D3.3 - Analysis of transport network architectures for structural convergence

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Executive Summary of the Deliverable

COMBO's Work Package (WP) 3, is mainly focused on fulfilling the first target of the project:

- **Target 1**: 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.

This deliverable (D3.3) addresses the Specific Objective SO1.4 to "*develop FMC architectures*" or, more specifically, develop converged network architecture options for fixed and mobile access and aggregation networks. This is necessary in order to cope with the high cost pressure and stagnating network operator revenues from the current network architecture as well as to deal with the steep increase in traffic demand. As a matter of fact, the transport architecture for future access and aggregation networks need to be much more streamlined and cost-efficient than current solutions; understanding the potential of structural convergence of fixed and mobile networks is vital for achieving this goal.

One central question regarding convergence is the following: Assuming there is a widespread fixed fibre infrastructure for residential customers in 2020, can it be reused for/shared with mobile small cell and macro cell deployments or do operators need to deploy a dedicated transport network for mobile traffic?

To answer this question, COMBO developed FMC architecture options taking into account the expected evolution in fixed and mobile networks, such as centralised RAN, heterogeneous networks, and CO consolidation:

- Backhaul with radio coordination controller centralised at the Main CO
- Fronthaul with RCC and BBU hotel centralised at the Main CO

The WS/WR-WDM-PON and NG-PON2 were the investigated transport technologies for the converged architecture options. These were compared with the PtP CWDM technology for a 2020 reference architecture, which was developed assuming a non-converged evolution of today's network architecture. The target in all converged scenarios was to combine as much as possible all backhaul (fixed and mobile) and/or fronthaul clients on the same transport technology and fibre infrastructure. NG-PON2 is the only transport technology supporting convergence at technology- as well as fibre infrastructure-level. All other technologies require separate fibre infrastructure for fixed residential and mobile fronthaul/backhaul services, allowing "only" technology-level convergence. The developed converged architecture options are dimensioned and analysed for different transport technologies.

To summarise, the key findings from the investigations in this deliverable are:

- The reference PtP CWDM solution, with limited convergence potential, is in all cases the most expensive solution.
- In an FTTC deployment scenario, WR-WDM-PON is always the cheapest solution independent of fibre cost.
- For low number of deployed small cells NG-PON2 suffers from the bad utilization of PtP WDM hardware, such as AWGs, due to the pre-defined mass

market splitting structure. This drawback of NG-PON2 can be somewhat mitigated by adapting the design of the system architecture.

- 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.
- Considering only system CapEx without fibre cost as an artificial case, WR-WDM-PON is always the cheapest solution, independent of backhaul/fronthaul architecture, or the number of deployed small cells.
- The preferred location for BBU placement is at or even below the level of the Main CO, due to the LTE HARQ latency requirements leaving only 75-250 μs one-way delay for the fibre transport between an RRU and BBU. However, in case Main COs are equipped with switching equipment supporting also optical bypass, fronthaul traffic can be transported over the existing aggregation network, resulting in a more aggressive scenario where BBU hotels could be located at higher levels than Main COs.
- As for BBU hotel deployment strategies, a preliminary analysis of a novel BBU cost model shows that costs savings are more pronounced in more centralized options, and this strongly depends on the pooling gain that can be offered.
- A key question for the control/management is what type of coordination will be required/beneficial between different domains (radio, transport, fixed access, IT, etc.) in different convergence scenarios. Flexible system variants based on flexibility in the WDM layer are designed to demonstrate the degree of flexibility that is feasible. It is found that flexible WDM systems are feasible for urban and ultra-dense urban scenarios while sub-urban and rural scenarios require extensive use of optical amplifiers.

Based on the work in this deliverable, Task 3.3's second and final deliverable (D3.4), will "*determine [the] most suitable FMC architectures*" (SO1.5). While D3.3 is focused on the evolution of existing networks towards convergence, D3.4 will consider the requirements from 5G and assess their impact on the convergence of access and aggregation networks.

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1 Introduction

Current mobile and fixed networks have been developed and standardized almost independently from each other over the last decades. Therefore, the current level of pooling and sharing between fixed and mobile infrastructure and equipment resources, called structural convergence [1], is low and does not support an efficient use of all available network resources, whether fixed, mobile or Wi-Fi. However, upcoming 5G networks are envisioned to be designed with a high level of network convergence in mind [2]. Whereas Task 3.2 is focused on the functional convergence of networks [3], the goal of COMBO's Task 3.3 is to define and develop candidate architecture 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 site up to the Core Central Office (CO), which is the boundary between the aggregation network and the core network.

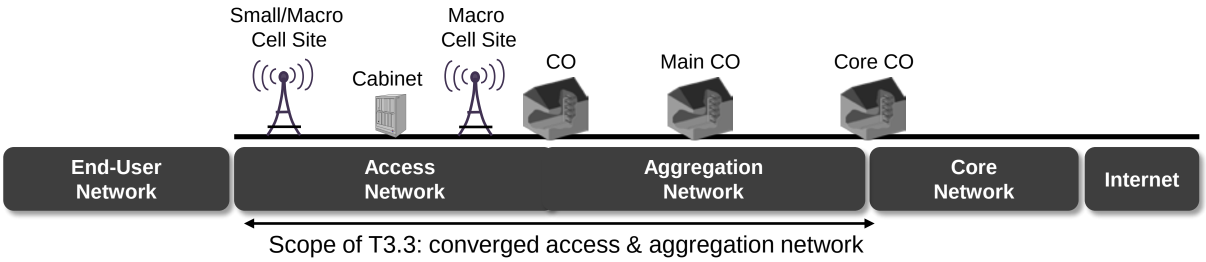


Figure 1: The scope of study of Task 3.3 – from cell sites up to the Core CO

This deliverable describes and analyses converged access and aggregation transport architecture taking into account the boundary conditions from fixed access network evolution (like access node consolidation) and from mobile networks evolution (like need for coordination between new mobile sites). As a matter of fact, the future transport architecture needs to be much more cost-efficient than current solutions. Understanding the potential of structural convergence based on available transport technologies and the requirements from network evolution paths is vital for streamlining future fixed and mobile infrastructures.

This deliverable addresses one central question regarding convergence: Assuming there is a widespread fixed fibre infrastructure for residential customers in 2020, can it be reused for/shared with (possibly with some adaptations) mobile small cell and macro cell backhaul traffic? Or do operators need to deploy a dedicated network for mobile traffic?

The focus of this deliverable is on the network evolution path towards convergence, whereas D3.4 will take into account the requirements from 5G, which are still under discussion, and assess their impact on the convergence of access and aggregation networks.

The deliverable is organized as follows:

Chapter 2 presents the motivations for structural convergence. In Chapter 3, we present the Radio Access Network (RAN) architecture options investigated in the two deliverables of this task, including the data rate and latency requirements on the transport network. These converged architecture options are further detailed in Chapter 4.

In Chapter 5, we present the baseline or reference architecture used in the comparison with the converged architecture options. This reference architecture in 2020 includes no or a low level of convergence. Chapter 6 presents different technologies for the converged architecture options, including a qualitative comparison between these options, whereas an initial quantitative cost comparison and analysis is presented in Chapter 7.

Chapter 8 complements the previous work by analysing the assumptions and making a case study. Chapter 9 presents a future outlook towards 5G and the expected requirements based on an analysis of the NGMN 5G white paper [2] and the work in FP7 METIS [4], which will be used to further investigate the scaling potential of the proposed transport technologies.

Finally, Chapter 10 summarizes the achievements and findings of this work as well as how it will be used in the future work of the project.

2 Motivation for Structural Convergence

Fixed, Wi-Fi and mobile networks have been independently developed and are, especially in the access network segment, separated in terms of infrastructure (fibres), systems as well as planning, design and operation. Today, there is only a partial convergence in the aggregation network [1]. Furthermore, the network termination points of fixed and mobile networks are not at the same location. There is typically no common location between the fixed network nodes (e.g., the cabinets) and the mobile network nodes (e.g., the radio base stations) because these are planned by different criteria. Due to the huge number of end points in the fixed network, the access structure and topology is clearly determined by the fixed network. In the past (2G, 3G and initial deployments of 4G), the number of radio base stations (mobile and public Wi-Fi) and the low traffic amount generated in these networks, did not have a significant impact on the fixed access and aggregation network traffic (Chapters 3 and 5 in [6]).

With the evolution of 4G, Wi-Fi, and the future development of 5G, including 3rd Generation Partnership Project (3GPP) radio access over unlicensed bands, a strong increase of wireless traffic is forecasted, which leads to both a capacity upgrade of existing macro base stations and Wi-Fi access points but as well as a significant deployment of new low cost radio sites with smaller cell diameter. The densification of radio sites brings the fixed and mobile network topologies closer together and the strongly increasing numbers of radio sites require new cost-efficient connections. Furthermore, new centralised RAN concepts [55] and fixed-access network-node consolidation [61] enables co-location of equipment from fixed and mobile networks. These developments together with increasing fibre roll out in the fixed access network towards Fibre to the Cabinet (FTTC) or even Fibre to the Home (FTTH) deployments foster the design of a structurally converged access and aggregation network targeting clearly cost-minimised network deployments. This can be achieved by an optimal pooling / sharing of available network infrastructure (e.g., ducts, cables, fibres, and locations) between the different types of networks as well as the usage of a common transport technology as far as possible.

The development of a converged access and aggregation network has to cope with the foreseeable network evolution for the fixed, Wi-Fi and mobile networks, including the evolution to 5G. For the fixed access network, this evolution includes node consolidation, concentration of access equipment in the Main CO, and the roll out of a passive fibre network towards the residential customers in an FTTC or FTTH approach, as studied in the FP7 project OASE [61]. Besides enhancements of mobile network capacity on the antenna side by technology improvements (e.g., Multiple Input, Multiple Output [MIMO]) and new frequency spectra, which already generate higher requirements on the transport network to connect the sites, densification of radio sites raises other challenges. The addition of a potentially large amount of new sites operating on the same radio frequencies, which will be necessary because of the scarce frequency resources, creates interference problems that significantly limit the throughput performance of the air interfaces. To avoid this and to get maximum coordination gain, coordination among the neighbouring radio cells is preferred. Therefore, it is preferred to have a radio coordination controller in the network, either centralised or distributed, to take care of the coordination between adjacent radio sites. The challenge is how and where to place such coordination controllers, which have an impact on the required site interconnections because the exchange of necessary information for coordination results in additional traffic and delay constraints.

Another strong impact comes from RAN centralisation aiming at better pooling of radio resources and compact radio units. The related challenges are illustrated in particular in [55]. This approach also drives the transport requirements. All these aspects will be discussed in detail in Chapter 3.

Based on the requirements and restrictions arriving from future mobile evolutions, COMBO proposes options for a converged architecture handling fixed access, Wi-Fi backhaul and mobile backhaul/fronthaul. This deliverable analyses these architecture options by applying different transport technologies to establish the required connections on the same fibre or wavelength. The driver here is to technically realize as much convergence as possible and then review this converged solution by its associated cost structure. As already analysed by OASE [61], solutions based on Time and Wavelength Division Multiplexing (TWDM) and Wavelength Division Multiplexing (WDM) were identified as the most cost-effective solutions for residential access supporting node consolidation compared to Orthogonal Frequency Division Multiplexing (OFDM) or Code Division Multiplexing (CDM), etc. Therefore, COMBO focuses on Next Generation Passive Optical Network version 2 (NG-PON2), and WDM PON in different flavours as solutions for achieving convergence. Today's preferred backhaul solution, Coarse WDM (CWDM), is assumed as a reference for the comparison. NG-PON2 and WDM for access are currently under development and partly standardised. Note that other technologies for residential broadband access, such as Hybrid Fibre Coaxial (HFC), could be considered and integrated into the COMBO architecture options in a similar way as Digital Subscriber Line (DSL). However, these alternative technologies have not been included in order to focus on the most realistic solutions for integration of fixed access with mobile backhaul and fronthaul networks.

The essential questions are: "*Does structural convergence provide an economical benefit?*" and if so, "*Which transport technology is most suitable for structural convergence*?" In more detail, the research questions for structural convergence considered in this deliverable D3.3 and in next deliverable D3.4 are:

- How much structural convergence can be reached technically and economically?
- Which are the advantages and disadvantages of the different architecture variants?
- Given a start scenario with NG-PON2 TWDM PON for fixed access with Optical Line Termination (OLTs) at the Main CO, what is the optimal way to serve mobile fronthaul and backhaul?
- What is cost vs benefit of flexible wavelength switching for different convergence scenarios?

- Is a full convergence with an NG-PON2 mass-market system approach economically feasible compared with transport convergence with dedicated WDM PON?
- How do the technologies support network adaptability and scalability to deal with continuously increasing data rates, specifically with respect to 5G, and between geographical areas?
- What is the impact of delay requirements arising from RAN centralisation and coordination on the architecture?
- Where to place the commonly used resources in a centralised RAN architecture?

3 Network Design Considerations for 2020 and Beyond

This chapter deals with structural convergence architecture, targeting a unified and cost-efficient access and aggregation network for fixed and mobile services.

Densification of cells in a heterogeneous network architecture drives the need for scalable and cost-efficient networks and is a promising option to increase mobile capacity. On one hand, this could be achieved by increasing the number of Macro Base Stations (MBSs). However, this will be very cost intensive, especially in ultra-dense and dense urban areas, due to required long-term planning, renting agreements and identifying suitable locations. On the other hand, capacity could be increased where needed by adding more simple and less expensive small cells as a supplement to the existing MBSs. This approach is in the focus of COMBO. Nevertheless, in certain (e.g., rural) areas, MBS could be densified as well. The small cells are part of the heterogeneous network concept.

The interference situation due to operation of MBS and small cells on the same frequencies in such heterogeneous networks requires radio coordination. In general, there is also the option to avoid coordination by operation on separate frequencies. However, due to the scarce spectrum it is most likely that neighbouring cells will operate on the same frequencies requiring coordination. The radio coordination as well as the RAN implementation has strong impact on the architecture design with respect to topology, transport delay and bandwidth as well as the placement of equipment. This is described in the following sections.

3.1 Impact of Radio Coordination

Coordination in a radio network takes place among a group of radio cells operating on the same frequency band. The Remote Radio Units (RRUs) of the corresponding radio cells that are coordinated form a so-called coordination cluster. The cluster can include either RRUs that are located at the same site (intra-site coordination) or also RRUs spread over different sites (inter-site coordination).

Today, there are two dominant RAN transport architecture options: backhaul and fronthaul. Backhaul links enable the so-called Distributed RAN (D-RAN), whereas fronthaul links enable Centralised RAN (C-RAN) [55]. In a C-RAN, the radio coordination is controlled by centralised Baseband Units (BBUs), located in a BBU Hotel (BBUH). In a D-RAN, the coordination can be done with or without a central entity; called Radio Coordination Controller (RCC) in the following [59], [60].

The link between the central coordinator (RCC/BBUH) and the coordinated radio cells must fulfil certain requirements, especially in terms of delay, related to Coordinated Multi-Point (CoMP) transmission and reception [66]. Table 1 shows a broad classification of coordination schemes including their expected gains and delay requirements. Radio coordination will be required even in 5G (which is just in the starting phase of description) in co-channel deployments. It is currently expected that these requirements will not be more stringent than the very tight coordination schemes of Long Term Evolution-Advanced (LTE-A).

Table 1: Coordination schemes and their requirements

Coordination Classification	Coordination Feature	Max Throughput Gain	Max Capacity Gain	One-Way Delay Class
Very Tight Coordination	Fast UL CoMP (UL joint reception/selection)	High	High	0.1-0.5 ms
	Fast DL CoMP (coordinated link adaptation, coordinated scheduling, coordinated beamforming, dynamic point selection)	Medium	Medium	
Tight Coordination	Slow UL CoMP	Medium	Small	1-20 ms
	Slow DL CoMP (e.g., Postponed Dynamic Point Blanking)	Small	Small	
Moderate Coordination	FeICIC	Medium	Small	20-50 ms

Small: ≤20%
Medium: 20-50 %
High: ≥ 50%

The focus of the work in COMBO is on the tight and very tight coordination schemes requiring very low delay, below 1 ms, since these schemes are enabling the highest coordination gains and at the same time putting the most tight delay constraints for the potential architecture options and underlying transport solutions.

3.2 RAN Architecture Options

Whilst there is an absolute ambition in COMBO to secure future support for 5G, the nature of this 5G is still under definition. The telecom industry seems to be reaching a consensus regarding how 5G relates to its predecessors, not least LTE and LTE-A, which have proven to provide extremely robust and optimised solutions. One still open key issue from a transport/backhauling perspective and, hence, of high relevance to COMBO and structural convergence, is how the new 5G radio nodes will be backhauled. One obvious direction would be by looking at 4G, where we see two dominant ways of connecting the small cell sites: Packet-based backhauling of a full MBS or Common Public Radio Interface (CPRI)-based fronthauling of RRUs. With 5G, the industry is also exploring other options, including splitting higher up in the RAN stack in order to keep the 5G small cells as simple as possible as well as to be able to sustain their requirements for connectivity. At the same time, there are also efforts ongoing to explore less demanding versions of fronthauling. As for COMBO, the only reasonable approach has been to base our assumptions on existing models, and not speculate too much on potential 5G scenarios. As 5G gets increasingly clear, we will analyse potential network impacts and account for this in the next deliverable.

Today, radio sites are typically connected via dedicated fixed access links or microwave to the fixed aggregation network. From there the traffic is tunnelled through towards the mobile core following the fixed network structure. This results in a centralised topology where all physical network links are through-connected up to an access router in a Core CO.

The LTE RAN architecture is designed without any centralised RCC. Therefore, communication among the eNBs is required to enable, e.g., handover or radio coordination. For this purpose, a so called X2 interface is established and standardised. The interconnection of the X2 links is done via the access router in the Core CO. Today's LTE RAN architecture requires end-to-end delays for S1 user plane transport between 10 ms (near EPC) and 50 ms (far EPC) according 3GPP TS23.203 as well as for X2 control plane transport between 30-50 ms according to 3GPP TS 36.133 for classical handovers and simple coordination schemes like enhanced Inter-Cell Interference Coordination (eICIC) of 3GPP Release 10. As shown in Table 1 for tight coordination, latencies < 1 ms are required. Due to this requirement X2 links for coordination cannot be connected up to a centralised access router at the core node as done today. Instead, they need to be connected to a less centralised location, e.g., to a RCC at the Main CO.

The following sections discuss the impact and interdependencies of backhaul and fronthaul architecture options and the coordination requirements and conclude this chapter by describing different implementation strategies.

3.2.1 Backhaul Architecture

The following figure shows a high-level overview of the backhaul transport network principal. The macro- and small- cell BBUs are located in its own cell site and backhauled via Internet Protocol of Ethernet (IPoE) links. The backhaul transport dimensioning in the access network mainly depends on the mobile technology, the radio configuration as well as the applied radio coordination schemes of Section 3.1, taking into account data rate, latency and synchronisation requirements. The radio configuration is typically designed for offering a sustainable data rate during the busy hour and a certain peak data rate, driven by technology evolutions. The backhaul link is typically dimensioned according to the peak data rate of cell, e.g., 150 Mb/s for 20 MHz LTE [43].

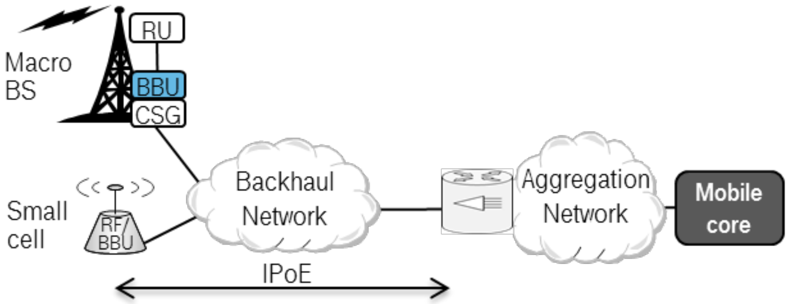


Figure 2: Backhaul transport network principal

Radio coordination in heterogeneous networks, as explained in Section 3.1, and features such as dual-mode LTE-TDD/FDD result in higher backhaul requirements as shown below:

- Additional traffic on X2 interface for radio coordination
- Round Trip Time (RTT) latency <1 ms is required for some schemes (e.g., CoMP JT, see Table 1)
- Frequency synchronization, e.g., via Ethernet Physical Layer Synchronization (SyncE) +/-50 ppb for conventional transmission and ±5 ppb for some coherent CoMP schemes

- Phase/time synchronization coherency via Precision Time Protocol (PTP) according to IEEE1588-2008 and ITU-T G.827x with max phase time error ±500 ns (location based services ±200 ns) and max. delay difference of 2.6 µs

For the dimensioning of the backhaul link capacity the sum of LTE-A S1 (user traffic) and X2 (eNB interconnection traffic) peak traffic per site, and for MBS also Universal Mobile Telecommunications Service (UMTS) and GSM traffic, have to be taken into account per operator. According to NGMN backhaul dimensioning rules, backhauling with peak data rate of one sector is sufficient for a site (90% quantile) [43] due to statistical gains. Larger spectrum and HO-MIMO as well as additional X2 traffic for radio coordination drive the need for backhaul link capacities of >1 Gb/s, especially for MBS with up to 4 Gb/s in extreme cases with, e.g., 100 MHz spectrum and 8x8 MU-MIMO, as shown in the Figure 3. Based on expert estimations by Ericsson and Deutsche Telekom, a typical mixture of the radio coordination schemes will be considered as start configuration for the capacity dimensioning, resulting in additional 30% of the S1 data rate for the X2 interface. Additionally, UMTS and GSM data rates estimation of entirely 50 Mb/s for one operator will be considered for MBS backhaul.

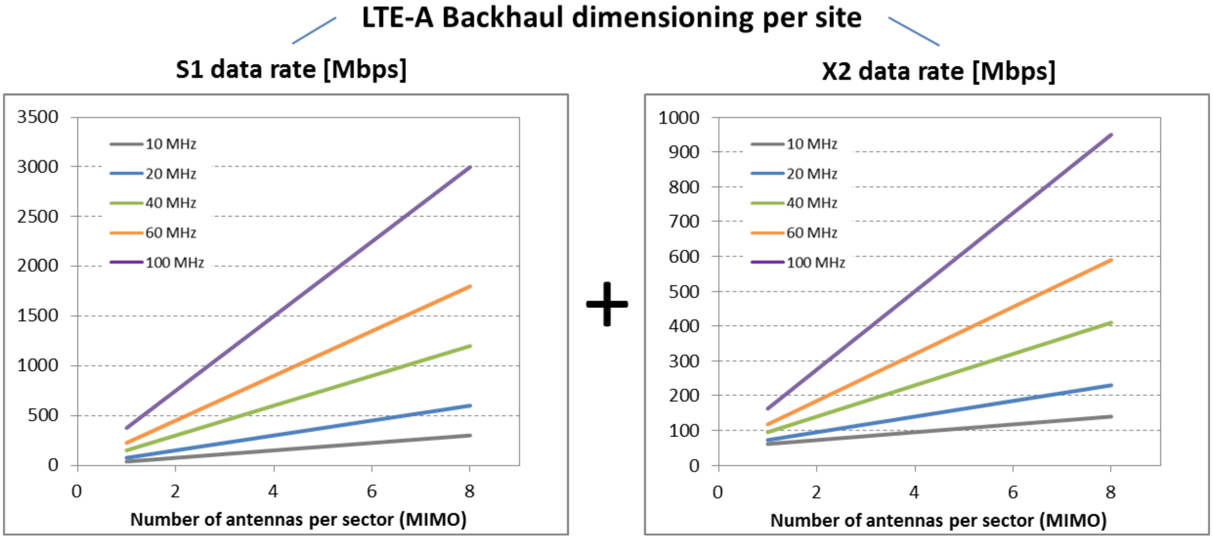


Figure 3: LTE-A Backhaul dimensioning per site

3.2.2 Fronthaul Architecture

The following figure shows a high-level overview of the fronthaul transport network principal. The BBUH is located in a central location (e.g., Main CO), leaving only the RRU at the cell site. The distance between the RRU and the BBUH is constrained by the timing requirement of the respective radio technology. For LTE, the Hybrid Automatic Retransmit reQuest (HARQ) protocol is used as a retransmission mechanism between UE and eNB. The standard foresees less than 3 ms for BBU processing. If the BBU is moved away from RRU, the additional delay caused by the fibre transport needs to be considered. To limit the impact of the additional delay on HARQ, the delay needs to be very restricted [56]. Depending on vendor implementation, the RTT is in the range of 150-500 µs [12], [57].

Between RRU and BBU, digital complex antenna baseband data (I/Q samples) are transported, resulting in high bandwidth [55]. Different transport protocols like CPRI or Open Base Station Architecture Initiative (OBSAI) have been proposed, where CPRI is the most common [55].

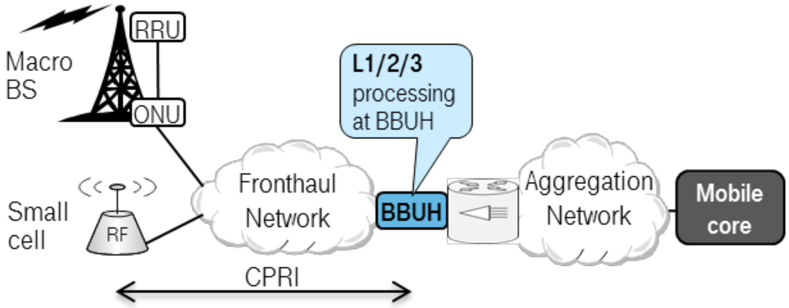


Figure 4: Fronthaul transport network principal

The main driver for the fronthaul concept is improved operational efficiency by reducing space at the antenna site, joint location of BBUs from different antenna sites in a BBUH and thus enabling sharing of BBU resources.

Figure 5 shows exemplarily a fibre link based latency analysis for a maximum tolerable transport delay (RTT) of 400 µs. In this study, no data processing in between is considered. We chose 400 µs rather than 500 µs as stated in [12], [57] in order to allow a safety margin for the upper-bound RTT / reach calculation.

A placement of the BBUH at a Core CO would limit the reachable antennas to less than 37%. Therefore, the Main CO location is the preferred location for placement of active equipment and offers the best opportunity for both a high BBUH centralisation degree and a high number of reachable antennas, while also supporting fixed network node consolidation. The analysis of the low delay requirement for fronthaul as well as for coordination also confirms this location.

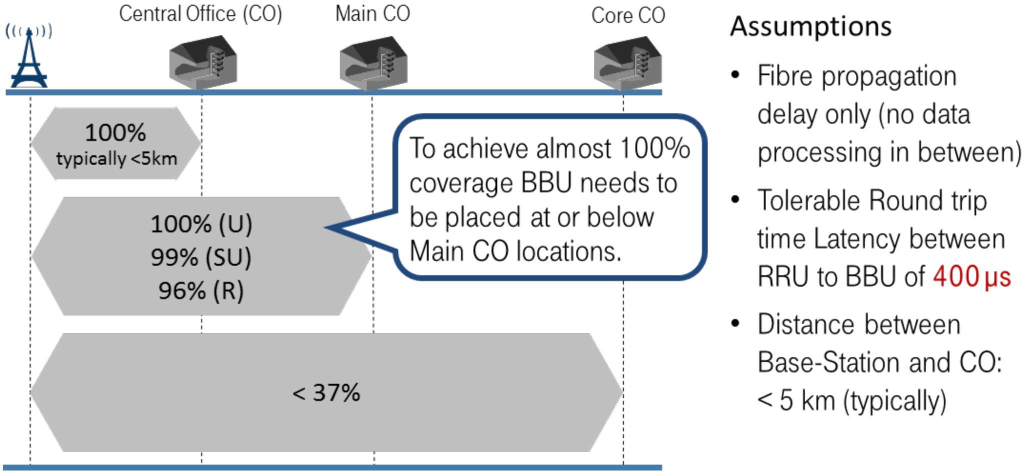


Figure 5: Antenna coverage for different BBU placements and different geotypes (urban, sub-urban, and rural) for a RTT latency of 400 µs

As already mentioned, the exact latency constraint for fronthaul links is still under discussion. A liaison was sent in April 2015 by ITU-T on this subject [62]. By this liaison statement, ITU-T Q2/15 asks 3GPP as well as NGMN for timings clarification between BBU and RRU, i.e., the fronthaul link. For example, Ericsson considers a rule of thumb of 150 µs RTT for current LTE Centralised-RAN deployments, to be compatible with LTE-Advanced, and possibly even lower values for 5G. In order to illustrate the impact of this latency requirement on coverage of antenna sites by COs, Figure 6 represents the cumulated number of antenna sites versus the link length between the antenna site and the nearest Main CO, Core CO, or IP mobile backbone node of the operator. These numbers were derived from a sample of more than 9,000 antenna sites in typical high density areas (urban and ultra-dense urban) in a European country. Even with the tight 150 µs RTT limit, 90% of the antennas are under the fronthaul coverage of a Main CO, which confirms the Main CO as the best trade-off between BBUH centralisation degree and reachable antennas. Figure 6 also shows the coverage with maximum allowed RTT, where again we used 400 µs.

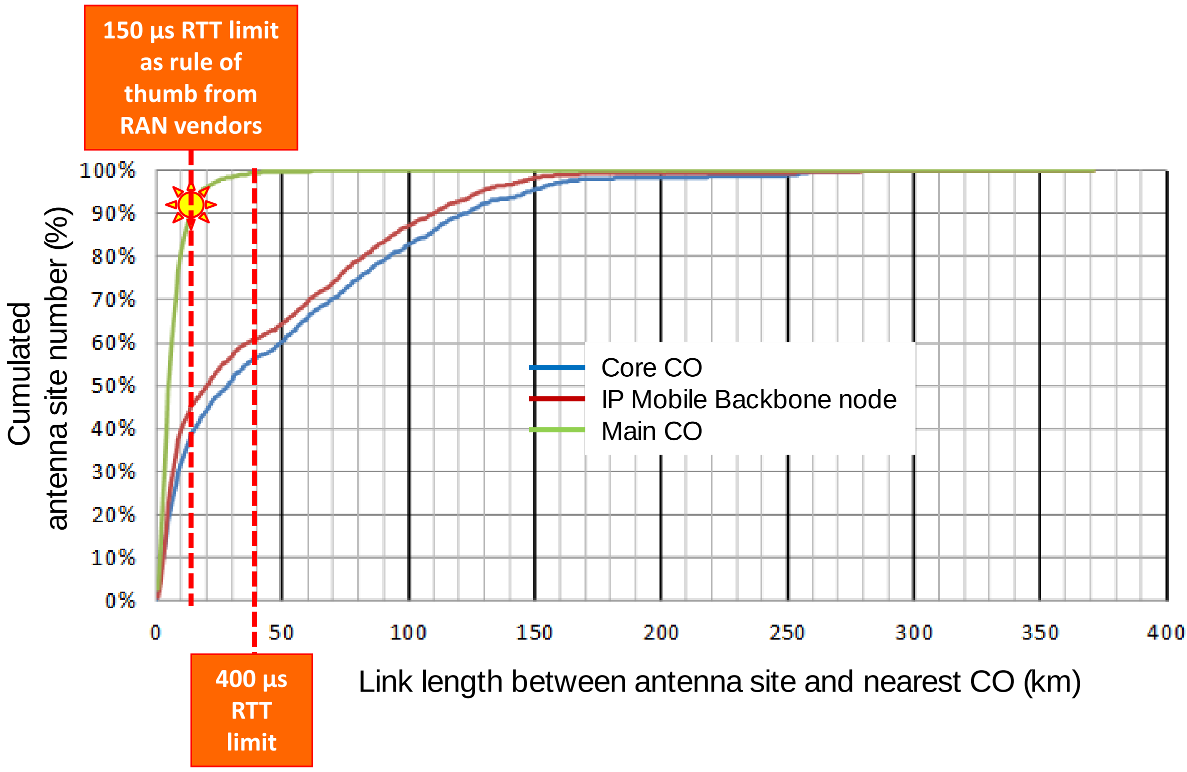


Figure 6: Coverage of antenna sites by Main COs, Core COs and IP mobile backbone node, in relation to fronthaul link maximum length

The fronthaul concept supports inherently all radio coordination schemes, described in Section 3.1, since the BBUH is in charge of processing the entire baseband signals on L1/2/3. Basically, the BBUH has X2 Interfaces for the communication between the BBU processing of neighbouring cells. The fronthaul transport dimensioning in the access network mainly depends on the mobile technology and the applied radio configuration, which determine the CPRI radio signal data rate.

Since the complex I/Q samples are transported via CPRI, the traffic is constant and independent from the real user traffic.

The fronthaul link capacity demand depends on the used spectrum and MIMO configuration as shown in Figure 7.

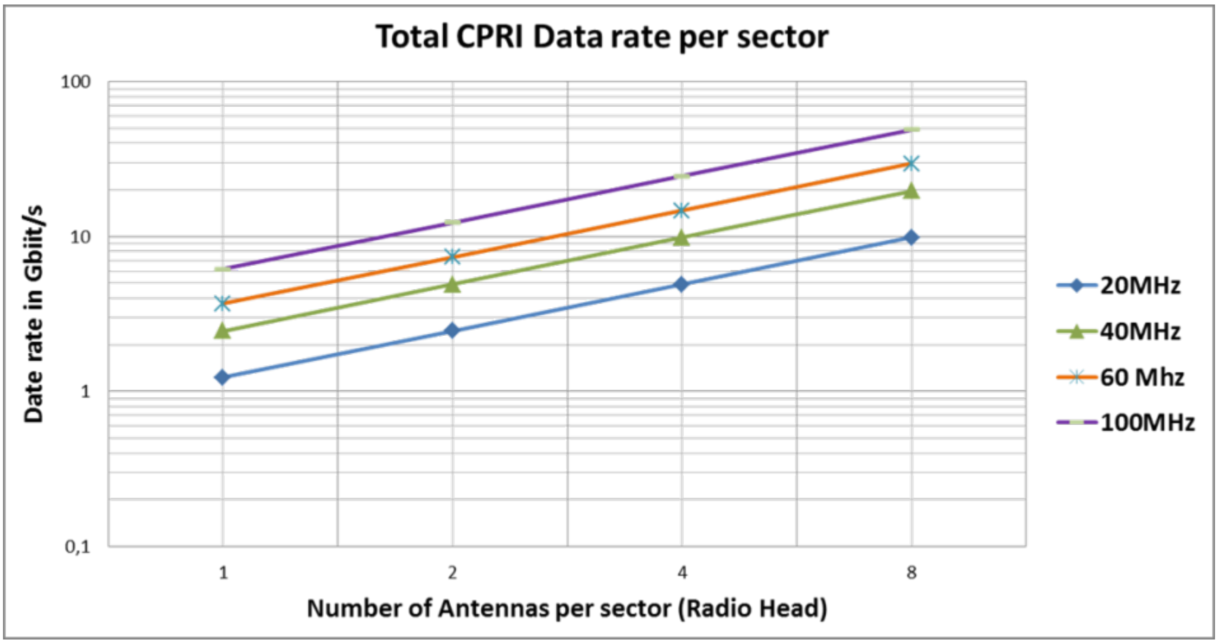


Figure 7: LTE-A CPRI data rate per sector

As obvious in Figure 7, fronthaul of MBS may become challenging under consideration of significant spectrum increase and massive MIMO due to the high transport capacity, which will result in scalability and cost issues.

3.2.3 Midhaul Architecture

Between backhaul and fronthaul as described in sections 3.2.1 and 3.2.2, a third variant is likely to develop in the future, called *midhaul*. Depending on the exact definition, the resulting architecture will be different from the ones described before. Currently, the term midhaul is ambiguous since two completely different definitions exist. One definition of midhaul is based on a different functional RAN split of the respective cell-site equipment. It is sometimes also regarded as a re-definition, or future version, of fronthaul and is mostly related to small cells. The different functional split is indicated in Figure 8 [7], [8], [10].

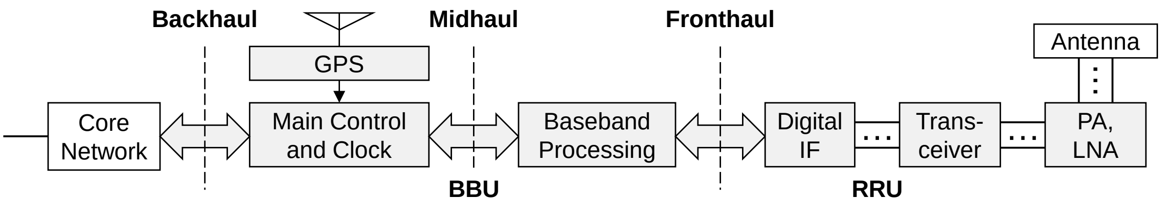


Figure 8: Midhaul resulting from functional split of (macro or) small cell

The exact functional split of a small cell today is not yet clear. This definition of midhaul is mainly pushed by the upcoming 5G radio technology, which would require vast bandwidths and strict synchronization, jitter and delay specifications for its fronthaul. Therefore, different functional splits are considered for relaxing these specifications. This is, amongst others, followed in the EU H2020 project iCirrus [9].

A different definition of midhaul is used by Metro Ethernet Forum (MEF) [11]. Instead of functional split, it relates to a certain (part of the) RAN. In particular, MEF refers to *midhaul as SC backhaul to the nearest Macro BS*. This midhaul definition is, e.g., also used in [12]. It is relevant to note that this definition of midhaul is still based on standard Ethernet (instead of something that is not yet defined for the midhaul which is based on different functional cell-site split). The respective architecture view is shown in Figure 9.

