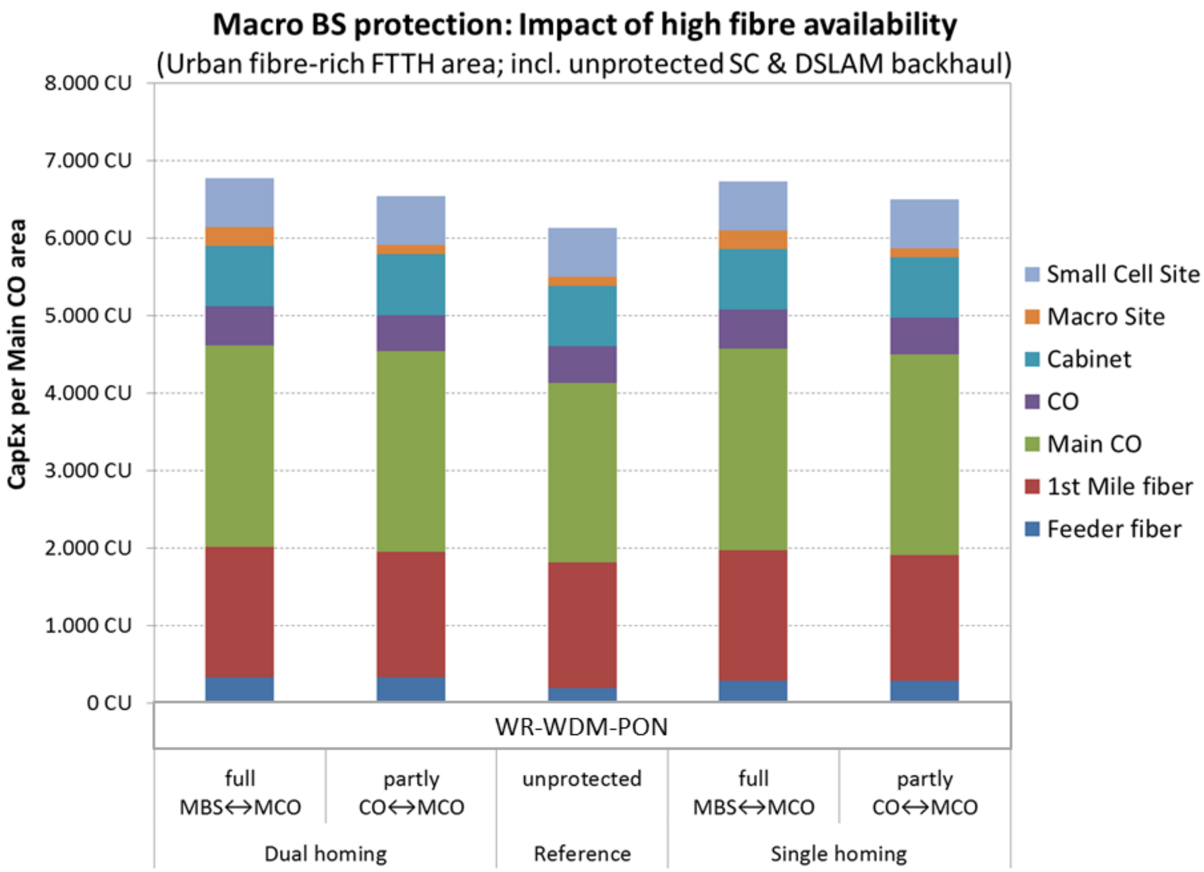


Figure 97: CapEx – Macro BS protection: Impact of high fibre availability in fibre-rich FTTH area (Urban)

Figure 97 shows the CapEx breakdown of the different protection architctures for the example of an urban fibre-rich FTTH Main CO area with a high availability of free fibre resources and a WR-WDM PON deployment, including the CapEx of the SC and DSLAM backhaul links.

Figure 97 shows that the cost ratio of full protection vs. unprotected declines from +25% in FTTC areas to +10% in areas with a high availability of free fibre resources.

- Whereas the cost ratio of partial protection vs. unprotected rises slightly from +3.5% to +6.5%, caused by the reduced 1st mile cost block, which is equal for both variants.
- Also in fibre-rich areas, the cost delta between dual and single homing is marginal.

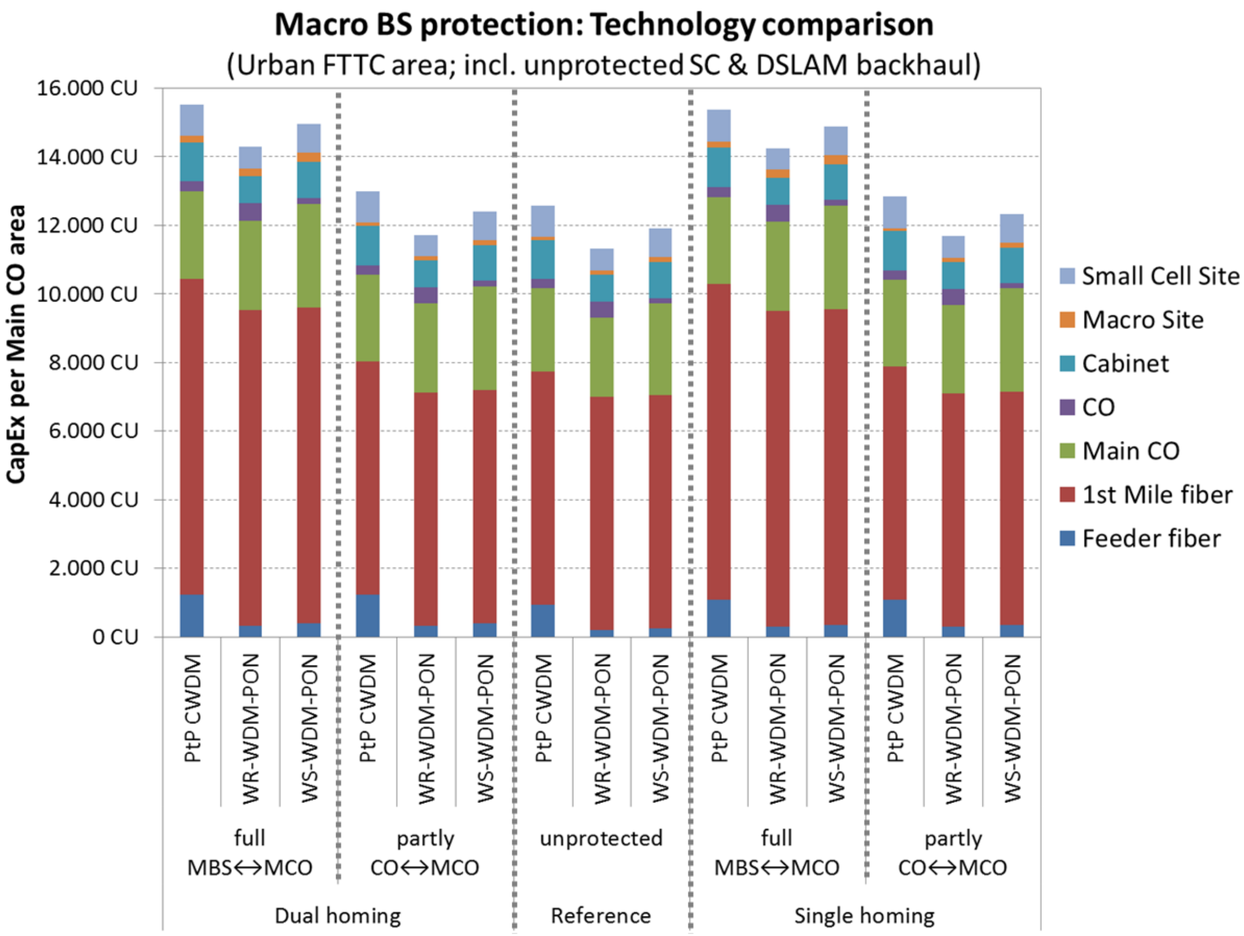


Figure 98: CapEx – Macro BS protection: Technology comparison (Urban FTTC area)

Figure 98 shows the CapEx breakdown of the different protection architctures and transport technologies for the example of an urban FTTC Main CO area, including the CapEx of the SC and DSLAM backhaul links.

Figure 98 shows that the MBS protection variants have no influence on the cost-relations between the technologies.

- Cost item differences are exclusively caused by technology specifics.
- WR-WDM-PON is the most cost-efficient technology in all variants.

6.5 Conclusions

A future FMC architecture will not change the fact that end to end protection is not possible in an economical way for residential user deployments. Therefore, the FMC architecture should minimize the risk of a total blackout (no fixed and no mobile access) especially for the voice service (emergency calls). On the one hand the failure penetration, failure impact, etc should be minimized but on the other hand a high level of convergence between fixed and mobile network is desired. This means protection in residential user deployments is a trade-off between level of convergence and failure penetration / failure impact.

Providing protection to the macro basestation sites can be used to guarantee a minimum level of connectivity. The analysis shows that all protection architectures allow a significant improvement of the backhaul link availability. It is highly recommended to consider a battery backup at the macro basestation site since the total backhaul link unavailability of all protection architecture variants is dominated by the unavailability of the BS location powering. Dual homing should only be considered in the case of a low MCO location availability, for example, caused by frequently power failures, climate failures, faulty connections, fire, vandalism etc.

The CapEx analysis shows that full path protection leads to a high relative cost increase by +125%, if only considering Macro BS backhaul cost whereas partly path protection reduces the increase to +50% compared to an unprotected backhaul link. In areas with a high availability of free fibre resources, full protection between MBS and MCO becomes more interesting from the economical point of view. In general, the Macro BS protection variants have no impact on the cost relations between the backhaul technologies.

7 Conclusion

Combined, the deliverables D3.3 and D3.4 present the COMBO analysis and results on structural convergence of fixed and mobile access networks. Several drivers for structural convergence in the 2020 time horizon were identified. Rapidly increasing traffic volumes in mobile networks are driving the need for RAN densification, mainly through large numbers of small cells. Small cell deployment will require low-cost connectivity, raising incentives for reusing existing deployed infrastructure, which in turn drives the need for convergence. In fixed access, fibre is penetrating further out towards the end-user, with FTTC/B/H deployment. Access systems (such as NG-PON2 and G.fast) are being standardized to cost effectively support such deployment scenarios with higher bitrates. These deployments will in turn determine the available infrastructure for the possible convergence scenarios.

RAN transport brings a different set of requirements on connectivity, compared to fixed access. New deployment models, exploiting fronthaul and/or new RAN splits considered in 5G, can enable pooling of RAN resources, site simplification and facilitate radio coordination. These deployments bring more stringent requirements on transport in terms of capacity and/or latency. Radio coordination which generally is thought to become increasingly important as the RAN is densified, introduces stringent requirements on latency irrespective of the deployment or RAN split. This raises questions regarding the overall optimization of fixed and mobile deployments, and how different functions should be centralised or distributed. In D3.3 and D3.4, a broad range of alterative scenarios was considered concering the placement of BBUs, the placement of radio coordination functions (RCC), how the small cells are aggregated, etc. A range of new RAN splits considered for 5G were also included in the analysis as well as the impact of 5G radio technologies in terms of massive antenna arrays, wider spectrum, etc.

Given the diverse requirements of fixed access and RAN transport, a major question from a convergence perspective is whether it is most efficient with a single access/transport system that can meet the combined requirements, or whether it is more efficient with dedicated solutions tailored for the individual requirements of each domain.

A broad range of systems and technologies were analysed with respect to the requirements from different deployment and convergence scenarios. The stringent requirements on connectivity for RAN transport were met in the most cost efficient way through dedicated wavelengths. This suggests that structural convergence should be based on wavelength multiplexing. With that in mind, four main technology options were identified, that in turn provide different degree of structural convergence, i.e., PtP CWDM, NG-PON2 with WDM overlay, WR-WDM-PON and WS-WDM-PON. PtP CWDM provides the least structural convergence, with dedicated infrastructure for cabinet backhaul and RAN transport in addition to the legacy FTTH infrastructure. WR-WDM-PON and WS-WDM-PON provide convergence through a common infrastructure for PtP WDM services. NG-PON2 with WDM overlay provides further convergence with a common infrastructure for both PtP WDM and TWDM services.

A large range of configurations (splitter/AWG configurations, amplifiers and amplifier placement, dispersion compensation, etc.) of the different technology options were considered and optimized for each deployment. Furthermore, a per-channel capacity range including 3G, 10G, 25G, 40G and 100G was considered for each of the technology options.

CWDM PtP is the reference technology used as baseline for quantifying the gains of convergence. Among the compared technologies, it has the lowest cost of optical interfaces but leads to poor utilization of fibres and filters. CWDM PtP is favorable only for some cases where there is high degree of fibre availability and a low number of sites to connect.

NG-PON2 with WDM overlay provides full convergence of fixed access and RAN transport over a single power-splitter-based ODN, which is favorable for fibre-poor areas but which comes at the expense of costly filters required at the end-points of the ODN. Optical power loss associated with the power-split-ODN as well as co-existence filters, lead to a greater need for optical amplification to support reach requirements, in particular for sub-urban and rural areas as well as for deployments that require high speed optical inferfaces. NG-PON2 with WDM-overlay is favorable for fibre-poor areas, for areas with high FTTH/FTTC ratios and high RAN densities, for deployments with low speed interfaces (i.e., 3G, 10G) and for scenarios where SCs are aggregated directly to the MCO. These are the scenarios where structural convergence brings the largest benefits.

WR-WDM-PON provides a dedicated DWDM-based solution over a filtered ODN for clients that require or are beneficially served by PtP wavelengths (RAN transport, cabinet backhaul). WR-WDM-PON is an efficient solution for PtP WDM services. Compared to convergence with NG-PON2 it requires less co-existence filters, less optical amplification and avoids tunable client receivers. The main drawback with WR-WDM-PON is the increased requirements on fibre. WR-WDM-PON is favorable for fibre-rich areas, for areas with low FTTH/FTTC ratios or low RAN densities, for deployments with high speed interfaces and for scenarios where SCs are aggregated directly via the MBS.

WS-WDM-PON provides a dedicated DWDM-based solution over a power-split ODN. The technology exploits the same ODN type as the FTTH solution with the drawback of reduced client count and reach compared to WR-WDM-PON. In none of the scenarios that were considered was WS-WDM-PON found to be the most favorable solution. This is because it is not as efficient as WR-WDM-PON for PtP WDM services, while it also does not exploit the convergence benefites of utilizing the same ODN as fixed access.

Task 3.3 shows that for many scenarios, WR-WDM-PON, with dedicated solutions for PtP WDM and TWDM, is the most favorable, in particular if we consider today's infrastructure and near term network plans. Convergence with NG-PON2 becomes favorable first at high FTTH/FTTC ratios and for high RAN densities, which generally is more compatible with long term network visions.

Given the basic technology options that were identified in COMBO, a number of flexible system variants were proposed. It is found that flexible system variants based on flexibility in the WDM layer are feasible for urban and ultra-dense urban scenarios while sub-urban and rural scenarios require extensive use of optical amplifiers. If no savings are taken into account in terms of resource sharing or facilitated service provisioning, flexible WDM systems lead to an added cost (~20% added to the total transport cost of the available fixed access). If large dynamicity is expected, savings (of the order of 10-15%) in total transport cost can be expected by pooling interfaces.

Although the major topic of structural convergence concerns fibres and connectivity of small cells, another aspect is the convergence of node resources where connectivity, compute, storage and functional resources are converged and where functions (e.g., RAN and fixed access functions) may be virtualized. This raises questions on how converged resources are jointly orchestrated between the different domains. Based on the COMBO scenarios, a number of management and orchestration architectures were outlined showing different options for how this can be realized.