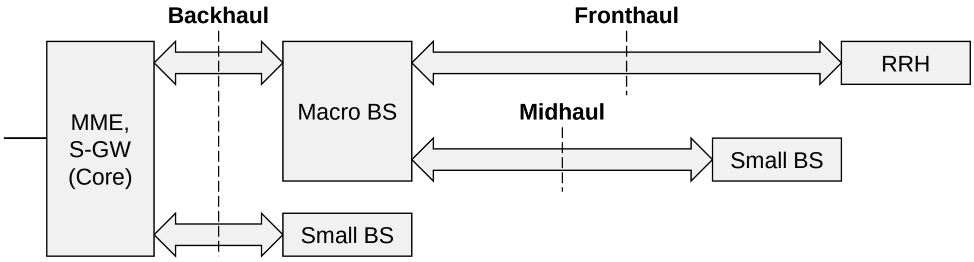


Figure 9: MEF definition of midhaul architecture as SC backhaul to nearest Macro BS

Throughout the COMBO architecture and technology analysis, only the second definition (the one from MEF, i.e., SC backhaul to nearest Macro BS) is followed. Different functional splits have not been considered. First, this is subject to other EU projects (e.g., iCirrus, 5G-PPP Xhaul [13], 5G-PPP 5G-XHaul [14]). Finally, the functional split is not clear at the time being (mid of 2015), so that various assumptions would have had to be made, leading to large uncertainty. Since the resulting transport requirements of different functional splits (bit rates, timing requirements) will fall in between the boundaries set by fronthaul on the one end and backhaul on the other, at least the technical requirements of whatever midhaul variant are covered by the COMBO solutions.

3.3 Summary

In Chapter 3 the key impacts of radio network evolution on the converged architecture were discussed briefly. The main points that need to be considered are:

- Capacity increase in the radio network will come through a combination of improving existing MBS, densifying the MBSs, and adding small cells [58]
- Co-channel operation of small cells and MBSs requires radio coordination, which can be realized in a centralised or decentralised way
- For backhaul as well as fronthaul transport, the tolerable delay between the controlling entity and the antenna sites is limited to less than 1 ms. This restricts the topology placement of a RCC to the Main CO or below.
    - Fronthaul inherently fulfils this low delay requirement.
    - For backhaul, the RCC needs to be placed close to the antenna similar to the BBUH for fronthaul.
- Fronthaul transport capacity demand is significantly higher than backhaul capacity demand and will not scale cost efficiently for MBS in a 5G scenario.

4 Converged Architecture Options

Depending on where the BBUs and RCCs are placed, several RAN architecture options can be identified that enable different implementation strategies under consideration of network transport and aggregation constraints such as maximal latency and meaningful numbers for aggregation as well as radio coordination.

Figure 10 shows the most likely options for placement of BBU and RCC in a centralised and decentralised flavour considering backhaul and fronthaul RAN architecture as well as MBS and small cell deployment.

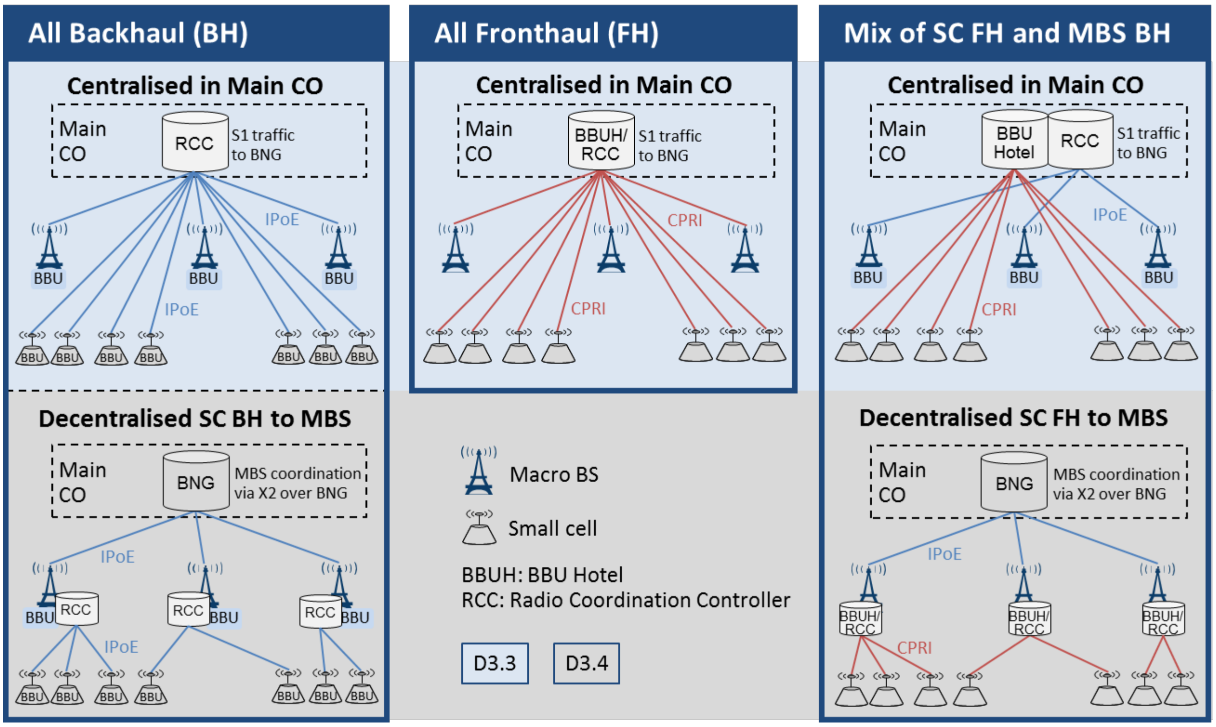


Figure 10: RAN architecture options in focus of COMBO

The focus of this deliverable is on centralised backhaul and fronthaul at Main CO (highlighted in light blue in Figure 10). The decentralised architecture options where the small cells are directly connected to the MBS, either via backhaul or via fronthaul will be described and analysed in D3.4.

4.1 Backhaul with RCC Centralised at Main CO

The small cells as well as the MBSs are connected via an access/aggregation technology directly to a centralised RCC in the Main CO as shown in Figure 11. In this case, the S1 and X2 traffic is terminated in the RCC, whereas the S1 traffic is forwarded towards the Evolved Packet Core (EPC). The RCC receives the X2 traffic of all connected cells and handles among other things the interference coordination between neighbouring macro and small cells. Low latency switching at the IP edge Broadband Network Gateway (BNG) might alternatively allow an aggregation of backhaul links by connecting them first through the IP edge BNG node towards the RCC, under consideration of the CoMP latency requirements.

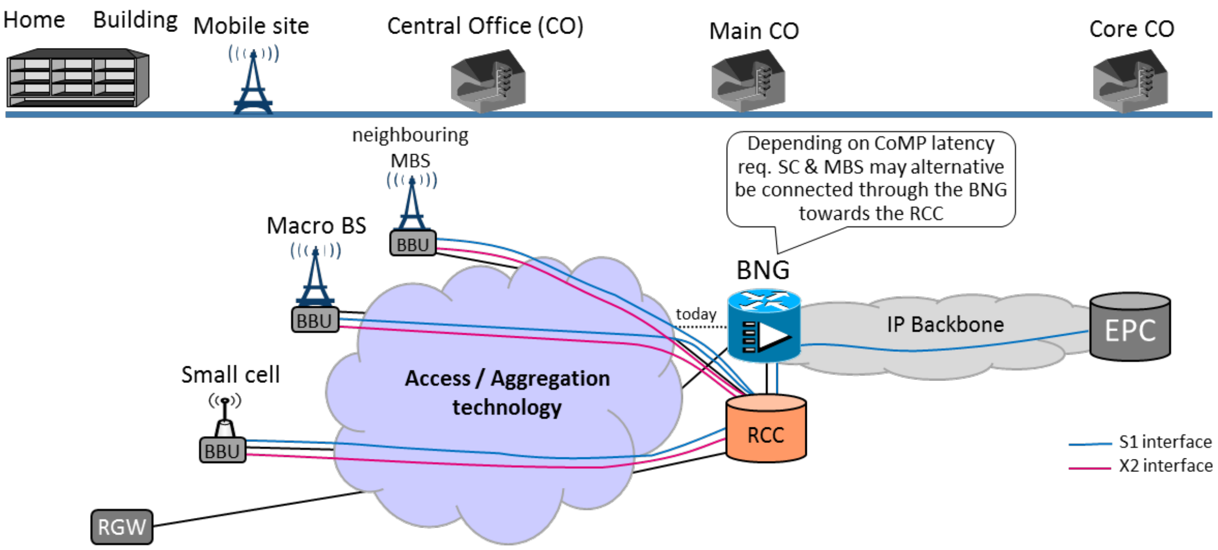


Figure 11: All-backhaul variant – Centralised RCC in the Main CO

4.2 Fronthaul with BBU Hotel Centralised at Main CO

The small cells as well as the MBS CPRI links are connected via an access/aggregation technology directly to a centralised BBUH in the Main CO. A connection of the CPRI links through the IP edge BNG node towards the BBUH would not be feasible due to the stringent latency requirement. Therefore, the CPRI links are terminated in the BBUH, whereas the S1 traffic is forwarded towards the EPC. The X2 links for inter-BBU communication between the basebands of all connected cells are forwarded to the RCC, which is located next to or even integrated into the BBUH. Figure 12 shows the fronthaul architecture with a centralised BBUH and exemplarily an integrated RCC unit.

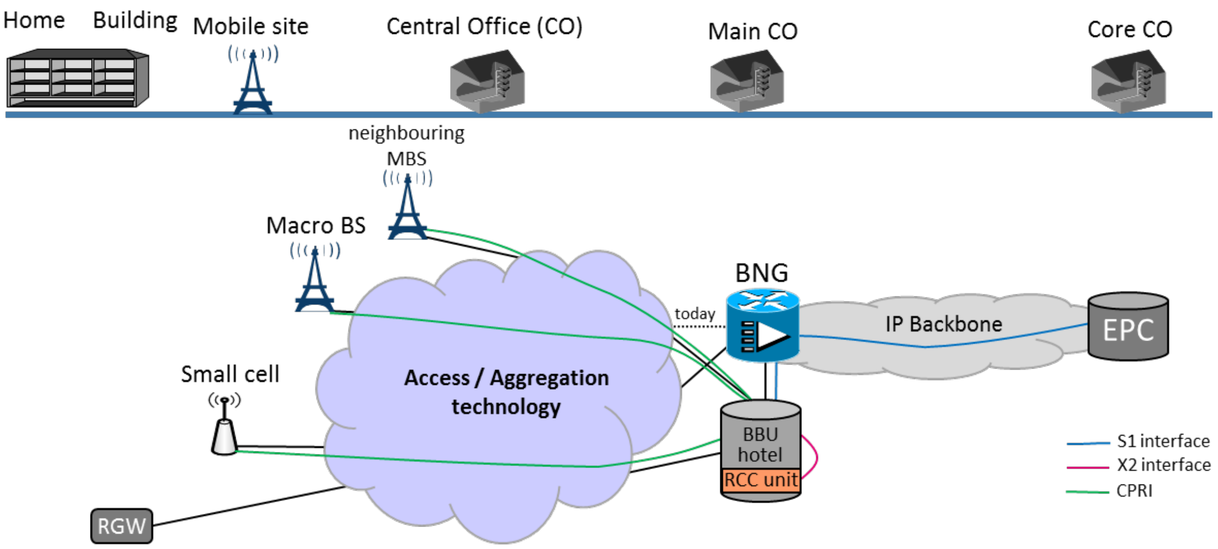


Figure 12: All-Fronthaul variant – BBU hotel and RCC in the Main CO

4.3 Mixture of Fronthaul and Backhaul Centralised at Main CO

The motivation for this mixed variant comes from the expected high transport capacity and associated cost for MBS fronthaul. In this mixed variant the MBS are still connected via backhaul, and only the small cells are connected via fronthaul. Figure 13 shows the mixed back-/fronthaul architecture with a centralised BBUH and a centralised RCC, which serves for backhaul as well as fronthaul links.

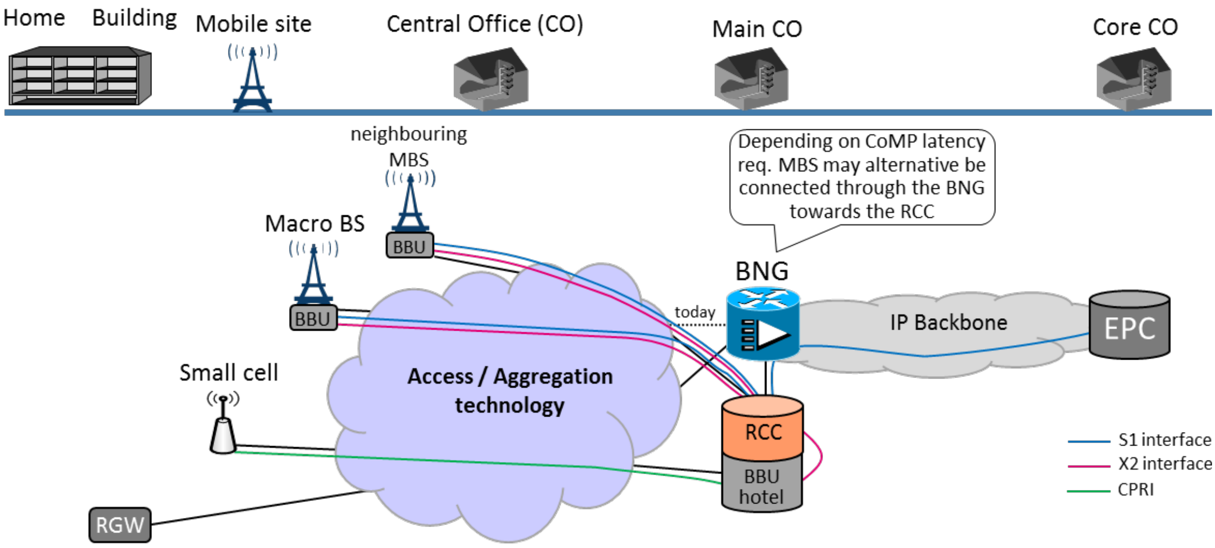


Figure 13: Mixed back-/fronthaul variant – small cell fronthaul and MBS backhaul

5 The 2020 Reference Network Architecture

This chapter describes the reference network architecture for 2020 and the assessment methodology for the comparison with the FMC network architecture options analysed in Chapter 6. The proposed architecture represents a fixed and mobile network architecture for 2020 and beyond assuming some basic convergence aspects between fixed and mobile.

5.1 Assessment Methodology

The structural convergence architecture evaluation comprises the assessment fields shown in Figure 14 as input for the converged architecture design and dimensioning.

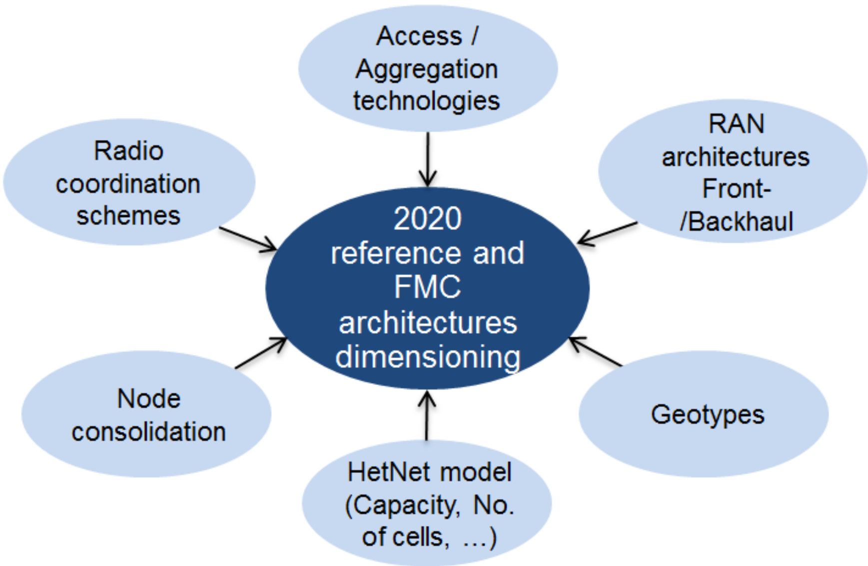


Figure 14: Key topics for structural convergence architecture evaluation

Radio coordination and RAN topologies design considerations are described in chapters 3 and 4. Different access and aggregation technologies are considered for the design of the 2020 reference architecture and for FMC architecture options in Chapter 6. Node consolidation is included in the motivation and in the design considerations, deploying the access nodes in the Main CO as described in previous chapters.

The developed converged architecture options from Chapter 4 are dimensioned and analysed in the segments between the base stations and the Main CO location for different transport technologies based on these assessment fields. The results are compared against the 2020 reference network architecture (described in Section 5.2), which assumes a non-converged evolution of today´s networks.

The reference network architecture for 2020 represents the starting point of the assessment, taking into account the existing fixed mass-market access and aggregation technologies and different geotypes. The PtP CWDM technology is considered for the backhaul and fronthaul deployment from 2020 and beyond as a reference in the comparison with converged backhaul and fronthaul solutions taking into account next-generation fixed access technologies, which are described in detail in Chapter 6.

The study starts from a brownfield approach, which basically means that available fixed access network infrastructure assets like ducts, cables, fibres, and power can be reused or shared depending on the convergence degree.

5.1.1 Heterogeneous Network Model

As initial heterogeneous network deployment scenario we assume a moderate small cell deployment with average 10 small cells per underlying MBS, as shown in Table 3, and a single provider operation per small cell location. The impact of the small cell density and capacity on architecture scalability and cost will be analysed in Section 7.3 through variation of the density between 3 and 150 small cells per MBS and enhancement of the small cell radio configuration. For MBS a multi-operator environment and the need for a demarcation device for operational purposes have to be taken into account. In the backhaul case ONUs with multi-operator support will be considered at MBS for the next-generation access technologies, whereas coloured PtP CWDM pluggable will be used at the Cell Site Gateway (CSG) in the reference architecture as widely implemented today. In the fronthaul case a multi-port Optical Network Unit (ONU) will be considered per operator for the CPRI links towards the RRUs. In contrast to the MBS, pluggable SFP-based ONUs will be considered for small cell backhaul and fronthaul as well as DSLAM backhaul, taking into account the expected space restrictions at small cell locations and inside cabinets.

A typical radio start configuration from the operator perspective will be assumed, taking into account the characteristics shown in Table 2. From an operational point of view it is assumed that fronthaul of MBS will be realised for all mobile technologies GSM, UMTS and LTE-A in order to reduce the active equipment diversity and the number of connections, whereas small cells will only support LTE. For small cells, two different radio configurations will be considered. The resulting backhaul and fronthaul dimensioning capacities are derived from the design considerations in sections 3.2.1 and 3.2.2, respectively.

Table 2: Radio configuration for MBSs and small cells

Heterogeneous Network Radio Configuration	**Macro Base Station**	**Small Cell Var.1**	**Small Cell Var.2**
Radio technologies	2G / 3G / 4G	4G only	4G only
Sectors per technology	3	1	1
LTE-A frequency spectrum	40 MHz	20 MHz	40 MHz
LTE-A frequency carriers	2	1	2
HO-MIMO	4 x 4	2 x 2	4 x 4
Backhaul capacity per site / operator (S1+X2)	**830 Mb/s + 50 Mb/s***	**245 Mb/s**	**830 Mb/s**
Fronthaul capacity per site / operator**	**3x CPRI 10 Gb/s 2x CPRI 3 Gb/s**	**1x CPRI 3 Gb/s**	**1x CPRI 10 Gb/s**

* UMTS/GSM data rates estimation of entirely 50 Mb/s in case of MBS backhaul

** LTE-A: Daisy chaining of frequency carriers per sector → 3 CPRI links each with 10 Gb/s;
GSM/UMTS: Daisy chaining of sectors → 2 CPRI links each with 3 Gb/s

As obvious in the table above the required backhaul capacity, derived from the assumed radio configuration, is below 1 Gb/s for both MBSs as well as small cells. However in order to reduce the interface diversity, 3 Gb/s interfaces will be considered for backhaul in general as it is expected that the price difference compared to 1 Gb/s interfaces is marginal. For fronthaul 3 Gb/s and 10 Gb/s interfaces will be considered depending on the radio configuration.

Table 3: MBSs and small cell deployment numbers

Heterogeneous Network Number of Mobile Sites		**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 small cells	Med. case 10 per MBS	80	230	290	0
	Max. case 30 per MBS	240	690	870	

Wi-Fi is considered in this study as a fixed technology to provide connectivity to private networks and in that sense it is part of the fixed network. Although public Wi-Fi can be also provided with the different options (e.g., Figure 16), this study is only focused on wireless connectivity in public areas via small cells and MBS.

5.1.2 Geotypes

The evaluation considers four different geotypes (ultra-dense urban, urban, sub-urban, rural) for a typical Main CO area in Central Europe in 2020, as exemplarily shown for the urban scenarios in Figure 15. Geotypes are useful to compare different architecture options in different environments. However, they are not intended to compare a single architecture among the four area types as they consider different area sizes. The considered geo-data of a typical Main CO area in Central Europe are summarised in Appendix A.1.

In order to show the impact of very high-density areas on the technology dimensioning, ultra-dense urban areas are taken into account additionally to the considerations in WP2. Ultra-dense urban and urban areas are of main interest, because of the expected earlier and higher demand for small cell deployments as capacity extension to the underlying MBS network compared to sub-urban areas. For rural areas only MBS enhancements without additional small cell deployments are considered for the initial assessment, because of the expected lower mobile traffic demand, which does not rule out sporadic small cell deployments in certain rural hotspots in the future.

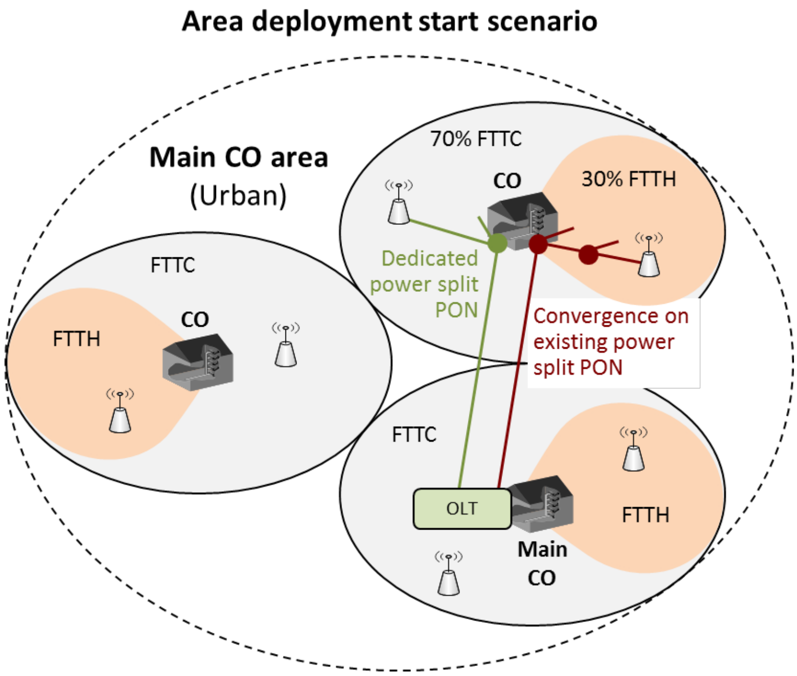


Figure 15: Area deployment start scenario – showing exemplary power splitter based PON

In principle, we assume an initial deployment start situation with two main area types.

- **FTTC area:** Is an access area with an FTTC deployment with active nodes (Digital Subscriber Line Access Multiplexers - DSLAMs) at the street cabinets that are connected via fibre to the CO. Beside cable routes and empty ducts also available fibres between the cabinet and the CO will be reused or shared depending on the convergence degree. In this area typically no fibre infrastructure exists in the first mile distribution section between buildings and cabinet. Fibre cabling and partly trenching is usually needed between cabinet and small cells including new trenches between cable route and small cells, e.g., at lantern.
- **FTTH area:** Is an access area with an assumed Passive Optical Network (PON) based FTTH deployment. The passive fibre network infrastructure in the entire first mile between buildings and the CO will be reused or shared depending on the convergence degree. New trenches and fibre cabling only needed between FTTH cable route and small cells, e.g., at lantern. Fibre to the Building or distribution point (FTTB/FTTdp) with G.fast is for optional study.

The methodology includes a fibre cost model for FTTC and FTTH areas as described in Appendix A.2.

It is assumed that the whole area is covered with FTTC. In addition to that, there are parts that are covered via FTTH (excluding rural areas). The study starts with an assumed 30% FTTH mass-market deployment, which will be varied between 0% up to 100% FTTH ratio as an analysis of the convergence potential in Section 7.3. 50% of the residential homes in the FTTH areas are assumed as being connected with fibre. The structural convergence study takes into account that the considered FTTC/H deployments exist or will be deployed in 2020. The initial assessment in

D3.3 considers a power splitter-based FTTH mass-market PON deployment, which could be, for example, GPON or TWDM PON. The TWDM PON (typically 4 or 8 bidirectional channels at 10 or 2.5 Gb/s shared by multiple ONUs) is considered for the assessment of the technology convergence potential, because it is expected to be the most challenging technology due to the assumed high power splitting ratio of, e.g., 1:128 and the limited PtP WDM overlay wavelength number in the shared spectrum of maximal 16 bidirectional wavelengths, whereas the Gigabit Passive Optical Network (GPON) is basically wavelength-compatible with the expanded spectrum of the NG-PON2 technology. In D3.4, also other mass-market deployments will be considered as start scenarios, for instance, Wavelength-routed (WR) DWDM PON or AON.

The higher small cell density, compared to MBS, motivates scalable and cost-efficient backhaul solutions by reuse of fixed access infrastructure assets and fixed access mass-market technologies if applicable. The aim is to compare full converged access solutions with access solutions that allow only partly convergence. In the latter case, the access technology is used for the connection of mobile BSs and DSLAMs as well as partially business customers but not for residential users, whereas in the full convergence case a common mass-market access technology is used for all fixed and mobile broadband services.

The architecture dimensioning is described in the following chapters taking into account the previous methodology and different level of convergence with the fixed mass-market solutions. The mass-market network dimensioning itself is considered when necessary for the dimensioning of the required coexistence elements (e.g., number of mass-market T(W)DM-PONs in order to derive the number of required CEMx for NG-PON2 WDM overlay). The dimensioning tables in Chapters 5 and 6 do not include the network elements required to provide connectivity to the residential users using TWDM-PON or DSL as these elements remain constant for the comparison.

Additionally, the methodology includes an OLT model for the different architecture options described in Chapter 6, which follows the OLT model used in the EU FP7 IP OASE project (deliverable D4.2.2) as described in Appendix A.3.

5.2 Description of the 2020 Reference Network Architecture

The 2020 reference network proposes architecture for fixed and mobile networks for the access and aggregation network segments for 2020 and beyond. This 2020 reference network will be used as the baseline for the assessment of the candidate FMC architecture options, assuming the same services and traffic forecast for 2020 included in D2.3 [6]. Note that since 5G is still essentially unknown in its approach to backhauling, we assume that the existing models from 4G apply also to 5G. When 5G backhauling/fronthauling is getting clearer, we will possibly need to amend our studies.

In the reference an incremental evolution of current fixed and mobile networks is assumed, taking into account the status of these networks today (see Section 2.1 in D3.1 [1]) and the current trends in both networks towards 2020 (see D2.1 [5]).

The 2020 reference architecture is not driven by FMC targets, and in that sense, it does only include minor incremental FMC advances in addition to what exists today in current networks.

The fixed access network in the 2020 reference architecture is mainly based on FTTH (TWDM-PON) and FTTB/C (VDSL2 with vectoring or G.fast) technologies for residential and business markets. An incremental FMC evolution compared to today's situation taking into account, e.g., convergent usage of CWDM for mobile back-/fronthaul and DSLAM connections of the fixed mass-market (including Wi-Fi APs which can be connected via copper or fibre) is included. The fixed and mobile access networks remain independent in the first mile, i.e., from the CO to the customer or base station. Other technologies for residential broadband access, such as HFC, could be considered and integrated into the COMBO architecture options in a similar way as DSL. However, these alternative technologies have not been included in order to focus on the most realistic solutions for integration of fixed access with mobile backhaul and fronthaul networks.

The back/fronthaul technology for macro and small cells is based on fixed networks when fibre and copper links are available and can provide enough capacity. Microwave is a quick and cost-efficient solution to transport 3 or 10 Gb/s channels when fixed network infrastructure is not available. This study only focuses on fibre technology as it can bring the maximum benefit for structural FMC. Microwave could be also used to complement the fibre reach up to the MBS/SC. However, it would add a constant offset for the FMC network architecture comparison.

The 2020 reference architecture does not consider protection in the access network (for FTTH/B/C and base stations), nor in the feeder fibre between the CO and the Main CO. That will reduce the active elements in the CO, which will be mainly passive.

The aggregation network included in the 2020 reference architecture will be similar to today's network, i.e., it is shared by mobile and fixed services. L2VPN and L3VPN tunnels can be used to transport mobile residential and business traffic. The fixed, mobile and Wi-Fi cores have the same architecture as today's networks, including the foreseen evolution, for example, the IP edge from the Broadband Remote Access Server (BRAS) located at the Core CO towards the BNG located to the Main CO, and the Wi-Fi core for public Wi-Fi connected to the mobile core but keeping separate entities, interfaces and equipment.

The Figure 16 depicts the 2020 reference network architecture exemplary with a mobile backhaul approach:

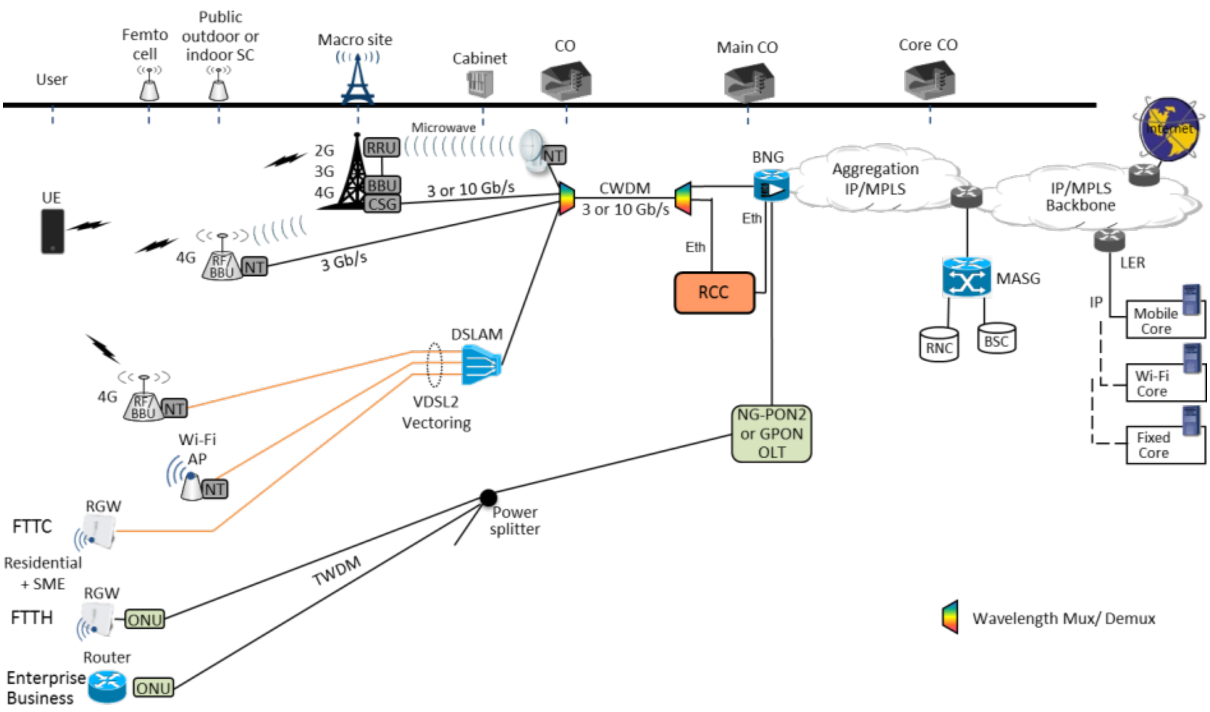


Figure 16: The 2020 reference network architecture exemplary with mobile backhaul

The previous picture shows the Main CO as the common location used for comparison with FMC architecture options. In the left side are represented the different customers connected to the access network following the previous assumptions whereas in the right side is shown the aggregation and backbone network with the different mobile/Wi-Fi/fixed cores.

The Main CO connects the IP/MPLS aggregation network to the IP/MPLS backbone and it contains also other mobile network elements for 2G/3G networks, such as the BSC and the RNC, connected to the Mobile Aggregation Site Gateway (MASG), needed to de-encapsulate the Ethernet traffic and send it to the core controllers.

5.3 Analysis of the 2020 Reference Architecture including Mobile Backhaul

Figure 17 provides more details about how a mobile backhaul service with radio coordination can be provided in the reference architecture (including fixed services). Figure 17 focuses on the network segments from the customer premises up to the Main CO, as the main differences will be in these areas. CWDM bidirectional Coloured Transceivers (CTs), using Single Fibre Single Wavelength (SFSW), have been considered as an evolution of what it is deployed in today's backhaul networks. This is a result of network operators' interest in saving fibres and the increased level of maturity of the CWDM technology until 2020 (1 Gb/s SFSW CWDM technology with a reach of 60 km is currently available and 10 Gb/s modules will be ready before 2020).

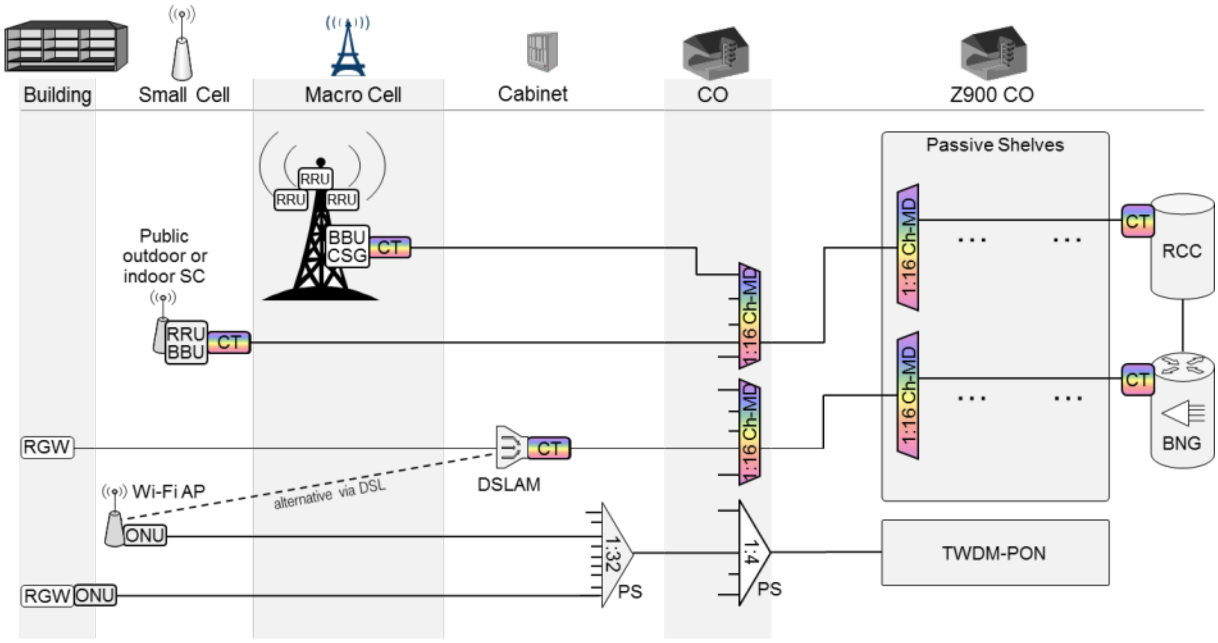


Figure 17: Detailed 2020 reference network architecture for 2020 with mobile backhaul for MBS and SC

At the Main CO, the BNG is the fixed IP edge and forwards the traffic for all services towards the Core CO, the OLTs aggregates the residential and business traffic, and the RCC aggregates the mobile traffic and manages the scheduling of transmissions to the UE to minimize interferences.

CWDM CTs are connected directly to the BNG and the RCC, so there is no need to use additional active OLT shelves in between. It is worth to mention that a solution based on passive shelves and CTs in the Main CO could not be always possible and it could be needed to add a CWDM demarcation point to separate the backhaul network to the internal network. That could be the case for a multivendor or a multi-operator scenario.

Table 22 included in Appendix A.5 contains the summary of the quantitative analysis with the main network elements following the methodology described in Section 5.1. This table is used in used in Chapter 6 for comparison with other architecture options and in Chapter 7 for the cost analysis.

5.4 Analysis of the 2020 Reference Architecture including Mobile Fronthaul

Figure 17 represents a similar network architecture taking also fronthaul into account. In this case, CPRI is used instead Ethernet in a centralised RAN environment. CPRI links are transmitted over CWDM and they terminate at the Main CO, where a BBUH terminates the BBUs of the mobile BS. This scenario requires higher bandwidth than mobile backhaul (see CPRI transport requirements in Section 3.2.2), for that reason CPRI over CWDM has been considered the best solution for the 2020 reference network to transport the mobile data.