Finally, as society to large extent relies on connectivity, the infrastructure has become increasingly critical. Although convergence brings benefits in terms of resource savings, it may also introduce vulnerability. Hence, different protection alternatives were considered and analysed in COMBO Task 3.3. The FMC architecture should minimize the risk of a total blackout (no fixed and no mobile access) especially for voice services (emergency calls). Failure penetration, failure impact, etc. should be minimized, but a high level of convergence between fixed and mobile network is desired (trade-off between level of convergence and failure penetration / failure impact).

Providing protection to the macro base station sites can be used to guarantee a minimum level of connectivity. All protection architectures allow a significant improvement of the backhaul link availability. It is highly recommended to consider a battery backup at the macro base station site since the total backhaul link unavailability of all protection architecture variants is dominated by the unavailability of the BS-location powering. Dual homing should only be considered in the case of frequent low MCO location, for example, caused by frequent power failures, climate failures, faulty connections, fire, vandalism, etc.

References

[1] COMBO Deliverable 3.3, Analysis of transport network architectures for structural convergence, V2.0, July 2015

[2] COMBO Deliverable 6.1, Technology Lead Practical Work - Partner Activities, June, 2014

[3] MEF Implementation Agreement 22.1.1, Mobile Backhaul Phase 2 Amendment 1 – Small Cells, Jul 2014

[4] Ericsson: Product description for RBS6201, online https://lafibre.info/images/4g/ 201004_ericsson_rbs6201_lte1800.pdf

[5] Cisco 7600 Series: Ethernet Services 20G Line Cards for Carrier Ethernet http://www.cisco.com/c/en/us/products/collateral/routers/7600-series-routers/product_data_sheet0900aecd8057f3ad.pdf

[6] Marilet De Andrade, Massimo Tornatore, Achille Pattavina, Ali Hamidian, Klaus Grobe, "Cost Models for Baseband Unit (BBU) Hotelling: from Local to Cloud", IEEE 4th International Conference on Cloud Networking (CloudNet), 2015.

[7] B. Haberland, F. Derakhshan, H. Grob-Lipski, R. Klotsche, W. Rehm, P. Schefczik, and M. Soellner, "Radio base stations in the cloud," Bell Labs Technical Journal, General Papers Issue, vol. 18, no. 1, June 2013

[8] Michelle M. Do and Harrison J. Son, "CoMP (1): CoMP types – CS, CB, JT and DPS", *Netmanias Tech-Blog*, available at www.netmanias.com, Aug. 2014.

[9] C. Bellanzon, "Enhancing Throughput in Centralized Radio Access Network by Intelligent Controller Placement", *MSc Thesis*, Apr. 2016.

[10] 3GPP Technical specification group radio access network, "Coordinated Multi-Point operation for LTE physical layer aspects (release 11)". *3GPP Technical report 36.819*, 2013.

[11] S. Parkvall, "Release 14 – the start of 5G standardization", Ericsson Research Blog, available at www.ericsson.com/research-blog/lte/release-14-the-start-of-5g-standardization/

[12] 3GPP Technical specification group radio access network, "Feasibility study for Further Advancements for E-UTRA (LTE-Advanced) (release 13)". *3GPP Technical report 36.912*, 2015.

[13] NGMN Alliance, NGMN 5G White Paper, version 1.0, Feb 2015.

[14] Ericsson Mobility Report, November 2015

[15] CPRI Specification V6.1 (2014-07-01), Interface Specification Common Public Radio Interface (CPRI), © 2014 Ericsson AB, Huawei Technologies Co. Ltd, NEC Corporation, Alcatel Lucent, and Nokia Networks.

[16] Small Cell Virtualization: Functional Splits and Use Cases, *Small Cell Forum release 6*, January 2016.

[17] Network Functions Virtualisation (NFV); Use Cases, ETSI GS NFV 001, V1.1.1, Oct. 2013.

[18] NGMN Alliance: Further study on Critical C-RAN Technologies, *NGMN Alliance white paper*, March 2015.

[19] iCIRRUS: intelligent Converged network consolidating Radio and optical access aRound USer equipment, EU Horizon 2020 project, online: http://www.icirrus-5gnet.eu/project/

[20] 5G-Crosshaul: The 5G Integrated fronthaul/backhaul transport network, EU Horizon 2020 project, online: https://5g-ppp.eu/5g-xhaul/
[21] 5G-XHaul: Dynamically Reconfigurable Optical-Wireless Backhaul/Fronthaul with Cognitive Control Plane for Small Cells and Cloud-RANs, EU Horizon 2020 project, online: https://5g-ppp.eu/5g-xhaul/
[22] J. D'Ambrosia (Chair, IEEE P802.3bs 400 GbE Task Force): IEEE P802.3bs Baseline Summary (Post July 2015 Plenary Summary), July 18, 2015
[23] J.L. Wei, K. Grobe, H. Grießer: Cost-efficient High-Speed Modulation for Next-Generation PONs, ITG Conference Photonics Networks, Leipzig, Germany, May 2015
[24] J.L. Wei, K. Grobe, C. Sanchez, E. Giacoumidis, H. Grießer: Comparison of cost- and energy-efficient signal modulations for next generation passive optical Networks, Optics Express, Vol. 23, No. 22, Nov. 2015, pp. 28271 ff.
[25] J.L. Wei, N. Eiselt, H. Grießer, K. Grobe M. Eiselt J.J. Vegas Olmos, I. Tafur Monroy, J.-P. Elbers: First Demonstration of Real-Time End-to-End 40 Gb/s PAM-4 System using 10-G Transmitter for Next Generation Access Applications, ECOC 2015, Valencia, Spain, Sep. 2015
[26] J.L. Wei, K. Grobe, C. Wagner, E. Giacoumidis, H. Grießer: 40 Gb/s Lane Rate NG-PON using Electrical/Optical Duobinary, PAM-4 and Low Complex Equalizations, OFC 2016, Anaheim, CA, March 2016, accepted
[27] N. Eiselt, H. Grießer, J.L. Wei, A. Dochhan, M. Eiselt, J.-P. Elbers, J.J. Vegas Olmos, I. Tafur Monroy: Real-Time Evaluation of 26-GBaud PAM-4 Intensity Modulation and Direct Detection Systems for Data-Center Interconnects, OFC 2016, Anaheim, CA, March 2016, accepted
[28] N. Eiselt, J.L. Wei, H. Grießer, A. Dochhan, M. Eiselt, J.-P. Elbers, J.J. Vegas Olmos, I. Tafur Monroy: First Real-Time 400G PAM-4 Demonstration for Inter-Data Center Transmission over 100 km of SSMF at 1550 nm, OFC 2016, Anaheim, CA, March 2016, accepted
[29] ETSI GS NFV-MAN 001 V1.1.1, "Network Functions Virtualisation (NFV); Management and Orchestration", Dec. 2014
[30] UNIFY Deliverable 2.2: Final Architecture, V1.0, Nov. 2014
[31] COMBO Deliverable 6.3, Report describing results of operator testing, capturing lessons learned and recommendations, July 2016
[32] COMBO Deliverable 2.4, Requirements for converged fixed and mobile networks, V2.0, June 2015
[33] G Köles, A Mitcsenkov, T Cinkler, "Topology-dependent selective and partial protection of optical access networks", ONDM 2014, Stockholm, Sweden
[34] FNN: Versorgungszuverlässigkeit und Spannungsqualität in Deutschland, online: https://www.vde.com/de/fnn/arbeitsgebiete/versorgungsqualitaet/documents/fnn-fakten-versorgungsqualitaet_2013-03-11.pdf

8 APPENDIX

8.1 Summary of results from D3.3

A number of architectures and solutions were analysed and compared in D3.3. The main comparison relates to convergence based on NG-PON2 vs. dedicated systems for PtP wavelength services:

- NG-PON2 convergence (Figure 99):
    - NG-PON2 TWDM PON for FTTH (fixed access)
    - NG-PON2 WDM PtP wavelength overlay for FTTC backhaul (fixed access)
    - NG-PON2 WDM PtP wavelength overlay for RAN backhaul/fronthaul (mobile access)
- WR-WDM-PON (Figure 100):
    - Stand-alone (separated) TWDM PON for FTTH (fixed access)
    - WR-WDM-PON for FTTC backhaul (fixed access)
    - WR-WDM-PON for RAN backhaul/fronthaul (mobile access)

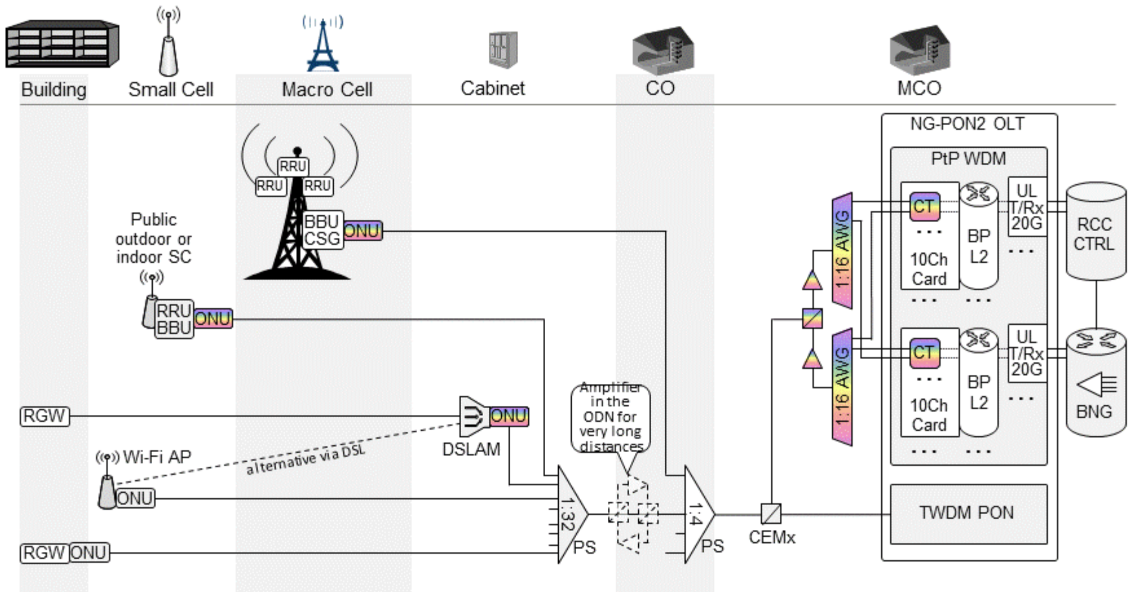


Figure 99: Converged NG-PON2 (backhaul): ODN co-existence with typical 1:128 split for residential customers due to mass market roll out (16 wavelengths of PON2 are delivered to 4 Cabinets)

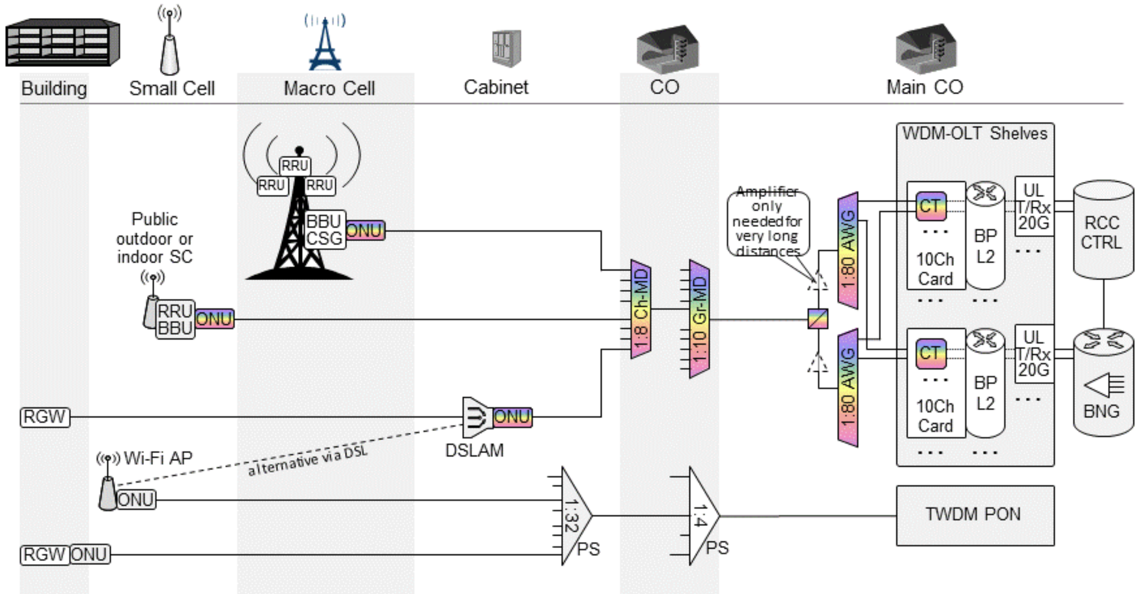


Figure 100: WR-DWDM-PON (backhaul): dedicated ODN for services that require PtP wavelength services, i.e., mobile backhaul and cabinet backhaul (80 wavelengths)

Several other flavors were also considered, e.g., CWDM, WS-WDM-PON, and flexible variants.

Main results are summarized here in Figure 101 for the urban geotype only. One can derive that:

- In an FTTC deployment scenario, WR-WDM-PON always has lowest cost independent of fibre cost.
- In an FTTH area, the mass-market NG-PON2 fibre infrastructure could be re-used for PtP overlay
  - Fibre-poor: Convergence with NG-PON2 has the lowest cost
  - Fibre-rich: Convergence with NG-PON2 has the lowest cost for higher RAN densities
- For low numbers of deployed small cells, NG-PON2 suffers from the bad utilization of PtP WDM hardware (such as AWGs).
- As both the FTTH/FTTC ratio and the RAN density increase, the NG-PON2 converged architecture has the lowest cost.

Detailed results for other geotypes are found in D3.3.

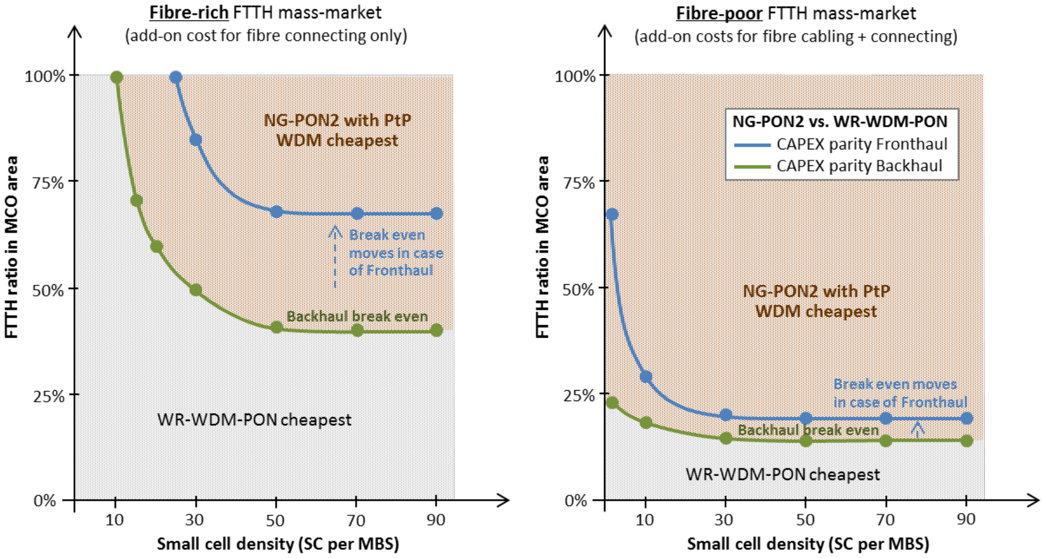


Figure 101: Results for both fronthaul and backhaul showing that high FTTH/FTTC ratio and high small-cell (SC) density favor convergence with mass-market solutions (NG-PON2)

8.2 CoMP throughput gain and coordination traffic latency

In this section we provide further details on the impact of cluster size and coordination traffic latency on the CoMP throughput gain, also detailing factors that contribute to the total latency budget for coordination traffic.

8.2.1 Impact of cluster size and X2 latency on CoMP throughput gain

For our study, we need to model the throughput gain (i.e., how much additional traffic can be served thanks to coordination) that can be obtained using CoMP, for different combinations of cluster size and latency. The throughput gain curves in Figure 102 were calculated by interpolating the measured throughput gains for JT reported in [10] and show the gain as a function of cluster sizes (from 3 to 18 cells) and latency (from 5 to 1200 µs). Similar curves have been obtained for the case of CS, but they refer to a much larger latency range [0.25-9 ms], as CS has looser latency requirements. In general JT has much higher throughput gain (up to 40% for 18-cells clusters and 5 µs latency) in comparison to CS (whose gain is up to 20% for 18-cells clusters and 250 µs latency), but more stringent latency requirements must be met with JT.

Note that, in our study, besides the RCC placement, we also decide the cell clustering, i.e., we decide the set of cell sites to be coordinated together by the same RCC. In the following we refer to a *clustering* to indicate a set of admissible clusters covering all the cell sites in the network.

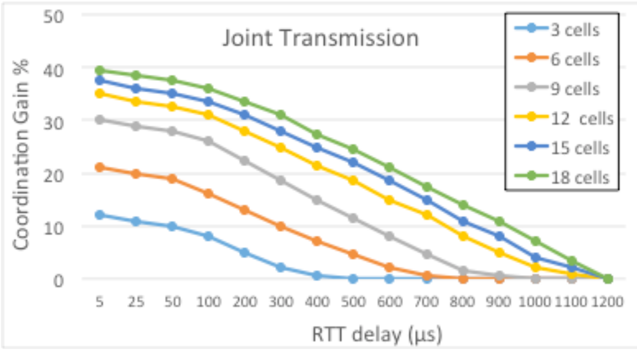


Figure 102: Throughput gain for varying cluster size and latency (Joint Transmission – JT – CoMP technique).

8.2.2 X2 coordination traffic and latency budget

CoMP coordination data is exchanged between the RCC and cell sites through the LTE X2 interface, while user traffic is transported via the S1 interface. We calculated the amount of X2 coordination traffic using data from [10]. The coordination data for CS requires an exchange of Channel State Information (CSI), so we considered an overhead of about 16% with respect to S1 traffic. For JT, X2 traffic is assumed as 116% of the S1 bit rate, as in this case, besides the CSI, also user traffic (S1) is transported with coordination traffic (X2).

In this study, we consider that coordination between cells is performed through the X2 interface interconnecting the BBU at the cell site (i.e., no BBU hotelling is assumed in this work) and the RCC. Moreover, we assume that coordination and user traffic types are multiplexed into a common physical interface, and a switch, co-located with the RCC, is needed to separate S1 and X2 traffic. Thus, the network elements contributing to total latency of coordination traffic are (see Figure 103): 1) *propagation delay* (τ), which depends on the overall length of the traversed links; 2) *switching delay* (t_{sw}) of the switch deployed in the RCC node, that introduces a fixed delay of 20 µs; 3) *RCC processing delay* (t_{RCC}), introduced by the RCC when processing coordination information.

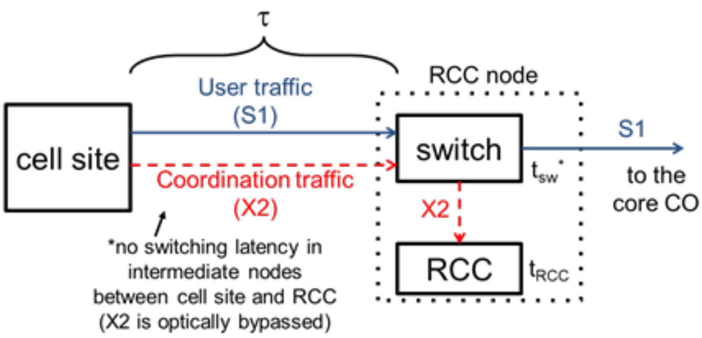


Figure 103: Schematic representation of X2 latency contributions.

8.3 X-haul bandwidth calculation

For the different RAN split options, we provide here the details of the bandwidth requirement calculations, which are based on the model in [16]. We refer to the basic scenario considered in [16], i.e., the case of antenna configuration with 20 MHz – 64 QAM – 2x2 MIMO, and then scale the various parameter involved in the calculations to fit with the antenna configurations described in Section 4.4.1.2, that is, according to the variation of utilized spectrum, modulation format and MIMO.

8.3.1 Basic parameters

The involved parameters are listed below in *Table 27*, where we also provide their description as well as the values considered for the basic antenna configuration.

Table 27: Reference parameters for the base case 20 MHz – 64 QAM – 2x2 MIMO.

Parameter	Value	Description
Hdr_{PDCP}	2	Physical Downlink Control Channel (PDCP) header in bytes
Hdr_{RLC}	5	Radio Link Control (RLC) header (estimate per IP packet) in bytes
Hdr_{MAC}	2	MAC header (estimate per IP packet) in bytes
IP_{pkt}	1500	IP packet size in bytes
TBS_{DL}	75376	Transport Block Size (TBS) for downlink in bits
IP_{DL}^{TTI}	6.2	downlink IP packets per transport block $= \frac{TBS_{DL}}{(IP_{pkt} + Hdr_{PDCP} + Hdr_{RLC} + Hdr_{MAC}) * 8}$
TBS_{UL}	48936	Transport block size (in bits) for uplink
IP_{UL}^{TTI}	4.1	uplink IP packets per transport block $= \frac{TBS_{UL}}{(IP_{pkt} + HDR_{PDCP} + HDR_{RLC} + HDR_{MAC}) * 8}$
N_{DL}^{TBS}	2	DL number of TBS per Transmission Time Interval (TTI)
N_{UL}^{TBS}	1	UL number of TBS per TTI
$FAPI_{DL}$	1.5	DL Femto Application Transport Interface (FAPI) overhead per UE in Mb/s
$FAPI_{UL}$	1	UL FAPI overhead per UE in Mb/s
N_{RB}	100	Number of resource blocks per user
N_{SYM}^{SUB}	14	Number of symbols per subframe
N_{SC}^{RB}	12	Number of subcarriers per Resource Block (RB)
N_{SYM}^{Data}	12	Number of data carrying symbols per sub-frame
N_{UE}	1	Number of UEs per TTI
N_{Ant}	2	Number of antennas
CFI	1	Number of Control Format Indicator (CFI) symbols
Qm_{PDSCH}	6	64QAM modulation used for Physical Downlink Shared Channel (PDSCH)
Qm_{PUSCH}	4	16QAM modulation used for Physical Uplink Shared Channel (PUSCH)
Qm_{PCFICH}	2	QPSK modulation used for Physical CFI Channel (PCFICH)
Qm_{PDCCH}	2	QPSK modulation used for Physical Downlink Control Channel (PDCCH)
$Layers_{DL}$	2	Number of DL layers

$Layers_{UL}$	1	Number of UL layers
$RefSym_{REs}$	6	Number of REs for reference signals per RB per sub-frame
$PDSCH_{REs}$	14400	PDSCH Resource Element per UE $= N_{RB} * [N_{SC} * (N_{SYM} - CFI) - (RefSym_{REs} * N_{ant})]$
$PCFICH_{REs}$	16	Number of REs for PCFICH
$PHICH_{REs}$	12	Number of Res for Physical Hybrid ARQ Indicator Channel (PHICH)
$PDCCH_{REs}$	144	Number of REs for PDCCH
N_{IQ}	32	Number of I/Q bits (16I + 16Q)
$PUCCH_{RB}$	2	Number of RBs for PUCCH
N_{LLR}	8	8-bit LLRs
$N_{SICiter}$	1	Number of Successive Interference Cancellation (SIC) iterations (no SIC)
N_{CPRI}	32	15I+15Q bits (CPRI adds 1 control bit per word)
f_s	30.72	Sapling rate at 20 MHz, in MHz

8.3.2 Bandwidth calculation

Given the input parameters described in Table 27, where the reported values refer a 20 MHz – 64 QAM – 2x2 MIMO as in [16], the x-haul bandwidth requirements are shown below for the downilk and uplink cases.

- Downlink bandwidths (in Mb/s)

$$MAC - PHY = \frac{IP_{DL}^{TTI} * \left(IP_{pkt} + Hdr_{PDCP} + Hdr_{RLC} + Hdr_{MAC}\right) * N_{DL}^{TBS} * 8 * 1000}{1000000} + FAPI_{DL}$$

$$Split\ I = \frac{(N_{UE} * PDSCH_{REs} * Qm_{PDSCH} * Layers_{DL} + PCFICH_{REs} * Qm_{PDSCH} + PHICH_{REs} + PDCCH_{REs} * Qm_{PDCCH}) * 1000}{1000000}$$

$$Split\ II = \frac{(N_{UE} * PDSCH_{REs} + PCFICH_{REs} + PHICH_{REs} + PDCCH_{REs}) * N_{IQ} * N_{Ant} * 1000}{1000000}$$

$$Split\ III = \frac{N_{SC}^{RB} * N_{RB} * N_{SYM}^{SUB} * N_{IQ} * N_{Ant} * 1000}{1000000}$$

$$Split\ IIIb = f_s * N_{IQ} * N_{Ant}$$

$$Split\ IV\ (CPRI) = f_s * N_{Ant} * N_{CPRI} * \frac{10}{8}$$

- Uplink bandwidths (in Mb/s)

$$MAC - PHY = \frac{IP_{UL}^{TTI} * \left(IP_{pkt} + Hdr_{PDCP} + Hdr_{RLC} + Hdr_{MAC}\right) * N_{UL}^{TBS} * 8 * 1000}{1000000} + FAPI_{UL}$$

$$Split\ I = \frac{N_{SYM}^{Data} * N_{SC}^{RB} * (N_{RB} - PUCCH_{RBs}) * Qm_{PUSCH} * Layers_{UL} * N_{SICiter} * N_{LLR} * 1000}{1000000}$$

$$Split\ II = \frac{N_{SYM}^{Data} * N_{SC}^{RB} * (N_{RB} - PUCCH_{RBs}) * N_{Ant} * N_{IQ} * 1000}{1000000}$$

$$Split\ III = \frac{N_{SYM}^{Data} * N_{SC}^{RB} * N_{RB} * N_{Ant} * N_{IQ} * 1000}{1000000}$$

$$Split\ IIIb = f_s * N_{IQ} * N_{Ant}$$

$$Split\ IV\ (CPRI) = f_s * N_{Ant} * N_{CPRI} * \frac{10}{8}$$

Given these formulas, for each RAN split option and for the different antenna configurations described in Section 4.4.1.2, we obtain the required x-haul bandwidth as the maximum between downlink and uplink values.

8.3.3 Effect of changing antenna configuration

Varying the antenna configuration under consideration, i.e., varying its utilized spectrum, modulation format or MIMO degree, not only affects the radio throughput, as shown in Section 4.4.1.2, but also impacts on the required x-haul capacity. Specifically, keeping the 20 MHz – 64 QAM – 2x2 MIMO case in [16] as the reference configuration, every change in the utilized spectrum, modulation format or MIMO degree is assumed to impact the parameters in *Table 27* as shown in the following *Table 28*.

Table 28: Impact of the antenna configuration on parameters in Table 27 (we report parameters affected by the adoption of antenna configuration S MHz – M QAM – NxN MIMO instead of 20 MHz – 64 QAM – 2x2 MIMO).

Effect of…	**Scaling factor**	**Affected parameters**
changing the utilized spectrum: 20 MHz → *S* MHz	*S*/20	N_{DL}^{TBS}, N_{UL}^{TBS}, N_{SC}^{RB}, $PDSCH_{REs}$*
changing the modulation format: 64 QAM → *M* QAM	$\log_2(M)/\log_2(64)$	TBS_{DL} ,IP_{DL}^{TTI} , TBS_{UL} ,IP_{UL}^{TTI}, Qm_{PDSCH}, Qm_{PUSCH}
changing the MIMO configuration: 2x2 → *N*x*N*	*N*/2	N_{DL}^{TBS}, N_{UL}^{TBS}, N_{Ant}, $Layers_{DL}$, $Layers_{UL}$, $PDSCH_{REs}$*

* Parameters marked with "*" are not simply scaled as they are obtained through a non linear formula (see Table 27).

Note that, to compute uplink bandwidth values, we assume that the uplink MIMO configuration is halved with respect to the downlink value. Moreover, as far as the modulation format is concerned, we assume that 16 QAM is always considered as uplink modulation format, regardless the corresponding downlink value.

Furthermore, note that, for the Split IV (i.e., CPRI) option, in both downlink and uplink cases a factor 10/8 is used in the equations of Section 8.3.2 to account for the CPRI 8B/10B line coding. For antenna configurations with radio peak rate greater than or equal to 10 Gb/s (i.e., starting with option n. 12 in Table 9), this factor is assumed as equal to 66/64 since we assume that 64B/66B CPRI line coding is used in those cases.

8.3.4 Example

As an example, to obtain the x-haul bandwidth values for the 5G reference antenna configuration, i.e., 125 MHz – 256 QAM – 16x16 MIMO, shown in Table 13, we used the equations in Section 8.3.2, varying the parameters of Table 28 with respect to those reported in Table 27. The new values considered in this case are shown in *Table 29*.

Table 29: Parameters changed with respect to those in Table 28 in the case of the reference antenna configuration 125 MHz – 256 QAM – 16x16 MIMO.

Parameter	Value	Calculation
N_{DL}^{TBS}	100	$= 2 * \frac{125}{20} * \frac{16}{2}$
N_{UL}^{TBS}	50	$= 1 * \frac{125}{20} * \frac{16}{2}$
N_{SC}^{RB}	75	$= 12 * \frac{125}{20}$
TBS_{DL}	100501.3	$= 75376 * \frac{8}{6}$
TBS_{UL}	48936	$= 48936 * \frac{4}{4}$
IP_{DL}^{TTI}	8.3	$= 6.2 * \frac{8}{6}$
IP_{UL}^{TTI}	4.1	$= 4.1 * \frac{4}{4}$
Qm_{PDSCH}	8	$= 6 * \frac{8}{6}$
Qm_{PUSCH}	4	$= 4 * \frac{4}{4}$
N_{Ant}	16	$= 2 * \frac{16}{2}$
$Layers_{DL}$	16	$= 2 * \frac{16}{2}$
$Layers_{UL}$	8	$= 1 * \frac{16}{2}$

8.4 Reference numbers for techno-economic studies

8.4.1 Radio configuration for MBSs and SCs

Table 30 shows the main parameters of radio configuration used and the backhaul and fronthaul capacity needed per site.