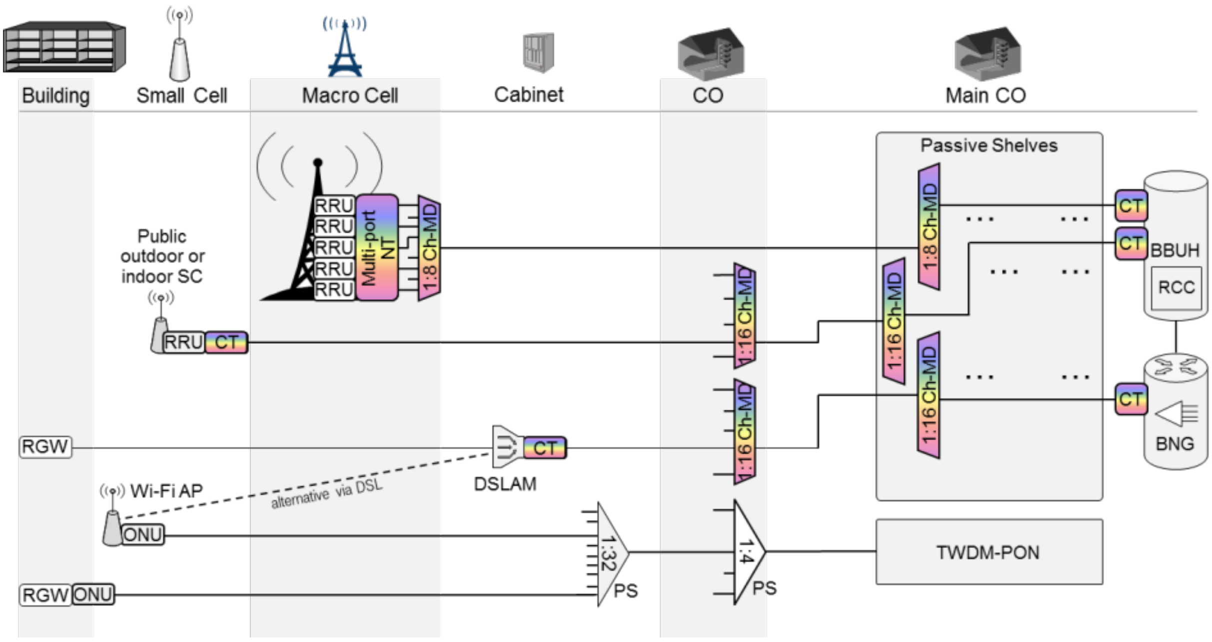


Figure 18: Detailed 2020 reference network architecture with mobile fronthaul for MBS and SC

Table 22 included in Appendix A.5 contains the summary of the quantitative analysis with the main network elements following the methodology described in Section 5.1. This table is used in used in Chapter 6 for comparison with other architecture options and in Chapter 7 for the cost analysis.

5.5 Summary of the 2020 Reference Network Architecture

The reference network architecture for 2020 is the starting point of the comparison with other FMC network architecture options detailed in the next chapters. From the FMC point of view, the same technology (i.e., PtP CWDM) is used for mobile back- and fronthaul and for DSLAM backhaul. However, there is no convergence at system level in the Main CO for fixed and mobile services. Additionally, TWDM-PON is only used for fixed services and fibres are not shared between fixed and mobile services up to the Main CO.

The 2020 reference framework architecture based on CWDM does not need any optical amplifiers and only requires a passive shelf in the Main CO as the coloured transceivers are directly plugged to the BNG and the RCC. However, coloured transceivers add a high complexity to the operation. The main reason for that complexity is that 16 different types of CWDM transceivers multiplied by 2 or 3 maximum reach types will require an exhaustive operational management during the purchase, planning, deployment and replacement activities, compared to tuneable solutions that only deal with a small number of variants.

Comparing mobile backhaul and fronthaul, the number of transceivers needed is around 38% higher in the fronthaul case (requiring 18% of them an increased bitrate of 10 Gb/s instead of 3 Gb/s), the length of fibres is higher in less populated areas (e.g., 5% in the urban case and 35% in rural areas) and the number of CWDM mux/demux devices is also increased (e.g., 64% in the urban case). The main reason for such increase is the higher capacity demands in fronthauling, which impact on the number of transmissions channels needed. The increased number of channels implies a higher number of fibres between the CO and the Main CO to transport them, more transceivers with higher transmission speeds, more WDM mux/demux devices and additional network elements in the MBS with grey transceivers.

Table 4 summarizes the main pros and cons of the 2020 reference architecture, which is to be compared to the FMC architecture options described in Chapter 6.

Table 4: Pros and cons of the 2020 reference architecture

Pros	Cons
• Passive shelves in the Main CO • No amplification needed • It is an incremental evolution (more mature well-known technology with a similar architecture) • Allows an independent evolution of mobile and fixed networks • No additional network protection is needed (fixed and mobile services are carried over different networks)	• Complex operation and logistic (coloured TRx) • No FMC benefits • Active shelves in the Main CO could be also required in some scenarios • There is no traffic aggregation as there is no OLT in the Main CO (more access interfaces are needed)

6 Transport Design for Converged Architectures

This chapter analyses the most relevant FMC infrastructure system and architecture solutions in detail. Calculations are done based on fronthaul and mobile and wireline backhaul convergence. In addition, residential access is considered via both, DSL and PON. According to Section 3.2, consolidation of all OLTs and, where applicable, BBUHs/RCCs, together with the BNG, in the Main COs is considered hereinafter. At the end of this chapter, possible alternative placements of the BBUH in the aggregation network are investigated by modelling the placement problem through integer linear programming.

6.1 Relevant System Solutions

The systems solutions which are analysed in detail hereinafter must be limited for two reasons. First, a number of different (architecture) scenarios needs to be considered. In order to limit the number of resulting system-scenario (or system-architecture) combinations, the system number should be limited to the most relevant solutions. Then, due to the challenging FMC requirements – capacity (including future scaling capability), reach (also considering site consolidation), potential transparency (e.g., for CPRI) [54] – only *fibre-optic solutions which make use of wavelength-division multiplexing and which can support passive infrastructure* need to be considered. A similar result was already derived in [24]. By passive infrastructure, an infrastructure without active fan-out elements like switches or routers is meant. This helps consolidating the active aggregation toward fewer levels and less sites. Passiveness also supports minimum energy consumption, which has been shown, e.g., in [25], [26].

Since passive WDM, in the form of CWDM [27], has already been considered for the reference architecture, the only remaining system solutions are NG-PON2 [15], [16], and more general variants of passive DWDM or DWDM-PON (i.e., wavelength-multiplexed PON which are not compliant with the NG-PON2 recommendations). These systems can, e.g., comply with the ITU-T Recommendations G.698.1 [28], G.698.2 [29], G.9802 (former G.multi) [30], or the upcoming International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T) Recommendation G.metro [31]. These systems are analysed hereinafter.

6.2 Basic Design Considerations

Almost all FMC solutions that are analysed hereinafter are based on wavelength-division multiplexing (according to ITU-T Recommendations G.694.x, G.698.x, G.989.x, G.multi, G.metro) on a more or less passive infrastructure (an infrastructure which is passive where possible and active, e.g., by means of reach extenders, where necessary). In order to avoid confusion, and more clearly separate the solutions discussed in here, it is necessary to clarify two major aspects before going into the individual solutions. The first aspect relates to the overlap and the differences between NG-PON2 and WDM-PON. The second aspect relates to relevant differences between WR- (i.e., filtered) Optical Distribution Network (ODN) and Wavelength-Selective (WS-, i.e., power-split) ODN, where both ODN types are allowed for both, NG-PON2 and WDM-PON.

6.2.1 NG-PON2 and WDM-PON

In Full Service Access Network (FSAN) and ITU-T SG15-Q.2, *NG-PON2 is regarded a specifically specified variant of WDM-PON*. Apart from the G.989.x Series of Recommendations, G.9802 and the draft recommendation G.metro, no further strict standards for WDM-PON exist. This is complemented by the G.698.x Recommendations that describe various aspects of passive DWDM systems. If we further assume that the most common understanding of WDM-PON refers to systems with 32-40 wavelength pairs for upstream and downstream in C-band and L-band, respectively, then there is overlap of this WDM-PON definition and one possible NG-PON2 variant. In addition, there are NG-PON2 variants with smaller wavelength-channel count and certain added, specific requirements.

According to the requirements defined in [15], NG-PON2 can be split into several distinct variants.

For residential access, the most relevant part of NG-PON2 are 4-8 channel pairs (with each channel pair comprising one downstream and one upstream wavelength channel) which make use of combined Time- and Wavelength-Division Multiplexing, TWDM. Per-channel-pair TWDM bit rates are 10 Gb/s downstream (DS) and 10 Gb/s upstream (US), 10 Gb/s DS and 2.5 Gb/s US, or 2.5 Gb/s DS and 2.5 Gb/s US, respectively.

In addition to the 4-8 TWDM channel pairs, so-called point-to-point (PtP) WDM channel pairs are required as an option. These PtP WDM channels must be based on tuneable lasers. The PtP WDM channels have to support all relevant bit rates known from Ethernet, SDH/OTN, and also CPRI [22]. These protocols form three bit rate classes around 1.25 Gb/s, 2.5 Gb/s, and 10 Gb/s, respectively.

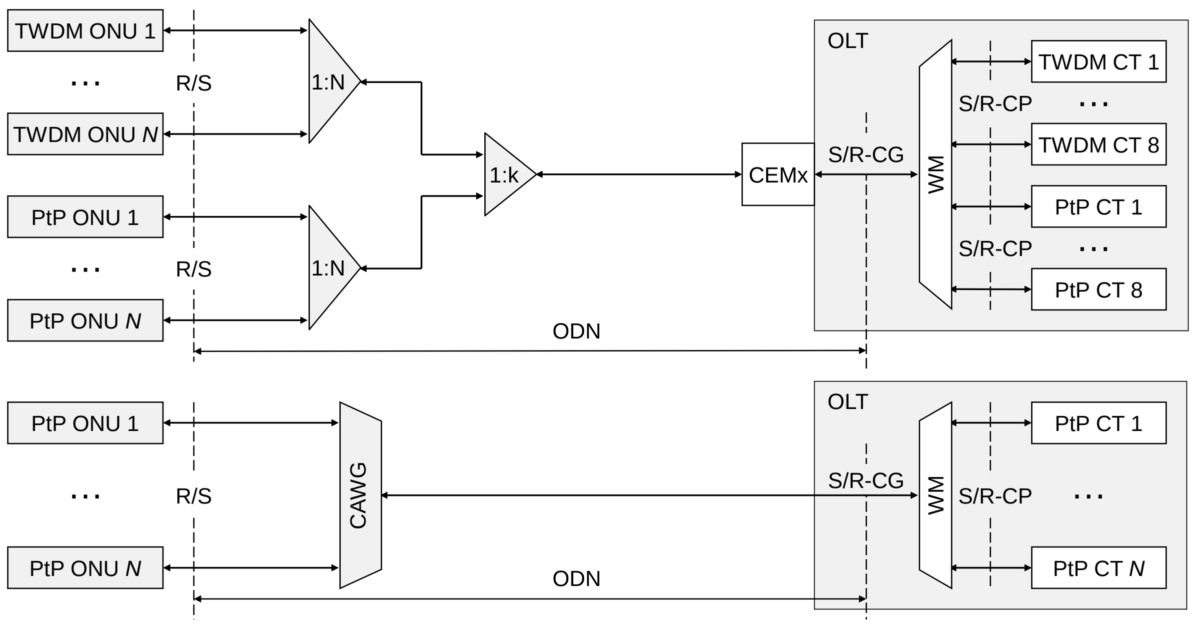


Figure 19: Shared-Spectrum TWDM plus PtP WDM NG-PON2 system (top, with WS-ODN, and connected via coexistence element CEMx), and Expanded-Spectrum PtP WDM NG-PON2 system (bottom, with WR-ODN). CAWG: Cyclic Arrayed Waveguide Grating. WM: Wavelength Multiplexer. R/S and S/R-CG/P: NG-PON2 reference points acc. to G.989.2 [16].

A first typical NG-PON2 configuration is shown in the upper part of Figure 19. It runs, as required, via power-split ODN. Cascaded power splitters are shown as one deployment example. Several TWDM and PtP WDM channel pairs are combined and separated in a wavelength multiplexer (WM) which is connected to the Coexistence Element, CEMx. The CEMx may also have additional ports for legacy PON systems; including the RF video overlay channel and an Optical Time-Domain Reflectometry (OTDR) monitoring band. Figure 19 also shows the NG-PON2 reference points S/R-CP (channel pair) and S/R-CG (channel group) at the OLT, and R/S at the ONUs, respectively. They are used, for example, to define the respective PON power budgets. Note that the CEMx is part of the ODN (budget) definition.

The NG-PON2 variant shown in the upper part of Figure 19 is also referred to as *Shared Spectrum* with regard to the wavelength allocation in particular of the PtP WDM channels [16]. Wavelength bands are 1596 to 1603 nm for TWDM downstream operation and 1524 to 1540/1544 for upstream operation. The PtP WDM channels can use the wavelength range of 1603-1625 nm.

Several options have been discussed with regard to NG-PON2 channel spacing and exact wavelengths. One of these options is based on using cyclic 4-skip-0 or 8-skip-0 Arrayed Waveguide Gratings (AWGs) with nominal 100 GHz or 50 GHz channel grid as WMs, respectively. These cyclic AWG have 4 or 8 ports and no band gaps between the cyclic filter orders; hence, they can route any wavelength from the multiplex-section port (connected to the CEMx in the OLT, at reference point S/R-CG) to one of the channel ports (connected to one of the OLT ports, S/R-SP). This allows the use of thermally tuned low-cost Distributed Feedback (DFB) lasers with limited tuning range (up to 5 nm) and calibration effort since it is always possible to tune the laser such that it supports one of the AWG channel ports. The cyclic AWGs can also be used for the P2P WDM channels. Depending on the exact filter specifications, filter orders in the wavelength range of 1617-1623 nm can be used for downstream, whereas orders in the range of 1610-1616 nm can be used for upstream. As an alternative to DFB lasers, (3-section) Distributed Bragg Reflector (DBR) lasers with somewhat broader tuning range (up to 14 nm) can be used.

Since ODNs with power splitters perform broadcast of all wavelengths in downstream, the ONUs must be equipped with wavelength-selective receivers. In the NG-PON2 case of direct detection, they must incorporate tuneable filters, e.g., thermally tuned thin-film filters [33].

An *Expanded-Spectrum variant* for the PtP WDM part of NG-PON2 is shown in the lower part of Figure 19. It uses PtP WDM channels in a broad wavelength range (1524 to 1625 nm), as co-existence with TWDM or legacy systems needs not to be supported. *WS-ODN support is still required, but WDM-filtered (WR-) ODN is allowed*. Hence, ODN can for example be based on Cyclic AWGs (CAWGs) with a wavelength grid according to ITU-T Recommendation G.698.3, as shown in the figure. *This configuration can be regarded as tuneable-laser based, wavelength-routed WDM-PON according to the definition stated before*. The lasers in the ONUs should now be full-band tuneable, across full C-band. Then, the downstream uses the L-band.

Note that a filtered ODN as shown in Figure 19 for the Expanded-Spectrum case has advantages with regard to lower insertion loss (and, hence, higher reach or the possibility to use lower-power-budget transceivers), and the possible avoidance of tuneable filters at the ONUs. It can also help mitigating linear coherent crosstalk in the upstream, which will be explained in the next chapter.

Various parameters for different NG-PON2 variants have been described in [16]. A majority of these describe transceiver parameters for the different bit rates, and for different reach classes. Similar to GPON and XG-PON1, several ODN power budget classes were defined for NG-PON2, see Table 5.

Table 5: NG-PON2 ODN budget classes

Class	W1 (prelim.)	W2 (prelim.)	N1	N2	E1	E2
Loss min.	16	24	14 dB	16 dB	18 dB	20 dB
Loss max.	7	15	29 dB	31 dB	33 dB	35dB

The table also includes the most recent additions, namely classes W1 and W2 with reduced power budget intended to support either Expanded-Spectrum WR-ODN or (Shared-Spectrum) WS-ODN with very small split ratio (1:4, 1:8). As per Q2/2015, these are still preliminary values.

The power-budget numbers cover the ODN between the S/R-CG and R/S reference points. This includes insertion loss of any power splitters (or filters) in the field and also the CEMx, but excludes any components required in the OLT or ONUs (WM, C/L-band diplexers). Depending on the split ratio, power budget translates to maximum passive reach.

Considering Figure 19 and Table 5, the following overlap of NG-PON2 and (more general) WDM-PON can be identified: *an Expanded-Spectrum PtP WDM NG-PON2 system and a more generic WDM-PON system* ***can be*** *identical*. This overlap can cover certain flexibility:

- WS-ODN or WR-ODN with lumped or cascaded passive components
- Bi-directional channel count can be anything between (and including) 16-96. This covers various wavelength grids. Best practice for both systems is 32/64 wavelength pairs for WS-ODN, and 40/80 pairs for WR-ODN.
- Bit rates around 1.25, 2.5, or 10 Gb/s
- May or may not use Reach Extenders (REs)
- No strict requirement for full-band tuneability; for example, two transceivers each with half-band tuning capability may be used.

The overlap is also subject to these conditions:

- Both systems have tuneable RX filters, even for WR-ODN. If the generic WDM-PON does not get these filters, it is no NG-PON2 system anymore!
- Both systems must at least comply with ODN class W1

- Both systems must comply with other physical-media-related NG-PON2 definitions (this can, in general be achieved for WDM-PON)
- The WDM-PON system must have an Auxiliary Management and Communications Channel (AMCC) – a signalling channel

From this we can derive that for example, 32-channel WDM-PON and NG-PON2 on WS-ODN or 40-channel WDM-PON and NG-PON2 on WR-ODN systems can, but not necessarily need to be identical. For WR-ODN, the most likely differentiator is the tuneable RX filters in the ONUs which the NG-PON2 system must have, whereas the WDM-PON likely will not have (for cost reasons).

From the above analysis, it can also be derived that WDM-PON with active filter technology, such as Reconfigurable Optical Add/Drop Multiplexers (ROADMs), will not comply with NG-PON2.

6.2.2 WR-ODN vs. WS-ODN

The question of WR-ODN vs. WS-ODN is relevant for both, NG-PON2 and (generic, non-NG-PON2) WDM-PON. Wavelength-routed infrastructure is used for most of today's WDM transport systems, where wavelength routing is either performed by static WDM filters (e.g., Optical Add/Drop Multiplexers, OADMs) or by ROADMs. WS-ODN is in use in almost all PONs (GPON, EPON, 10G-EPON, XG-PON1) which, apart from the separation of upstream and downstream, do not make use of WDM. The question is how easily WS-ODN can be used for WDM-PON, in particular if higher numbers of wavelengths (say, >10) are required.

Figure 20 shows the block diagrams of WR-WDM-PON (top) and WS-WDM-PON (bottom), respectively. The basic concept behind has been introduced earlier, e.g., [17], [18]. Both variants of the WDM-PON are based on tuneable laser diodes for the ONUs, rather than making use of seeded/reflective transmitter approaches. This choice is necessary due to the requirements regarding (per-channel) capacity and reach. For similar reasons, the same choice has been made for NG-PON2. For reference, comparisons between the two approaches to colourless ONUs are given, e.g., in [19], [20]. Here, we follow laser-diode-based WDM-PON because of its advantages with regard to reach and power-budget performance.

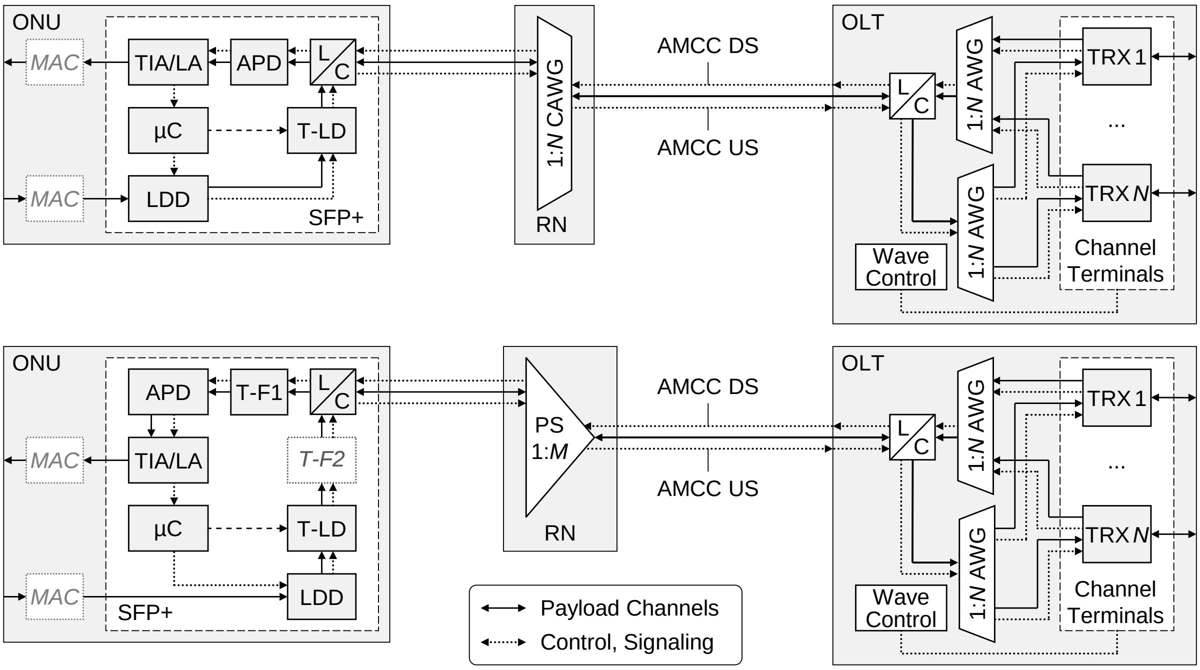


Figure 20: Differences between WR-WDM-PON (top) and WS-WDM-PON systems (bottom). Apart from the ODN, the main difference refers to additional components in the ONU which are required for WS-WDM-PON. RN: remote node. APD: avalanche photo diode. TIA/LA: transimpedance amplifier and limiting amplifier. AMCC: Auxiliary Management and Communications Channel. LDD: laser-diode driver

Both WDM-PON variants can use the same Optical Line Termination (OLT), i.e., the headend or CO equipment. In its simplest form, the OLT uses fixed-wavelength transceivers for downstream (DS) traffic in the L-band region. Upstream (US) traffic is then using the C-band. DS/US can be multiplexed/demultiplexed in the OLT with (cyclic) Arrayed Waveguide Gratings, AWGs. Then, the main differences between the WR and WS approach refer to the passive elements in the ODN (WDM filters vs. wavelength-agnostic power splitters), and to the required ONU functionality. Since WS-ODN broadcasts all DS signals, *WS-WDM-PON ONUs must have wavelength-selective receivers*. For direct detection (which is the choice today due to cost advantages, e.g., see [21]), the receive path in the ONU then requires tuneable filters (T-F1 in Figure 20). Such filters are not in common use today, but concepts have been presented, e.g., in [33]. The tuneable filter is one of the drivers behind cost differences between transceivers for WR- and WS-WDM-PON. In the WS-WDM-PON ONU, a second tuneable filter, T-F2, is shown (in a dashed box, indicating this is an optional device). This filter can become necessary for the US if a certain number of US channels is exceeded, and a certain ODN differential path loss is allowed, in order to prevent prohibitive intra-channel crosstalk. The DS/US AMCC is required to have new ONUs tune their lasers correctly. This channel is attached to each wavelength, e.g., by slow added amplitude modulation.

Example applications of WR-WDM-PON and WS-WDM-PON are shown in Figure 21. The upper part shows WR-WDM-PON for mobile fronthaul and wireline backhaul, the lower part of Figure 21 shows WS-POM-PON in a pure backhaul scenario. The figure also shows some details of the WDM-PON OLT and its connection to the BBUH, the RCC and the BNG, respectively. Since in scenarios with fronthaul/backhaul toward the Main CO the OLTs are co-located with the BBUH / RCC / BNG, these connections are based on pluggable short-reach (SR) grey interfaces.

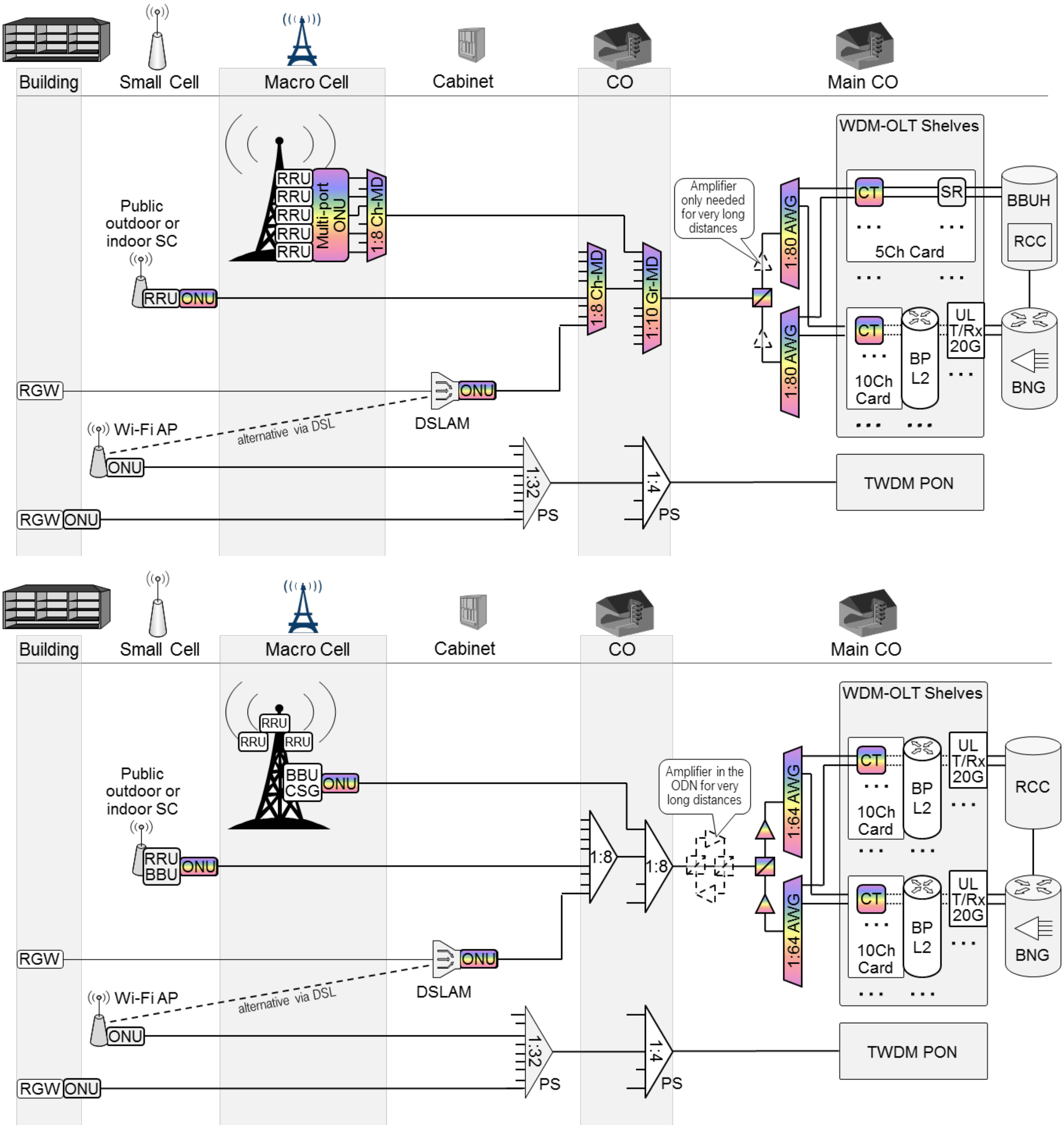


Figure 21: Application of WDM-PON in WR-ODN (top) and WS-ODN (bottom) in a fixed/mobile infrastructure convergence scenario. RGW: residential gateway. RRU: remote radio unit. BP L2: Layer 2 aggregation switch with backplane connectivity. UL: uplink interfaces.

For both ODN types (WR, WS), two-stage optics are shown in Figure 21. For WR-ODN, the first stage can be based on multiplexers/demultiplexers which combine/separate groups of wavelengths (Gr-MD), followed by a secondary stage of multiplexers/demultiplexers which combine/separate individual channels (Ch-MD). In WS-ODN, cascaded power splitters are used. Note that the secondary stage can be placed flexibly, as indicated, in the COs or in cabinets. Apart from the differences that result from the overall scenario (fronthaul vs. backhaul) and the ODN (WR vs. WS), a first difference can already been identified from in Figure 21: WS-ODN will lead to the necessity of amplifiers (shown here as small triangles in the Main CO between the diplexer used for directional separation and the related AWGs). This is explained in the WDM-PON reach analysis and in the respective system dimensioning in more detail.

The differences between WS-ODN and WR-ODN can first be split into operation-related aspects (which are partially very difficult to be quantified, and which lead to contributions to Operational Expenditures (OpEx)), and performance-related aspects which lead to further OpEx differences and contributions to Capital Expenditure (CapEx) differences.

Operations-related aspects include:

- Support of legacy ODN
- Wavelength-agnostic bandwidth provisioning
- Flexibility of ODN (fan-out) configurations, in terms of number and port-count of cascaded Remote Nodes (RNs), for those applications where single lumped RN are not appropriate
- Energy consumption
- Operations and maintenance cost
- Fibre-count requirements

Performance-related aspects include:

- Reach (which in turn can translate to the CapEx and OpEx aspects of running active REs in the ODN)
- WDM channel count
- Required transceiver complexity and resulting CapEx

The ability to support legacy ODN without restriction is given for WS-WDM-PON only. Some network operators have it as strict requirements. Others indicate that replacing power splitters by filters is a permitted option, as long as the ODN fibres themselves (whose laying is responsible for the majority of the cost) can be reused. In addition, by adding certain WDM filters to the ODN, WR-WDM-PON can at least co-exist with legacy power-split GPON on parts of the ODN (the feeder fibre). The requirement for legacy-ODN support may also be small in certain countries without significant installed base, for examples see [23].

Wavelength-agnostic bandwidth provisioning in WDM-PON refers to the ability to deliver bandwidth, i.e., wavelengths, in a way that any wavelength can go anywhere. This ability can make bandwidth planning and provisioning simple and may thus reduce OpEx over approaches that may require more complex (wavelength) planning. Full wavelength flexibility basically requires WS-ODN or an ODN based on reconfigurable elements like Wavelength-Selective Switches (WSS) or ROADMs. Depending on implementation, these may be too costly for access networks. The disadvantage of a static WR-ODN is at least partially compensated by several advantages of this ODN type with regard to several performance parameters, as discussed later. In addition, it is at least questionable that a high level of flexibility is necessary in an ODN that primarily targets wireline backhaul, mobile front- or backhaul, and business access, all of which only require infrequent reconfigurations in today's network. Finally, certain variants of WR-ODN can support certain levels of wavelength assignment. This requires, in the remote nodes, using cyclic $N \times M$ arrayed waveguide routers (i.e., AWGs with multiple input and multiple output ports) [32].

Flexibility of the ODN with regard to simple adaptation to the needs is another potential area for differences between WS- and WR-WDM-PON. This refers to number and port-count granularity of cascaded remote nodes, assuming that single lumped RNs are no preference for most applications. For WS-WDM-PON, such flexibility can easily be achieved since cascaded power splitters with the common split ratios (1:2, 1:3, 1:4, 1:8, etc.) can be used. This is, however, subject to accumulated insertion loss of the longest path. For WR-WDM-PON, such flexibility may be less obvious but is possible. Instead of using a lumped AWG in a single RN, cascaded add/drop filters (of any add/drop wavelength number) can be used, much the way it has been done in metro WDM rings for almost two decades. Figure 22 shows different implementations for such add/drop nodes. Hence, regarding ODN flexibility, no significant differences can be identified. An interesting difference however is given for sites which need to, e.g., be served with 7 wavelengths. Both, WR- and WS-ODN can provide means for providing 8 wavelengths (as the nearest number of common filter and power-splitter design). The difference is that in WR-WDM-PON, the eighth wavelength is lost (it cannot be reused elsewhere since it has been routed to that particular site and, hence, contributes to underutilization of the system). On the other hand, if in the given example an additional requirement is to provide an eighth spare wavelength for future capacity increase, no wavelengths are lost.

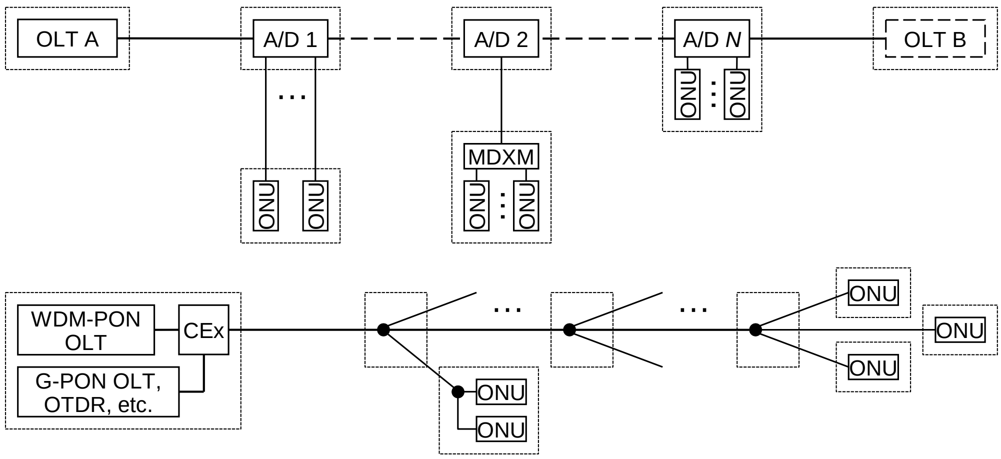


Figure 22: Options for filter implementation in WR-WDM-PON (top), and distributed power splitters (bottom). All add/drop (A/D) nodes add and drop groups of (e.g., 8) WDM channels. For A/D 1 and A/D 2, the add/drop filter in the main PON line and the clients are not co-located, keeping the add/drop nodes potentially fully passive. The two differ in the number of required drop-line fibres. For node *N*, the add/drop filter is co-located with the client equipment, making it an active node. The architecture can support a second OLT (B) for dual parenting.

In WS-WDM-PON, no wavelengths are lost, but unnecessary power-splitter ports considerably contribute to the accumulating power-splitter loss (hence, they reduce reach).

Energy consumption of the access network will differ between WR- and WS-WDM-PON solutions. A small contribution to this comes from the tuneable filters which are required for the ONUs of WS-WDM-PONs. Tuneable filters for these purposes can be expected to have power consumption as small as 100 mW. This compares to 1.5-1.8 W, which must be taken into account for the remote ONU transceiver (i.e., laser and photo diodes plus electrical drivers and amplifiers). Possibly, ONU base power consumption (client interface, management unit, power supply inefficiency) must be added which may account for another 3 W or so. Finally, similar power consumption must be considered for the OLT side. A somewhat larger contribution to power-consumption differences, however, comes from the fact that WS-WDM-PON would require active RE (i.e., optical amplifiers) in the ODN for many links outside urban areas, where distances get larger. Such bi-directional amplifiers may account for ~20 W which have then to be divided by the number of (bi-directional) channels, leading to potential per-channel power-consumption increase in the range of 500 mW. An increased number of REs will also lead to higher operational costs, driven by the necessary maintenance and truck-rolls. This cost is operator-specific, depending on various details (placement of the REs, organization of the maintenance work, etc.) and in general cannot be quantified.

The required number of fibres will also slightly differ between WR and WS variants, especially toward network areas which have to carry aggregated traffic (i.e., the closer one gets toward CO and Main CO). Differences in fibre count result from two aspects. First, WS-WDM-PON has lower reach, which has to be compensated either by using REs as explained before, or by reducing the split ratio. In the latter case, active REs can be avoided by directly trading off reduced split ratio against better reach (for any saved 1:2 split, one gets additional ~10 km). For the same total number of required WDM connections, more fibres then become necessary. The second contributor relates to typical design of WDM-PON. Although other channel numbers could be implemented, the most typical channel numbers for WS-WDM-PON are 32 and 64, simply because these are split ratios which can most easily be realized. The corresponding WR-WDM-PONs most likely will implement channel numbers of 40 and 80, respectively. This aligns well with common filter designs and makes better use of the spectrum available. Since WR design with 40/80 channels (which is also followed by G.metro) leads to 25% increase in system capacity (at, on average, better reach), up to 25% less fibres may be required in the feeder sections (around the CO).