Table 30: Radio configuration for MBSs and small cells

Heterogeneous Network Radio Configuration	**4G Macro Base Station**	**4G Small Cell**	**5G Macro Base Station**	**5G Small Cell**
Radio technologies	2G / 3G / 4G	4G only	2G / 4G / 5G	5G only
Sectors per technology	3	1	3	1
Frequency spectrum	40 MHz 4G	20 MHz	40 MHz LTE 125 MHz 5G	125 MHz
HO-MIMO	4 x 4	2 x 2	4 x 4 LTE 16x16 5G	16x16
Backhaul capacity per site / operator (S1+X2)	830 Mb/s + 50 Mb/s*	245 Mb/s	Up to 75Gb/s**	Up to 69 Gb/s**
Fronthaul capacity per site / operator**	3xCPRI 10 Gb/s 2xCPRI 3 Gb/s	1x CPRI 3 Gb/s	Up to 101 Gb/s**	Up to 101 Gb/s**

* UMTS/GSM data rates estimation of entirely 50 Mb/s in case of MBS backhaul
** Depends on the RAN split point considered

Table 31 shows the MBS density and the number of MBS per geotype.

Table 31: MBSs and small cell deployment numbers

Heterogeneous Network Number of Mobile Sites per Main CO area		**Ultra-Dense Urban**	**Urban**	**Sub-Urban**	**Rural**
MBS density		4/km²	1.5/km²	0.2/km²	0.05/km²
Number of MBS		8	23	29	31
Number of SC per MBS	Base case 10 / MBS	80	230	290	0
	Variation 1…150 / MBS	8…1200	23…3450	29…4350	

8.4.2 Geo-Data of a typical Main CO

The geo-data of a typical Main CO area in Central Europe, which have been considered for the assessment, are summarised in the following table for all area types.

Table 32: Geo-data of a typical Main CO area in Central Europe

Avg. Geo-data of a typical Main CO area in Central Europe	Ultra DU	Urban	Sub-urban	Rural
Number of COs	1	2.9	5.9	10.8
Main CO area size	2 km²	15 km²	142 km²	615 km²
Number of buildings	2,440	6,850	20,400	22,000
Number of homes	15,820	44,500	51,000	33,000
Number of cabinets	100	285	380	325
Avg. distances BS ↔ CO	0.5 km	1.5 km	2.5 km	3.5 km
Max. distances BS ↔ CO	2 km	3 km	4 km	5 km
Avg. distances CO ↔ Main CO	-	1.9 km	5.9 km	15.6 km
Max. distances CO ↔ Main CO	-	10 km	30 km	50 km

8.4.3 Fibre Infrastructure Cost Model

The fibre infrastructure cost model takes all cost items into account which cause a difference for the technology comparison. The model differentiates between FTTC and FTTH areas and the different parts in the first-mile and feeder network. Since no splitting stage has been chosen between the mobile BS and the cabinets, this first-mile network part is equal in all variants and has therefore not been considered for the comparison. From the operator experience, a certain degree of fibre over-provisioning can be considered in mass-market FTTH areas, offering a sufficient amount of available reserve fibres, which can be used for mobile x-haul. However, also in those areas fix cost per used fibre, e.g., for planning, travelling, preparation, and fibre splicing needs to be considered. In FTTC areas, it is assumed that the amount of fibres between the cabinets and the CO will typically not be sufficient, requiring additional costs for new fibre cabling including, e.g., exploration, planning, travelling, preparation, fibre-cable blowing or pulling, fibre splicing, documentation, etc. Fibre cabling in FTTC areas would be required for all technology variants, and thus, the potential demand for digging and ducting can be regarded as the same in all variants and has therefore not been considered for the assessment. The feeder-fibre network between the CO and the Main CO is usually dimensioned by demand with a low over-provisioning degree, causing the need for new fibre cabling in addition to the fix costs per fibre. The cabling cost per fibre is lower in the feeder part compared to the first mile, because of the larger feeder-cable size, whereas the fix cost per fibre is higher in the feeder part typically. The following table summarises the fibre cost model assumptions.

Table 33: Fibre infrastructure cost model

Cost model for fibre usage, connecting and cabling (excl. digging and ducting)		**Fix cost per fibre**	**Cabling cost per fibre km**
First mile network **mobile BS ↔ Cab**	FTTH area	same in all variants; not considered for comparison	
	FTTC area		
First mile network **Cab ↔ CO**	FTTH area	3.0 CU	existing fibre
	FTTC area	3.5 CU	8.7 CU
Feeder network **CO ↔ MCO**	FTTC/H areas	23.8 CU	2.0 CU

8.5 Decentralised small cell x-haul architectures

The following pictures show the detailed network architectures for the solutions considered in Chapter 3. All of them follow a similar approach, where the main differences are the system solution used to provide the connectivity for the mobile backhaul or fronthaul and the level of FMC achieved.

Figure 104 shows the network architecture based on NG-PON2 including additional PtP WDM channels for the decentralised SC backhaul to its nearest MBS. In this decentralised architecture, an NG-PON2 OLT in the MBS connects all SCs through a power splitter located at the CO and assigns a dedicated PtP WDM channel to each of them. The OLT is also connected to the RCC (which performs the coordination of the MBS and the SCs connected to that MSB) and to NG-PON2 ONUs used to backhaul the S1 traffic coming from the SCs and the S1 and X2 traffic from the MBS towards the mobile core. In the Main CO, a second NG-PON2 OLT assigns a dedicated PtP WDM channel to each of the previous ONU, sharing the same ODN with other fixed services. Finally, that NG-PON2 OLT is connected to the BNG, which provides the connectivity to the IP backbone and the Core CO.

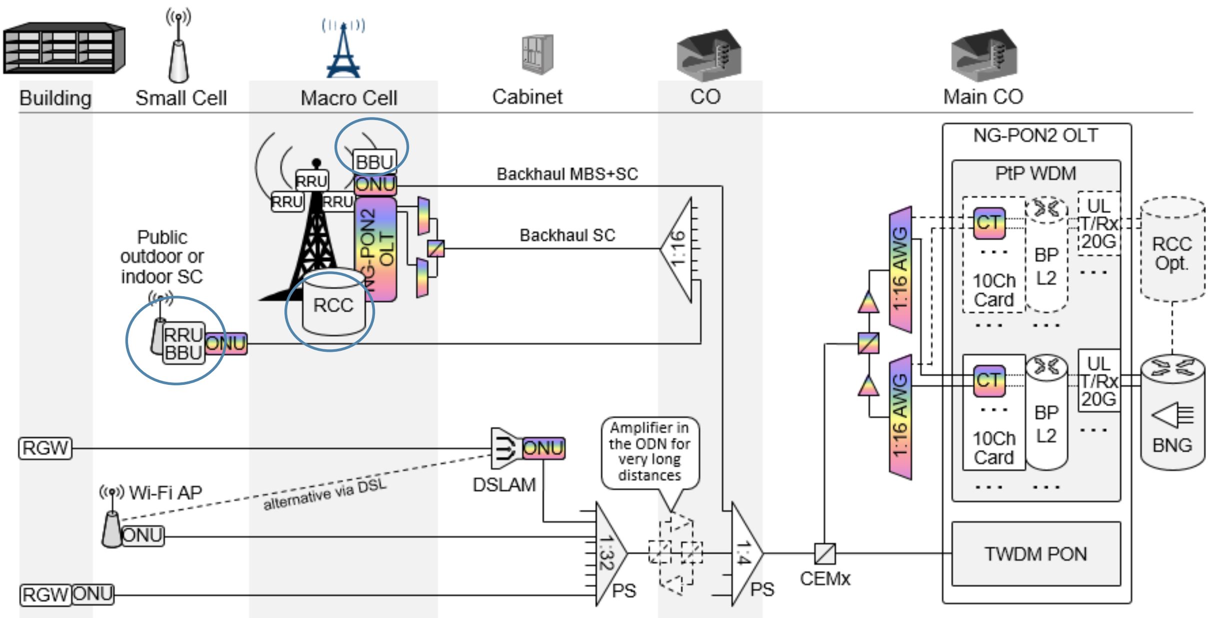


Figure 104: NG-PON2 network architecture with SC backhaul to the MBS

Figure 105 shows the network architecture based on NG-PON2 including additional PtP WDM channels for the decentralised SC fronthaul to its nearest MBS. It follows an approach similar to the decentralised backhaul; however, in this architecture a fronthaul link connects each SC with its corresponding MBS, where the local BBUH terminates the CPRI traffic and forwards S1 traffic to the mobile core. The BBUH is connected to the MCO through an NG-PON2 system, as in the backhaul case.

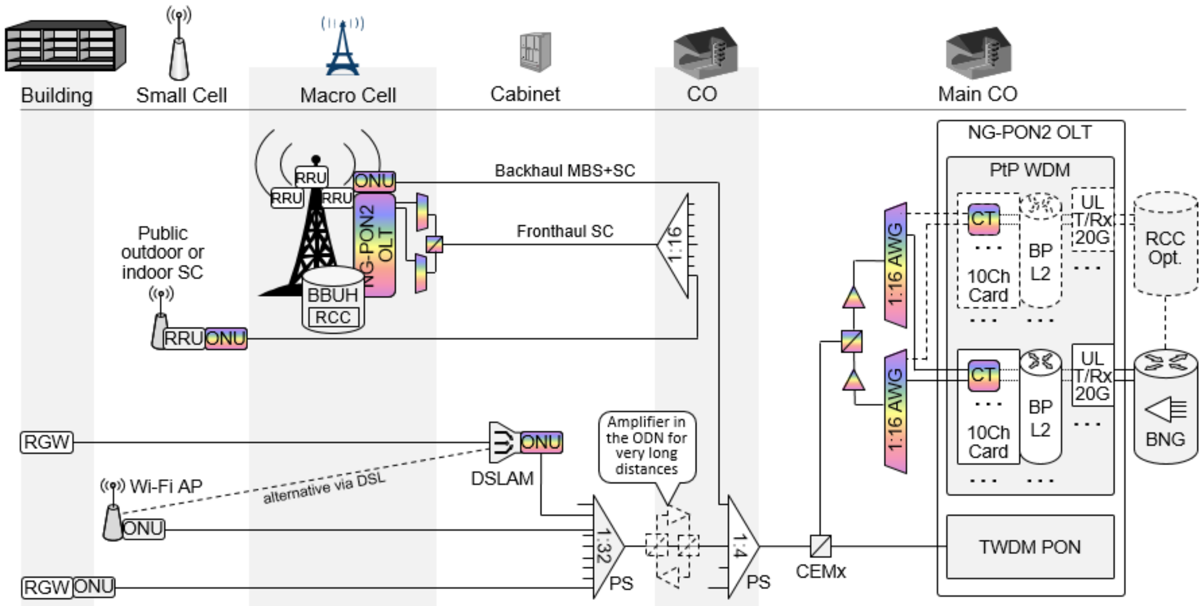


Figure 105: NG-PON2 network architecture with SC fronthaul to the MBS

Figure 106 and Figure 107 depict the network architecture for the decentralised SC fronthaul and backhaul to the MBS based on WR-WDM-PON. Two level of WR-WDM OLTs are used: an OLT dedicated to the mobile fronthaul or backhaul of the SCs located at the MBS, and an OLT in the MCO dedicated to aggregate the mobile traffic in combination with the fixed one.

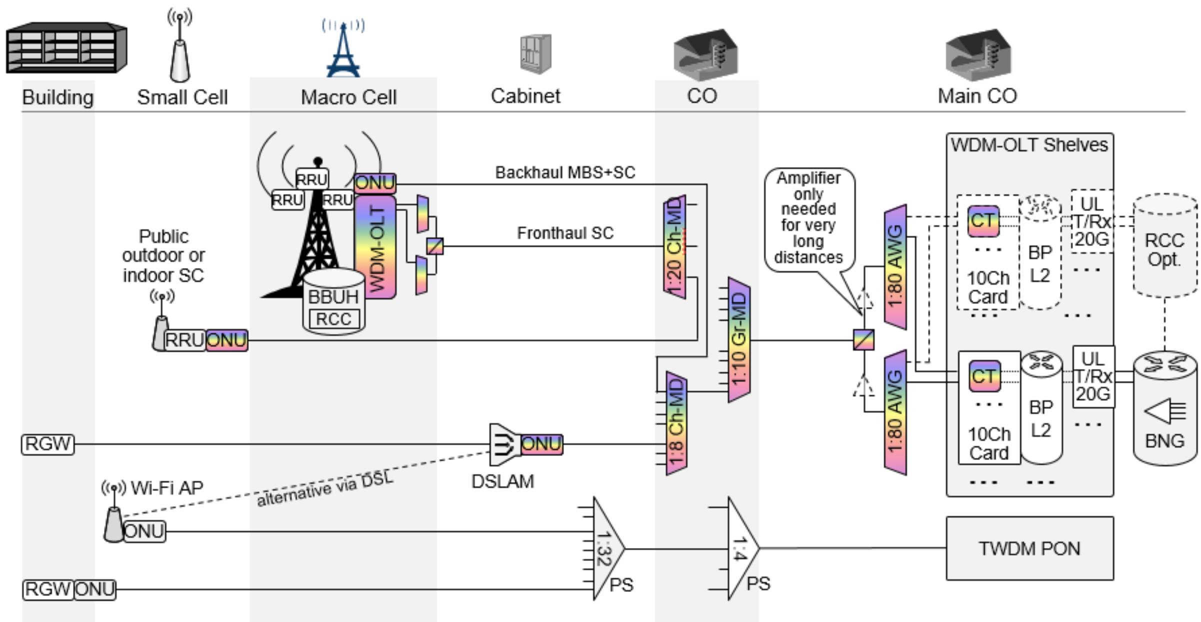


Figure 106: WR-WDM-PON network architecture with SC fronthaul to the MBS

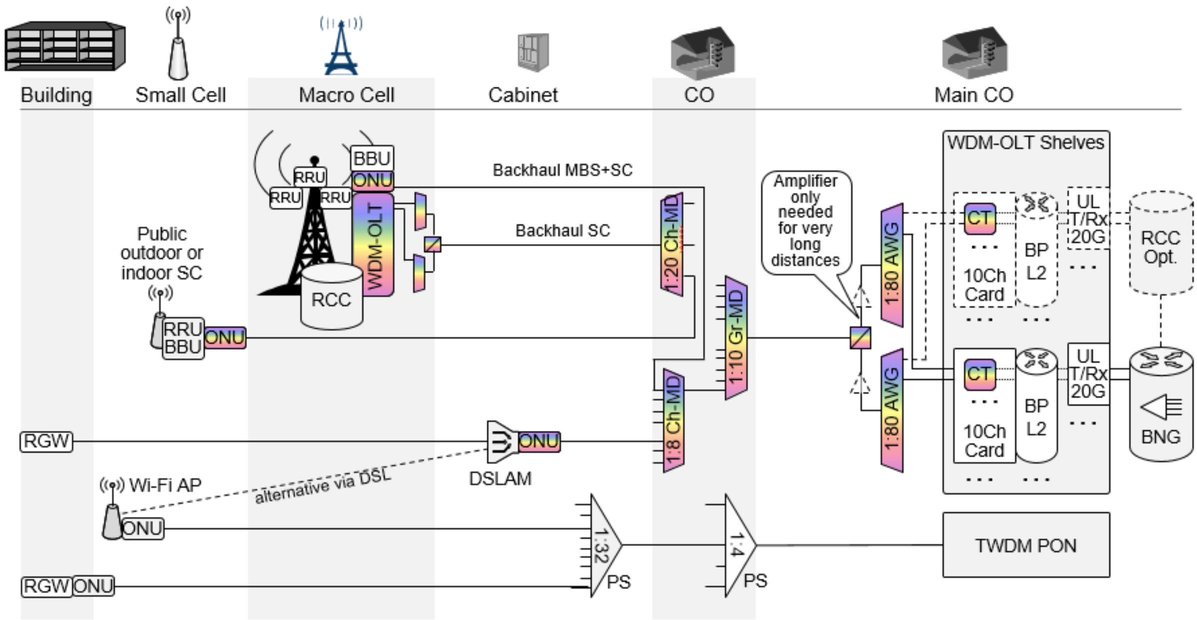


Figure 107: WR-WDM-PON network architecture with SC backhaul to the MBS

Figure 108 and Figure 109 illustrate the network architecture for the decentralised SC fronthaul and backhaul to the MBS based on WS-WDM-PON. These network architectures are similar to the ones based on WR-WDM-PON, however a PS is used at the CO instead a mux/demux to split and combine optical channels, affecting the technology of the optical receiver at OLT and ONU sides.

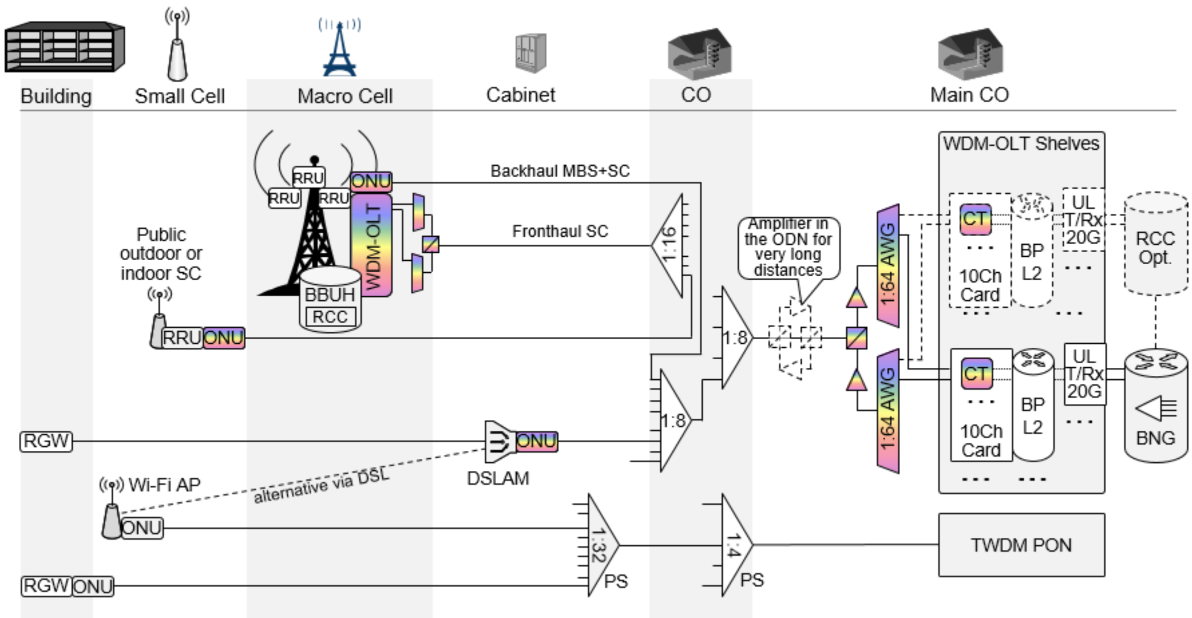


Figure 108: WS-WDM PON network architecture with SC fronthaul to the MBS

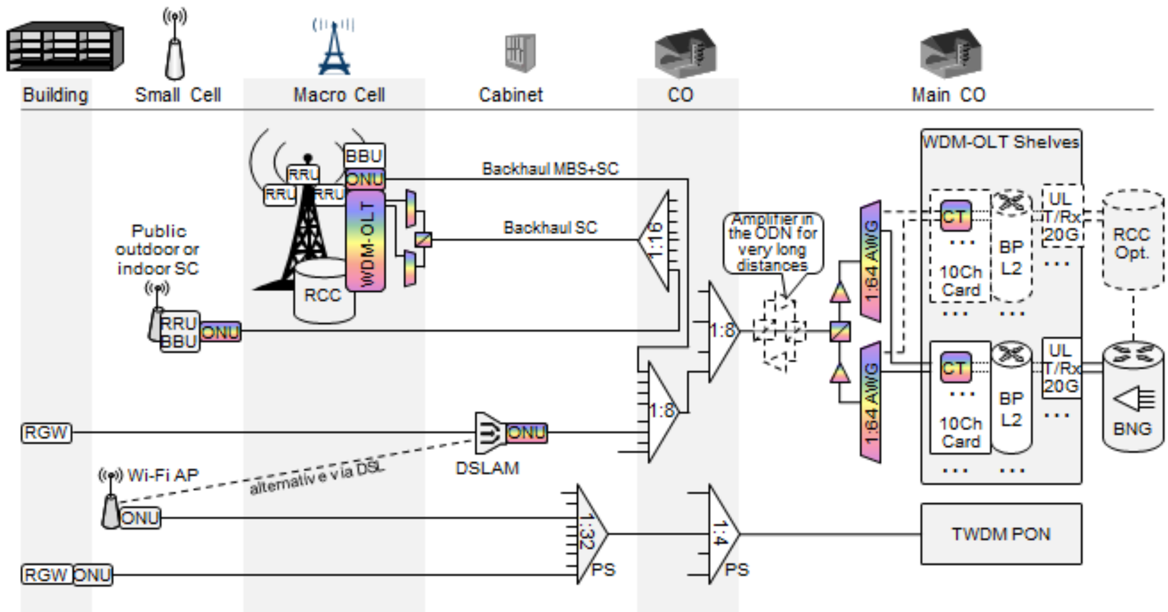


Figure 109: WS-WDM PON network architecture with SC backhaul to the MBS

Finally, Figure 110 and Figure 111 show the network architecture for the decentralised SC fronthaul and backhaul to the MBS using PtP BiDi-CWDM as system solution as for the decentralised version of the 2020 reference solution assuming some basic convergence aspects between fixed and mobile.

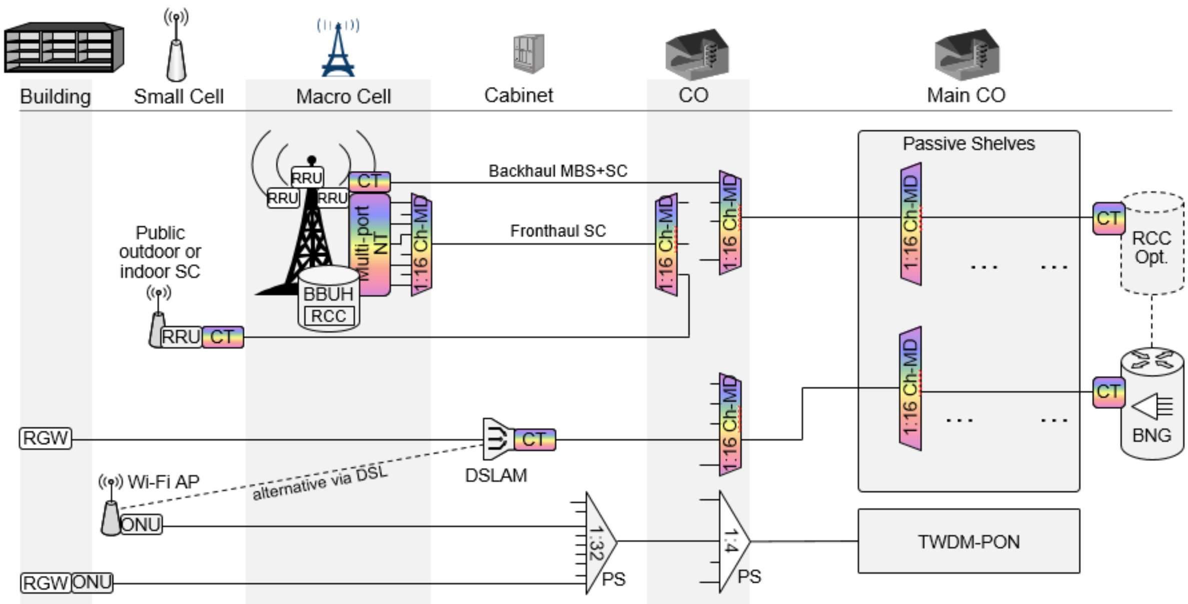


Figure 110: Reference network architecture for 2020 with SC fronthaul to the MBS

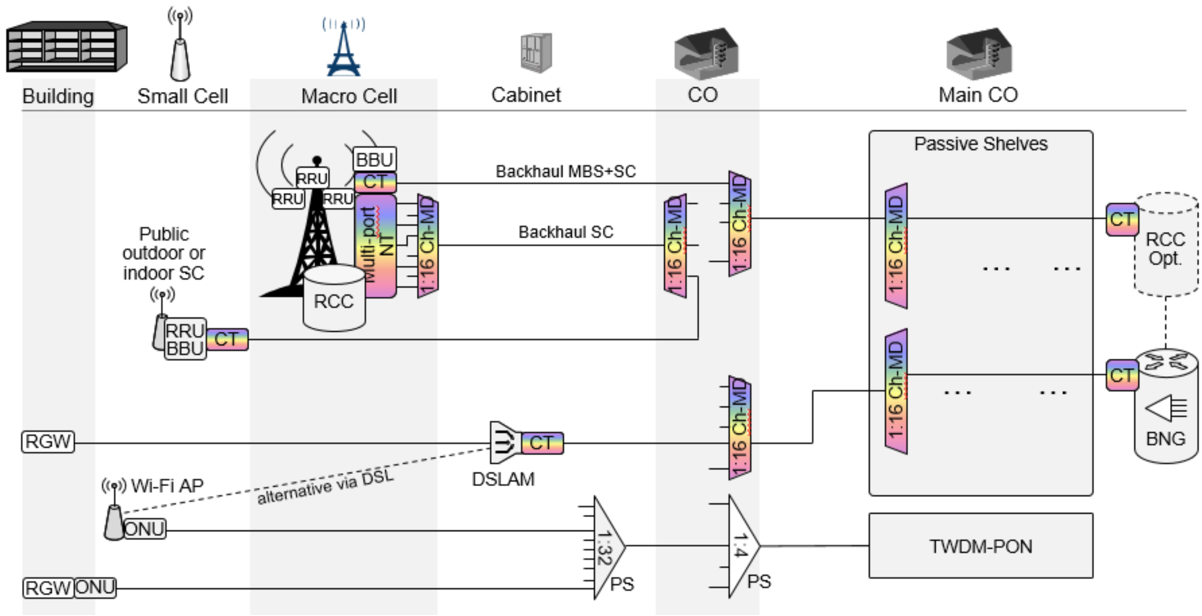


Figure 111: Reference network architecture for 2020 with SC fronthaul to the MBS

8.6 Amplification for high speed optical interfaces

The following figures show the amplification needs for the transport technologies included in this study for 25 Gb/s, 40 Gb/s and 100 Gb/s. CWDM (up to 16 channels per fibre), WR-WDM-PON (up to 80 channels per fibre), NG-PON2 (up to 16 channels per fibre and 1:128 splitting ratio), WS-WDM-PON (up to 64 channels per fibre) were considered. Amplification requirements are represented through the percentage of clients per each geotype that will need optical amplification in different locations. Four levels of amplification are considered:

- No amp: amplification is not needed
- OLT: amplification is needed only next to the OLT in the Main CO
- ODN: amplification is needed only in the ODN, for example inside the CO
- OLT/ODN: amplification is needed in the OLT and in the ODN