Reach between WR and WS variants differs significantly. Main reason for this is the insertion loss of power splitters which scales with $\sim\log_2(N) \cdot 3.5$ [dB], with N the split ratio, compared to 5-7 dB insertion loss of AWGs with 40-80 ports. If we consider transceiver back-to-back power budget of 27 dB (which is *optimistic* for cost-efficient full-band tuneable 10 Gb/s transceivers without FEC for services like 10GbE or CPRI line-rate options 7, 7A, 8 or 9), and combine this with commonly used insertion-loss data for the other optical components, we can derive the resulting reach *R*.

$$R = (TX_{\min} - RX_{\min} - IL - \text{Penalties}) / \alpha_F \qquad (1)$$

Here, $TX_{\min}$ and $RX_{\min}$ are the guaranteed minimum channel launch power and sensitivity, respectively. *IL* is the accumulated insertion loss of all components along the optical path, Penalties covers the relevant penalties caused by path propagation effects and also a margin for repair work, and α_F is the fibre loss.

We used the parameters listed in Table 6. These parameters have partially already been used in [34]. Components specifications are End-of-Life (EoL) values. In addition, an EoL penalty is stated that accounts for insertion-loss increase of the ODN due to added splices, patches, etc. (e.g., repair work to account for fibre cuts).

Table 6: Parameters for PON reach calculation

Component	**Insertion Loss [dB]**
1:40 AWG in CO / in ODN	5.0 / 6.0
1:80 AWG in CO / in ODN	6.0 / 7.0
1:8 / 1:12 AWG in CO	2.5
C/L Band Filter ONU	1.0
C/L Band Filter OLT (premium)	0.5
Tuneable Filter (RX or TX)	1.0
Power Splitter 1:8 / 1:32 / 1:64	9.9 / 16.5 / 19.8
TXmin, HP [dBm]	+1.0
RXmin, 10G APD [dBm] at BER = 10^{-12}	-26.0
Fibre Loss C/L [dB/km]	0.35
Limits and Penalties	**[dB]**
Optical Path Penalty EML 10G 40 km [dB]	2.0
End-Of-Life Penalty [dB]	3.0
Crosstalk Penalty [dB]	1.0
SBS-limited maximum Channel Launch Power [dBm]	8.0
Laser Safety Class 1M	21.0
Maximum Cost-efficient Gain [dB]	21.0

The reach calculations can be extended toward options of placing REs either in the OLT or in the ODN. In the OLT, this refers to using a booster amplifier (DS) / pre-amplifier (US) combination. In the ODN, it refers to a bi-directional line amplifier, similar to the ones used in all active WDM systems, but most likely with asymmetric DS/US power levels and gain. The combination of both RE, in OLT and ODN, does not make sense since the additional gain in reach is small compared to the additional cost.

When using REs, the potential amplification limits which are given by laser safety, amplifier gain and saturation, and maximum per-channel power allowance (in order to avoid nonlinear Brillouin backscattering, SBS) must be considered. When also considering low-cost amplifiers, restriction of Laser Safety Class 1M (~21 dBm total for systems using C- and L-band) and amplifier saturation (~20 dBm for the multiplex section, this is relevant for the booster amplifier) lead to similar constraints. In addition, the per-channel fibre launch power is restricted to +8 dBm to avoid the necessity of additional anti-SBS means. Then, reach of unamplified and amplified WR- and WS-WDM-PON can be derived, see Figure 23.

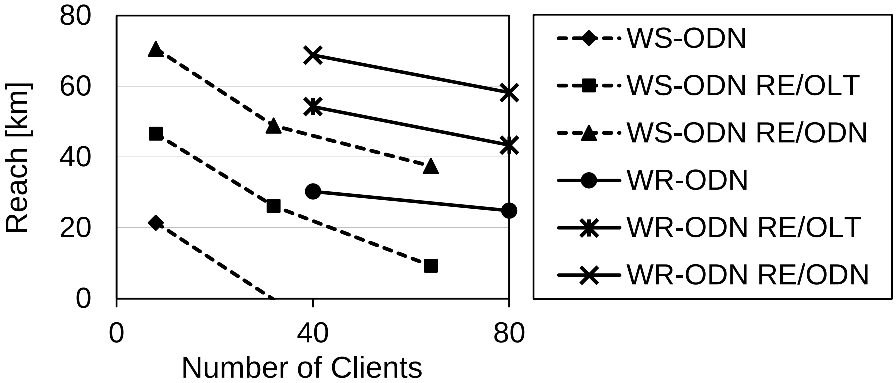


Figure 23: Reach of WR- and WS-WDM-PON with different channel count, and with and without added amplification.

Here, WR-WDM-PON variants with 40 and 80 channels have been analysed, respectively. They are compared to WS variants with 32 and 64 channels, respectively. In addition, 8-channel variants for WS-ODN have been considered here. Such channel number may result, e.g., in NG-PON2 systems when limited spectrum is available for reasons of coexistence requirements (Shared-Spectrum variant of NG-PON2 PtP WDM PON).

From Figure 23, *significantly* higher reach of unamplified WR-WDM-PON can be derived. It can also be clearly seen that OLT-based RE only gives a moderate reach increase for both WDM-PON variants (shifting, however, WR-WDM-PON into the 50-60 km region). With ODN-based RE, WS-WDM-PON can heavily benefit in reach, achieving almost similar distances than the filtered variants. This assumes placement of the RE in the first RN, seen from the OLT, and that the fibre in-between (the feeder fibre) accounts for the majority of the distance to be traversed in the respective PON. The massive gain in reach then relates to the fact that the RE is almost perfectly placed between strong feeder-fibre loss on one side and strong power-splitter loss on the other side, compensating both equally good.

It must be noted that the reach performance shown in Figure 23 is achieved according to Table 6, i.e., for 10-Gb/s channels without additional Forward Error Correction (FEC), and with moderately low launch power. These settings have been used to calculate the reach which is achievable under the worst-case conditions of highest considered bit rate (10 Gb/s), no permission of FEC (e.g., in cases of CPRI transport), and full-band tuneability of the transceiver in an SFP+ form factor (which limits the maximum allowance for complexity and heat dissipation, and thus the launch power).

The aspect possibly leading to the strongest difference between WR-ODN and WS-ODN is *linear crosstalk*, specifically in the upstream direction, in a multi-channel PON.

In general, linear crosstalk in a WDM system splits into two categories; see, e.g., [35]:

- *Inter-channel crosstalk* occurs when several WDM channels are demultiplexed (in the OLT) and the signals of other channels are insufficiently suppressed in the demultiplexer. Their remains can then still be detected by the broadband photo detector of the channel under consideration (the victim). The worst case for any victim is for its power to be at the minimum and the power of all other channels (interferers or aggressors) to be at the maximum. Hence, inter-channel crosstalk is the dominant crosstalk in correctly tuned and wavelength-stabilized WR-WDM-PON with significant uncontrolled differential path loss and large uncontrolled range for guaranteed launch powers.
- *Intra-channel or interferometric crosstalk* occurs when the disturbing channel and the wanted channel are at the same nominal wavelengths. Obviously, the disturbing channel contributions cannot be suppressed with WDM demultiplexers. In PON US, this crosstalk is *caused by insufficiently suppressed laser side modes* of co-propagating signals in other WDM channels. Interferometric crosstalk behaves differently as compared to inter-channel crosstalk between two WDM signals. Now, optical fields rather than the related intensities generate the crosstalk. Consequently, lower crosstalk levels lead to particular penalties. Interferometric crosstalk is the dominant crosstalk in the US of correctly tuned and stabilized WS-WDM-PON since the side modes of all other channels are not further suppressed in a multiplexing filter.

Both versions of crosstalk can further occur during activation of new ONU lasers given these are tuneable and for cost reasons are not fully calibrated and do not have dedicated wavelength lockers. In such cases, the ONU cannot precisely know where in the spectrum the laser starts emitting once the gain section (and the shutter section, if applicable) is enabled. This situation is somewhat relaxed in WR-ODN, but even here, certain levels of inter-channel and interferometric crosstalk can occur, in particular if ODN differential path loss is not controlled or restricted. In general, however, the silent-start problem of new ONUs that have to enter the PON can be tackled by special start procedures. These conditions are somewhat more difficult in WS-ODN since now the new ONU laser can start emitting, without any additional filter suppression, directly in the wavelength channel of another payload signal which is already active. In general, this prohibits the use of uncalibrated lasers in WS-ODN.

A quantitative crosstalk analysis can follow references [35], [36], [37]. There, penalties that a victim suffers are derived from varying crosstalk levels, with Extinction Ratio (ER) of the transmitters (i.e., a quantitative measure of the intensity levels in on/off keying), receiver decision threshold and the use of FEC as relevant parameters.

Given the penalty attributed to interference, it is possible to derive the relative crosstalk (ε) using Eqn. (1) for an average power-decision threshold setting:

$$\text{Penalty (dB)} = -10\log\left(1 - 4\varepsilon Q'^2\,\frac{1+r}{(1-r)^2}\right) \qquad (1)$$

where r is the signal extinction ratio and Q' is derived from the required BER using:

$$\text{BER} = \frac{1}{4}\,\text{erfc}\left(\frac{Q'}{\sqrt{2}}\right) \quad (2)$$

The BER of the victim channel is largely dictated by whether FEC is used or not.

To account for the reduction in extinction ratio after transmission, r is replaced with an effective extinction ratio (r') given by Eq. (3).

$$r' = \frac{(r+1)+10^{-E/10}(r-1)}{(r+1)-10^{-E/10}(r-1)} \quad (3)$$

where *E* is the eye-closure penalty in dB and equivalent to the optical path penalty.

A 1-dB relaxation of the permitted relative crosstalk (ε) is included here to account for the randomised polarisation states of the transmitters, and consequently reduced coherent beat noise.

A relevant source for (coherent) crosstalk is diode-laser side modes. In the upstream direction of power-split ODN, these are not suppressed since no multiplexing filter (in the ODN) is present. Rearranging Eqn. (1), the allowed laser side-modes power P_{SM} in dependence of the tolerated penalty can be expressed:

$$P_{SM}\,(\text{dBm}) = P_{Tx}\,(\text{dBm}) - \varepsilon\,(\text{dB}) - P_{OP}\,(\text{dB}) - L_{DODN}\,(\text{dB}) - 10\log_{10}(N) \quad (4)$$

Here, P_{Tx} is the interferer launch power, ε is the crosstalk allowed by a given penalty (which must then be considered in the system parametrization and power budget), P_{OP} is the optical path penalty (caused, e.g., by residual chromatic dispersion), L_{DODN} is the differential ODN path loss, and *N* is the number of aggressor channels (in the same wavelength band). Note that effects of ER and FEC are implicitly covered by Eqns. (2) and (3).

Eqn. (4) is *pessimistic* in that it does not assume side modes which decay with increasing spectral distance (i.e., side modes from channels that are far away are considered to contribute equally to next neighbours).

On the other hand, diode lasers with only very weakly decaying side modes have been shown in the past, an example of which is shown in Figure 24. Here, optical-spectrum-analyser traces of several DFB lasers are shown. The traces clearly show that the side modes almost stay stable in relative power toward higher wavelengths for more than 25 nm.

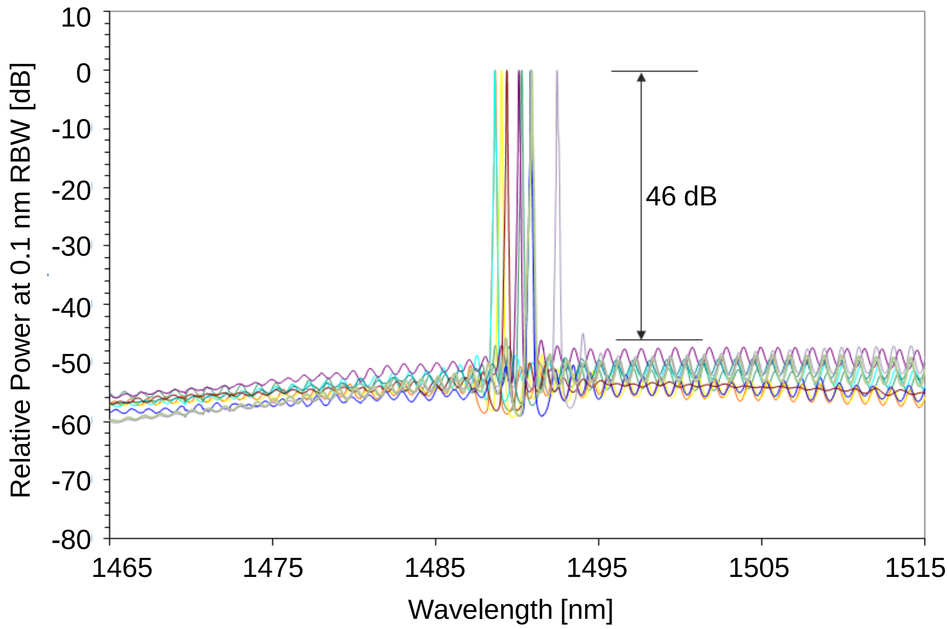


Figure 24: Spectra of several DFB lasers. RBW: resolution bandwidth. Measurement courtesy of British Telecom.

For an analysis of the required side-mode suppression in WS-ODN, the following values have been used: crosstalk penalty = 1.0 dB, P_{OP} = 1.0 dB, *ER* = 10 and L_{DODN} = 5.0 dB. All aggressors are set to guaranteed launch power that is 2 dB above the launch power of the victim. In total, these settings are *optimistic*, thus compensating for the side-mode decay assumption and over all giving realistic results. In particular, the crosstalk penalty must be considered carefully, since it leads to a related requirement of sensitivity and/or guaranteed launch power increase. Also, the *ER* and P_{OP} values would not allow the use of cost-efficient, directly modulated lasers. Likewise, L_{DODN} has been massively decreased, e.g., compared to initial NG-PON2 requirements. It would therefore require power-levelling techniques, something that so far has not been described in relevant PON standards (GPON, EPON, 10G-EPON, XG-PON1).

The resulting SMSR (side-mode suppression ratio) for all lasers in WS-WDM-PON is shown in Figure 25 for target BER of 10^{-12} and for increasing WDM channel number.

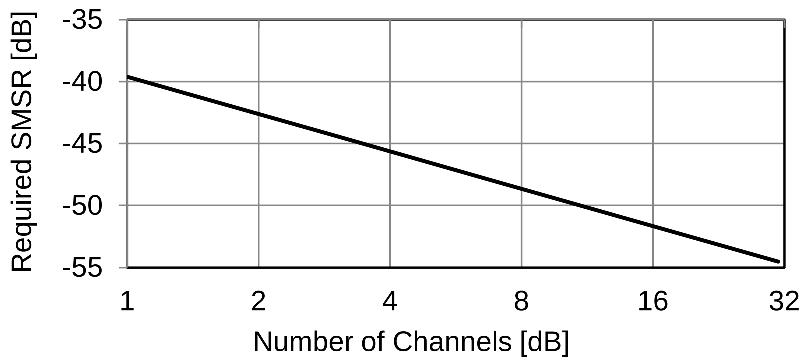


Figure 25: Required SMSR as a function of channel count in WS-WDM-PON without additional side-mode filtering.

SMSR of most diode lasers is in the range of 45-50 dB. This sets the upper limit of channel count in WS-WDM-PON without further SMSR improvement to $N = 8$.

Figure 26 demonstrates that in WR-WDM-PON (i.e., in particular with the addition of multiplexers for the upstream), the next critical parameter for crosstalk is the ODN differential path loss. Here, an 80-channel system with $ER = 10$, crosstalk penalty = 0.1 dB (i.e., almost negligible penalty, a requirement which is made when adding the filter effort), $P_{OP} = 1.0$ dB and total crosstalk of the AWG of -20 dB have been used. The total-crosstalk value is a typical specification for AWGs with 80 WDM channels.

Figure 26 shows that even with high uncontrolled differential path loss up to at least 15 dB, no strict requirements on SMSR result.

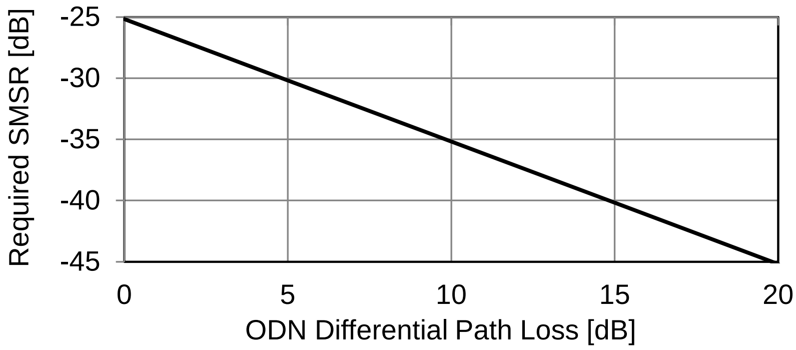


Figure 26: Required SMSR as a function of ODN differential path loss in WR-WDM-PON

The crosstalk penalty can be decreased by:

- Higher ER and optimized decider threshold, i.e., better transceivers
- Polarization scrambling amongst interferers
- Decreased number of WDM channels
- Higher suppression of side modes, e.g., in (WDM) filters
- Limitation of ODN min/max power dynamics and min/max power level control
- Use of FEC (Forward Error Correction). In many CPRI cases, FEC may not be allowed due to added latency.

In addition, the crosstalk penalty can be increased to >1 dB. This, however, must effectively be compensated by increasing the launch power or receiver sensitivity by the same amount and may thus further increase transceiver cost.

In general, decreasing channel count may not be an option for WS-WDM-PON. SMSR improvement in diode lasers is also limited to certain extent since SMSR is related to the dimension of the cavity and the associated Bragg gratings. Typical DFB and DBR lasers have 45-50 dB SMSR, whereas VCSELs can even have SMSR <40 dB. Further, transceiver improvements (ER, decider threshold) may be too costly, or impossible beyond certain parameters (e.g., $ER > 10$ dB) so that the related effects are limited. Interferer polarization scrambling only avoids worst-case conditions, and also has limited effect. FEC may not be allowed in all cases of CPRI fronthaul.

Under these conditions, additional filtering of the side modes must be introduced. This can be done by a filter in the ODN (which then becomes a WR-ODN, which by definition is not possible in a WS-ODN). The remaining way to allow higher channel count in WS-WDM-PON is to make use of additional tuneable filters in the ONUs for the US (transmit) direction. This means that in general (for $N > 8$), ONUs in WS-WDM-PON have both, tuneable filters for transmit and receive. This clearly increases cost, complexity of the ONU tuning procedures (the tuneable TX filter must be calibrated, or it needs to be locked to the downstream somehow), energy consumption, and it decreases availability (because a tuneable component is added in both directions) and also ODN power budget (because now tuneable filters have to be inserted in both directions). (This has been considered in Figure 23, with insertion loss of 1.0 dB per tuneable filter.)

It has to be noted though, that the additional filters are only required in the ONUs. OLT transceivers do not require these filters since the OLT has a multiplexer/demultiplexer which also suppresses (DS) laser side modes.

If equipped with these filters, WS-WDM-PON can support any channel count. If further equipped with reach extenders, it can also support reach which is sufficient in FMC and site-consolidation scenarios, i.e., up to 50 km. The added cost for this consists of the CapEx of the tuneable filters and the REs. According to discussions in FSAN, this can increase the end-to-end channel cost (of transparent PON channels, i.e., without any (Layer2) aggregation in the OLT) by ~10% (filters) and ~5% (RE). In addition, OpEx for RE maintenance evolves, and due to higher complexity, ONUs in WS-WDM-PON may have somewhat lower availability (which translates into a similar OpEx contribution).

It must be noted that, although the cost mark-up of WS-WDM-PON with added tuneable filtering is relatively small, there is also substantial risk for the availability of the respective tuneable filters. So far, the filters which have been presented (e.g., [33]) are narrow-band, covering only up to ~7 channels or so, spaced 100 GHz. Development of full-band tuneable filters is still due, and the resulting filters may deviate from the data used in here with regard to cost, insertion loss and also energy consumption.

It also needs to be kept in mind that the addition of tuneable (transmit) filters does not change the general characteristic of a WS-ODN as a broadcast medium. This means that intentional rogue behaviour (i.e., a malicious user intending to perform what meanwhile is also known as crosstalk attack) cannot be prevented any better by the filter addition. This is only achieved to a better degree (i.e., the crosstalk suppression of the filters) in WR-ODN where all users have to pass the filters in the infrastructure. *Potentially, this leads to more stable operations of the network*.

Two aspects of WR-ODN have not been considered so far. First, WDM filters in the ODN must be athermalized. They may require athermalization over the full industrial temperature range, i.e., from -40°C to +85°C. For certain filters, athermalization below -20°C is difficult (but not impossible) to achieve, which may translate to added cost.

The second aspect relates to NG-PON2-compliant WR-WDM-PON. According to initial requirements [1], a single type of ONU (per TWDM and PtP WDM PON subsystem) has to serve all ODN conditions. This would mean that even for WR-ODN with one of the new reduced-power-budget classes W1 or W2, the respective ONUs would always have to be equipped with everything which is required to also allow their use in WS-ODN with high ODN power budget (which, currently, for 10-Gb/s PtP WDM channels, and without added forward error correction, is 29 dB), i.e., the tuneable filters and high-performance transceivers. Then, no transceiver cost advantage will be seen for WR-ODN, even if only small ODN power budgets have to be overcome.

6.3 NG-PON2 with PtP WDM

This section describes an FMC network architecture solution for 2020 based on NG-PON2 including additional PtP WDM channels. The NG-PON2 allows full convergence for all fixed and mobile access services in areas with mass-market FTTH deployments, aiming maximal reuse of existing network resources. It also supports node consolidation through extending the access reach towards the aggregation network. The NG-PON2 can either be operated as PtP WDM overlay solution using the shared spectrum or as dedicated PtP WDM PON using the expanded spectrum. Table 7 shows the specified wavelength ranges for both TWDM PON and PtP WDM from ITU-T Recommendation G.989.2 [16].

Table 7: NG-PON2 wavelength bands

Wavelength compatible systems	**NG-PON2**		
	TWDM PON		**PtP WDM**
	DS	**US**	**US/DS**
GPON, RF Video, XG-PON1	1596-1603 nm	Wide Band option 1524-1544 nm Reduced Band option 1528-1540 nm Narrow Band option 1532-1540 nm	Expanded Spectrum 1524-1625 nm (PtP WDM PON) Shared Spectrum 1603-1625 nm (PtP WDM overlay)

Figure 27 demonstrates that NG-PON2 has the reach capability to support FMC even with reach requirements which are increased by node consolidation. The diagram compares reach for channels with 3 Gb/s and 10 Gb/s, with or without FEC, and for three options regarding reach extension, respectively.

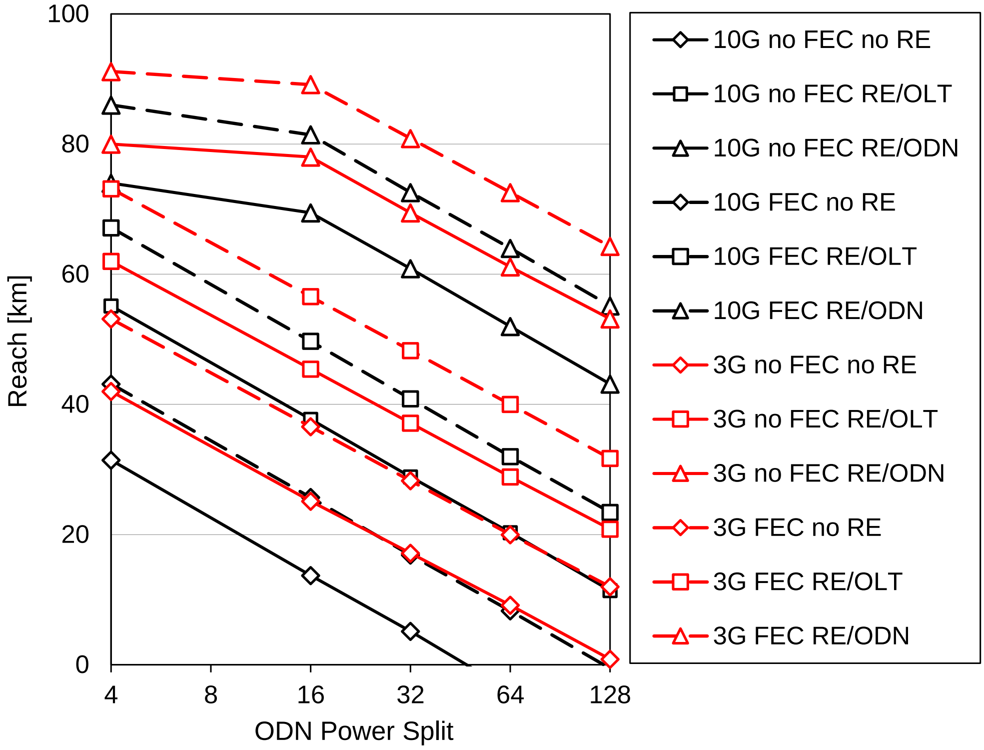


Figure 27: Reach of Shared-Spectrum NG-PON2 with a maximum of 16 channels on WS-ODN with variable power split. Resulting reach is shown for 10 Gb/s (black) vs. 3 Gb/s per channel (red), and without FEC (solid lines) and with FEC (dashed lines), respectively

Even for splitting ratio as high as 1:128, reach up into the range of 60 km is possible. Figure 27 shows that reach for 3 Gb/s is always somewhat better than the respective 10-Gb/s configuration. This is due to the receiver sensitivity which is better at lower bit rates. The reach increase by using FEC is clearly visible. It is ~13 km, assuming coding gain of 4.5 dB (which is the gain in NG-PON2). Similar to Figure 23, reach increase enabled by REs (placed either at the OLT, or in the ODN) can also be identified. When comparing the reach shown here to the results from Figure 23, it must be noted that we used high-power transmitters with guaranteed launch power of +4 dBm here. The higher launch power is possible by narrowing down the tuning range (and thus complexity) to the Shared-Spectrum range. This allows a maximum of 16 channels. The respective transceiver configurations are compatible with ODN class N1 (with FEC, but without RE), and with class E2 (with FEC, with RE) according to Table 5, respectively.

The general NG-PON2 full convergence architecture is shown in Figure 28, exemplarily for the backhaul case. The fronthaul case looks somewhat different since for example, the MBSs are connected via dedicated fronthaul links and a BBUH is placed at Main CO, which will be described in more detail in Section 6.2.2.

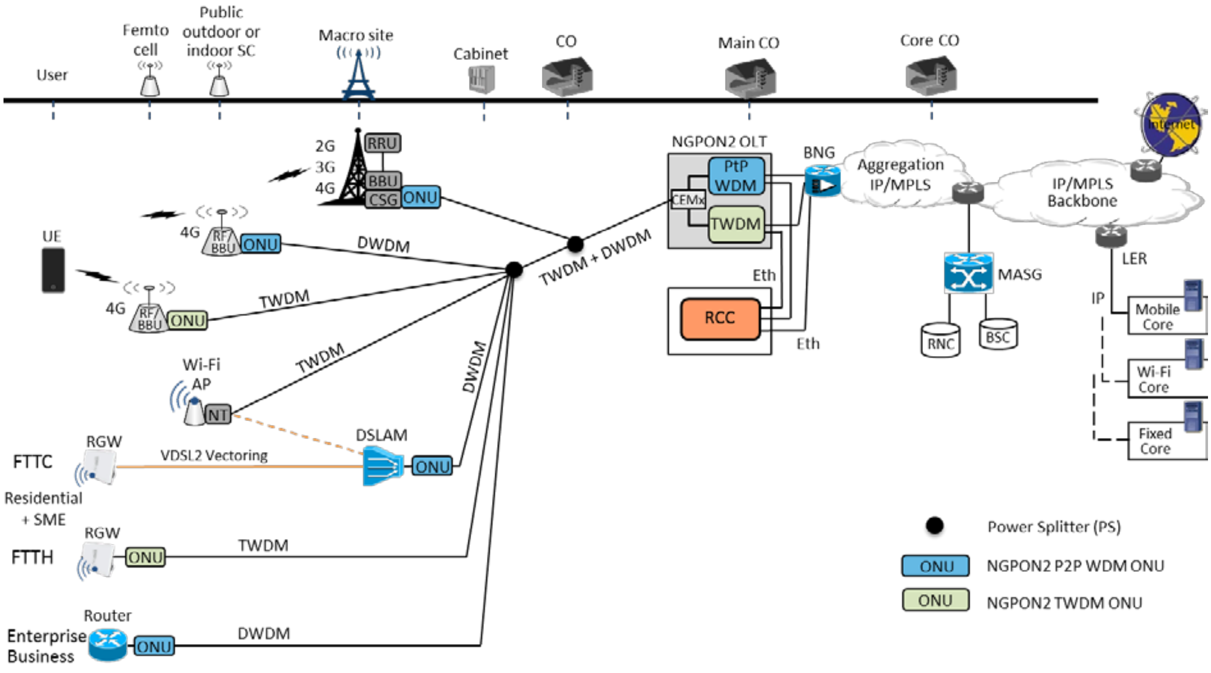


Figure 28: NG-PON2 network architecture exemplary for the mobile backhaul case

Some alternatives to the full convergence architecture can be proposed depending on the fibre convergence degree:

- Feeder convergence: The feeder fibre between the CO and the Main CO is shared for all services and a new WDM filter in the CO named CEMx is used to combine mobile and fixed traffic.
- Feeder and first mile main cable convergence: The feeder fibre between the CO and the Main CO and the first mile main cable between the CO and the cabinet (or in the outside plant) are shared for all services and a new WDM filter in the cabinet named CEx 2 is used to combine mobile and fixed traffic.

6.3.1 Analysis of NG-PON2 including Mobile Backhaul

Figure 29 illustrates how a mobile backhaul service with radio coordination can be provided using NG-PON2. As it is shown, the MBSs and the small cells as well as the fixed access mass-market lines are connected by a full-convergence access solution, which combines PtP WDM overlay channels with a TWDM-PON, and additional GPON wavelengths if needed, through a Coexistence Element (CEMx) in the Main CO. In those convergence solutions the shared spectrum band must be used, resulting in wavelength numbers of up to 16 bidirectional channels, depending on the operator needs.

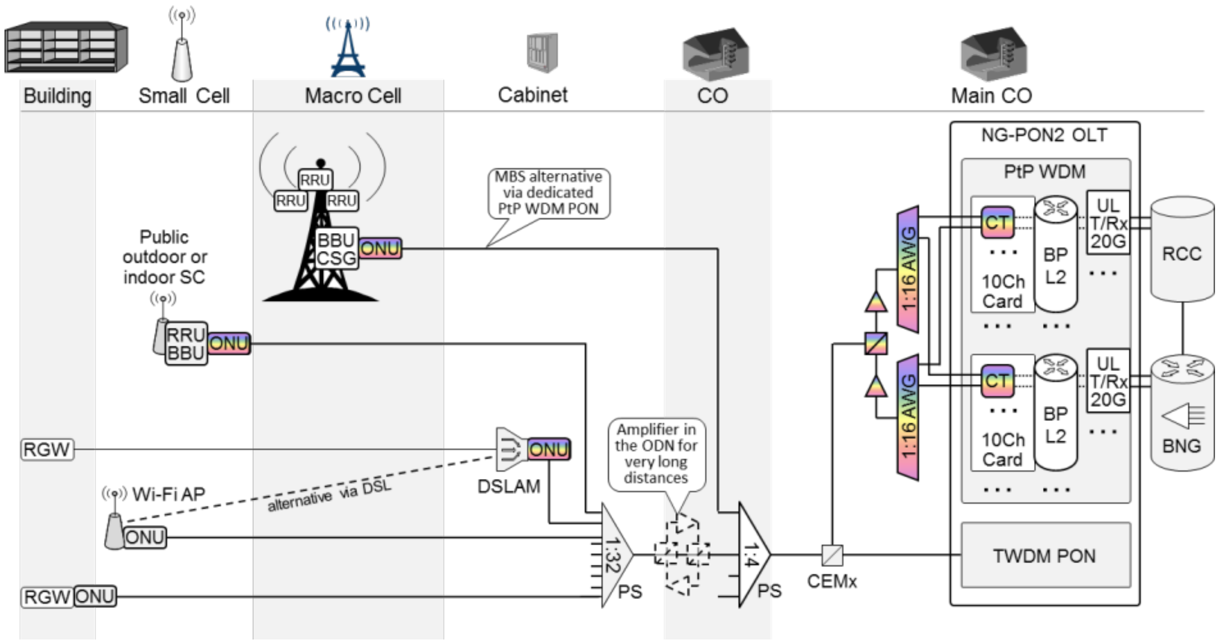


Figure 29: NG-PON2 network architecture and mobile backhaul

A different NG-PON2 deployment is considered in FTTC areas for comparison reasons with the other technologies, using only the PtP WDM overlay part (i.e., no TWDM) and a single-stage power splitter in the CO, as shown in Figure 101 in Appendix A.4. This gives the opportunity for a later integration of convergence in case of a subsequent mass-market TWDM-PON rollout in those areas via adding CEMx and an additional power splitting stage, depending on the operator needs.

In order to fulfil the stringent CoMP latency requirements (less than 1 ms), the public outdoor and indoor small cells as well as MBSs are connected via PtP WDM overlay without Time-division multiplexing (TDM) using data rate channels of 3G. In exceptional cases with locally huge small cell demand, an AWG, e.g., at the cabinet, could be used in order to save power splitter ports for the FTTH mass-market (limited to maximal 16). In this study, the DSLAMs are connected via PtP WDM overlay, but could alternative also be connected via TWDM, whereas FTTH residential users, femto cells at home and Wi-Fi access points are connected via TWDM, because of the less stringent latency requirements and the limited WDM overlay wavelength number in the shared spectrum band.

The NG-PON2 OLT and the RCC are located in the Main CO next to the BNG. All mobile backhaul connections are terminated at the PtP WDM module of the NG-PON2 OLT using coloured pluggable transceivers, which allow growing according the wavelength demand. The mobile backhaul traffics are aggregated on Layer 2 and sent via grey uplink interface(s) towards the RCC for interference coordination, whereas the DSLAM traffic are directly sent to the BNG. Instead of pluggable transceivers, multi-channel photonic-integrated circuits (PIC) could be used alternatively, allowing "zero touch" operation at the OLT, however potentially at lower wavelength utilisation. Simplified operations then result from the fact that the respective transceivers have already been installed in the beginning and only need to be activated via software. Reduced utilization results since in most cases, even toward end-of-life, not all channels of the PIC may be used.

The RCC forwards the S1 data traffic towards the core node and handles the X2 traffic from all connected small cells and MBSs for interference coordination between neighbouring cells. Low latency switching at BNG might alternatively allow an aggregation of backhaul links by connecting them first through the IP edge BNG node towards the RCC, under consideration of the CoMP latency requirements. This might require a separation of S1 and X2 traffic at the base stations, if the BNG does not support S1 and X2 traffic handling.

Table 24 in Appendix A.4 contains the summary of the quantitative analysis with the main network elements following the methodology described in Chapter 5.

6.3.2 Analysis of NG-PON2 including Mobile Fronthaul

Figure 30 illustrates how a mobile fronthaul service can be provided using NG-PON2. As it is shown, it keeps the Main CO as the reference CO, so the location of the NG-PON2 network access OLT node at the Main CO does not change compared to mobile backhaul. The main reason for that is because the service area of the Main CO is below the maximum reach required by latency constrains in mobile fronthaul (less than 40 km).

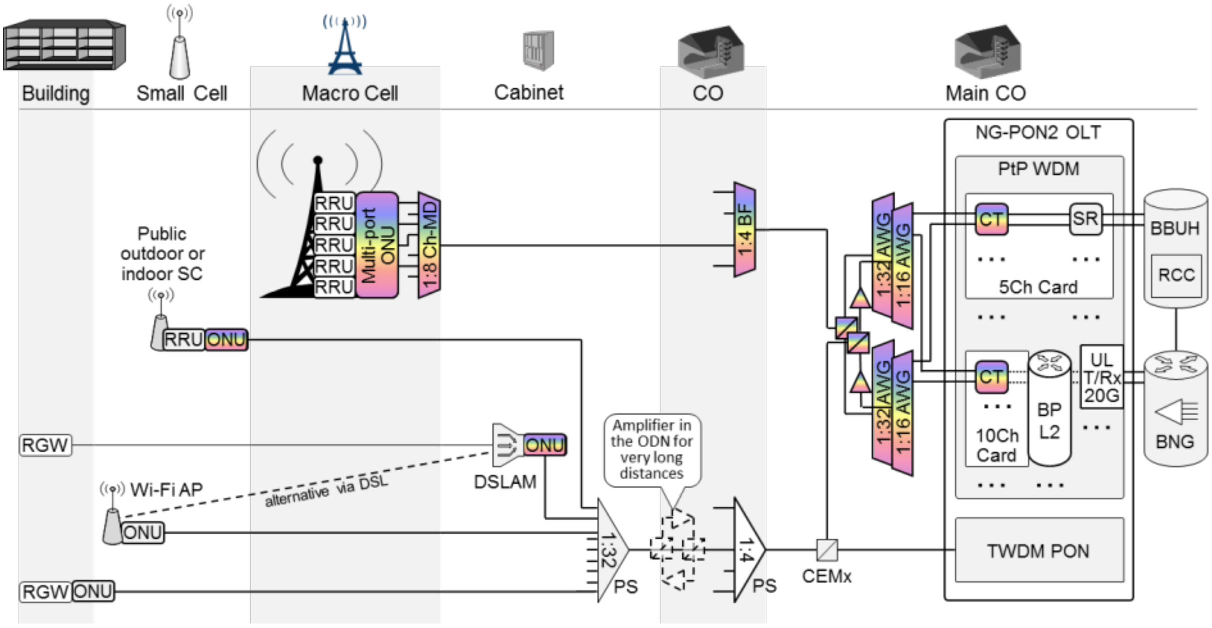


Figure 30: NG-PON2 network architecture and mobile fronthaul

A different NG-PON2 deployment is considered in FTTC areas, using only the PtP WDM overlay part (i.e., no TWDM) and a single-stage power splitter in the CO. In contrast to the backhaul case (Appendix A.4, Figure 101), the MBSs stay fronthauled via the NG-PON2 PtP (WR) WDM PON option also in FTTC areas.