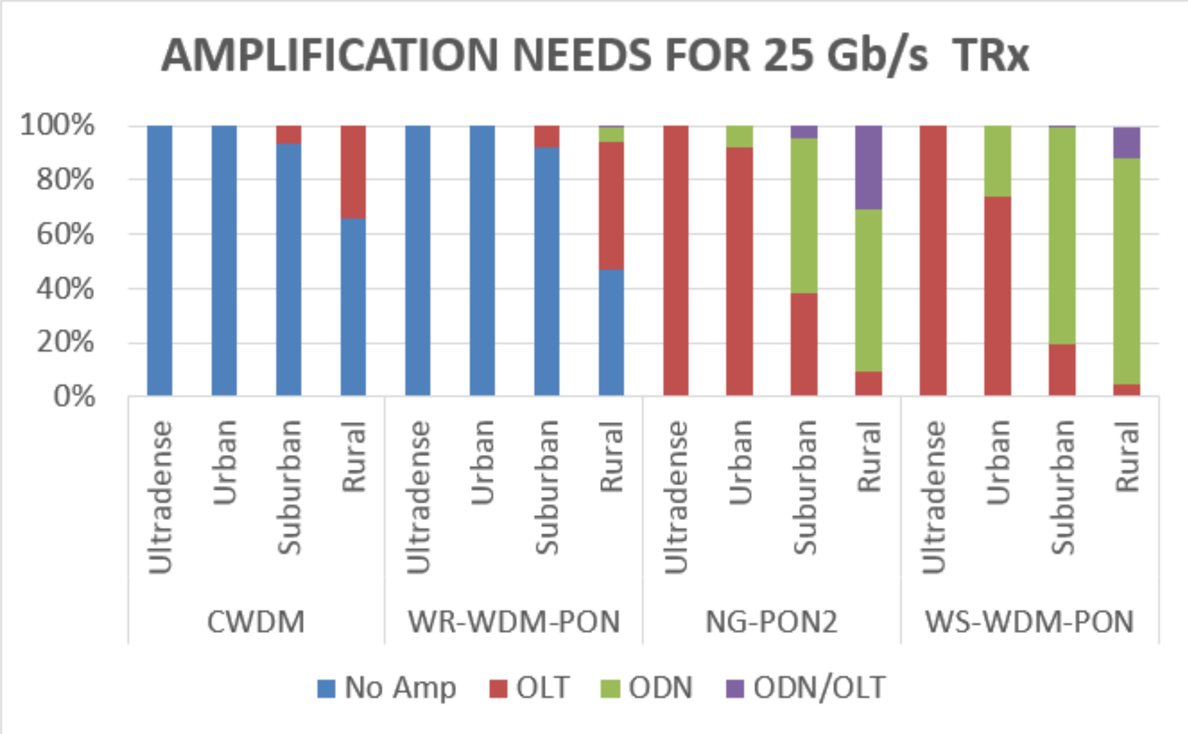


Figure 112: Amplification needs for 25 Gb/s TRx

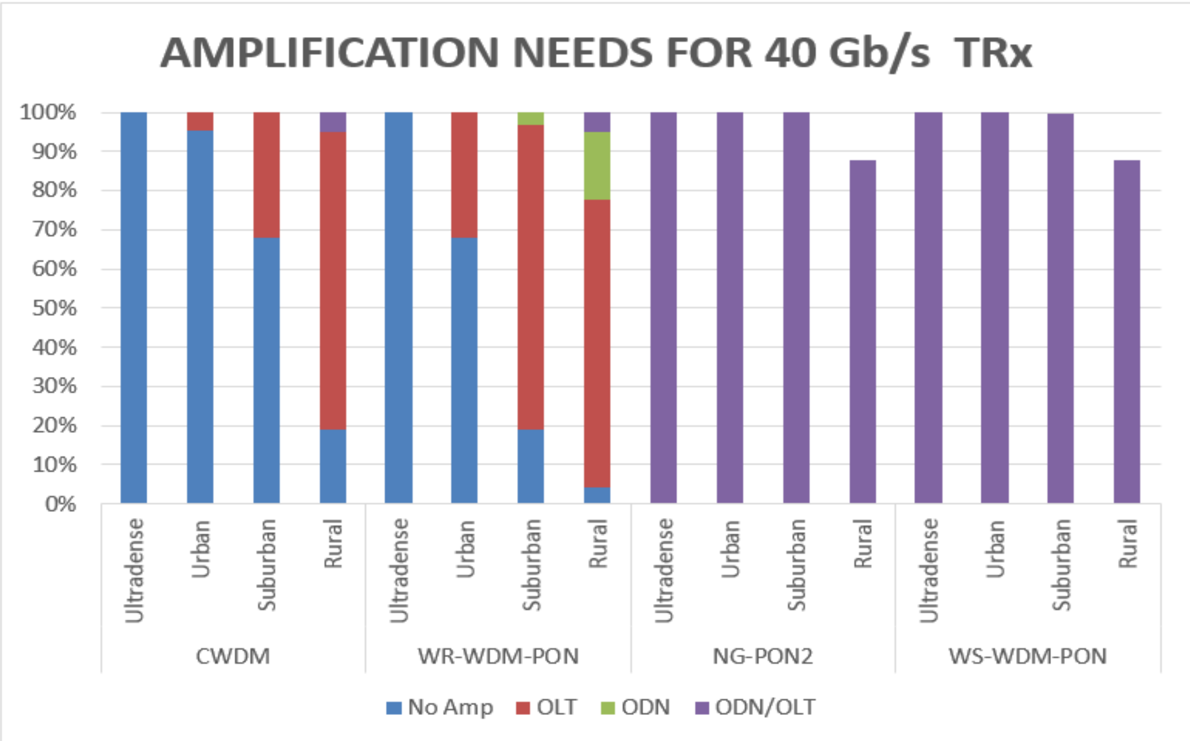


Figure 113: Amplification needs for 40 Gb/s TRx

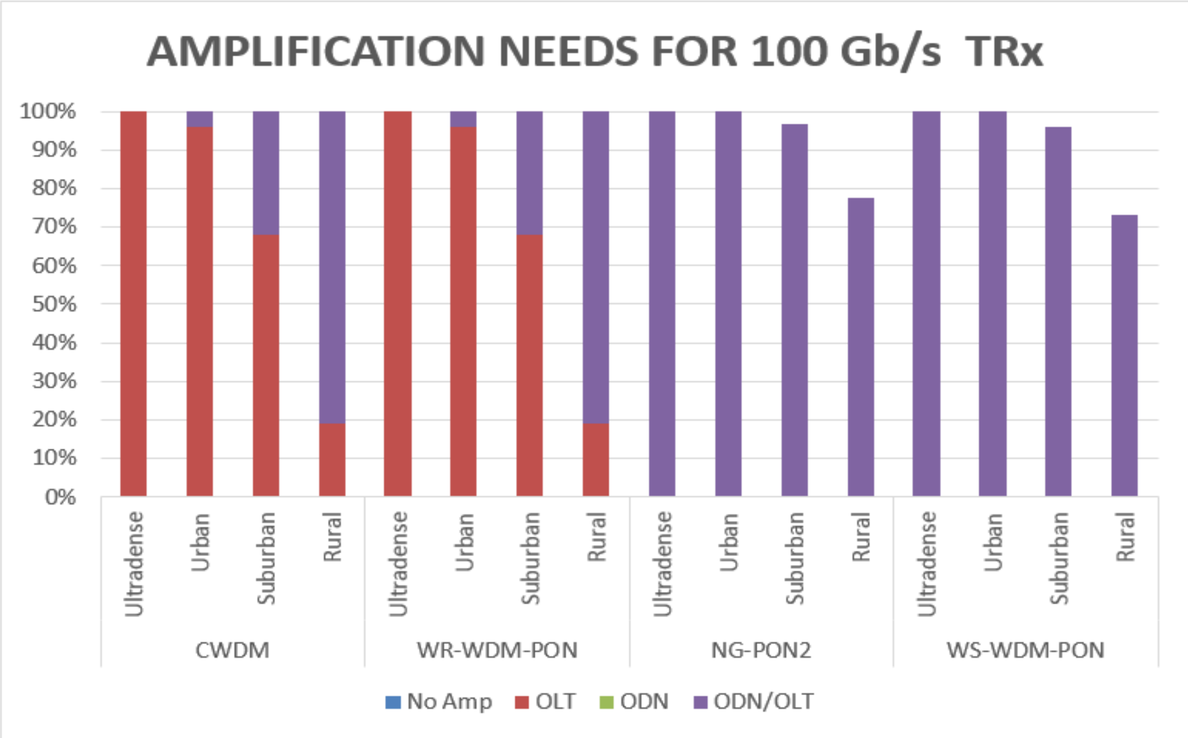


Figure 114: Amplification needs for 100 Gb/s TRx

8.7 Dimensioning tables

The tables in this section summarise the quantitative analysis with the main network elements for the four geotypes following the methodology described in 4.7, inside the chapter 4. These results were used for the cost analysis and comparison between the 2020 reference architecture and the converged architecture options.

The rows with the system elements count the number of OLT shelves in the Main CO, the number of transceivers for each type, and the required number of amplifiers and filters. The fibre information details the number of individual fibres needed to connect all network elements and the fibre length for each network section.

The following tables contain the dimensioning results for the 2020 reference network, NG-PON2, WR-WDM-PON and WS-WDM-PON for the different RAN split points considered.

Table 34: Dimensioning result for the 2020 reference network for 5G

2020 reference architecture	**Ultra-Dense Urban (2 km^2)**	**Urban (15 km^2)**	**Sub-Urban (142 km^2)**	**Rural** (no small cells) **(615 km^2)**
1- System elements per service area				
OLT shelves	0	0	0	0
Main CO BiDi CWDM TRx	MP: 408 (25G) S1: 408 (40G) S2:0 S3: 108 (3G) S4: 0	MP: 1173 (25G) S1: 1117 (40G) S2: S3: 308 (3G) S4:	MP: 1380 (25G) S1: 1005 (40G) S2: S3: 409 (3G) S4:	MP: 20 (25G) S1: 6 (40G) S2: S3: 356 (3G) S4:
Remote BiDi	MP: 408 (25G)	MP: 1173 (25G)	MP: 1380 (25G)	MP: 20 (25G)

CWDM TRx	S1: 408 (40G) S2: S3: 108 (3G) S4:	S1: 1117 (40G) S2: S3: 308 (3G) S4:	S1: 1005 (40G) S2: S3: 409 (3G) S4:	S1: 6 (40G) S2: S3: 356 (3G) S4:
Main CO and remote grey TRx	MP: 5 (100G) S1: 5 (100G) S2: 821 (100G) S3: 860 (100G) 16 (3G) S4: 821 (100G)	MP: 15 (100G) S1: 15 (100G) 111 (40G) S2: 2361 (100G) S3: 2472 (100G) 46 (3G) S4: 2361 (100G)	MP: 19 (100G) 197 (25G) S1: 19 (100G) 947 (40G) S2: 2977 (100G) S3: 3117 (100G) 58 (3G) S4: 2977 (100G)	MP: 2 (100G) 21 (25G) S1: 2 (100G) 50 (40G) S2: 64 (100G) S3: 190 (100G) 62 (3G) S4: 64 (100G)
Amplifiers	0	0	0	0
CWDM mux/demux 1:16	MP: 66 S1: 66 S2: 14 S3: 14 S4: 14	MP: 184 S1: 176 S2: 36 S3: 36 S4: 36	MP: 222 S1: 174 S2: 48 S3: 48 S4: 48	MP: 46 S1: 44 S2: 42 S3: 42 S4: 42
2- Fibres per service area				
BS ↔ Cab count	MP: 408 (61 km) S1: 408 (61 km) S2: 816 (122 km) S3: 856 (128km) S4: 816 (122 km)	MP: 1173 (528 km) S1: 1229 (553 km) S2: 2346 (1056 km) S3: 2461 (1107km) S4: 2346 (1056 km)	MP: 1578 (1183 km) S1: 1953 (1465 km) S2: 2958 (2218 km) S3: 3103 (2327km) S4: 2958 (2218 km)	MP: 42 (44 km) S1: 56 (59 km) S2: 62 (65 km) S3: 217 (228km) S4: 62 (65 km)
Cab ↔ CO count	MP: 508 (178 km) S1: 508 (178 km) S2: 916 (321 km) S3: 956 (335 km) S4: 916 (321 km)	MP: 1458 (1531 km) S1: 1514 (1589 km) S2: 2631 (2763 km) S3: 2746 (2883 km) S4: 2631 (2763 km)	MP: 1958 (3426 km) S1: 2333 (4082 km) S2: 3338 (5841 km) S3: 3483 (6095 km) S4: 3338 (5841 km)	MP: 367 (898 km) S1: 381 (934 km) S2: 387 (948 km) S3: 542 (1328 km) S4: 387 (948 km)
CO ↔ MCO count	MP: 0 (0 km) S1: 0 (0 km) S2: 0 (0 km) S3: 0 (0 km) S4: 0 (0 km)	MP: 92 (175 km) S1: 199 (379 km) S2: 2364 (4492 km) S3: 2479 (4710 km) S4: 2364 (4492 km)	MP: 308 (1818 km) S1: 1034 (6103 km) S2: 2982 (17594 km) S3: 3127 (18449 km) S4: 2982 (17594 km)	MP: 44 (690 km) S1: 72 (1127 km) S2: 83 (1295 km) S3: 238 (3713 km) S4: 83 (1295 km)
BS ↔ MCO length	MP: 239 km S1: 239 km S2: 443 km S3: 463 km S4: 443 km	MP: 2234 km S1: 2521 km S2: 8310 km S3: 8701 km S4: 8310 km	MP: 6427 km S1: 11650 km S2: 25654 km S3: 26872 km S4: 25654 km	MP: 1632 km S1: 2120 km S2: 2308 km S3: 5269 km S4: 2308 km

* 30% FTTH with no converged usage of existing TWDM PON fibres; in rural 0% FTTH
RAN Splits: MP MAC-PHY; S1 Split I; S2; Split II; S3 Split III; S4 Split IV

Table 35: Dimensioning result for the NG-PON2 network for 5G

2020 reference architecture	Ultra-Dense Urban (2 km^2)	Urban (15 km^2)	Sub-Urban (142 km^2)	Rural (no small cells) (615 km^2)
1- System elements per service area				
OLT shelves	MP: 3 S1: 3 S2: 4 S3: 7 S4: 7	MP: 9 S1: 9 S2: 12 S3: 18 S4: 19	MP: 11 S1: 12 S2: 14 S3: 23 S4: 24	MP: 2 S1: 2 S2: 2 S3: 4 S4: 5
Main CO BiDi CWDM TRx	MP: 408 (25G) 100 (3G) S1: 408 (40G) 100 (3G) S2: 408 (100G) 100 (3G) S3: 424 (100G) 108 (3G) S4: 424 (100G) 24 (10G) 108 (3G)	MP: 1173 (25G) 285 (3G) S1: 1173 (40G) 285 (3G) S2: 1173 (100G) 285 (3G) S3: 1219 (100G) 308 (3G) S4: 1219 (100G) 69 (10G) 308 (3G)	MP: 1479 (25G) 380 (3G) S1: 1479 (40G) 380 (3G) S2: 1479 (100G) 380 (3G) S3: 1537 (100G) 409 (3G) S4: 1537 (100G) 87 (10G) 409 (3G)	MP: 31 (25G) 325 (3G) S1: 31 (40G) 325 (3G) S2: 31 (100G) 325 (3G) S3: 93 (100G) 356 (3G) S4: 93 (100G) 93 (10G) 356 (3G)
Remote BiDi CWDM TRx	MP: 408 (25G) 100 (3G) S1: 408 (40G) 100 (3G) S2: 408 (100G) 100 (3G) S3: 424 (100G) 108 (3G) S4: 424 (100G) 24 (10G) 108 (3G)	MP: 1173 (25G) 285 (3G) S1: 1173 (40G) 285 (3G) S2: 1173 (100G) 285 (3G) S3: 1219 (100G) 308 (3G) S4: 1219 (100G) 69 (10G) 308 (3G)	MP: 1479 (25G) 380 (3G) S1: 1479 (40G) 380 (3G) S2: 1479 (100G) 380 (3G) S3: 1537 (100G) 409 (3G) S4: 1537 (100G) 87 (10G) 409 (3G)	MP: 31 (25G) 325 (3G) S1: 31 (40G) 325 (3G) S2: 31 (100G) 325 (3G) S3: 93 (100G) 356 (3G) S4: 93 (100G) 93 (10G) 356 (3G)
Main CO and remote grey TRx	MP: 12 (100G) 16 (25G) 6 (10G) S1: 12 (100G) 16 (40G) 6 (10G) S2: 28 (100G) 8 (10G) S3: 908 (100G) 14 (10G) 32 (3G) S4: 908 (100G) 110 (10G) 32 (3G)	MP: 34 (100G) 46 (25G) 18 (10G) S1: 34 (100G) 46 (40G) 18 (10G) S2: 80 (100G) 24 (10G) S3: 2610 (100G) 36 (10G) 92 (3G) S4: 2610 (100G) 314 (10G) 92 (3G)	MP: 43 (100G) 58 (25G) 22 (10G) S1: 43 (100G) 58 (40G) 24 (10G) S2: 101 (100G) 28 (10G) S3: 3291 (100G) 46 (10G) 116 (3G) S4: 3291 (100G) 396 (10G) 116 (3G)	MP: 4 (100G) 62 (25G) 4 (10G) S1: 4 (100G) 62 (40G) 4 (10G) S2: 66 (100G) 4 (10G) S3: 376 (100G) 8 (10G) 124 (3G) S4: 376 (100G) 382 (10G) 124 (3G)
Amplifiers	MP: 16 S1: 24 S2: 60 S3: 62 S4: 64	MP: 44 S1: 74 S2: 175 S3: 182 S4: 184	MP: 56 S1: 130 S2: 236 S3: 247 S4: 251	MP: 5 S1: 7 S2: 8 S3: 16 S4: 20
CWDM mux/demux 1:16	MP: 84 S1: 84 S2: 84 S3: 22 S4: 22	MP: 236 S1: 236 S2: 236 S3: 63 S4: 63	MP: 293 S1: 293 S2: 293 S3: 81 S4: 81	MP: 45 S1: 45 S2: 45 S3: 15 S4: 15
2- Fibres per service area				
BS ↔ Cab count	MP: 408 (61km) S1: 408 (61km) S2: 408 (61km) S3: 408 (61km) S4: 408 (61km)	MP: 1173 (528km) S1: 1173 (528km) S2: 1173 (528km) S3: 1173 (528km)	MP: 1479 (1109km) S1: 1479 (1109km) S2: 1479 (1109km) S3: 1479 (1109km)	MP: 31 (33km) S1: 31 (33km) S2: 31 (33km) S3: 31 (33km) S4: 31 (33km)