The NG-PON2 OLT is composed of a small set of TDM/TDMA wavelengths shared by multiple ONUs at residential users, business users or other network access nodes, such as DSLAMs or Wi-Fi access points and an additional set of PtP WDM overlay wavelengths (up to 16 bidirectional channels, depending on operators' needs) each operating at 3 or 10 Gb/s. PtP WDM ONUs use these overlay wavelengths to transport CPRI traffic between the RRU modules of the mobile base stations or small cells and the BBUH co-located with the OLT. The WDM PtP module inside the OLT performs an O-E-O conversion to adapt the “grey” wavelengths from the BBUH to the “coloured” wavelengths used in the WDM system and vice versa. Additionally it could be complemented with a GPON system, if needed, using the same ODN to provide FTTH services at lower bitrates and with a lower cost.

The BBUH is in charge of processing the baseband signals. The internal structure of the BBUH is commented in Section 7.5.1. Figure 30 shows that the interface between the BBUH and the OLT uses grey optics transceivers modules (e.g., 1310 or 1550 nm on SMF). Additionally, the BBUH is connected to the RCC (implemented as an external equipment or integrated), which manages the scheduling of transmissions to the UE to minimize interferences.

AWGs are used in the Main CO to multiplex and demultiplex the PtP WDM wavelengths. The CEMx element in the Main CO is used for convergence via multiplexing and demultiplexing the TWDM-PON and WDM PtP wavelengths and additional GPON wavelengths if needed.

In the ODN power splitters are installed, which broadcast the TDWM signal towards the TWDM-PON ONUs. For the MBS fronthaul the PtP WDM PON option of the NG-PON2 OLT is used as dedicated fronthaul connection allowing a higher number of wavelengths compared to the PtP WDM overlay option in order to meet the high wavelength demand of the MBS. In this study a dedicated WR-WDM-PON is considered for MBS fronthaul using an AWG at each MBS site and a band-filter in the CO in order to reduce the amount of feeder fibres between the CO and the Main CO. Alternatively, a dedicated WS-WDM-PON might be used depending on operators' needs.

Table 25 in Appendix A.4 contains the summary of the quantitative analysis with the main network elements following the methodology described in Chapter 5.

6.3.3 Mixture of Fronthaul and Backhaul

As introduced in Section 4.3, the motivation for this mixed variant comes from the expected high transport capacity for MBS fronthaul. Therefore this mixed variant aims to optimise the MBS connections keeping them still connected via backhaul, while only the small cells are connected via fronthaul. In order to show the impact of this optimisation on the network dimensioning and the cost, the mixed variant will only be evaluated for the NG-PON2 technology exemplarily.

For the dimensioning of the mixed architecture variant, the same radio configuration assumptions and transport requirements are taken into account as in the all-backhaul variant for MBS and in the all-fronthaul variant for small cells.

Figure 31 illustrates how a mixed architecture with mobile fronthaul for small cells and backhaul for MBS services can be provided using NG-PON2. As it is shown, the structural architecture is similar compared to the all-backhaul case described in Section 6.3.1. It keeps the Main CO as the reference CO, so the location of the NG-PON2 OLT node at the Main CO does not change, but an additional BBUH is placed in the Main CO in contrast to the all-backhaul case.

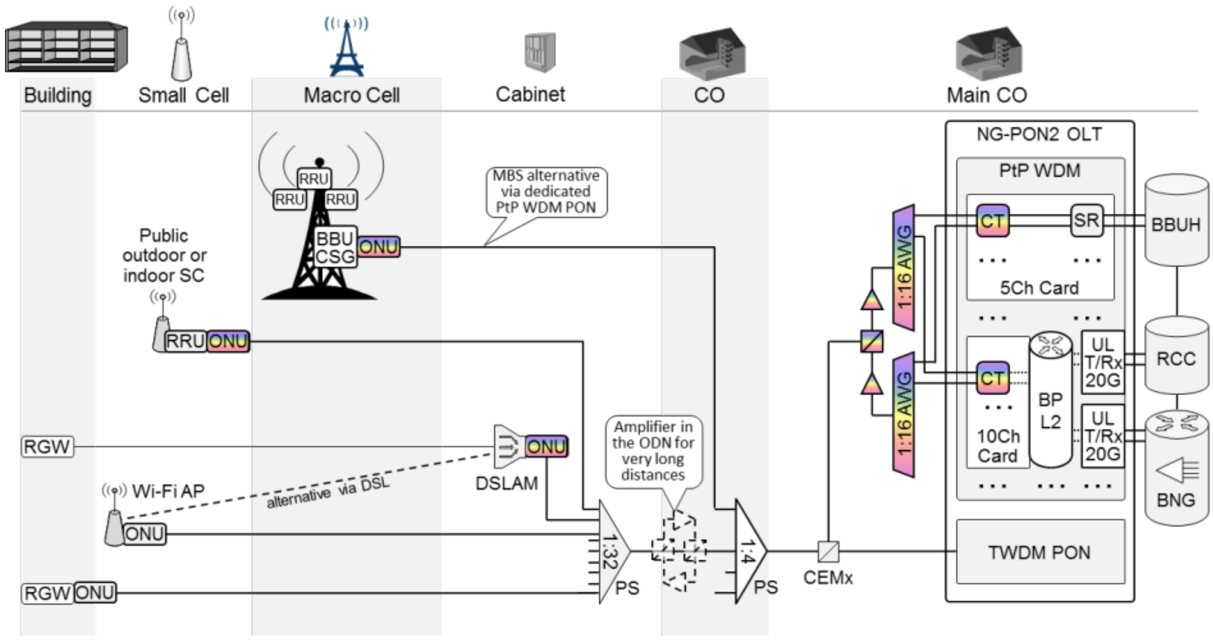


Figure 31: TWDM-PON with WDM overlay mixed network architecture with SC fronthaul and MBS BH

6.3.4 Comparison of Backhaul, Fronthaul and Mixed Back-/Fronthaul

The following table compares the backhaul and fronthaul dimensioning results for the NG-PON2 technology exemplarily for an urban area. The main difference of the all-fronthaul case results from the almost twice as high interface amount and higher interface capacity up to 10 Gb/s compared to the all-backhaul case, which also causes a higher amount of OLT shelves and AWG/BF. Reasons are the higher number of wavelengths primary for MBS fronthaul as well as additional grey interfaces between the NG-PON2 OLT and the BBUH and also between the Multiport ONU and the RRUs at the MBS. The mixed back-/fronthaul variant allows a significant reduction of the interface amount of more than 25% compared to the all-fronthaul case, while keeping the best radio cell coordination performance for small cells by the fronthaul concept. Furthermore, photonic integrated circuit interfaces (PICs) may significantly reduce the difference of the physical interface number between backhaul and fronthaul, which will be further studied in D3.4. Much fewer amplifiers are required in the all-backhaul case, because interfaces with FEC can be used especially for small cell backhaul, supporting a higher power budget class in contrast to the all-fronthaul and the mixed back-/fronthaul cases. The difference in the total fibre length is negligible, because of the similar splitting structure for small cell and DSLAM back-/fronthaul via 1:128 power split as well as for MBS back-/fronthaul using either the 1:4 power splitter or the 1:4 band-filter in the CO.

Table 8: NG-PON2 backhaul vs. fronthaul vs. mixed back-/fronthaul dimensioning

NG-PON2 Backhaul vs. Fronthaul (exemplarily Urban)		**Backhaul**	**Fronthaul**	**Mixed Back-/Fronthaul**
System	OLT shelves	3	6	5
	∑ 3 Gb/s interfaces	1122	1766	1582
	∑ 10 Gb/s interfaces	-	414	-

	Amplifiers (bi-directional)	1	20	22
	AWG / BF / CEMx	95	130	95
	New PS (FTTC area)	24	23	24
	x-haul specifics	Layer 2 OLT; Ctrl.; FEC for MBS and SC; Multi-Vendor ONU at MBS	Transparent + L2 OLT; BBUH with Ctrl.; Multi-port ONU per operator at MBS	Transparent + L2 OLT; BBUH; Ctrl.; FEC for MBS backhaul; Multi-Vendor ONU at MBS
Fibres	Total count (length)	661 (562 km)	666 (572 km)	661 (562 km)

Table 9 summarizes the main pros and cons of the architecture with NG-PON2 in comparison with the 2020 reference architecture.

Table 9: Pros and cons of the architecture with NG-PON2 with PtP WDM

Pros	**Cons**
• Reduced number and length of fibres • FMC at system and fibre level • Simpler to deploy and operate (tuneable TRx) • More wavelengths per fibre	• Amplification needed especially in the fronthaul case • More grey TRx compared to reference although not big impact on cost • Passive coexistence elements are needed (CEMx)

6.4 Expanded-Spectrum WDM-PON Options

The network architecture overview for infrastructure convergence using WDM-PON is shown in Figure 32. Here, a WDM-PON variant with Wavelength Routing (WR-WDM-PON, or WDM-PON with WR-ODN) is shown. A similar overview results for Wavelength-Selective WDM-PON by replacing the filters by power splitters. Likewise, fronthaul toward a BBUH in the Main CO is shown. Again, this figure will not look much differently for the backhaul case. Further, we refer to WDM-PON which has no coexistence requirements (in Figure 32, NG-PON2 runs on a separate ODN, serving residential access and Wi-Fi and femto-cell backhaul), and which consequently can make use of broad spectral ranges – e.g., C-band plus L-band – as Expanded-Spectrum WDM-PON. Such a solution is also possible; refer to Ch. 6.2.1 as NG-PON2 PtP WDM PON[1] without any coexistence requirements.

[1] Note we use the correct FSAN and ITU-T SG15 wording for NG-PON2 here, i.e., without dashes between PtP and WDM, and WDM and PON, respectively. This also helps separating NG-PON2 variants from other WDM-PON which may not be compliant with NG-PON2.

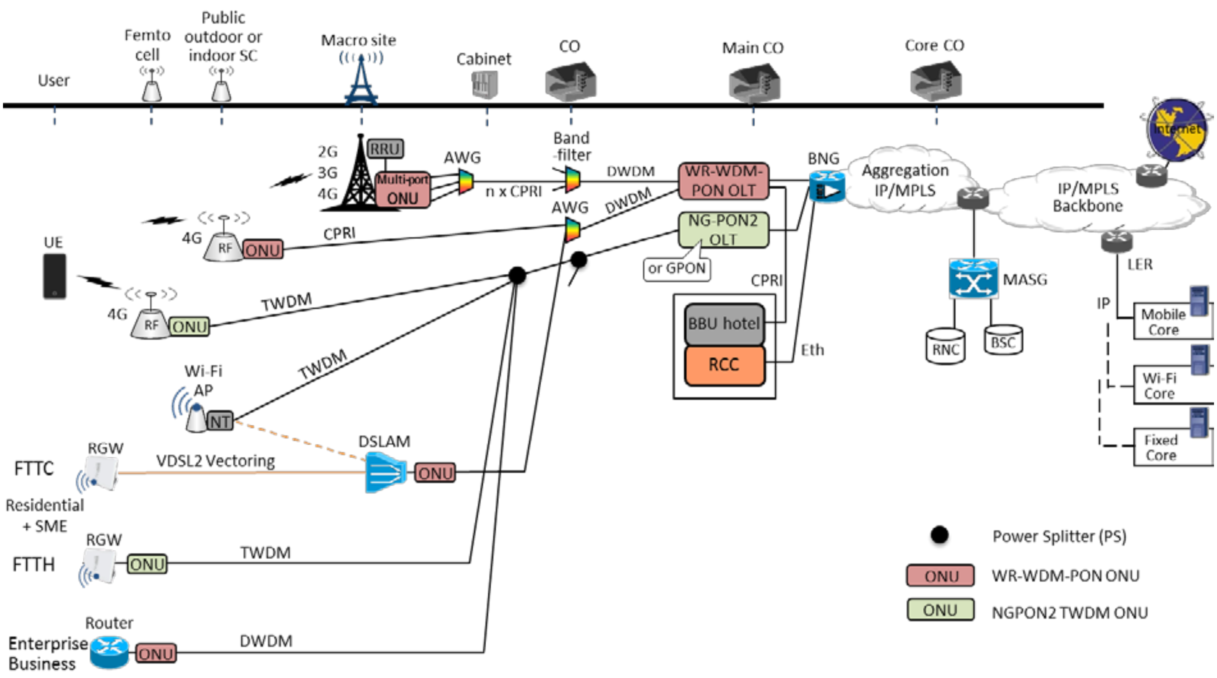


Figure 32: WDM-PON network architecture. Here, the WR-ODN and mobile fronthaul case is shown

This WDM-PON-based infrastructure serves DSL cabinets, (existing, 2G, 3G, 4G) macro cells or macro base stations, new (4G, 5G) small cells, and potentially also dedicated broadband enterprise access. Without certain additions (per-wavelength TDMA burst mode), it will not directly support residential access. In Figure 32, this is done by NG-PON2.

WDM-PON can support the related requirements due to its inherent capabilities with regard to bandwidth scaling, reach, transparency, jitter, and latency (given proper implementation).

Amongst the most important requirements are reach up to the 50 km range for rural areas (as already stated in [21]), and per channel bit rate capability of ~10 Gb/s, thus covering 10GbE for next-generation backhaul and dedicated broadband business access, and CPRI line rate options 7, 7A, 8 and 9 (8.11008…12.16512 Gb/s) [22]. Also, WDM-PON can natively support any protocol without added framing (but then also without added forward error correction), thus enabling low latency (<10 ns end-to-end for all electronics, without any fibre propagation delay) and, given proper design, low differential directional latency. The latter can be kept <50 ns for both, single- and dual-fibre working.

For the dimensioning, WDM-PON systems with 80 bi-directional channels (2×80 wavelengths in C-band and L-band, WR-WDM-PON) and 64 bi-directional (2×64 wavelengths in C-band and L-band, WS-WDM-PON), respectively, were used.

6.4.1 Analysis of Expanded-Spectrum WDM-PON Options including Mobile Backhaul

The backhaul scenario with WS-WDM-PON as infrastructure solution was already shown in the bottom part of Figure 21. As a complement, the backhaul solution based on WR-WDM-PON is shown in Figure 33.

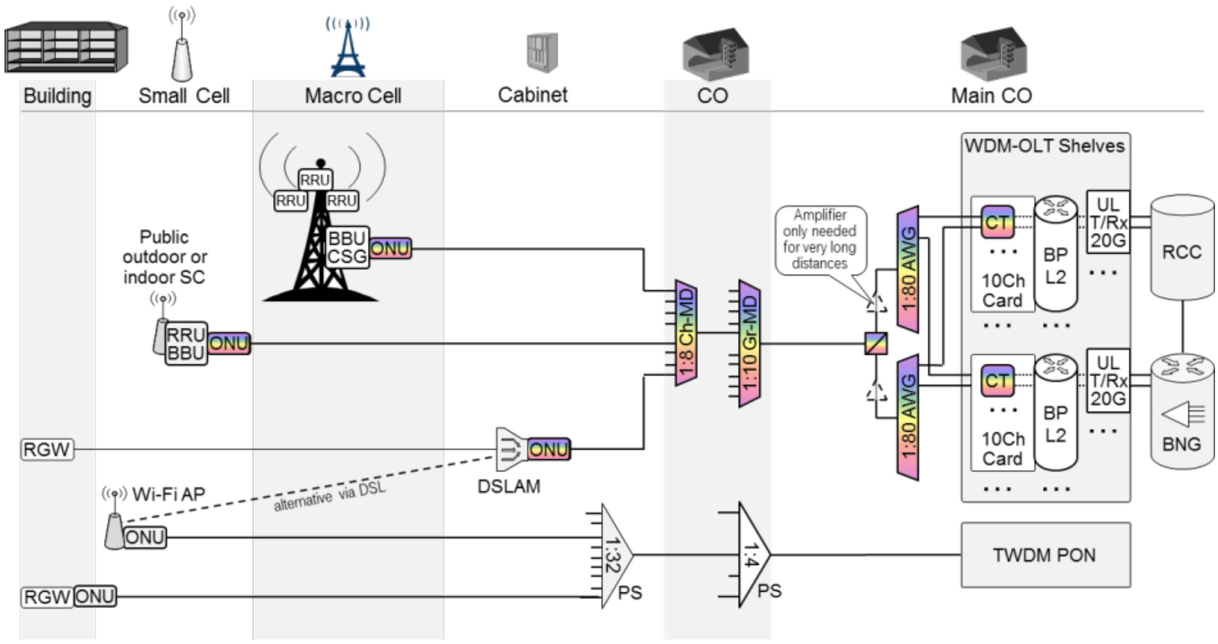


Figure 33: Backhaul scenario with WR-WDM-PON

Again, the two backhaul WDM-PON solutions are similar to each other, and also similar to the respective part of the NG-PON2 solution. The main difference again refers to the required amplifiers, and also to the number of feeder fibres, as can be derived from Table 26 and Table 27, included in Appendix A.5.

From these tables, it can be seen that no differences with regard to interface numbers exist. This is clear since the same number of clients (BBUs, cabinets) is supported. However, for WR-ODN, the WDM interfaces do not need any tuneable filters, whereas for WS-ODN, they must be equipped with tuneable filters, making them slightly more costly.

The main difference refers to the number of amplifiers. It is higher for WS-ODN due to the higher accumulated insertion loss of the passive optics. Outside ultra-dense urban areas, WS-ODN also leads to somewhat higher feeder-fibre requirements.

6.4.2 Analysis of Expanded-Spectrum WDM-PON Options including Mobile Fronthaul

The fronthaul scenario for WR-WDM-PON has already been shown in the upper part of Figure 21. For comparison, Figure 34 shows the fronthaul scenario based on WS-WDM-PON.

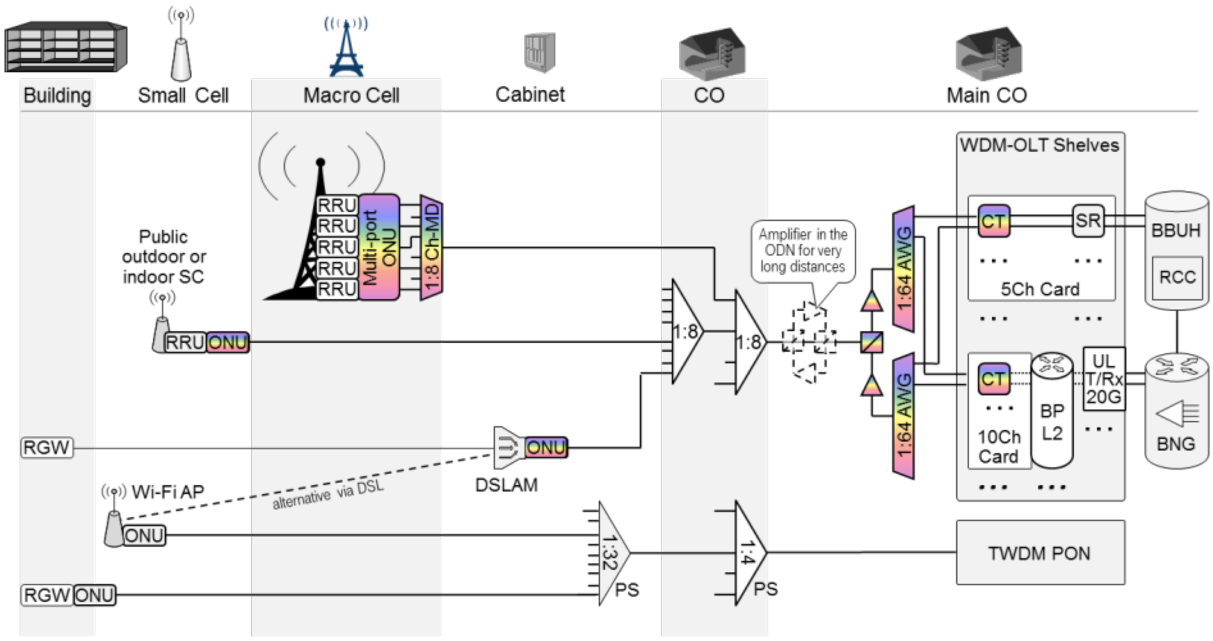


Figure 34: Fronthaul scenario with WS-WDM-PON

Basically, the WDM-PON fronthaul solution looks similar to the one based on NG-PON2, compare Figure 30. This specifically holds for the OLTs and the use of multi-port ONUs for macro-cell fronthaul. The main difference relates to the strict ODN separation between mobile fronthaul and cabinet backhaul (WDM-PON) on the one hand, and residential access and Wi-Fi access-point backhaul (TWDM) on the other.

Apart from the difference between WDM filters and power splitters, the solutions based on WR- and WS-WDM-PON look similar. One major difference relates to the number of amplifiers (REs). Dimensioning results for both WDM-PON variants are summarized in Table 28 and Table 29 in Appendix A.5, respectively.

Differences between WR-ODN and WS-ODN similar to the ones for backhaul can be identified. In particular, WS-ODN leads to the requirement for significantly more amplifiers.

6.4.3 Comparison of Backhaul and Fronthaul

The overview comparison of backhaul vs. fronthaul for the WDM-PON variants and for the urban area-type can be derived from Table 26 to Table 29. The relevant results are summarized in Table 10 and Table 11.

Table 10: Comparison of backhaul and fronthaul for WR-WDM-PON

WR-WDM-PON (Urban)		Backhaul	Fronthaul
System elements per service area	OLT shelf	3	5
	∑ 3 Gb/s interfaces	1122	1766
	∑ 10 Gb/s interfaces	-	414
	Passive optics (filters)	89	115
	Amplifiers (bi-directional)	0	0
	System specifics	2×80 channels	2×80 channels

Fibres per service area	Total count (length)	789 (692 km)	800 (696 km)

Table 11: Comparison of backhaul and fronthaul for WS-WDM-PON

WS-WDM-PON (Urban)		**Backhaul**	**Fronthaul**
System elements per service area	OLT shelf	3	6
	∑ 3 Gb/s interfaces	1122	1766
	∑ 10 Gb/s interfaces	-	414
	Passive optics (filters, power splitters)	118	121
	Amplifiers (bi-directional)	9	12
	System specifics	2×64 channels	2×64 channels
Fibres per service area	Total count (length)	800 (696 km)	802 (700 km)

It can be seen that WR-WDM-PON does not need any amplifiers (urban area), and has slight advantages in the range of 1% with regard to total fibre-length requirement. In addition, the fronthaul variant also requires one shelf less, compared to WS-WDM-PON. WR-WDM-PON also requires less passive optics (however, all optics required are filters rather than power splitters).

The backhaul variants require significantly less interfaces (where a part of these interfaces are local, grey, short-reach interfaces). Backhaul also requires less shelves in the MCOs, and slightly less (again, ~1%) total fibre length. It also requires less passive optics.

Table 12 summarizes the main pros and cons of the WR/WS-WDM-PON architecture in comparison with the 2020 reference architecture.

Table 12: Pros and cons of the WR/WS-WDM-PON architecture

Pros	**Cons**
• Reduces the number and length of fibres • Simpler to deploy and operate (tuneable TRx) • Reduces the number of active shelves • FMC at system level • More wavelengths per fibre	• Amplification is needed in WS (also for WR very long distance) • More grey TRx compared to reference although not big impact on cost • No FMC convergence at fibre level

6.5 Comparison of Transport Technology Options

The comparison of the transport solutions analysed so far is done for the urban geo type, exemplarily. Due to complexity, we split the comparison into two parts, backhaul and fronthaul, respectively. Further, we restrict the comparison to those aspects (components) which have significant relevance, and can influence the total resulting cost and latency. The related cost analysis is done in Chapter 7.

Table 13 provides the overview for the infrastructure *backhaul* solutions on the relevant components, the resulting *system* end-to-end latency, and the resulting total fibre length. The latency refers to the system only, i.e., it does not consider fibre delay. Fibre length refers to FTTC areas for comparability.

Table 13: Comparison for backhaul

Backhaul, urban		**Reference**	**NG-PON2**	**WR-WDM-PON**	**WS-WDM-PON**
System elements per service area	∑ OLT shelves	n/a	3	3	4
	∑ Interfaces (3 Gb/s)	1076	1122	1122	1122
	∑ Passive optics	68	172	89	118
	∑ Amplifiers	0	1	0	9
	Total Latency [µs]	~10	~10	~10	~10
Fibres per service area	Total count (length)	825 (743 km)	661 (562 km)	789 (692 km)	800 (696 km)

Table 14 compares relevant components and total system latency and fibre lengths for the different fronthaul solutions discussed herein earlier.

Table 14: Comparison for fronthaul

Fronthaul, urban		**Reference**	**NG-PON2**	**WR-WDM-PON**	**WS-WDM-PON**
System elements per service area	∑ OLT shelves	n/a	6	3	6
	∑ Interfaces (3 Gb/s & 10 Gb/s)	1490	2180	2180	2180
	∑ Passive optics	112	206	115	121
	∑ Amplifiers	0	20	0	12
	Total Latency [µs]	~0.01	~0.02	~0.02	~0.02
Fibres per service area	Total count (length)	847 (785 km)	666 (572 km)	800 (696 km)	802 (700 km)

From Table 13 and Table 14, certain key differences between the solutions can be derived. Most notably, the number of (optical) interfaces is significantly higher in fronthaul, compared to backhaul. This is particularly true for the PON solutions (less so for the CWDM network reference), since these require local grey interfaces for the fronthaul channels. The higher interface number results from the need to support individual RRUs, instead of BBUs (which can in turn support multiple RRUs). It also leads to somewhat higher numbers of passive components (filters, power splitters where applicable) and shelves, respectively. The network reference also does not require shelves at the MCO, but the use of coloured transceivers introduces a high complexity to the network operation.

The other relevant difference between backhaul and fronthaul refers to total system latency. Under the assumption of *standard* Layer 2 aggregation in the backhaul OLTs (i.e., no special low-latency switching), this difference is in the range of 10 µs and must thus be considered in the context of advanced radio techniques like CoMP. However, this difference must also be put into relation with absolute fibre delay (run time), which can be as high as up to 400 µs.

Significant differences can be identified between the solutions, and for backhaul or fronthaul, respectively. The CWDM network reference and WR-WDM-PON do not require any RE (in the considered urban area), due to the fact that they make use of wavelength routing.

There are also differences regarding total fibre length. First, fronthaul solutions require slightly more fibre length (an effect of the higher channel number). Then, there are certain differences between the solutions (per backhaul or fronthaul). Under similar assumptions regarding fibre re-usage (e.g., in FTTC areas), there are slight advantages for solutions with higher per-system channel count, i.e., WDM-PON and the most efficient solution is NG-PON2 in terms of number of fibres used and length.

The potential of network convergence of the different technology options with regard to system and fibre infrastructure levels of convergence is shown in Table 15. Duct and cable convergence is not considered because it is a common usage today.

Table 15: Technology potential for convergence with T(W)DM-PON

Technology	**Feeder fibre CO ↔ MCO**	**ODN fibre Cab ↔ CO**	**ODN fibre BS ↔ Cab**	**System level**
Mass-market NG-PON2 TWDM	X	X	(X)	Limited CoMP support with current MAC implementation (>>1 ms delay)
PtP CWDM reference				
NG-PON2 PtP WDM	X	X	(X)	X
WS-WDM-PON				X
WR-WDM-PON				X

(X) Depending on power splitter structure (e.g., additional building splitter stage)

A full convergence solution can be achieved using NG-PON2 on fibre and system level on the existing power splitter based mass-market PON with PtP WDM overlay. Also the NG-PON2 TWDM mass-market solution could allow full convergence but with the expected limited CoMP scheme support with current MAC implementations due to latency constraints, which will be further studied in D3.4.

In summary, we analysed different WDM-based FMC network architecture options including both backhaul and fronthaul scenarios. We identified significant differences with regard to the backhaul vs. fronthaul question, and also with regard to the systems solutions.

In general, backhaul leads to fewer components required with lower bitrates, leading to lower systems cost. Fibre length does not show a significant difference (because the same sites have to be connected and the same number of fibres per site is expected). Total system latency is higher compared to fronthaul, the difference being produced by the Layer 2 (Ethernet) aggregation in the PON OLTs.

Regarding the infrastructure systems solutions, wavelength-routed solutions show certain advantages in that they avoid (for ultra-dense and urban areas) any active reach extension (amplifiers). In addition, there are minor advantages with regard to total fibre length. The latter is driven by the number of bi-directional channels. From that, one can conclude that for infrastructure deployments, the number of wavelength channels per system should be as high as possible. Table 16 includes a summary of the performance of the different technology options against the most relevant parameters.

Table 16: Comparison of transport technology options

Per service area (urban)	**Reference**	**NG-PON2**	**WR-WDM-PON**	**WS-WDM-PON**
Reduction in fibre count and length	●	●●●	●●	●●
Reduction in number of interfaces	●●●	●●	●●	●●
Reduction in passive optics	●●●	●	●●●	●●
Reduction in amplifiers (reach)	●●●	●	●●	●
Potential of structural convergence		●●●	●	●
Number of wavelengths per fibre	●	●	●●●	●●
Bitrate per wavelength	●●	●●	●●	●●
Low latency (system level)	●●	●●	●●	●●
Simple to operate (colourless)		●●●	●●●	●●●
Reduction in active shelves in MCO	●●●		●	
Ethernet aggregation in Main CO		●	●	●
Legacy compatibility with fixed net.		●●●		
Re-use network infrastructure	●●	●●●	●	●●

6.6 Alternative Starting Scenarios

The starting scenario for fixed access defined in Chapter 5 assumes that there has been an investment in fixed access consisting of a mix of FTTC and FTTH with FTTH based on PON infrastructure. Furthermore, it is assumed that site consolidation will be an important driver in the continued evolution of the network where PONs are served from the Main COs rather than the traditional COs. This was identified as a likely starting scenario in the 2020 time horizon considering cost structure of the fixed access. As a basis for this scenario are assumptions on traffic and capacity requirements, access topologies and suitable fixed access technologies. The starting scenario is defined based on an assumed optimization of the cost of fixed access also considering time for migrating from typical DSL deployments of today (thereby 30% FTTH and 70% FTTC). In this section we consider alternative starting scenarios that may be a result of different factors:

Alternative FTTH solutions: TWDM is being standardized as the main technology for fixed access in NG-PON2. However, whether this becomes a commonly deployed solution in the year 2020 is still an open question, and there will be variations between regions and operators regarding both starting assumption for the FTTH solution/infrastructure and regarding plans for further evolving the fixed access. Some operators will invest in alternative FTTH solutions like active optical networks (AON), and solutions based on large numbers of active remote nodes in buildings or cabinets. Other operators may find already deployed GPON as a competitive solution for fixed access also in a longer time perspective. Some operators might upgrade to NG-PON2 but without node consolidation. These last two cases would resemble the starting scenario, but keeping the PON based FTTH solution served from the CO rather than the MCO, which in turn has implications on the aggregation network and RAN deployment.

Continued use of copper: Some operators may choose to continue to rely on copper technologies in the distribution segment of the fixed access where fibre deployment is costly. Migration to fibre could be slow or there could be a deliberate investment in copper based access. Continued evolution of DSL with G.fast will allow higher bandwidths to be supported although shorter reach pushes the DSLAMs closer to the customers. Compared to the original starting scenario this would lead to a lower ratio of FTTH with fixed access based on FTTC/B with a larger number of active remote nodes.

Investments in mobile networks: With rapid increase in mobile traffic and evolution toward 5G, upgrade and build out of capacity in mobile networks may be more critical compared to fixed access. Mobile access may evolve to replace fixed access for many end-user broadband services, thereby absorbing a share of traditional fixed access traffic. The starting scenario in Chapter 5 assumes an existing infrastructure for fixed access capable of supporting high Gb/s fixed access rates. Such investments in the fixed access infrastructure might not have happened or the starting scenario infrastructure is already strongly influenced by mobile deployment and mobile requirements. With mobile densification, the cost of mobile transport will increase and have a larger impact on the infrastructure for the starting scenario which no longer is just driven by fixed access considerations. Systems assumed to shape the infrastructure of the starting scenario (i.e., G-PON) are effective for residential access but do not provide idle transport capabilities for mobile backhaul in terms of latency, jitter, and capacity as well as in terms of connectivity. Hence, a starting scenario shaped by investments in mobile networks would be characterized by more cell-sites, PtP backhaul links (fibre, WDM, copper, wireless, free space optics), preferably connecting Macros to neighbouring small cells, while fixed access would be characterized by old DSL technologies. Instead of optimizing mobile transport on top of an evolved fixed access infrastructure, the fixed and mobile infrastructure would need to be jointly optimized with focus on providing 5G capacities in the mobile network. Without an extensive fixed access fibre infrastructure, densification of mobile networks evolves through a plurality of access technologies (copper, free space optics, microwave or wireless technologies) but also through fibre deployment based on mobile transport requirements. This may lead to the presence of a large number of active nodes with high sustainable bandwidth needs.

In this section we consider alternative starting scenarios compared to the scenario described in Chapter 5 (also depicted in Figure 35). Five alternative starting scenarios are described in Section 6.6.1 and different solution alternatives for some of these are further analysed in sections 6.6.2-6.6.4.

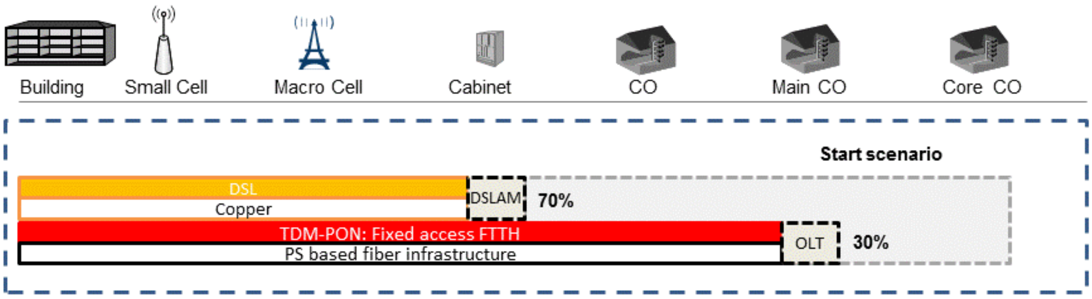


Figure 35: Reference figure of the starting scenario described in Chapter 5

6.6.1 Description of Alternative Scenarios

Figure 36 shows a starting scenario consisting of fixed access based on TDM-PON served from the CO. The scenario resembles the original starting scenario defined in Chapter 5 in terms of the deployed residential fibre infrastructure but differs in terms of system assumptions. In the scenario considered here, the operator keeps the TDM-PON system for fixed access. The scenario is relevant for the case where the operator sees little benefit in replacing deployed GPON with TWDM. Based on this starting point, several convergence alternatives exist of which three are depicted in Figure 36.

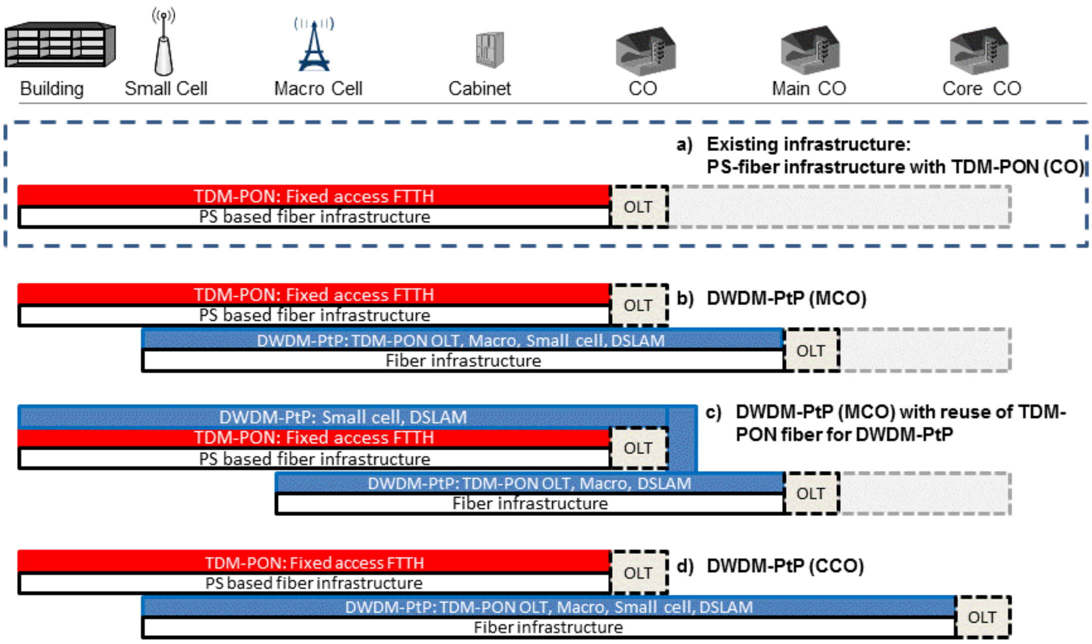


Figure 36: Alternative starting scenario a) consisting of power splitter based fibre infrastructure and a TDM-PON system (red) at CO for fixed access and different convergence cases b), c) and d) based on the alternative starting scenario considering different extensions of a DWDM-centric domain (blue)

Figure 37 depicts a second alternative starting scenario where the operator keeps deployed PtP residential access systems at the CO, whether it is DSL or Ethernet PtP. The convergence cases are similar to that of GPON (Figure 36) except that the DSL case limits possible fronthaul deployments. For Ethernet PtP the fibre based infrastructure can be reused by connecting access fibres directly to the DWDM-centric domain.