		S4: 1173 (528km)	S4: 1479 (1109km)	
Cab ↔ CO count	MP: 358 (125 km) S1: 358 (125 km) S2: 358 (125 km) S3: 358 (125 km) S4: 358 (125 km)	MP: 1028 (1079 km) S1: 1028 (1079 km) S2: 1028 (1079 km) S3: 1028 (1079 km) S4: 1028 (1079 km)	MP: 1310 (2293 km) S1: 1310 (2293 km) S2: 1310 (2293 km) S3: 1310 (2293 km) S4: 1310 (2293 km)	MP: 356 (872 km) S1: 356 (872 km) S2: 356 (872 km) S3: 356 (872 km) S4: 356 (872 km)
CO ↔ MCO count	-	MP: 64 (122 km) S1: 64 (122 km) S2: 64 (122 km) S3: 69 (131 km) S4: 69 (131 km)	MP: 82 (484 km) S1: 82 (484 km) S2: 82 (484 km) S3: 89 (525 km) S4: 89 (525 km)	MP: 16 (250 km) S1: 16 (250 km) S2: 16 (250 km) S3: 26 (406 km) S4: 26 (406 km)
BS ↔ MCO length	MP: 187 km S1: 187 km S2: 187 km S3: 187 km S4: 187 km	MP: 1728 km S1: 1728 km S2: 1728 km S3: 1738 km S4: 1738 km	MP: 3886 km S1: 3886 km S2: 3886 km S3: 3927 km S4: 3927 km	MP: 1154 km S1: 1154 km S2: 1154 km S3: 1310 km S4: 1310 km

* 30% FTTH with no converged usage of existing TWDM PON fibres; in rural 0% FTTH
RAN Splits: MP MAC-PHY; S1 Split I; S2; Split II; S3 Split III; S4 Split IV

Table 36: Dimensioning result for the WR-WDM-PON network for 5G

2020 reference architecture	**Ultra-Dense Urban (2 km^2)**	**Urban (15 km^2)**	**Sub-Urban (142 km^2)**	**Rural** (no small cells) **(615 km^2)**
1- System elements per service area				
OLT shelves	MP: 3 S1: 3 S2: 3 S3: 6 S4: 6	MP: 8 S1: 8 S2: 9 S3: 15 S4: 16	MP: 10 S1: 11 S2: 11 S3: 19 S4: 20	MP: 2 S1: 2 S2: 3 S3: 4 S4: 5
Main CO BiDi CWDM TRx	MP: 408 (25G) 100 (3G) S1: 408 (40G) 100 (3G) S2: 408 (100G) 100 (3G) S3: 424 (100G) 108 (3G) S4: 424 (100G) 24 (10G) 108 (3G)	MP: 1173 (25G) 285 (3G) S1: 1173 (40G) 285 (3G) S2: 1173 (100G) 285 (3G) S3: 1219 (100G) 308 (3G) S4: 1219 (100G) 69 (10G) 308 (3G)	MP: 1479 (25G) 380 (3G) S1: 1479 (40G) 380 (3G) S2: 1479 (100G) 380 (3G) S3: 1537 (100G) 409 (3G) S4: 1537 (100G) 87 (10G) 409 (3G)	MP: 31 (25G) 325 (3G) S1: 31 (40G) 325 (3G) S2: 31 (100G) 325 (3G) S3: 93 (100G) 356 (3G) S4: 93 (100G) 93 (10G) 356 (3G)
Remote BiDi CWDM TRx	MP: 408 (25G) 100 (3G) S1: 408 (40G) 100 (3G) S2: 416 (100G) 100 (3G) S3: 424 (100G) 108 (3G) S4: 424 (100G) 24 (10G) 108 (3G)	MP: 1173 (25G) 285 (3G) S1: 1173 (40G) 285 (3G) S2: 1196 (100G) 285 (3G) S3: 1219 (100G) 308 (3G) S4: 1219 (100G) 69 (10G) 308 (3G)	MP: 1479 (25G) 380 (3G) S1: 1479 (40G) 380 (3G) S2: 1508 (100G) 380 (3G) S3: 1537 (100G) 409 (3G) S4: 1537 (100G) 87 (10G) 409 (3G)	MP: 31 (25G) 325 (3G) S1: 31 (40G) 325 (3G) S2: 62 (100G) 325 (3G) S3: 93 (100G) 356 (3G) S4: 93 (100G) 93 (10G) 356 (3G)
Main CO and remote grey TRx	MP: 12 (100G) 16 (25G) 6 (10G) S1: 12	MP: 96 (100G) 46 (25G) 16 (10G) S1: 96	MP: 121 (100G) 58 (25G) 20 (10G) S1: 123	MP: 70 (100G) 62 (25G) 4 (10G) S1: 70

	(100G) 16 (40G) 6 (10G) S2: 28 (100G) 6 (10G) S3: 908 (100G) 12 (10G) 32 (3G) S4: 908 (100G) 108 (10G) 32 (3G)	(100G) 46 (40G) 16 (10G) S2: 98 (100G) 18 (10G) S3: 2610 (100G) 30 (10G) 92 (3G) S4: 2610 (100G) 308 (10G) 92 (3G)	(100G) 58 (40G) 22 (10G) S2: 123 (100G) 22 (10G) S3: 3291 (100G) 38 (10G) 116 (3G) S4: 3291 (100G) 388 (10G) 116 (3G)	(100G) 62 (40G) 4 (10G) S2: 72 (100G) 6 (10G) S3: 376 (100G) 8 (10G) 124 (3G) S4: 376 (100G) 382 (10G) 124 (3G)
Amplifiers	MP: 0 S1: 0 S2: 14 S3: 16 S4: 16	MP: 0 S1: 14 S2: 39 S3: 43 S4: 43	MP: 4 S1: 39 S2: 56 S3: 61 S4: 61	MP: 7 S1: 10 S2: 15 S3: 23 S4: 23
CWDM mux/demux 1:16	MP: 85 S1: 85 S2: 85 S3: 95 S4: 95	MP: 240 S1: 240 S2: 240 S3: 266 S4: 266	MP: 305 S1: 305 S2: 305 S3: 336 S4: 336	MP: 60 S1: 60 S2: 60 S3: 96 S4: 96
2- Fibres per service area				
BS ↔ Cab count	MP: 408 (61km) S1: 408 (61km) S2: 408 (61km) S3: 408 (61km) S4: 408 (61km)	MP: 1173 (528km) S1: 1173 (528km) S2: 1173 (528km) S3: 1173 (528km) S4: 1173 (528km)	MP: 1479 (1109km) S1: 1479 (1109km) S2: 1479 (1109km) S3: 1479 (1109km) S4: 1479 (1109km)	MP: 31 (33km) S1: 31 (33km) S2: 31 (33km) S3: 31 (33km) S4: 31 (33km)
Cab ↔ CO count	MP: 508 (178 km) S1: 508 (178 km) S2: 508 (178 km) S3: 508 (178 km) S4: 508 (178 km)	MP: 1458 (1531 km) S1: 1458 (1531 km) S2: 1458 (1531 km) S3: 1458 (1531 km) S4: 1458 (1531 km)	MP: 1859 (3253 km) S1: 1859 (3253 km) S2: 1859 (3253 km) S3: 1859 (3253 km) S4: 1859 (3253 km)	MP: 356 (872 km) S1: 356 (872 km) S2: 356 (872 km) S3: 356 (872 km) S4: 356 (872 km)
CO ↔ MCO count	-	MP: 19 (36 km) S1: 19 (36 km) S2: 19 (36 km) S3: 21 (40 km) S4: 21 (40 km)	MP: 24 (142 km) S1: 24 (142 km) S2: 24 (142 km) S3: 26 (153 km) S4: 26 (153 km)	MP: 5 (78 km) S1: 5 (78 km) S2: 5 (78 km) S3: 8 (125 km) S4: 8 (125 km)
BS ↔ MCO length	MP: 239 km S1: 239 km S2: 239 km S3: 239 km S4: 239 km	MP: 2095 km S1: 2095 km S2: 2095 km S3: 2099 km S4: 2099 km	MP: 4504 km S1: 4504 km S2: 4504 km S3: 4516 km S4: 4516 km	MP: 983 km S1: 983 km S2: 983 km S3: 1030 km S4: 1030 km

* 30% FTTH with no converged usage of existing TWDM PON fibres; in rural 0% FTTH
RAN Splits: MP MAC-PHY; S1 Split I; S2; Split II; S3 Split III; S4 Split IV

Table 37: Dimensioning result for the WS-WDM-PON network for 5G

2020 reference architecture	**Ultra-Dense Urban (2 km²)**	**Urban (15 km²)**	**Sub-Urban (142 km²)**	**Rural** (no small cells) **(615 km²)**
1- System elements per service area				
OLT shelves	MP: 3 S1: 3 S2: 3 S3: 6 S4: 6	MP: 9 S1: 9 S2: 9 S3: 16 S4: 16	MP: 10 S1: 11 S2: 11 S3: 20 S4: 21	MP: 2 S1: 3 S2: 3 S3: 4 S4: 5
Main CO BiDi CWDM TRx	MP: 408 (25G) 100 (3G) S1: 408 (40G) 100 (3G) S2: 408 (100G) 100 (3G) S3: 424 (100G) 108 (3G) S4: 424 (100G) 24 (10G) 108 (3G)	MP: 1173 (25G) 285 (3G) S1: 1173 (40G) 285 (3G) S2: 1173 (100G) 285 (3G) S3: 1219 (100G) 308 (3G) S4: 1219 (100G) 69 (10G) 308 (3G)	MP: 1479 (25G) 380 (3G) S1: 1479 (40G) 380 (3G) S2: 1479 (100G) 380 (3G) S3: 1537 (100G) 409 (3G) S4: 1537 (100G) 87 (10G) 409 (3G)	MP: 31 (25G) 325 (3G) S1: 31 (40G) 325 (3G) S2: 31 (100G) 325 (3G) S3: 93 (100G) 356 (3G) S4: 93 (100G) 93 (10G) 356 (3G)
Remote BiDi CWDM TRx	MP: 408 (25G) 100 (3G) S1: 408 (40G) 100 (3G) S2: 408 (100G) 100 (3G) S3: 424 (100G) 108 (3G) S4: 424 (100G) 48 (10G) 108 (3G)	MP: 1173 (25G) 285 (3G) S1: 1173 (40G) 285 (3G) S2: 1173 (100G) 285 (3G) S3: 1219 (100G) 308 (3G) S4: 1219 (100G) 138 (10G) 308 (3G)	MP: 1479 (25G) 380 (3G) S1: 1479 (40G) 380 (3G) S2: 1479 (100G) 380 (3G) S3: 1537 (100G) 409 (3G) S4: 1537 (100G) 174 (10G) 409 (3G)	MP: 31 (25G) 325 (3G) S1: 31 (40G) 325 (3G) S2: 31 (100G) 325 (3G) S3: 93 (100G) 356 (3G) S4: 93 (100G) 186 (10G) 356 (3G)
Main CO and remote grey TRx	MP: 12 (100G) 8 (25G) 6 (10G) S1: 12 (100G) 16 (40G) 6 (10G) S2: 28 (100G) 6 (10G) S3: 908 (100G) 12 (10G) 32 (3G) S4: 908 (100G) 108 (10G) 32 (3G)	MP: 34 (100G) 23 (25G) 18 (10G) S1: 34 (100G) 46 (40G) 18 (10G) S2: 80 (100G) 18 (10G) S3: 2610 (100G) 32 (10G) 92 (3G) S4: 2610 (100G) 308 (10G) 92 (3G)	MP: 43 (100G) 29 (25G) 20 (10G) S1: 43 (100G) 58 (40G) 22 (10G) S2: 101 (100G) 22 (10G) S3: 3291 (100G) 40 (10G) 116 (3G) S4: 3291 (100G) 390 (10G) 116 (3G)	MP: 4 (100G) 31 (25G) 4 (10G) S1: 4 (100G) 62 (40G) 6 (10G) S2: 66 (100G) 6 (10G) S3: 376 (100G) 8 (10G) 124 (3G) S4: 376 (100G) 382 (10G) 124 (3G)
Amplifiers	MP: 16 S1: 24 S2: 24 S3: 27 S4: 27	MP: 42 S1: 69 S2: 69 S3: 78 S4: 78	MP: 37 S1: 90 S2: 87 S3: 96 S4: 96	MP: 8 S1: 18 S2: 15 S3: 21 S4: 21
CWDM mux/demux 1:16	MP: 16 S1: 16 S2: 16 S3: 18 S4: 18	MP: 46 S1: 46 S2: 46 S3: 52 S4: 52	MP: 60 S1: 60 S2: 60 S3: 66 S4: 66	MP: 12 S1: 12 S2: 12 S3: 18 S4: 18
2- Fibres per service area				
BS ↔ Cab count	MP: 408 (61km) S1: 408 (61km) S2: 408 (61km) S3: 408 (61km) S4: 408 (61km)	MP: 1173 (528km) S1: 1173 (528km) S2: 1173 (528km) S3:	MP: 1479 (1109km) S1: 1479 (1109km) S2: 1479 (1109km) S3:	MP: 31 (33km) S1: 31 (33km) S2: 31 (33km) S3: 31 (33km) S4: 31 (33km)

		1173 (528km) S4: 1173 (528km)	1479 (1109km) S4: 1479 (1109km)	
Cab ↔ CO count	MP: 508 (178 km) S1: 508 (178 km) S2: 508 (178 km) S3: 508 (178 km) S4: 508 (178 km)	MP: 1458 (1531 km) S1: 1458 (1531 km) S2: 1458 (1531 km) S3: 1458 (1531 km) S4: 1458 (1531 km)	MP: 1859 (3253 km) S1: 1859 (3253 km) S2: 1859 (3253 km) S3: 1859 (3253 km) S4: 1859 (3253 km)	MP: 356 (872 km) S1: 356 (872 km) S2: 356 (872 km) S3: 356 (872 km) S4: 356 (872 km)
CO ↔ MCO count	-	MP: 23 (44 km) S1: 23 (44 km) S2: 23 (44 km) S3: 26 (49 km) S4: 26 (49 km)	MP: 30 (177 km) S1: 30 (177 km) S2: 30 (177 km) S3: 33 (195 km) S4: 33 (195 km)	MP: 6 (94 km) S1: 6 (94 km) S2: 6 (94 km) S3: 9 (140 km) S4: 9 (140 km)
BS ↔ MCO length	MP: 239 km S1: 239 km S2: 239 km S3: 239 km S4: 239 km	MP: 2102 km S1: 2102 km S2: 2102 km S3: 2108 km S4: 2108 km	MP: 4540 km S1: 4540 km S2: 4540 km S3: 4557 km S4: 4557 km	MP: 998 km S1: 998 km S2: 998 km S3: 1045 km S4: 1045 km

* 30% FTTH with no converged usage of existing TWDM PON fibres; in rural 0% FTTH
RAN Splits: MP MAC-PHY; S1 Split I; S2; Split II; S3 Split III; S4 Split IV

8.8 Equipment models

This section discusses extensions to the equipment models that were used in the techno-economic analysis. Section 8.8.1 considers OLT model and extensions toward the UAG. Section 8.8.2 considers implications of integration of WiFi APs in SCs.

8.8.1 The COMBO OLT Model

Figure 115 illustrates the OLT model used for the dimensioning and techno-economic studies. Note that the figure shows detailed modeling of the WDM OLT shelf while details of the TWDM PON OLT shelf are omitted as they are independent of the architectural options that were studied. The WDM OLT shelf model re-uses the work done in the EU FP7 IP OASE project (deliverable D4.2.2 “Technical Assessment and Comparison of Next-Generation Optical Access System Concepts”). The shelf is 11 rack units (approximately 48 cm) high and composed of 20 slots per shelf for line cards of multiple technologies, a switch and the power supply. There are two types of downlink cards for the WDM OLT shelf, i.e., one for mobile transport services (backhaul/fronthaul) and one for fixed access services (cabinet backhaul). The card for mobile transport services is configured as a transponder providing conversion between WDM and short-reach grey optics. The card is used both in a backhaul and fronthaul configuration. Each card is assumed to hold 10 cages supporting 5 channel terminations (fronthaul or backhaul). The second type of card supports fixed access services. It is assumed to hold 10 cages for WDM interfaces and connects to the electrical backplane. The card supports 10 channel terminations connected to the Layer 2 (L2) switch.