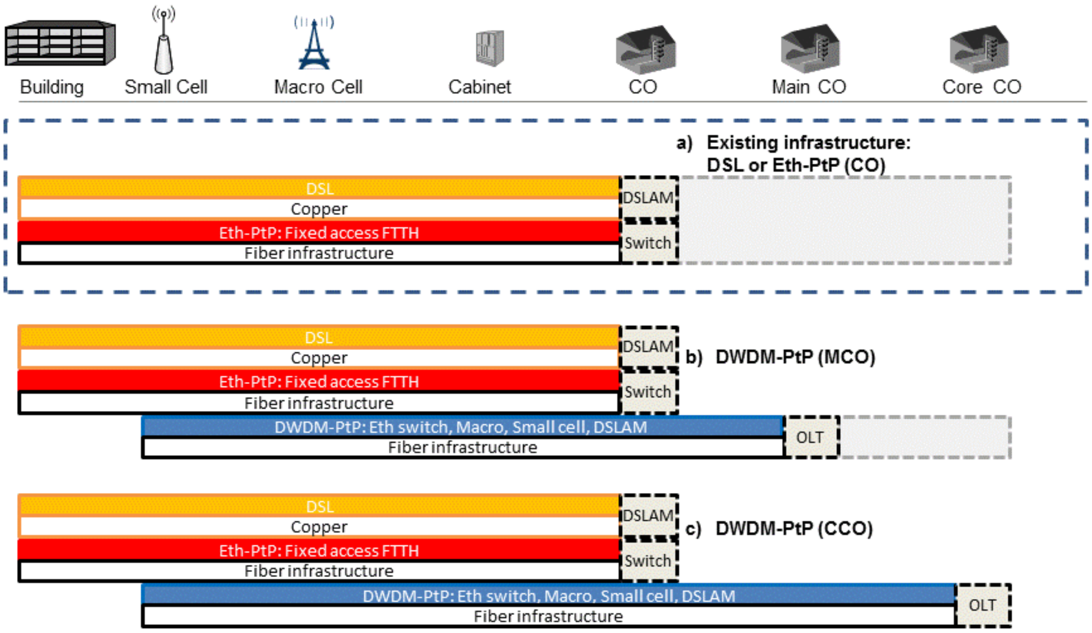


Figure 37: Alternative starting scenario a) based on DSL or Eth PtP from the CO and different convergence cases b) and c) considering different extensions of a DWDM-centric domain (blue)

Figure 38 depicts a third alternative where the operator, as part of the starting scenario already has upgraded to an FTTC deployment either based on Ethernet PtP or DSL and may not have plans to further migrate to PON. This case is partially addressed in the starting scenario in Chapter 5 as it considers 70% FTTC. For the case of 100% FTTC, two backhaul alternatives are depicted in Figure 38 differing in the extension of the DWDM-centric domain. A general disadvantage of any scenario with plenty of distributed active remote nodes is the operational cost associated with these. However, a potential advantage of distributed access nodes is the improved scalability towards higher data rates and more clients. In these scenarios, segments that need to be dimensioned for peak rate and sustainable rate are decoupled through the remote nodes and required data rates on each “side” of the remote node (uplink/downlink) can be evolved independently depending on evolution of traffic. In contrast, T(W)DM-PON systems are exposed to a more delicate cost balance where also forthcoming system generations require an optimal balance between peak rate, sustainable rate, reach, fan-out, etc. over the existing PON infrastructure at a sufficiently low interface cost.

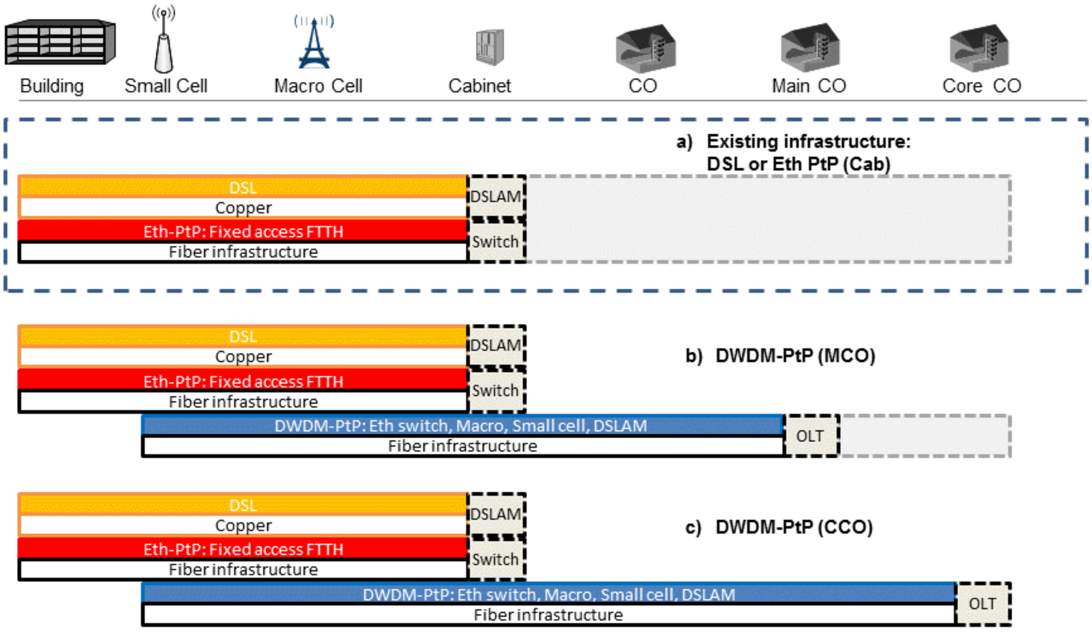


Figure 38: Alternative FTTC starting scenario a) with active remote nodes at the cabinet and different backhaul scenarios b) and c) considering different extensions of the DWDM-centric domain (blue)

Figure 39 depicts a fourth alternative where the operator, as part of the starting scenario already has upgraded to an FTTB deployment either based on Ethernet PtP or DSL. In Figure 39 two different backhaul solutions are depicted based on DWDM or TWDM. Operator preference may depend on the geotype, traffic volumes and preferred choice for RAN deployment.

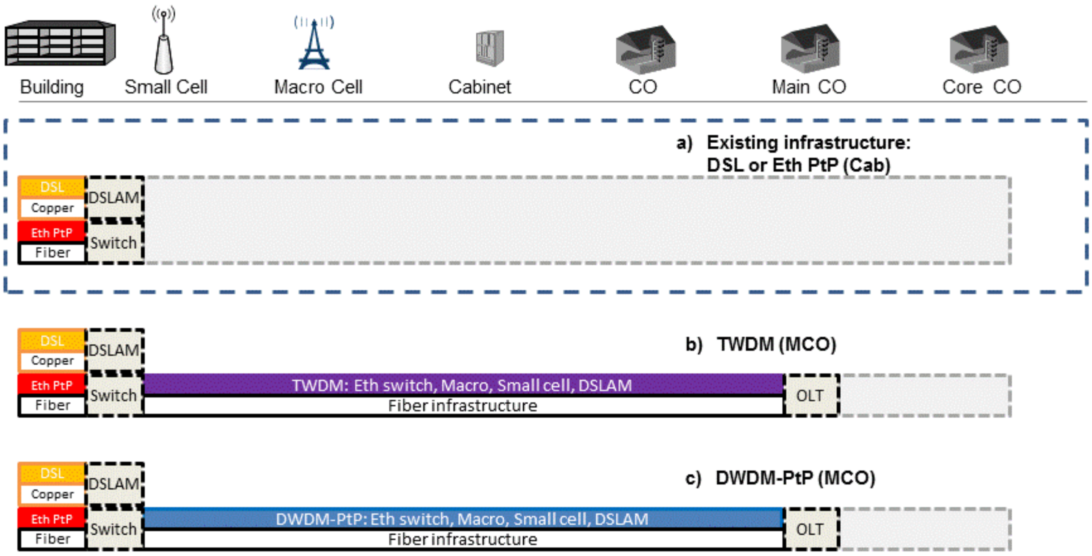


Figure 39: Alternative FTTB starting scenario a) with active remote nodes at the building and different backhaul scenarios b) and c) based on DWDM or TWDM

The fifth alternative scenario is shown in Figure 40 which may be the case where an operator has prioritized investments in the mobile transport. Existing fixed access systems are similar to what is described in Figure 36 and Figure 37. In addition to this the operator has already invested in small cells and small cell transport, which could involve systems and links for connecting small cells to neighbouring Macro sites.

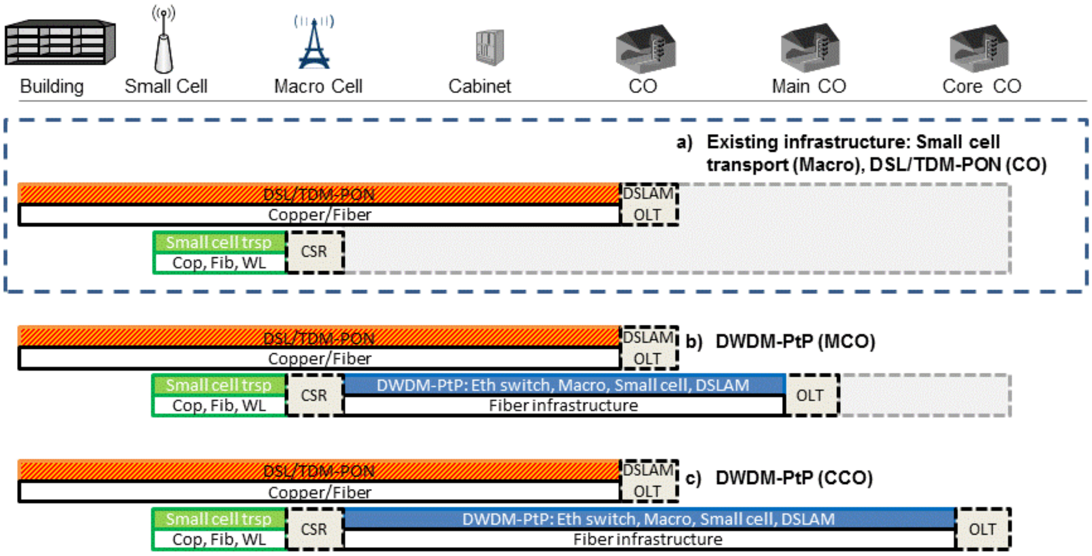


Figure 40: Alternative starting scenario a) based on existing fixed access (DSL/TDM-PON) and existing small cell transport (wireless, dedicated fibre/copper) and different backhaul scenarios b) and c) with different extensions of a DWDM-centric domain

The scenarios considered in Figure 36-Figure 40 all have in common that there is some fixed access system and/or small cell transport system that will be kept in the converged architecture. In the different scenarios these systems are hosted at different sites that need to be backhauled. As a result the different scenarios differ in the extension of the backhaul solution which could be of the following types:

- DWDM
  - WR-WDM-PON (static)
  - Programmable DWDM (flexible)
- TWDM
- Active solutions
  - Ethernet/IP with grey optical links

In many cases DWDM will be the basic technology for the backhaul but with different data plane alternatives. In some cases TWDM may be an option although it is less suitable as an aggregation solution. Active solutions are also possible but not shown in Figure 36-Figure 40. The following sections provide an analysis of selected scenarios with WR-WDM-PON as the solution for the converged access/aggregation. Variants where flexibility has been introduced in the DWDM layer are considered in Section 8.2.

6.6.2 Existing GPON with WR-WDM-PON (for Cell Sites and OLT Backhaul)

Figure 41-Figure 43 show the dimensioning of WR-WDM-PON for the convergence scenario depicted in Figure 36 for the three cases: fronthaul, backhaul via WDM, and backhaul via G-PON.

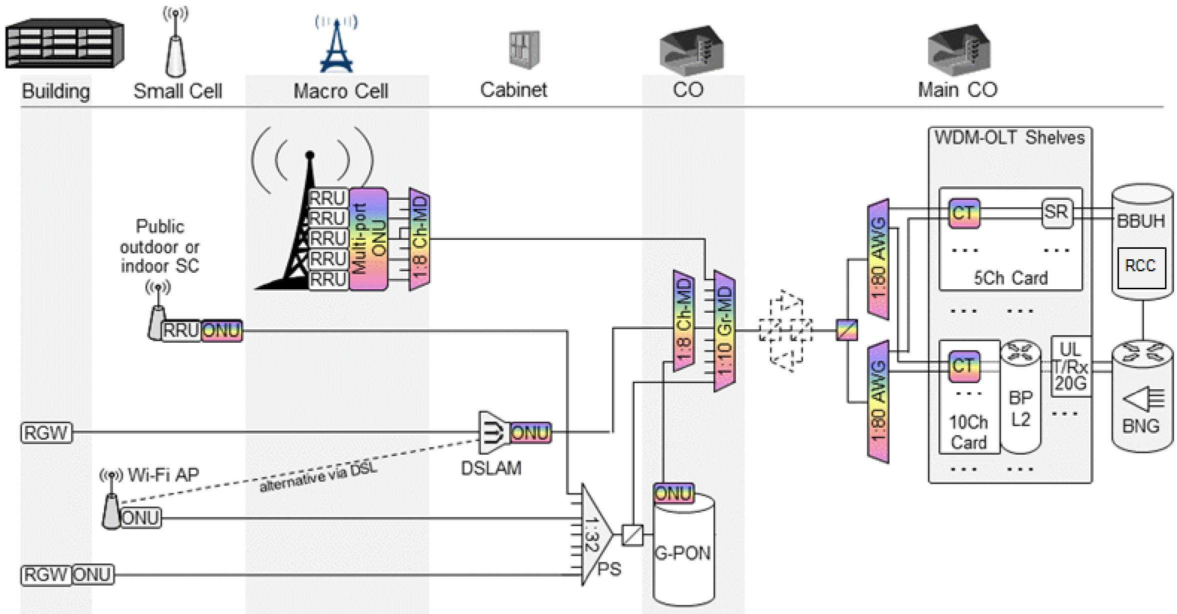


Figure 41: Convergence scenario based on a GPON starting scenario implementing fronthaul for small cells via WDM-PtP

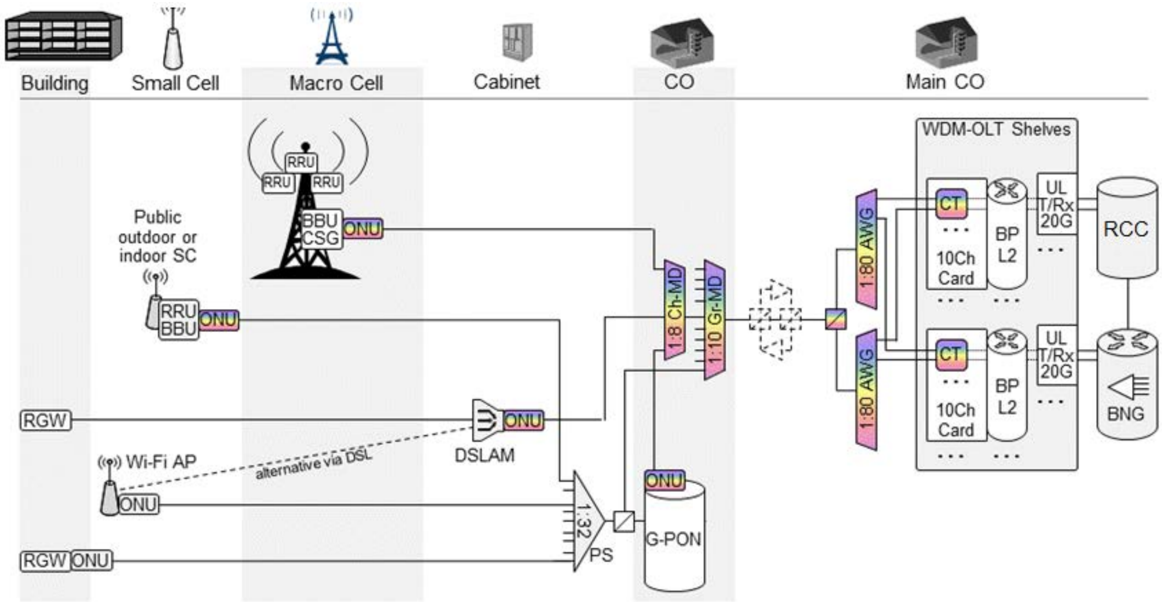


Figure 42: Convergence scenario based on a GPON starting scenario implementing backhaul for small cells via WDM-PtP

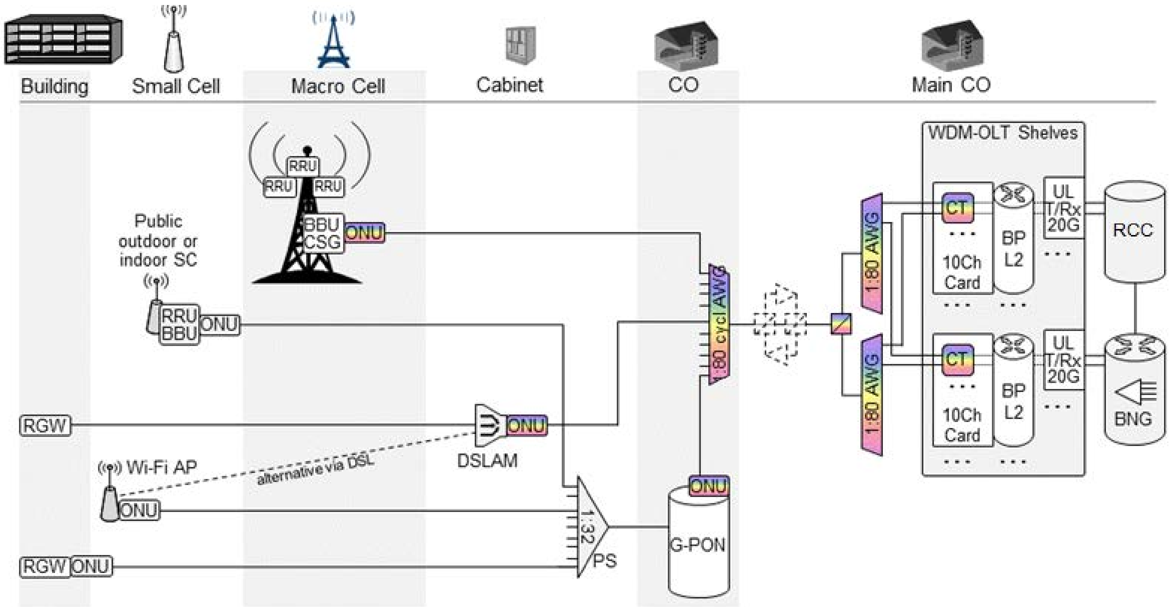


Figure 43: Convergence scenario based on a GPON starting scenario exploiting GPON for small cell backhaul

Figure 41 shows the case where the GPON infrastructure is exploited for fronthaul. Since the power splitter based GPON infrastructure is exploited for small cell connectivity the WDM-PON system is in reality a hybrid WR/WS-WDM-PON where tuneable filters are required at the clients (small cells) connected via the GPON ODN. The distribution of the small cells will determine the number of GPON ODNs that must be connected to the DWDM-centric domain. With large concentration of small cells to fewer areas only a few ODNs need to be connected. For a more even distribution of small cells there will be few small cells per ODN and more ODNs must be connected. Table 30 in Appendix A.5 details the dimensioning results for the previous scenarios.

6.6.3 Existing FTTC with WR-WDM-PON (for Cell Sites and OLT/DSLAM Backhaul)

Figure 44-Figure 45 show the dimensioning of WR-WDM-PON for the convergence scenario depicted in Figure 37 for the two cases fronthaul and backhaul. Table 31 in Appendix A.5 contains the dimensioning results for the following scenarios.

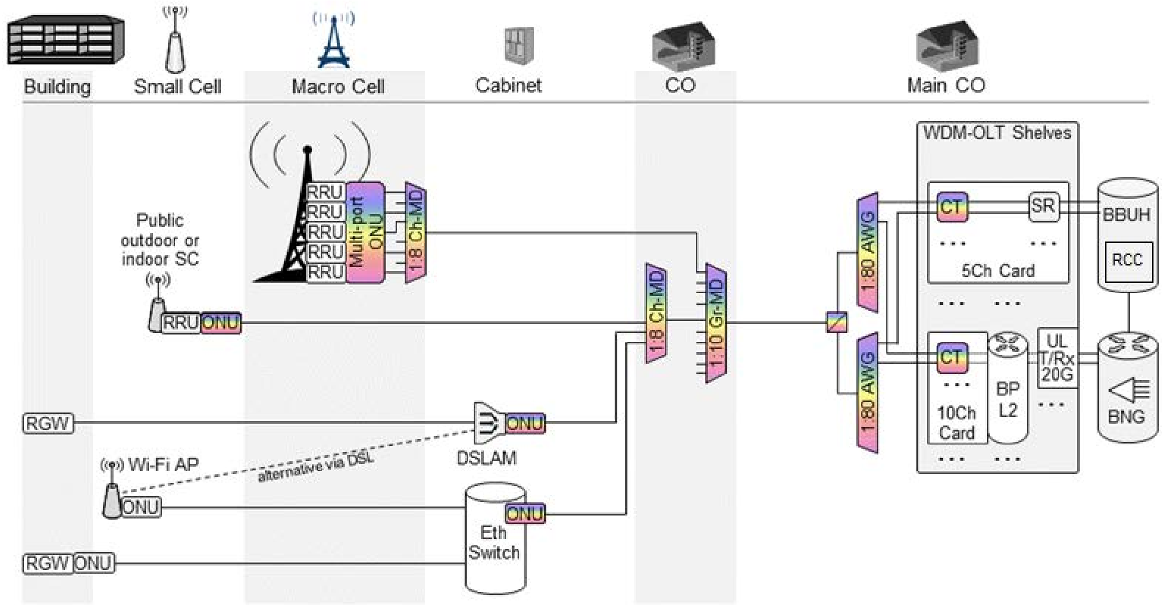


Figure 44: Convergence scenario based on an active cabinet starting scenario implementing fronthaul for small cells via WDM

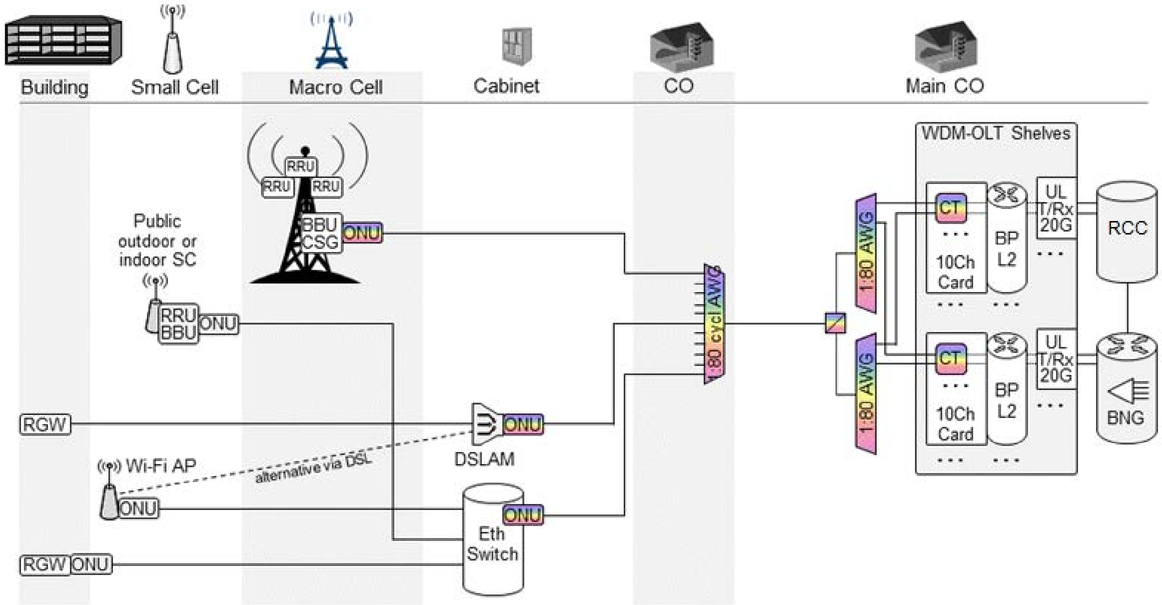


Figure 45: Convergence scenario based on an active cabinet starting scenario implementing backhaul for small cells via the active cabinets

6.6.4 Existing GPON/DSL and Dedicated Small Cell Transport, with WR-WDM-PON (for Macro Sites and OLT/DSLAM Backhaul)

Figure 46-Figure 47 show the dimensioning of WR-WDM-PON for the convergence scenario depicted in Figure 40 for the two cases fronthaul and backhaul. For this last example there are implications on the RAN architecture and suitable location of the BBU. Assuming direct links between small cells and macros, BBUs for the small cells

are with favour placed at the Macro site. Table 32 in Appendix A.5 contains the dimensioning results for the following scenarios.

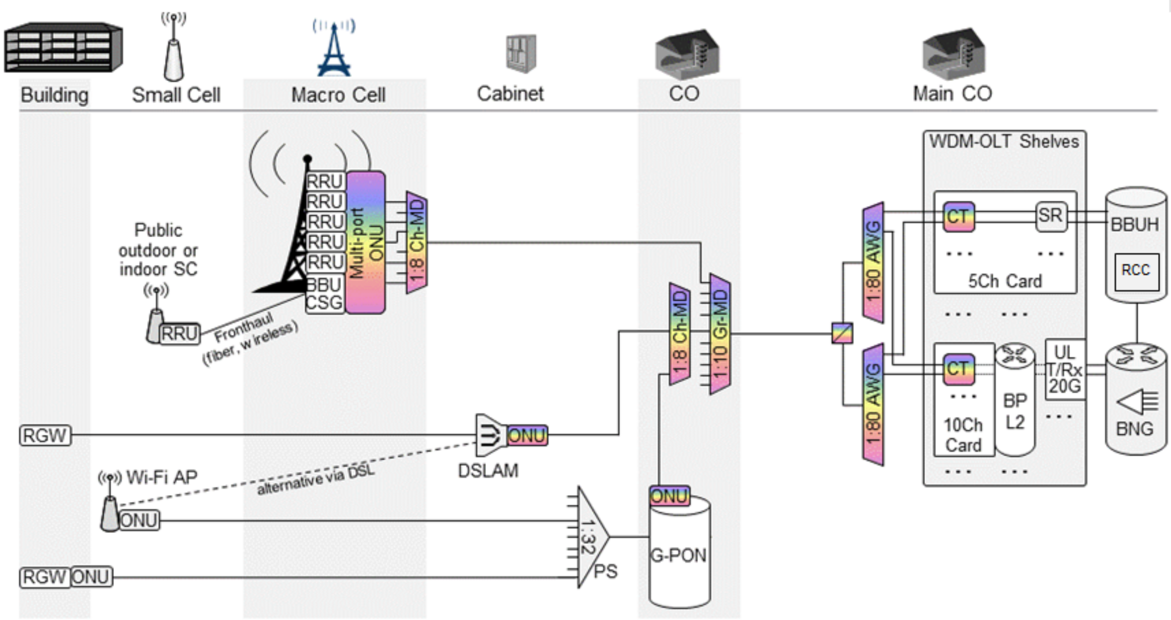


Figure 46: Convergence scenario for existing G-PON/DSL and small cell transport with WR-WDM-PON for backhaul

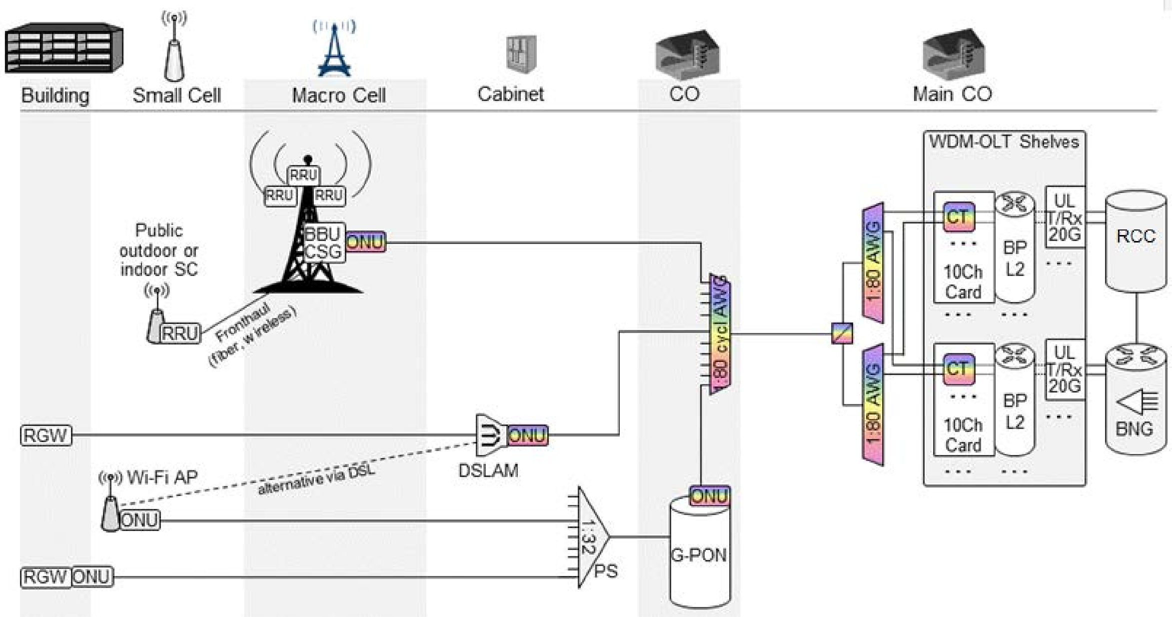


Figure 47: Convergence scenario for existing G-PON/DSL and small cell transport with WR-WDM-PON for backhaul

6.6.5 Conclusions

This section shows the importance of the starting scenario for how structural convergence can evolve. Depending on the starting scenario with the infrastructure and systems that will be reused, there will be different requirements on the deployed transport solution. For example, for the DWDM-centric solution considered in sections x-x there are large differences in number of clients, capacity and connectivity requirements. This affects the extension of the DWDM-centric domain toward the client and toward the core. Furthermore, this impacts the optimal RAN deployment and for the case of centralization, optimal placement of BBUHs. In the original starting scenario, placement of the BBUH at the CO makes little sense as any connection between Macros and small cells over the available fibre infrastructure would need to pass through the MCO (tromboning). For other starting scenarios with more distributed placement of nodes, more distributed placement of BBUHs could be an attractive option, also considering that radio coordination gains diminish rapidly with increased centralization as well as pooling gains which vanish beyond ~100 cells.

Furthermore, note that comparing these alternative starting scenarios to the original starting scenario is not trivial due to different assumptions on existing infrastructure and systems. One possibility is to include the cost of the starting infrastructure and systems in the total cost comparison between scenarios, in what could be seen as a green field comparison. However, if fixed access represents a dominating portion of the cost compared to mobile backhaul/fronthaul, such a comparison would essentially be a matter of optimizing the fixed access deployment. Results from such studies are for example found in [24] from FP7-project OASE and are consistent with the original starting scenario considered in this deliverable. Nevertheless, given that deployment of fixed access infrastructure represents a large cost compared to mobile backhaul/fronthaul, different brown field scenarios will be very important as RAN deployment may not be able to wait for investments in the fixed access infrastructure.

6.7 Alternative Placement of BBU Hotels Based on Network and Traffic Characteristics

The focus of this last section is on BBU hoteling. Since the main motivations behind hoteling (already discussed in Section 3.2.2) are cost/energy savings and increased radio performance by enabling coordinated processing, we argue that the possibility of centralizing even more BBUs into one site can increase such benefits [50]. This however implies that the fronthaul traffic shall be transported over the existing aggregation network, i.e., it shall be multiplexed and/or routed like conventional backhaul traffic [54]. In a more aggressive scenario where we consider that BBUHs are allowed to be located at higher stages of the aggregation network (i.e., even beyond the Main Cos), the choice of where to place each BBU is not trivial, because it is entangled in other network design choices, like traffic routing and multiplexing constraints. For these reasons, we introduce and formalize a “BBU placement” problem, and we solve it considering two alternative options for fronthaul transport: an *Overlay* approach, extending the fronthaul links transported in dedicated wavelengths (in line with Chapter 5 and 6 fronthaul architecture) and *OTN aggregation*, aggregating fronthaul links using OTN.

To model this problem, we relax some of the specific technological assumptions that have characterized Chapter 6 so far, and we adopt simplified aggregation/access network architecture as discussed in the following subsection.

6.7.1 A Generic Architecture for an Access/ Aggregation FMC Network

We consider a given aggregation network (as in Figure 1) that comprises several (either macro or small) Cell Sites (CS) and CO, according to a multistage hierarchy in which at stage 0 there are Access Cabinets, at stage 1 COs, at stage 2 Main COs, and at stage 3 a single Core CO. CSs and COs are demarcation nodes toward, respectively, the mobile and fixed access portion, whereas the Core CO interfaces toward the core network. An outside plant connects them through a generic physical-link topology (typically based on hierarchically interconnected rings). Each link is equipped with a number of fibres, and the capacity of each fibre is divided in a number of WDM channels.

Both CSs and COs insert access traffic into the aggregation network, but at the same time COs can perform aggregation of transit traffic coming from other nodes. Such aggregation can be purely optical, i.e., by means of transparent optical cross connect devices (e.g., ROADM), or optical/electronic, i.e., by means of electronic switches. Therefore, the traffic is routed over two layers: a lower WDM layer made of wavelength circuits, and an upper electronic layer where each traffic flow occupies only a fraction of wavelength capacity and can be routed and multiplexed using electronic switches.

In the following, if a node is equipped with at least one BBU, it is denoted as “hotel”, trivially including also CSs hosting their own BBU (i.e., conventional base stations).

6.7.2 Traffic Classes

In the BBU placement problem, we shall consider three classes of traffic: fixed between COs and Core CO, mobile (backhaul) between hotels and Core CO, and fronthaul between CSs and hotels. Specific constraints on traffic routing are applied, depending on the class. Fixed and mobile traffic is natively packed-based (e.g., IP), exhibiting some degree of tolerance on absolute and differential delay. Therefore, we assume that different requests can be routed along different paths. Fronthaul traffic is way more restrictive, because it is natively circuit-based, with hard synchronization and latency requirements [50], [55] (as explained in Section 3.2), that are expected to become even more binding when considering coordination schemes as CoMP. Therefore, as a difference from fixed and mobile traffic, fronthaul flows cannot be split among parallel light paths.

6.7.3 Fronthaul Options

We consider two kinds of transport strategies for fronthaul traffic: “OTN (Aggregation)” and “Overlay”.

In the *OTN*, both fronthaul and fixed/mobile backhaul are transported over a common OTN layer. This makes possible to multiplex them together into the same wavelengths. Fronthaul flows can traverse intermediate electronic switches, which in this case are implemented as OTN switches or “wrappers”, provided that the node-processing extra latency contribution is subtracted from the latency budget available for fibre propagation. It should be noted that at least two switches are traversed; one for ingress and another for egress of fronthaul. As current switching technologies (e.g., Ethernet or OTN) feature processing delays that are too far from the requirements of fronthaul transport, we assume “low-latency” switches, on-purpose tailored for fronthaul applications, adding a (one-way) delay of $t_{SW} = 20\ \mu s$, for each traversed switch [56].

In the *Overlay* case, fixed/mobile backhaul goes over a separate electronic layer (OTN or even Ethernet), while each fronthaul flow is directly transported over a dedicated wavelength, and no multiplexing with other flows can be performed (similarly to the approach taken in Section 6.2). Since there is no electronic transport, its only latency contribution is due to propagation.

6.7.4 Problem Statement

The resulting BBU placement problem can be summarized as follows. Details regarding the mathematical formulation and effective solving methods can be found in [49].

Given: the network physical topology, the maximum number of fibres for each link (K), the number of wavelengths (W), the line rate (capacity) of each wavelength, the set of traffic requests, the maximum fronthaul round-trip time (τ_{RTT});

decide: the placement of each BBU, the Grooming, Routing and Wavelength Assignment (GRWA) of all traffic requests, the installation of additional electronic switches;

to minimize: the number of hotels (*minHotel*), or the number of fibres (*minFibre*).

6.7.5 Case Study

The described placement problem is tested against several synthetic physical topologies and traffic matrixes. Topologies are “ring and spur” with three stages, in which a big ring at the higher stage comprising the Core CO is connected to a number of smaller rings at the intermediate stage, which are connected to trees at the lower stage. To generate them, a number ($n_N = n_{CO} + n_{CS}$) of nodes is uniformly scattered over a square coverage area, according to parameters of Table 17 for the three geotypes: urban, sub-urban and rural and then the nodes are interconnected through a realistic hierarchical-ring topology. Note that the ultra-dense urban scenario is not covered here as, given the short distances involved, placement of BBUs at higher layers is always feasible. More details on the generation of the topology instances can be found in [48].