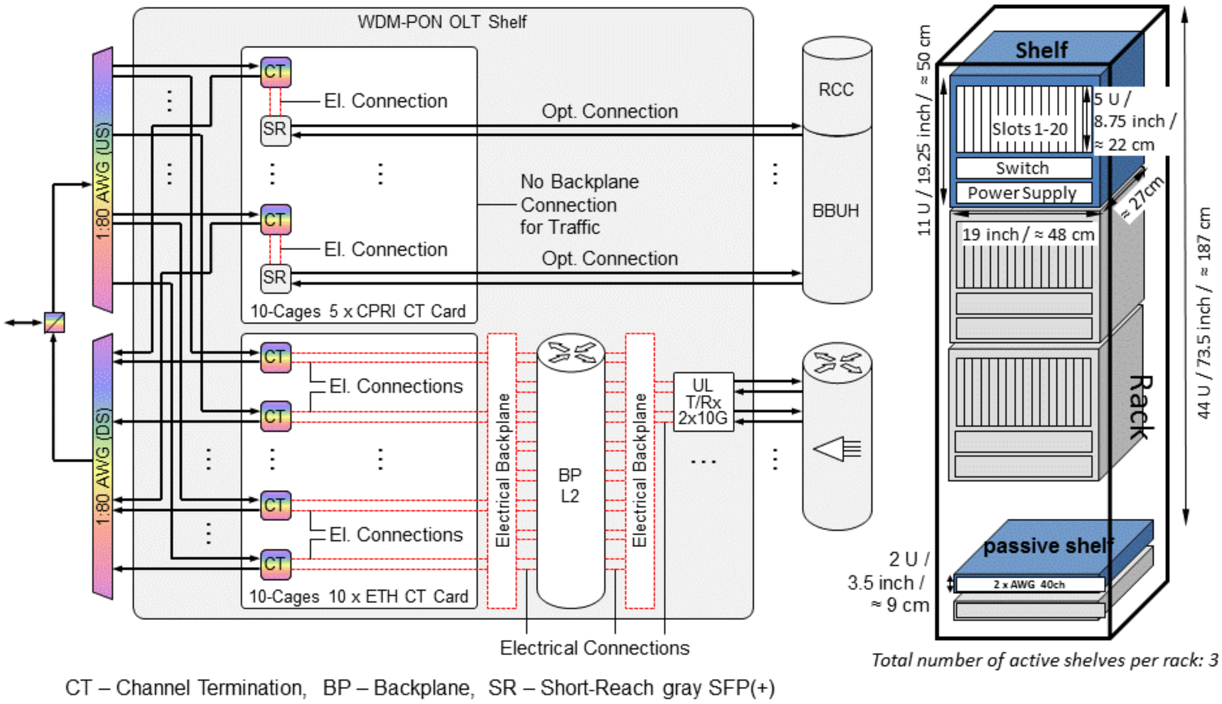


Figure 115: OLT shelf model

The COMBO OLT model includes relevant aspects for capturing cost drivers related to structural convergence.

In the overall COMBO vision, it is assumed that the main CO may be a suitable location for the Universal Access Gateway (UAG). The functionality of the UAG is schematically shown in Figure 116. The UAG has not been part of the modelling of structural convergence but the impact of hosting the UAG at the main CO is illustrated in *Figure 117*. There are several UAG design options, which may incorporate one or multiple of the following:

- Common UAG shelf for multiple types of access cards
- Compute cards (e.g, GPP blades)
- Ultra low latency switch (ULLS)

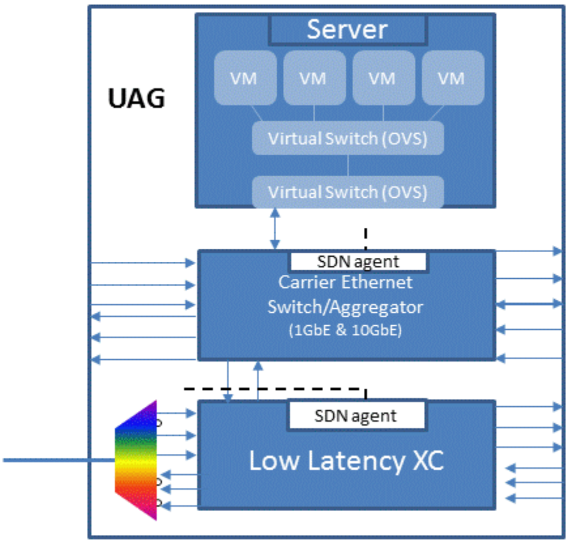


Figure 116: Schematic UAG model

Figure 117 illustrates a design which captures all of these features. Here, the UAG serves as a common shelf for both WDM services and TWDM services. Hence, cards for both TWDM, WDM, fixed/mobile service are supported within the same shelf. The low latency cross connect (XC) or ULLS serves as a backplane for the DL cards. This means that all transport services can be supported by the UAG backplane. Hence compared to the WDM OLT model, the mobile transport cards may be redesigned to exploit the backplane. Additional compute/storage and switching resources may be added to the UAG to provide the required capabilities for hosting various UAG functions.

No major difference concerning conclusions on structural convergence are expected from these modifications. Concerning the number of DL interfaces, footprint and associated costs, the models are more or less similar, with the main differnence concerning the cost difference between the conventional backplane and the ULLS.

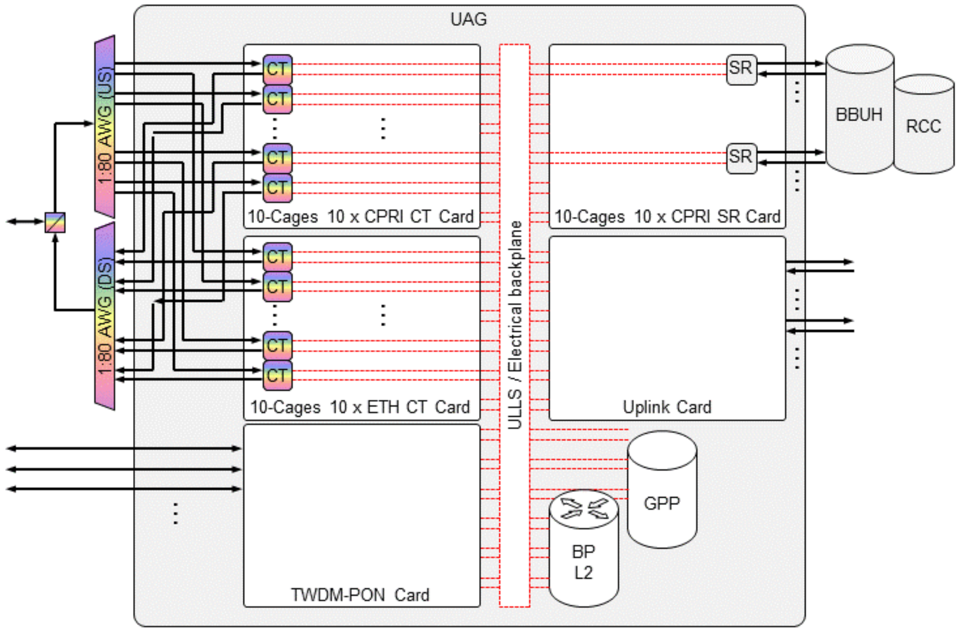


Figure 117: UAG shelf model with ULLS backplane, support for a variety of downlink cards (DWDM, TWDM-PON, etc) and support for processing/storage resources

Novel photonic technologies

Furthermore, photonic integration will bring new components that will impact also the way the OLT is built, which in turn affects modularity of the equipment and how costs scale. New multichannel transceivers will for example reduce costs per transceiver. At the same time, some of the flexibility that is found in an approach based on individual SFP-transceivers will be lost. With individual transceivers, host services (fronthaul, backhaul, residential access, etc.) can be manually configured in the OLT based on need. For multichannel transceivers, a new design of the OLT is required. Reduced flexibility can be compensated by either 1) increasing flexibility in the optical infrastructure or 2) increasing flexibility in the electrical domain for transparently connecting different services to the backside of different multichannel transceivers. The latter approach is depicted in *Figure 118* where each PON is served by a multi-channel transceiver array. A ULLS provides protocol agnostic switching, enables provisioning of different services onto different wavelength channels in the PON.

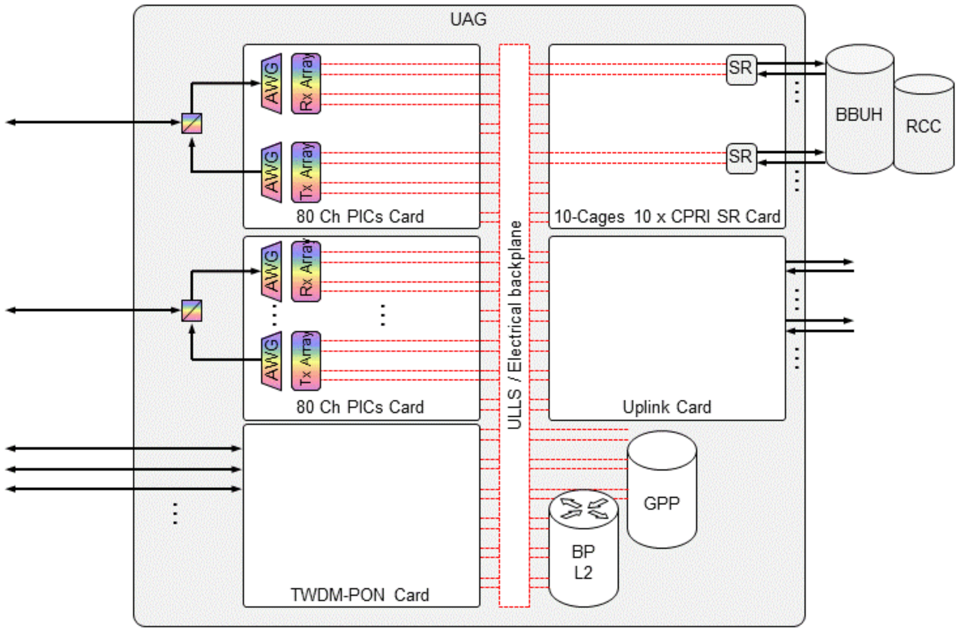


Figure 118: Alternative UAG shelf based on multichannel transceiver arrays

8.8.2 Simultaneous backhaul/fronthaul connectivity to a cell site

There may be several reasons for a site to require both backhaul and fronthaul connectivity simultaneously.

- Multiple RATs at a site which are deployed differently (e.g., fronthaul/backhaul)
- Wi-Fi AP integrated in site is deployed in a fronthaul configuration

The first case with multiple RATs is relevant primarily for macro sites, whereas the second case with integration of a Wi-Fi access point (AC) at the RRU is relevant also for small cells and will be discussed here.

Cell-site equipment (small cells and macro site) may include an integrated Wi-Fi AP. The additional cost of adding this is negigible. For architectures with integrated RBSs, the Wi-Fi backhaul is carried over conventional packet-based cell-site backhaul. For the case of fronthaul, exploiting an integrated Wi-Fi access point requires some additional effort in terms of providing necessary backhaul connectivity.

There are three basic ways of simultaneously providing RRU fronthaul and Wi-Fi AP backhaul to a cell site. These schemes are depicted in *Figure 119* and involve different degrees of convergence: 1) individual fibres, 2) common fibre with individual wavelengths, and 3) common wavelength exploiting TDM multiplexing.

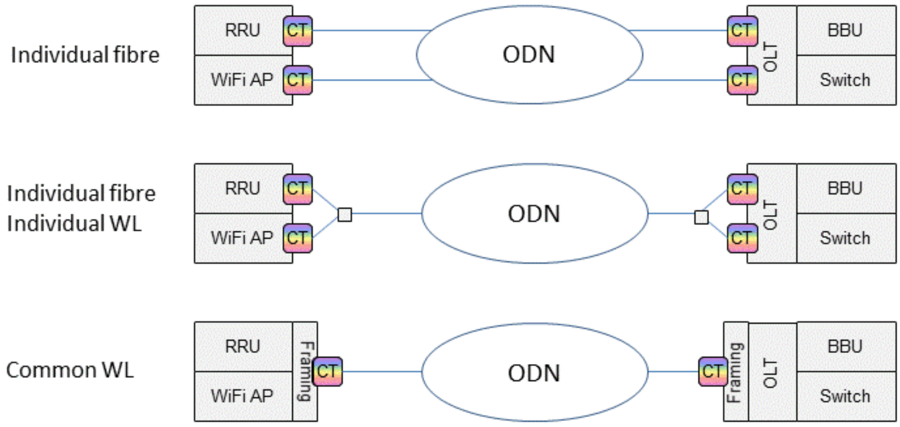


Figure 119: Three main alternatives for simultaneously providing fronthaul and backhaul to a cell site

Table 38 describes these three approaches in the context of the different convergence scenarios, i.e., PtP CWDM, NG-PON2 with WDM-overlay, WR-WDM-PON and WS-WDM-PON.

Table 38: Different approaches for RRU fronthaul and Wi-Fi AP backhaul to a cell site

	PtP CWDM	NG-PON2 w/ WDM-overlay	WR-WDM-PON	WS-WDM-PON
Individual fibre	RRU: CWDM Wi-Fi AP: NG-PON2 Comments: Preferable solution for this architecture	RRU: WDM overlay Wi-Fi AP: NG-PON2 Comments: Complex compared to common fibre and individual wavelengths	RRU: WR-WDM-PON Wi-Fi AP: NG-PON2 Comments: Preferable solution for this architecture	RRU: WR-WDM-PON Wi-Fi AP: NG-PON2 Comments: Preferable solution for this architecture
Common fibre, individual wavelength	RRU: CWDM Wi-Fi AP: CWDM Comments: Requires modification to ODN to support multiple clients in the drop segement. Uncessary complexity unless dedicated wavelengths are required for Wi-Fi backhaul.	RRU: WDM overlay Wi-Fi AP: NG-PON2 Comments: Preferable solution for this architecture	RRU: DWDM Wi-Fi AP: DWDM Comments: Requires modification to ODN to support multiple clients in the drop segement. Uncessary complexity unless dedicated wavelengths are required for Wi-Fi backhaul.	RRU: DWDM Wi-Fi AP: DWDM Comments: Uncessary complexity unless dedicated wavelengths are required for Wi-Fi backhaul.
Common wavelength	RRU: DWDM (framing) Wi-Fi AP: CWDM (framing) Comments: Requires additional complexity both cell site and the OLT	RRU: DWDM (framing) Wi-Fi AP: DWDM (framing) Comments: Requires additional complexity both cell site and the OLT	RRU: DWDM (framing) Wi-Fi AP: DWDM (framing) Comments: Requires additional complexity both cell site and the OLT	RRU: DWDM (framing) Wi-Fi AP: DWDM (framing) Comments: Requires additional complexity both cell site and the OLT

In all cases, the simplest solution is to provide a fixed access connection to the site for the Wi-Fi AP backhaul. For PtP CWDM, WR-WDM-PON, WS-WDM-PON this involves an extra fibre connection and per cell site. For NG-PON2, the available fibre can be reuesed, but an additional TRx per cell site is required.

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