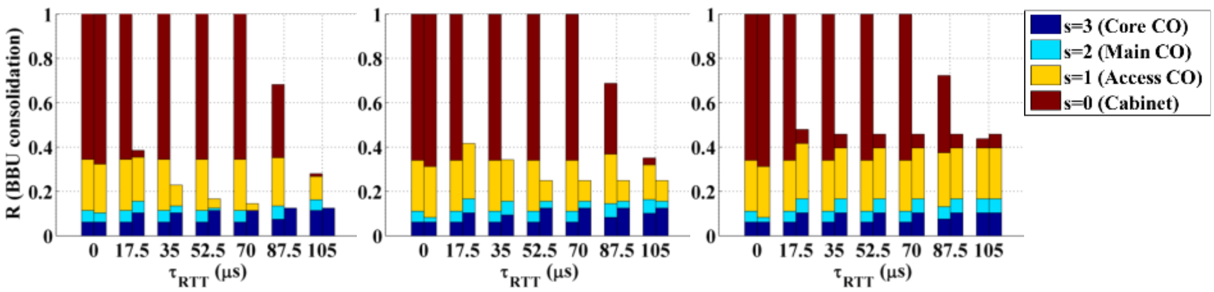
Table 17: Parameters of the three geotypes (urban, sub-urban, and rural), per Main CO area

Geotype	Urban	Sub-Urban	Rural
Coverage area (km^2)	15	142	615
Number of COs (n_{CO})	3	6	11
Number of CS (n_{CS})	23	29	31
CO density (per km^2)	0.193	0.042	0.018
CS density (per km^2)	1.5	0.2	0.05

For traffic matrixes, we assume that (as in [50]): each CS is configured as a LTE macro site with 3 sectors, 20 MHz bandwidth and 2x2 MIMO. The corresponding fronthaul is 6.29 Gb/s (as we are not including 8B10B CPRI line coding) and the backhaul is uniformly distributes in the range 300–750 Mb/s. Each CO demands fixed traffic uniformly distributed in the range 10–20 Gb/s.

6.7.6 Numerical Results and Discussion

Figure 48 (a, b, c) show the ratio R between the number of hotels and the number of CSs as a function of the maximum fronthaul round-trip time (τ_{RTT}). The metric R quantifies the degree of BBU consolidation, where $R = 1$ indicates no consolidation (each BBU hosted in the respective CS) and $R = 1/n_{CS}$ indicates the highest degree of consolidation (all BBUs in a single hotel).



(a) *minHotel*; *W* = 4, *K* = 10 (b) *minFibre*; *W* = 4, *K* = 10 (c) *minFibre*; *W* = 1, *K* = 6

Figure 48: Per-stage (*s*) breakdown of BBU consolidation (*R*), for urban geotype (left column: *OTN*; right: *Overlay*)

In Figure 48 (a) (*minHotel*), we can see that R significantly decreases for higher τ_{RTT} since a higher τ_{RTT} allows to route fronthaul flows over longer paths. Comparing the *OTN* (left column) to the *Overlay* (right column) case, we can also clearly notice that the *Overlay* case achieves much lower values of R (higher BBU consolidation), suggesting that the higher traffic multiplexing enabled by OTN does not compensate for the increased latency due to OTN encapsulation.

The columns in Figure 48 (a) depict also the breakdown of the BBU placement over the different stages, showing that, for higher values of τ_{RTT} BBUs are placed at higher stages, i.e., closer to the Core CO. Very similar results are shown in Figure 48 (b), where the main objective function is the minimization of number of fibres (*minFibre*), meaning that the achievable degree of BBU consolidation is not affected by changing the objective function (fibres). This result is counter-intuitive as *minFibre* should promote much tighter traffic aggregation and discourage BBUH consolidation (as fronthaul traffic uses much higher capacity). This result can be explained by the fact that, in our case study, the offered traffic is quite low and requires limited capacity, so the number of fibres can be easily minimized without affecting BBU consolidation. In contrast, if we now decrease the capacity of the network (see Figure 48 (c), where each fibre supports only a single wavelength), we can clearly see that the optimized solution results in a much higher value of R (i.e., less consolidation), especially for large values of τ_{RTT}.

Finally, Figure 49 shows that R strongly depends on the three geotypes (urban, sub-urban and rural), as a consequence of their different network sizes. Note that the difference between *Overlay* and *OTN* becomes less evident only for larger budget of latency (beyond 200 μs), where the impact of additional switching latency is lower.

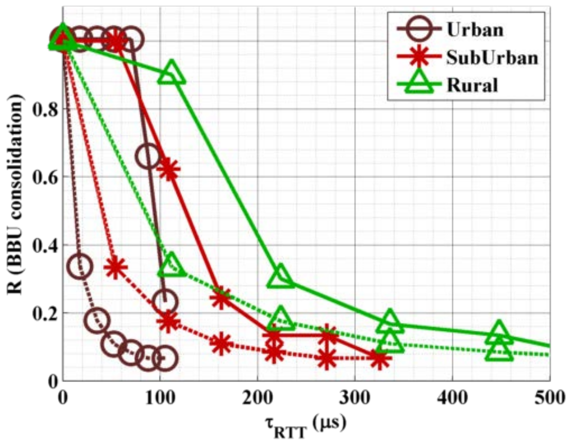


Figure 49: BBU consolidation (*R*), with *W* = 4, *K* = 6; for all the geotypes (continue line: *OTN*; dashed line: *Overlay*)

6.7.7 Conclusions

In this section, we have formalized the BBU placement problem for C-RAN infrastructures based on WDM aggregation networks, considering both *OTN aggregation* and *Overlay* for fronthaul transport. Numerical simulations obtained over realistic instances show that *Overlay* enables higher BBU consolidation (fewer BBUH sites). Using the proposed approach, we show also how, under different geotype scenarios, different multiplexing/routing choices for the fronthaul and placements of the BBUHs might appear in the optimized aggregation network design.

7 Cost Analysis

The architecture descriptions and design considerations are complemented by a technical and a cost assessment of the proposed FMC network architecture options. In this chapter, we present the main findings of the initial cost analysis and the methodology we have followed to achieve the results.

Clearly, the cost assessment, by the time of writing this deliverable was a "first glance" on the cost of the FMC network architecture, as it will be completed once the ongoing work on the architecture definitions and design considerations for FMC network scenarios is over. Therefore, the cost assessment in D3.3 is setting the ground for D3.4, and is a starting point for the deeper analysis, including analysis of the convergence potential, i.e., the sensitivity of the cost results to the most significant parameters influencing the costs.

In Section 7.1, an overview of the cost analysis methodology is given, followed by the initial results in Section 7.2. The initial results are based on a single combination of (representative) parameters, therefore we have analysed how changing some main parameters affects the results in Section 7.2.5. Finally, the cost modelling activity of a fundamental FMC network node, the BBU hotel, is outlined in Section 7 and is not yet linked to the cost assessment, but is an ongoing activity that will feed the final cost assessment in D3.4.

7.1 Methodology for Cost Analysis

The cost assessment is clear and simple in a high-level view, but leads to numerous questions in the details – to be discussed in this chapter and the upcoming deliverable D3.4. On a high level, the main drivers/inputs and the major steps of the cost assessment are listed below:

- Four **geotypes** (ultra-dense urban, urban, sub-urban, and rural), originally defined by WP2 [5] and further refined during the work in this deliverable, including the newly added ultra-dense urban geotype (see Appendix A.1).
- Several **FMC network architecture options**, including the 2020 reference network architecture using PtP CWDM technology, and the various proposed FMC technology options with different levels of convergence between the mobile backhaul/fronthaul and the fixed access network.
- These network architecture options were then applied to the defined geotypes, and a **network dimensioning** was carried out, which leads to the Bill of Material (BoM) calculations, i.e., the amount of various network elements needed in the network architecture to cover the respective area of a certain geotype.
- Finally, the network dimensioning results were coupled with a comprehensive **cost database** (based on contributions from the industrial partners in the consortium); the database contains cost information for all network elements included in the dimensioning.

These altogether lead to a first calculation of the deployment costs, and a comparison across the defined network scenarios (Figure 50).

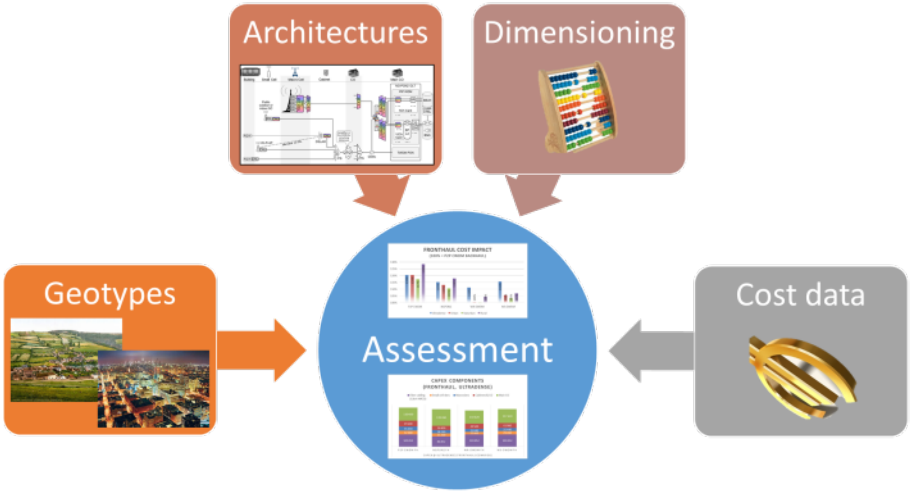


Figure 50: Cost Assessment Process

The **scope of the cost assessment**, after the restructuring of the COMBO project, was restricted to pure CapEx assessment, excluding OpEx and business aspects. Therefore, the study of the current deliverable will be focusing on deployment costs. As described in Chapter 5, we are considering a **brownfield deployment** for our FMC architecture options, reusing the available infrastructure of the fixed and mobile networks. The cost assessment focuses in the differences between the proposed converged network scenarios and the non-converged (or partially converged) 2020 reference network architecture. Therefore, cost elements independent from the deployment options outlined in Chapter 6 are not considered (e.g., mass-market fixed broadband CPEs, or the cost of mobile base stations themselves, besides the backhaul/fronthaul network).

The cost model and dimensioning of the fibre infrastructure is explained in Appendix A.2. In general, it follows the above described rationale, focusing on the differences brought by moving to one or the other FMC architecture, and excludes the costs independent from FMC.

7.1.1 Network Dimensioning

The BoM, i.e., the necessary amount of network elements (interfaces, splitters, AWGs, etc.), was calculated for each of the four investigated transport technologies: the "reference" PtP CWDM, and the FMC solutions NG-PON2, WR-WDM-PON and WS-WDM-PON. The dimensioning calculations were made for both the fronthaul and backhaul architectural versions of these network technologies, as described in the previous chapters.

The physical layer considerations of the dimensioning are detailed in chapters 5 & 6. Considering also physical constraints were necessary to reveal the impact of geographic characteristic on the network topologies, including, e.g., the different reach considerations of wavelength-routed or power-split technologies.

7.1.2 Cost Database

A comparison purely based on the BoM is difficult, as different systems use different components. Therefore, it is difficult to estimate the real cost difference. For the sake of a more meaningful comparison, a cost database was created, assigning a cost for each of the network elements. This cost database has been built starting from available data from the cost database of WP5 from Year 1 of the COMBO project [51], as well as earlier projects, such as OASE [52] [53] for optical components and the OLT model (Appendix A.3). However, technology has evolved since then so it was necessary to collect more up-to-date cost values. Based on the contribution from industrial partners (vendors and operators), a consensus was achieved on the reasonable cost of every network element, and these values were used to get the results presented in this deliverable.

The list of network elements with their respective costs is attached as a separate document (COMBO Cost Database) to this deliverable. Due to obvious confidentiality reasons, the cost values are normalized, instead of publishing EUR costs. During the normalization, a basic and widely used equipment, namely a standard ONU was used as a basis: its cost equals to 100 units. Throughout this chapter, this normalized Currency Unit (CU) is used.

7.2 Initial Cost Assessment of Transport Solutions in Converged Architecture Options

In this section, we introduce the numerical results of the initial cost assessment. All the cost results presented in Section 7.2 are based on the common initial assumptions presented in Section 5.1 as the “medium case”. Namely, for the heterogeneous radio network, we suppose 10 small cells per Base Station (except for the rural geotype without small cells), and an FTTC coverage over the whole area, and additional 30% FTTH coverage (excl. the rural geotype, without FTTH). The impact of changing these parameters is investigated in Section 7.3.

7.2.1 CapEx: Reference Architecture vs. FMC Architecture Options

Figure 51 shows the (CapEx) cost of all so far considered network architecture options over all four geotypes for fronthaul and backhaul. The cost is shown as cost per connection, i.e., the cost is divided by the number of cabinets, base stations and small cells. Such normalization was necessary, due to the different Main CO areas for the four geotypes.

As expected, the overall cost per connection increases from ultra-dense towards rural areas. Additionally, in all geotypes it can be seen that all three investigated transport technologies supporting FMC (i.e., NG-PON2, WR-WDM-PON and WS-WDM-PON) lead to lower costs than the 2020 reference PtP CWDM technology, especially in the fronthaul case.

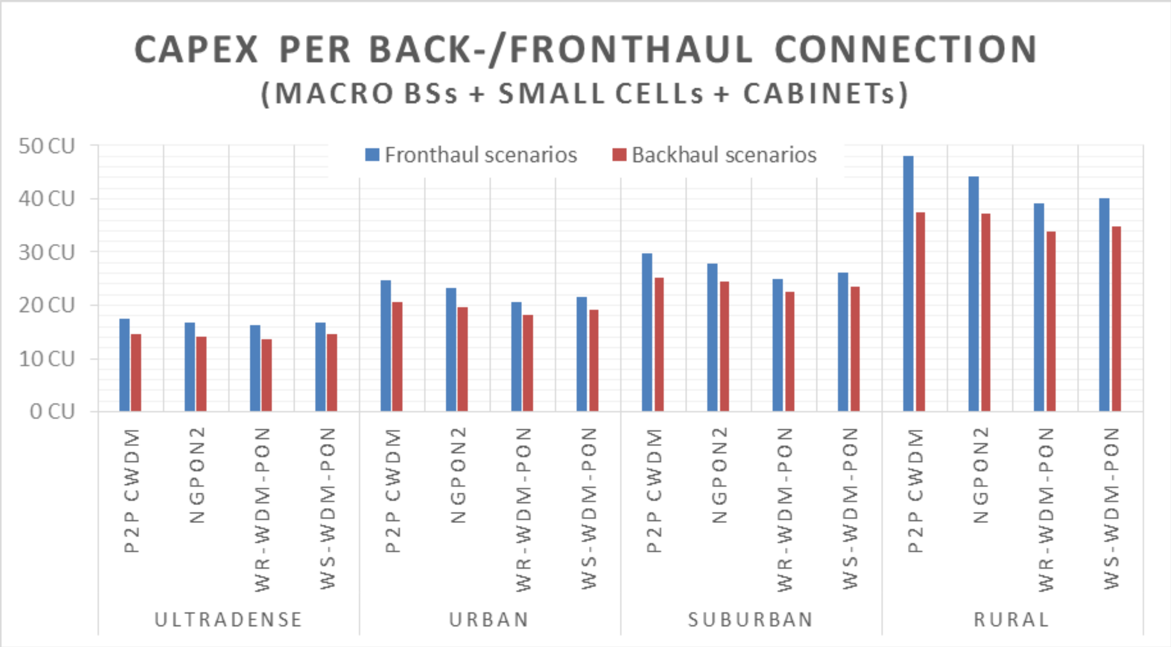


Figure 51: Total CAPEX of backhaul and fronthaul architecture per geotype

On the other hand, both for backhaul and fronthaul architecture, WR-WDM-PON leads to the lowest cost among the four investigated technologies, but the cost differences are more pronounced in the fronthaul case (up to 20-23%), while in the backhaul case the difference is in the range of 10%. NG-PON2 and WS-WDM-PON fall in between PtP CWDM and WR-WDM-PON.

Introducing fronthaul has a significant impact on the network dimensioning (including, e.g., different interfaces, higher fibre counts, amplifiers where needed). Fronthaul has the highest impact on the reference PtP CWDM costs and the lowest cost impact on the WR-WDM-PON is not surprising. A deeper investigation of this phenomenon is presented later, in the subchapter dedicated to the backhaul cost components.

7.2.2 Fronthaul vs. Backhaul Solutions

Figure 52 depicts the “fronthaul sensitivity”, i.e., the cost difference between the fronthaul and backhaul cases of each technology over all the geotypes (100% is the cost of the backhaul case of the same technology). The figure indicates that the FMC solutions are more “fronthaul-compliant”, i.e., adapt to fronthaul requirements with lower cost penalty than the reference PtP CWDM technology.

With lower connection densities, the fronthaul sensitivity difference between the reference and the FMC solutions becomes higher, especially on the rural geotype. However, evaluating a relative cost difference between fronthaul/backhaul cases of the investigated technologies is difficult, due to the absence of a common reference point. Therefore, in Figure 53, all fronthaul network costs are compared to a common reference: the cost of P2P CWDM backhaul equals to 100%. There, the cost values of the various fronthaul architecture options are cross-comparable.

The two figures together support the conclusion of the three FMC solutions being more “flexible” when fronthaul requirements have to be met: the introduction of fronthaul instead of backhaul in any case leads to higher costs, but as even the reference PtP CWDM backhaul was not more cost-efficient than the FMC solutions, in the fronthaul case, the converged solutions have a clear cost-efficiency gain.

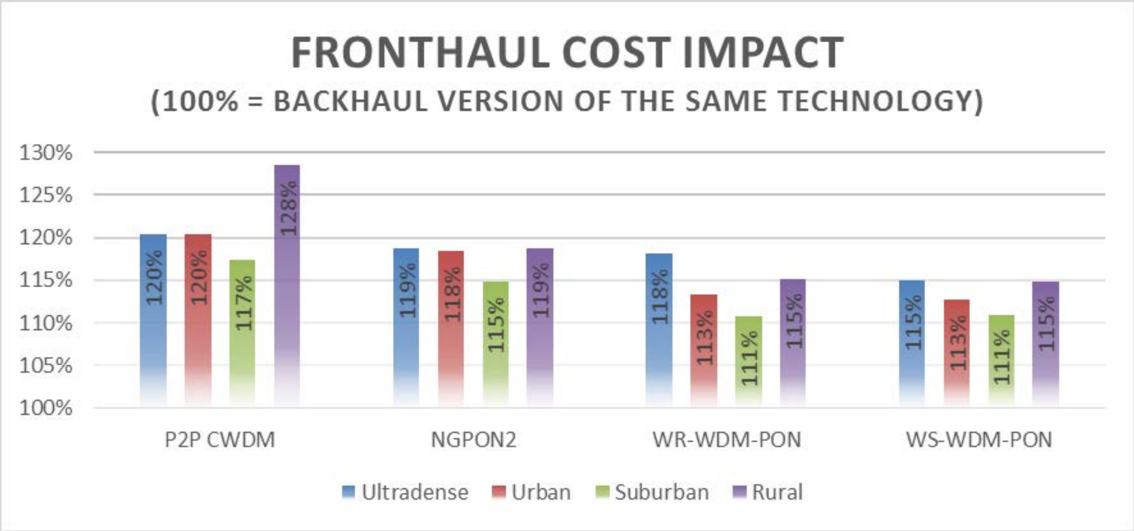


Figure 52: Fronthaul vs. Backhaul costs I

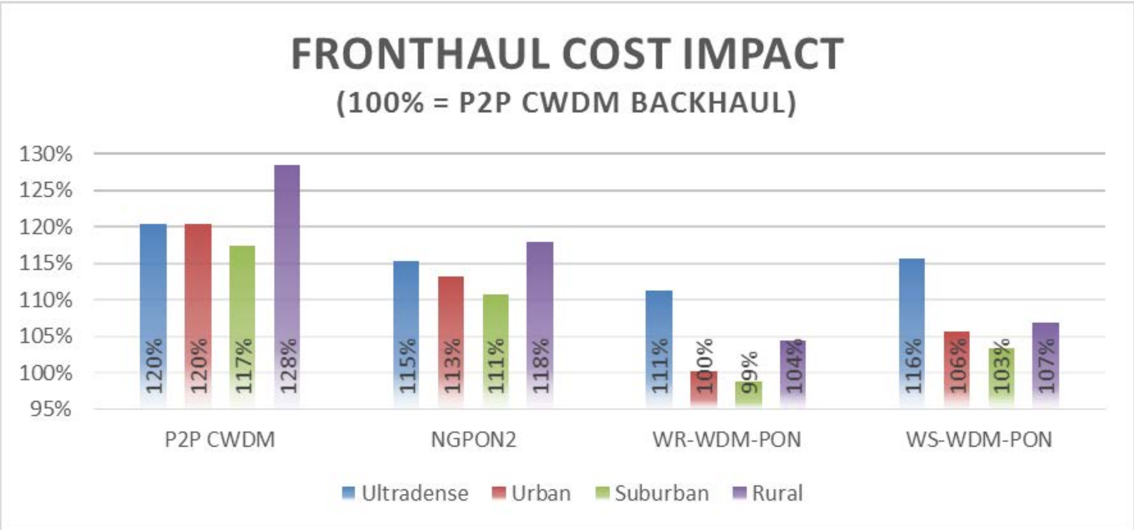


Figure 53: Fronthaul vs. Backhaul costs II

7.2.3 Cost Breakdown – Backhaul

In addition to the impact of population density and cost implications of backhaul vs. fronthaul, we can further dive in the details, to understand the factors being responsible for the cost differences. In Figure 54, not only the total cost, but also a partition of the cost per location type is depicted for the backhaul case, over the urban geotype. The ultra-dense and sub-urban geotypes show similar trends, whereas the rural case will be shown and discussed below. As the results show, the highest costs arise in the Main CO and for fibre cabling.

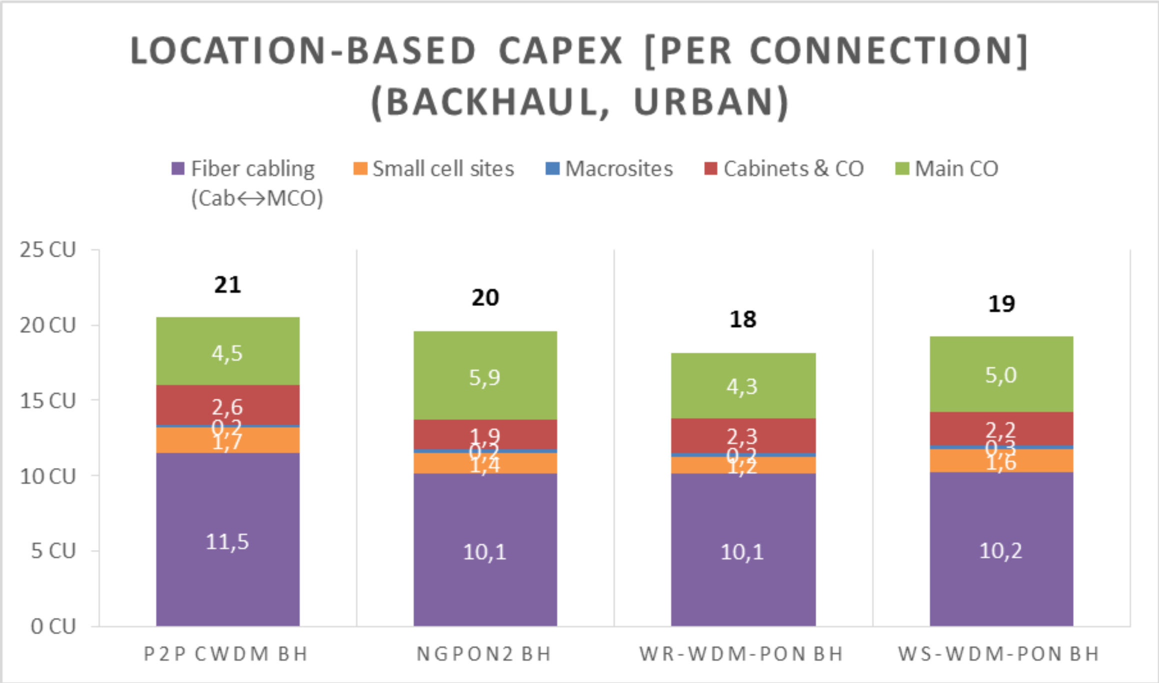


Figure 54: Location-based CapEx of urban backhaul architecture

The three FMC technologies have a cost advantage in the fibre cabling due to the higher wavelength count for the WDM PON options, and due to the fibre reuse for the NG-PON2. As the diagram clearly shows, the Main CO cost makes the power split technologies (NG-PON2 & WS-WDM-PON) more costly than WR-WDM-PON.

A "higher resolution view" of the Main CO costs is shown on Figure 55. The coloured interfaces, AWGs and amplifiers, are altogether responsible for 70-90% of the Main CO costs (depending on the technology and geotype). Hence, the diagram focuses on these cost components. Within the MCO, clearly the AWG costs (due to the higher port count AWGs) make the WR/WS-WDM-PON solutions more cost efficient than NG-PON2 with WDM overlay. In case of the reference PtP CWDM, the higher interface costs and the absence of AWGs compensate each other.

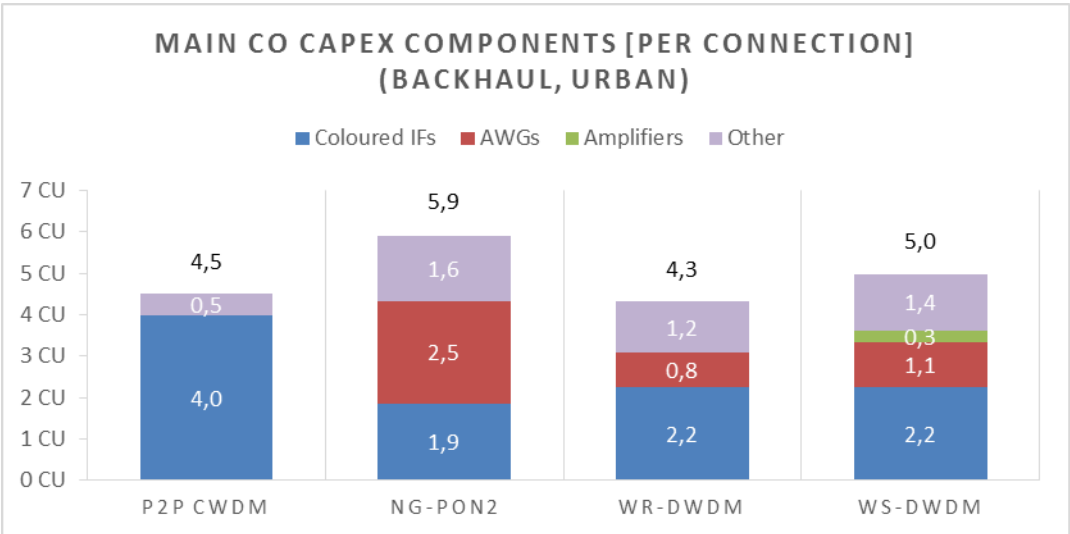


Figure 55: Main CO cost components of urban backhaul architecture

In case of the rural scenario (Figure 56), the cable plant costs become overwhelming. Therefore, the approximately 10% cost saving achieved there by the WDM PON technologies leads to an approximately 10% lower cost in total. NG-PON2 has lost its gain in fibre/cabling costs, as we do not assume existing FTTH deployments in rural areas. The absence of existing FTTH deployments does not allow the re-use of existing fibre. Therefore, in the rural scenarios, NG-PON2 WDM overlay structure leads to a fibre infrastructure like the other WDM PON networks.

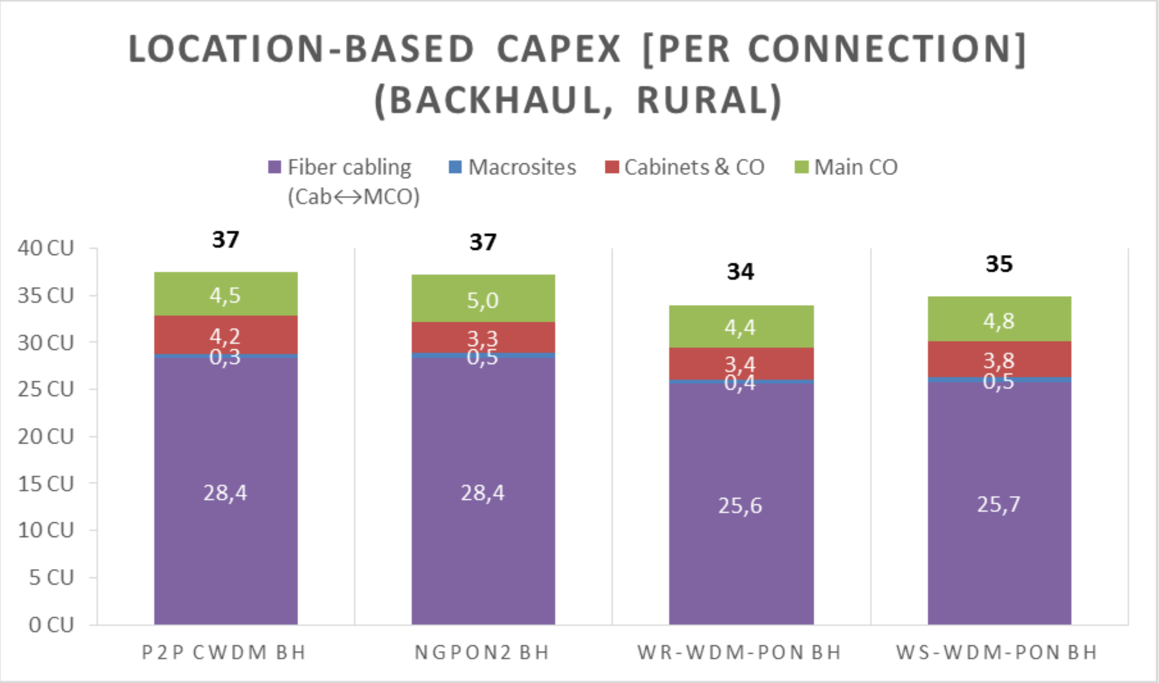


Figure 56: Location-based CapEx of rural backhaul architecture

7.2.4 Cost Breakdown – Fronthaul

The contribution of distinct cost components in the fronthaul case is shown in Figure 57, for the urban geotype. The ultra-dense and sub-urban geotypes show similar trends, whereas the rural case will be shown and discussed below.

A significant effect of structural convergence is visible in the fibre cabling: the three FMC solutions allow 20% cost saving in fibre/cabling compared to the PtP CWDM, which results in a total cost saving of 10% (fibre/cabling costs make approximately half of the total cost). The reason is the higher wavelength counts in case of WR/WS-WDM-PON and the fibre reuse in case of NG-PON2. These numbers are valid with respect to the initial assumptions of this chapter, i.e., full FTTC coverage, 30% FTTH penetration and 10 small cells per MBS; except for the rural geotype, only with FTTC coverage, and without small cell deployments.

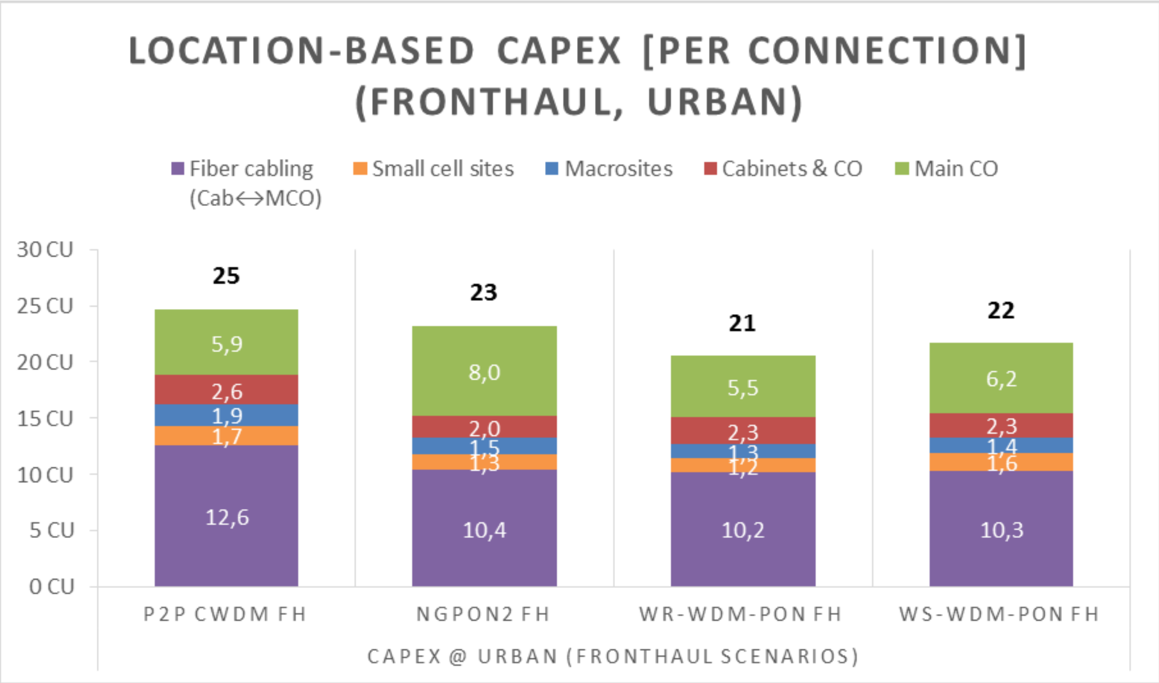


Figure 57: Location-based CapEx of urban fronthaul architecture

The cost of connecting macro sites is higher than that for the backhaul case (due to multiple higher bitrate interfaces), but the costs are similar for all four fronthaul architecture options. Similarly, no significant difference is visible at the small cell sites: both in the fronthaul or backhaul case, since the lower bit-rate (3Gb/s) optical interface is still sufficient to connect small cells.

Focusing on the three FMC options, WR/WS-WDM-PON FH have lower costs related to the Main CO. Since the differentiator between the FMC technologies are the Main CO costs, it is worth to have a deeper look on it. The detailed Main CO costs are depicted in Figure 58, which has some similarities with the respective figure for backhaul, in the previous section. PtP CWDM is a kind of an outlier here: it has by far the highest coloured interface costs, but no AWGs or amplifiers. The comparison of the three FMC options is more interesting and reveals that mainly AWGs make NG-PON2 more expensive than the WR/WS-WDM-PON technologies, as already shown in the backhaul case.

One of the reasons should be the different types of AWGs used: in case of NG-PON2 WDM overlay, 1:16 AWGs are deployed, as the narrow-band spectrum restricts the number of possible additional wavelengths sharing the fibre with the NG-PON2. In case of WDM PON technologies, the fibre is dedicated to the WDM system, therefore 1:80 AWGs are used – the lower per-wavelength cost of high port count AWGs explains the results. On the other hand, re-using the existing fibre for NG-PON2 (in case of existing FTTH deployments) leads to savings in the fibre costs for NG-PON2 – but not for the WDM PON solutions.

The FTTH penetration rate decides which effect becomes stronger: the higher channel (wavelengths) count leading to better utilization of the AWGs deployed at the Main CO; or fibre re-use leading to lower fibre costs for NG-PON2. The consequences of different FTTH deployment ratios will be analysed in Section 7.3.

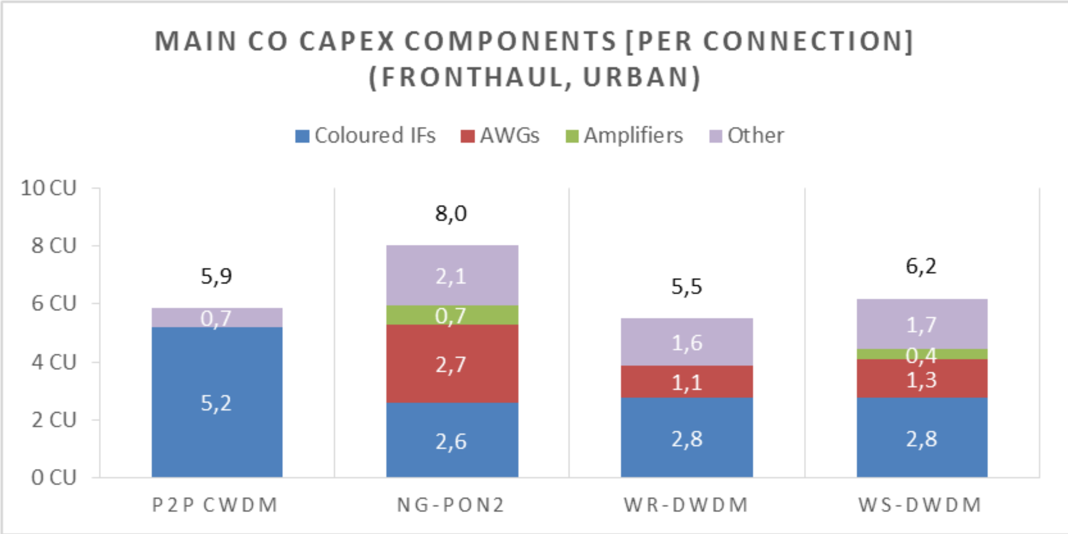


Figure 58: Main CO cost components of urban fronthaul architecture

Comparing the rural scenario (Figure 59) to the urban case shows the difference brought by the sparsely populated rural environment (small cells are not part of the rural scenarios, and no FTTH deployment is assumed there). The cost of the fibre/cabling was increased significantly, due to the higher distances traversed by the access network: a two-threefold growth can be observed versus the urban case (Figure 57). Therefore, in rural areas, the fibre/cabling is responsible for 2/3 of the total cost.

Besides the cable plant costs, also the (per connection) cost of equipment in the access/distribution segment, at cabinets or the CO is higher, while the central (Main CO) costs were increased by approximately 50% - which is also a consequence of the sparse population density and the adaptation of the network structure to the larger area with less connections.

Even if one could expect that the more advanced network technologies do not pay off in rural environments, due to the high importance of the cable plant costs, and the benefits of structural convergence on fibre level, the FMC options seem to provide cost-effective solutions even in rural areas.

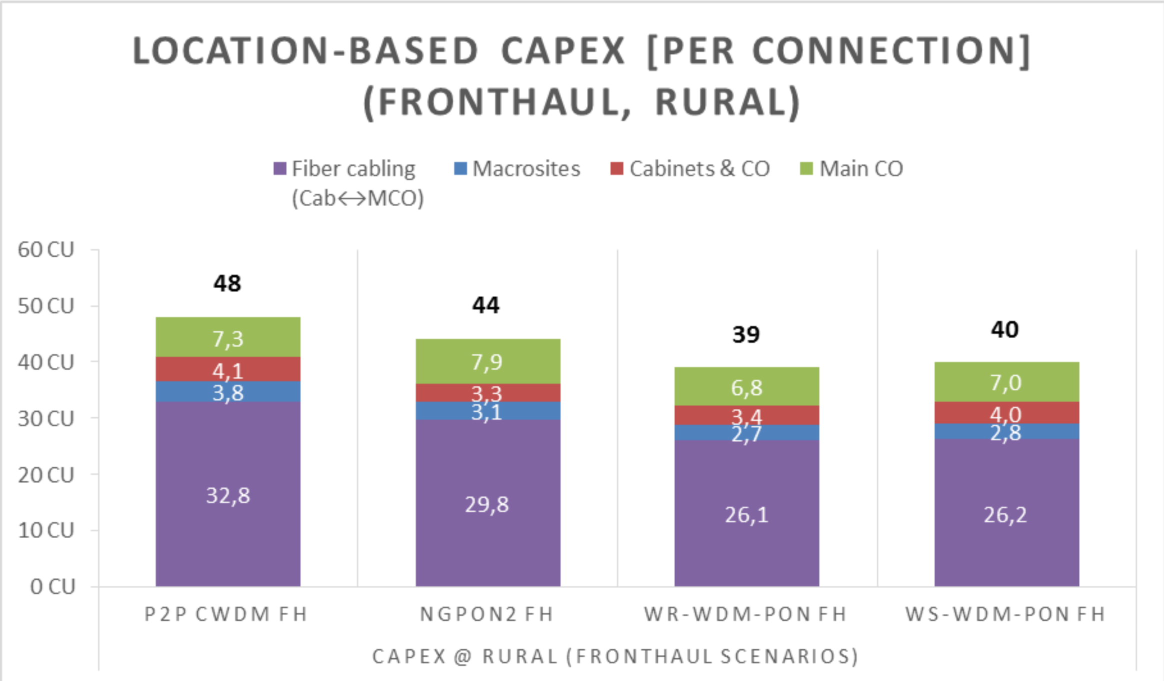


Figure 59: Location-based CapEx of rural fronthaul architecture

7.2.5 Cost Breakdown – Mixed Back-/Fronthaul

As introduced in Section 4.3 and detailed in Section 6.3.3, the motivation for this mixed variant comes from the higher transport capacity and cost for fronthaul of a MBS, especially in the Main CO and at the macro sites, which likely becomes more demanding with 5G evolutions. If looking at the cost per radio site, the situation of small cell fronthaul is more relaxed due to the lower interface capacity and lower wavelength count compared to MBS fronthaul. Therefore, this mixed variant aims to optimise the MBS connections keeping them still connected via backhaul, while only the small cells are connected via fronthaul. It is expected that the effect on costs, caused by this mixed variant, will be similar for the different technologies and geotypes and will therefore only be evaluated for the NG-PON2 technology exemplarily. Figure 60 shows a CapEx comparison between the all-backhaul, mixed back-/fronthaul and all-fronthaul variant for the NG-PON2 technology.

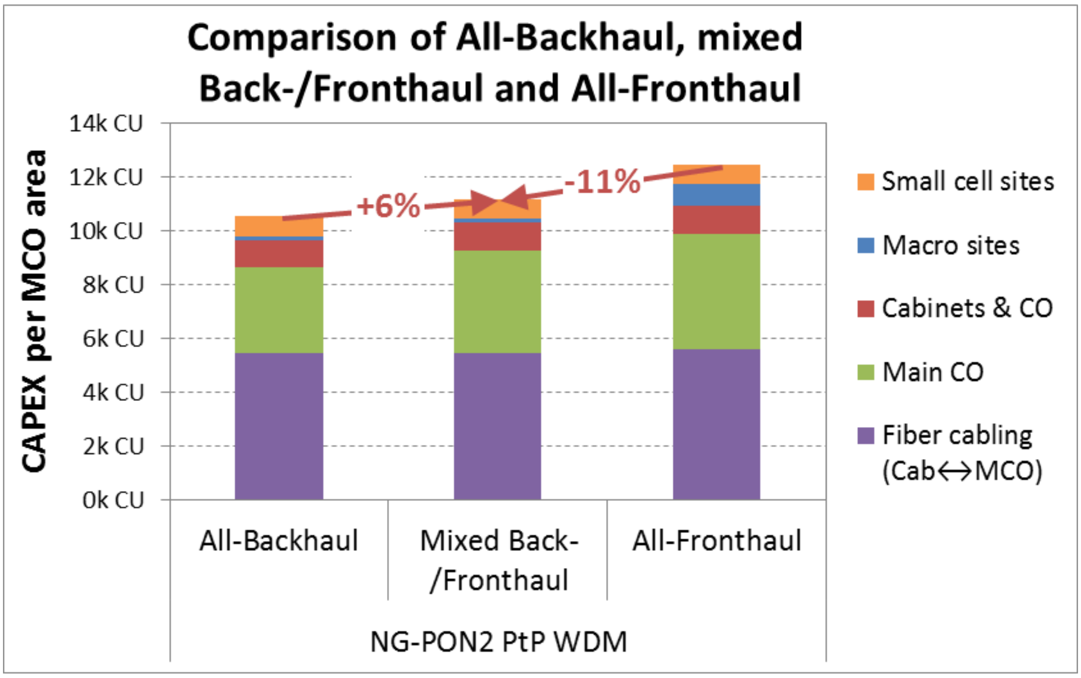


Figure 60: Cost comparison of all-backhaul, mixed back-/fronthaul and all-fronthaul for NG-PON2

The mixed back-/fronthaul variant causes 6% higher system cost in the Main CO at the NG-PON2 OLT due to the additional interface between the OLT and the BBUH for small cell fronthaul. On the other hand, the mixed variant allows total cost savings of about 11% compared to the all-fronthaul case, caused by the use of more cost-efficient backhaul for the MBS connections, while keeping the full baseband processing for small cells at a central location in the Main CO.

7.3 Analysis of Convergence Potential

So far, the CWDM network reference and variants of NG-PON2 and WDM-PON have been analysed and compared against each other for backhaul and fronthaul scenarios with fixed parameters (number of SCs, etc., including the respective bit rate requirements) according to Table 2 and Table 3. With these fixed parameters no prediction can be made if the different solutions behave differently under conditions of significantly deviating input parameters. Here, like in Section 6.5, we restrict the sensitivity analysis to the urban area geo type, because of the expected similar result relations between the different technologies in the other geotypes.

7.3.1 Variation of Small Cell Density and FTTC/FTTH Area Ratio

Since the scenarios evaluated so far, are based on a 30% FTTH and 70% FTTC area ratio and a small cell density of 10 SC per MBS, we therefore investigate variations of the mass-market FTTH deployment ratio between 0-100% as well as the small cell density from 3-150 SC per MBS.

Firstly we are looking at small cell density variations in pure FTTC and pure FTTH areas. The following figure shows for a pure FTTC area on the left side the total backhaul CapEx per technology and on the right side the relative CapEx compared to the NG-PON2 solution.

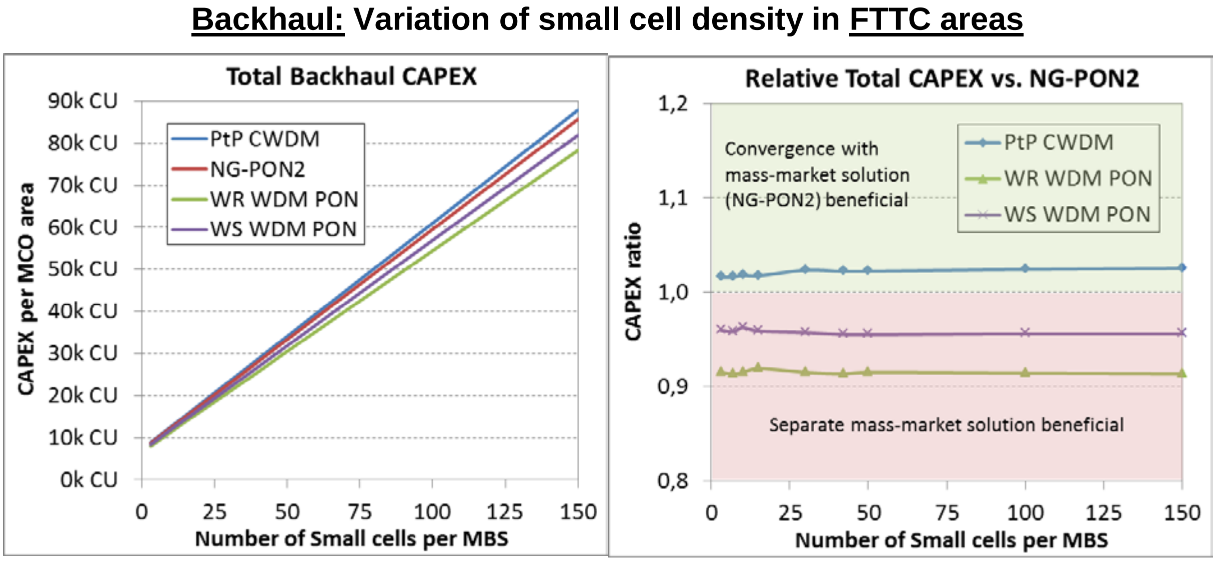


Figure 61: Backhaul CapEx: Variation of small cell density in FTTC areas

As obvious in Figure 61, as long as the relative cost value is below 1 a separate solution, not merged with the residential solution is preferable to connect the small cells. The dedicated WR-WDM PON is the cheapest technology in FTTC areas, which does not change with variation of the small cell density. It is mainly caused by the lower WR-WDM-PON system cost and higher wavelength count (up to 80 wavelengths) on the feeder fibres. The NG-PON2 cannot exploit its fibre infrastructure convergence potential in FTTC areas, since it is considered as dedicated PtP WDM solution like the other technologies. The PtP CWDM reference is the most-expensive solution with about 12% higher total CapEx compared to the WR-WDM-PON, due to the higher optics costs and lower wavelength count per fibre. The slight variations in the curves in the right figure result from the small cell density dependent system utilisation, which is different per technology, especially for low small cell densities.

Figure 62 shows for a pure FTTH area the total backhaul CapEx per technology and the relative CapEx compared to the NG-PON2 full-convergence solution. The variation of the small cell density has been evaluated for two different fibre deployment cases. In case 1, an existing fibre-rich mass-market FTTH deployment is assumed, requiring only low add-on costs for fibre-connections. In case 2, an existing fibre-poor mass-market FTTH deployment is assumed, requiring high add-on costs for new fibre cablings and connections (fibre cost model see annex chapter 12.2).

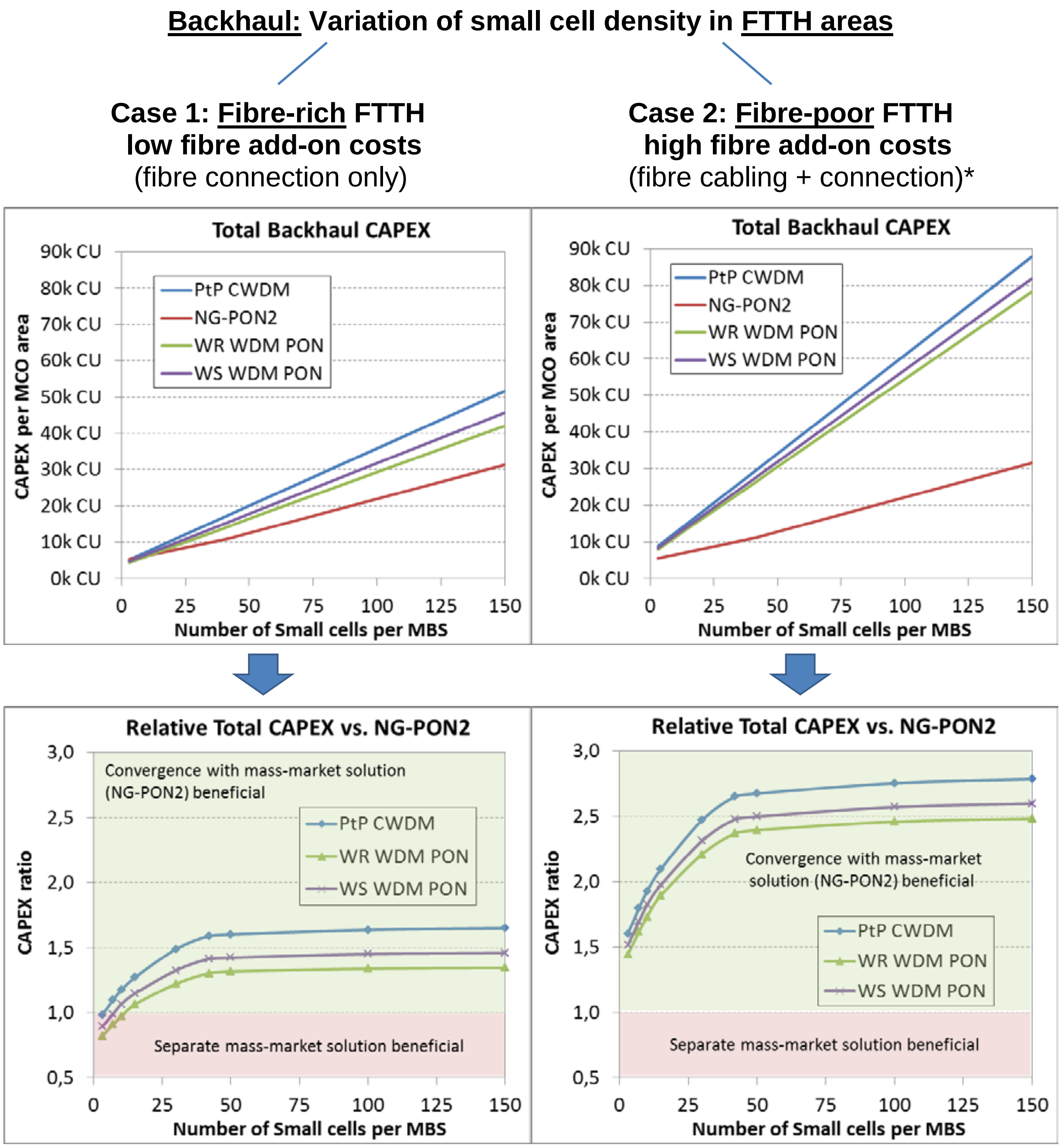


Figure 62: Backhaul CapEx: Variation of small cell density in FTTH areas

* **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

As illustrated in Figure 62, NG-PON2 is the cheapest technology for small cell densities higher than 12 SCs per MBS in an FTTH area with a fibre-rich deployment (relative cost value higher 1). In fibre-rich areas the NG-PON2 system cost is dominating for low small cell densities, but with increasing small cell density the NG-PON2 fully exploits its fibre infrastructure convergence potential through reuse of the FTTH mass-market infrastructure. The NG-PON2 convergence potential is even higher in FTTH areas with an assumed fibre-poor deployment, in which the NG-PON2 is the cheapest technology independent of the small cell density due to the high add-on costs for dedicated fibres of the other technologies. As it can be seen in both cases, the cost benefit of the NG-PON2 is higher in cases of high small cell densities, which is mainly caused by the somewhat lower NG-PON2 system utilisation in cases of low small cell densities and by the higher NG-PON2 upfront costs for introducing convergence with the mass-market. The 16 NG-PON2 PtP WDM overlay wavelengths are not optimal exploited in cases of low small cell densities when taking into account a 1:4 PS in the CO which serves 4 cabinet areas, resulting in 4λ per cabinet area from which not all are required if the small cells amount is low. The upfront cost causes a lower NG-PON2 cost increment up to a small cell density of about 40 SC per MBS, which results in a higher rise of the relative cost curves, ending up in a saturation of about 1.35 times higher CapEx (Case 1) and 2.5 times higher CapEx (Case 2) of the WR-WDM-PON compared to the NG-PON2 (i.e., NG-PON2 up to -26% Case 1 and -60% Case 2 for high small cell densities).

In order to show the fibre convergence effect, Figure 63 shows a comparison of the pure system CapEx without fibre infrastructure. The results show that the WR-WDM-PON would be the cheapest technology independent of the small cell density, when only looking at the system CapEx. However, from an operator point of view this case is artificial, because even in a fibre-rich FTTH mass-market deployment fibre add-on costs at least for through-connections of the required fibres would occur.

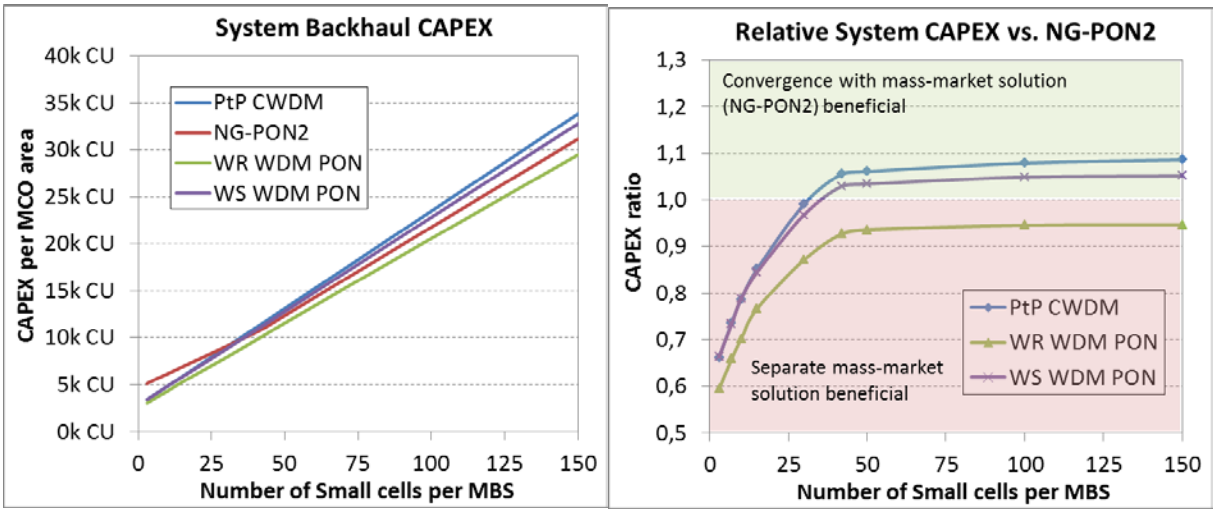


Figure 63: Backhaul system CapEx only: Variation of small cell density in FTTH areas

In addition to the above evaluated pure FTTC and pure FTTH areas, mixed deployments with, e.g., 100% FTTC and only a partly FTTH parallel deployment are also considered. Variations of the FTTH ratio cause only changes in the dimensioning numbers of the NG-PON2, because of the changed fibre convergence degree and the different NG-PON2 implementation in FTTC and FTTH areas, as described in Section 6.3. Despite of the fact that the total system numbers and fibre length stay constant in the PtP CWDM reference and the WDM PON variants, the total fibre costs decrease for all technologies in fibre-rich FTTH deployments ever higher the FTTH ratio is. The reason for this lies in the reuse of mass-market infrastructure assets and the lower fibre add-on costs in fibre-rich FTTH areas compared to the potentially higher fibre cabling efforts in FTTC areas and fibre-poor

FTTH areas, as shown in Case 1 of Figure 64. Equal fibre add-on costs are assumed in FTTC areas and fibre-poor FTTH areas, resulting in constant fibre cost when varying the FTTH ratio, as shown in Case 2 of Figure 64.

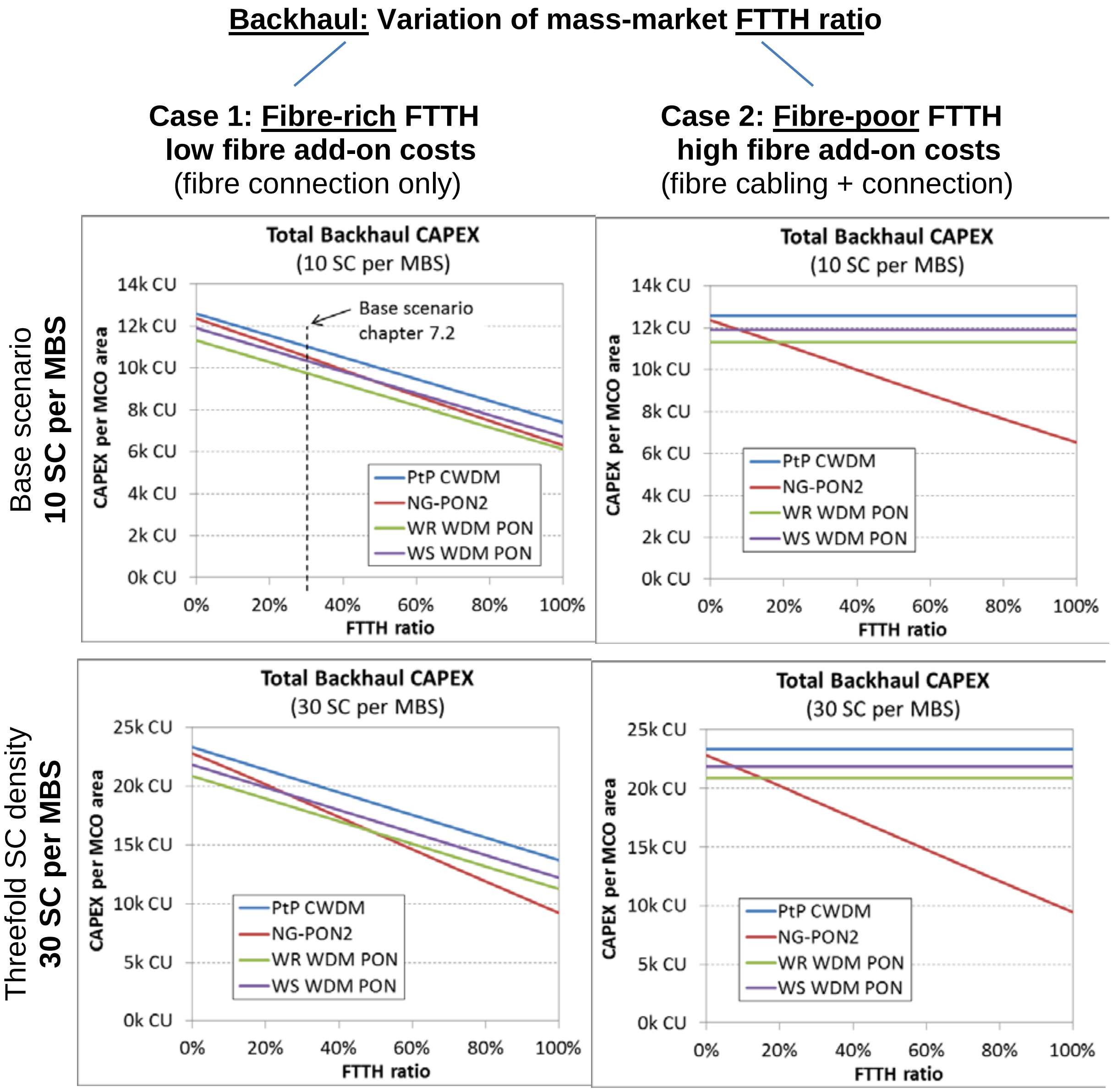


Figure 64: Backhaul CapEx: Variation of mass-market FTTH ratio

As shown in Figure 64, the fibre infrastructure convergence benefit (Cab↔MCO) of the NG-PON2 increases the higher the mass-market FTTH ratio is, reaching the highest benefit in areas with 100% FTTH deployment. The upper-left chart includes the assumed base scenario, which has been introduced in the assessment methodology in Section 5.1. In fibre-rich FTTH areas, the WR-WDM-PON is the cheapest technology independent of the FTTH ratio in case of a small cell density of 10 SC per MBS (see the base scenario in Section 7.2), whereas the NG-PON2 approaches the WR-WDM-PON CapEx. With an increased small cell density of 30 SC per MBS NG-PON2 becomes the cheapest technology for FTTH ratios of >50%. Under consideration of a fibre-poor FTTH deployment, NG-PON2 becomes the cheapest technology already for FTTH ratios >20% in case of 10 SC per MBS and for FTTH ratios >15% in case of 30 SC per MBS.

The same evaluation has been carried out for the Fronthaul case. As a general result compared to backhaul, the NG-PON2 convergence benefit gets lower in the fronthaul case, which is mainly driven by the higher NG-PON2 system related cost (incl. additional amplifiers) compared to the WDM PON variants. That means that the fibre infrastructure convergence benefit of the NG-PON2 has a slightly lower relevance in the fronthaul case.

Figure 65 shows for a pure FTTC area on the left side the total fronthaul CapEx per technology and on the right side the relative CapEx compared to the NG-PON2 technology.

Fronthaul: Variation of small cell density in FTTC areas

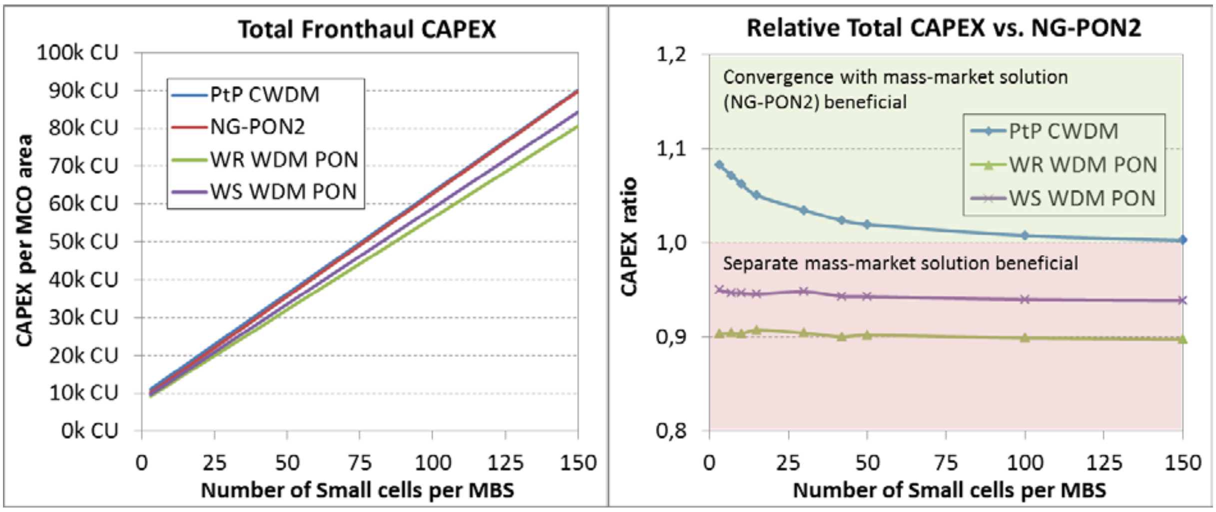


Figure 65: Fronthaul CapEx: Variation of small cell density in FTTC areas

Also in the fronthaul case, the dedicated WR-WDM-PON is the cheapest technology in FTTC areas, which does not change with variation of the small cell density. It is mainly caused by the lower WR-WDM-PON system cost and higher wavelength count on the feeder fibres. The NG-PON2 cannot exploit its fibre infrastructure convergence potential in FTTC areas, as it is considered as dedicated PtP WDM solution like the other technologies. As a difference to the backhaul case, the PtP CWDM reference has a higher cost delta compared to the other technologies for low small cell densities. The reason for this is the higher cost ratio of MBS fronthaul in case of low small cell densities, because additional feeder fibres are needed for MBS fronthaul in the PtP CWDM reference due to the movement of the CO wavelength mux towards the MBS (Figure 18). In the reference no additional band-filter are used in the CO, in contrast to the other technologies. Therefore, the PtP CWDM cost-delta reaches up to 20% higher CapEx for low small cell densities and about 13% higher CapEx for high small cell densities compared to the WR-WDM-PON.

Figure 66 shows for a pure FTTH area the total fronthaul CapEx per technology and the relative CapEx compared to the NG-PON2 full-convergence solution.

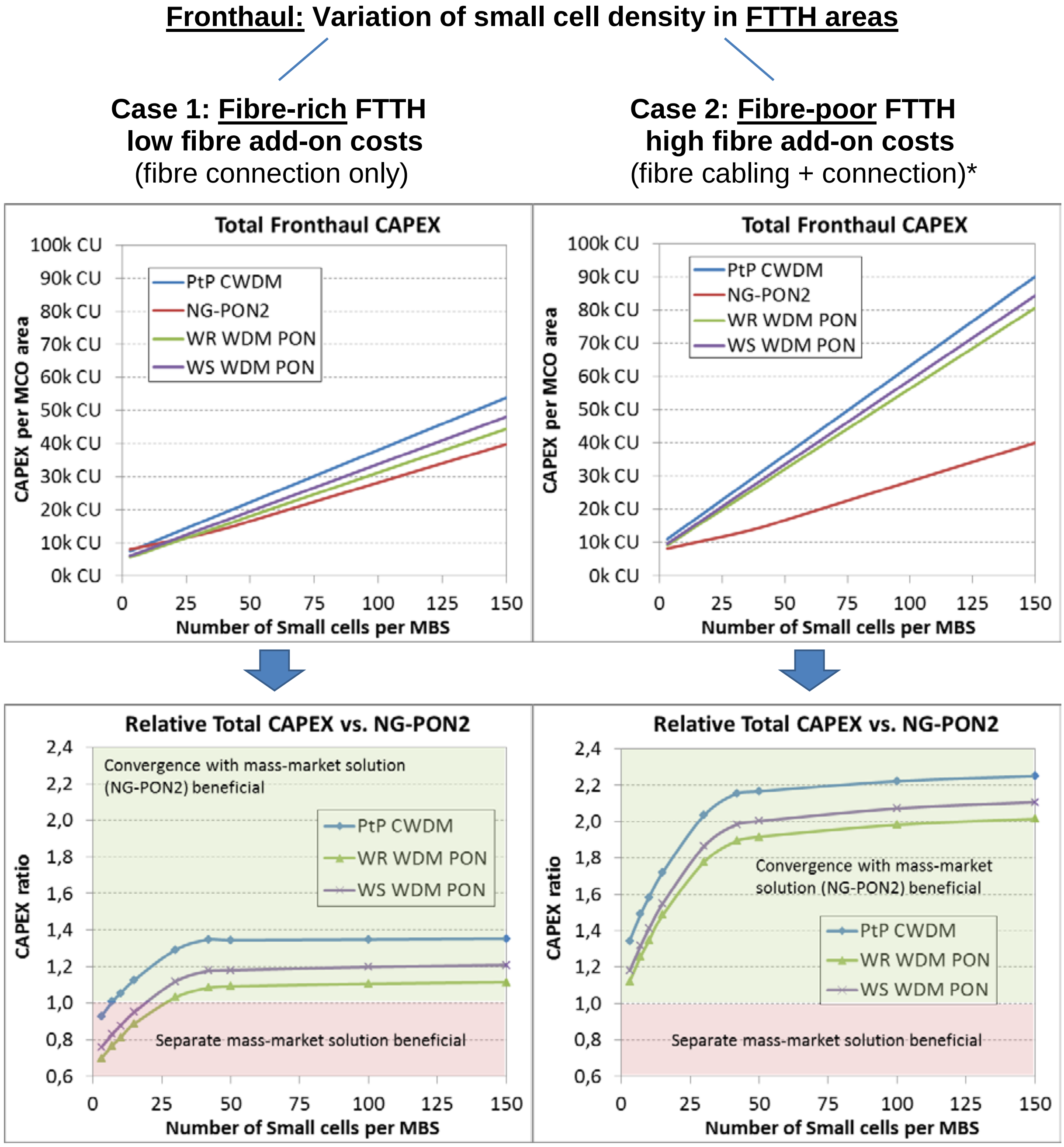


Figure 66: Fronthaul CapEx: Variation of small cell density in FTTH areas

* **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

Also in the fronthaul case, the NG-PON2 is the cheapest technology for higher small cell densities (crossing at higher small cell density than backhaul >25 SC per MBS) in FTTH areas with a fibre-rich deployment. The main reason for this lies in the exploitation of the fibre infrastructure convergence potential with the FTTH mass-market. The convergence potential is even higher in FTTH areas with a fibre-poor deployment in which the NG-PON2 is the cheapest technology independent of the small cell density, as in the backhaul case. The somewhat higher NG-PON2 upfront cost cause a lower cost increment up to a small cell density of about 35 SC per MBS, which results in a higher rise of the relative cost curves, ending up in a saturation of about 1.12 times higher CapEx (Case 1) and 2.0 times higher CapEx (Case 2) of the WR-WDM-PON compared to the NG-PON2 (i.e., NG-PON2 up to -11% Case 1 and -50% Case 2 for high small cell densities).

In order to show the fibre convergence effect, the following figure shows a comparison of the pure system CapEx without fibre infrastructure. Also in the fronthaul case, the WR-WDM-PON would be the cheapest technology independent of the small cell density, when only looking at the system CapEx. The NG-PON2 system CapEx is higher compared to the backhaul case, because of the additional amplifiers which are required due to the use of non-FEC interfaces in the fronthaul case. As already mentioned in the backhaul evaluation, from an operator point of view this case is artificial, because minimum fibre add-on costs will usually arise even in areas with a fibre-rich FTTH mass-market deployment.

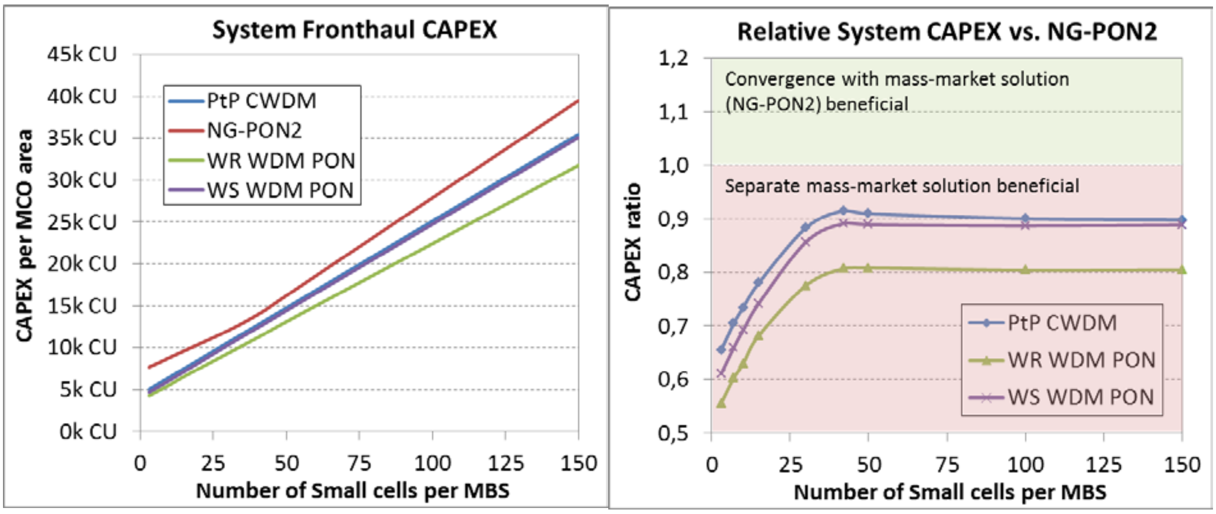


Figure 67: Fronthaul system CapEx only: Variation of small cell density in FTTH areas

Also for the fronthaul case, the fibre infrastructure convergence benefit (Cab↔MCO) of the NG-PON2 increases the higher the mass-market FTTH ratio is, reaching the highest benefit in areas with 100% FTTH deployment, as shown in Figure 68. In fibre-rich FTTH areas, the WR-WDM-PON is the cheapest technology independent of the FTTH ratio in case of a small cell density of 10 SC per MBS (see base scenario Section 7.2), whereas the NG-PON2 diverges from the WR-WDM-PON CapEx. In case of an increased small cell density of 30 SC per MBS the NG-PON2 would only become the cheapest technology for FTTH ratios of >85%. Under consideration of a fibre-poor FTTH deployment, the NG-PON2 becomes the cheapest technology already for FTTH ratios >30% in case of 10 SC per MBS and for FTTH ratios >20% in case of 30 SC per MBS (crossing at higher FTTH ratios than backhaul).

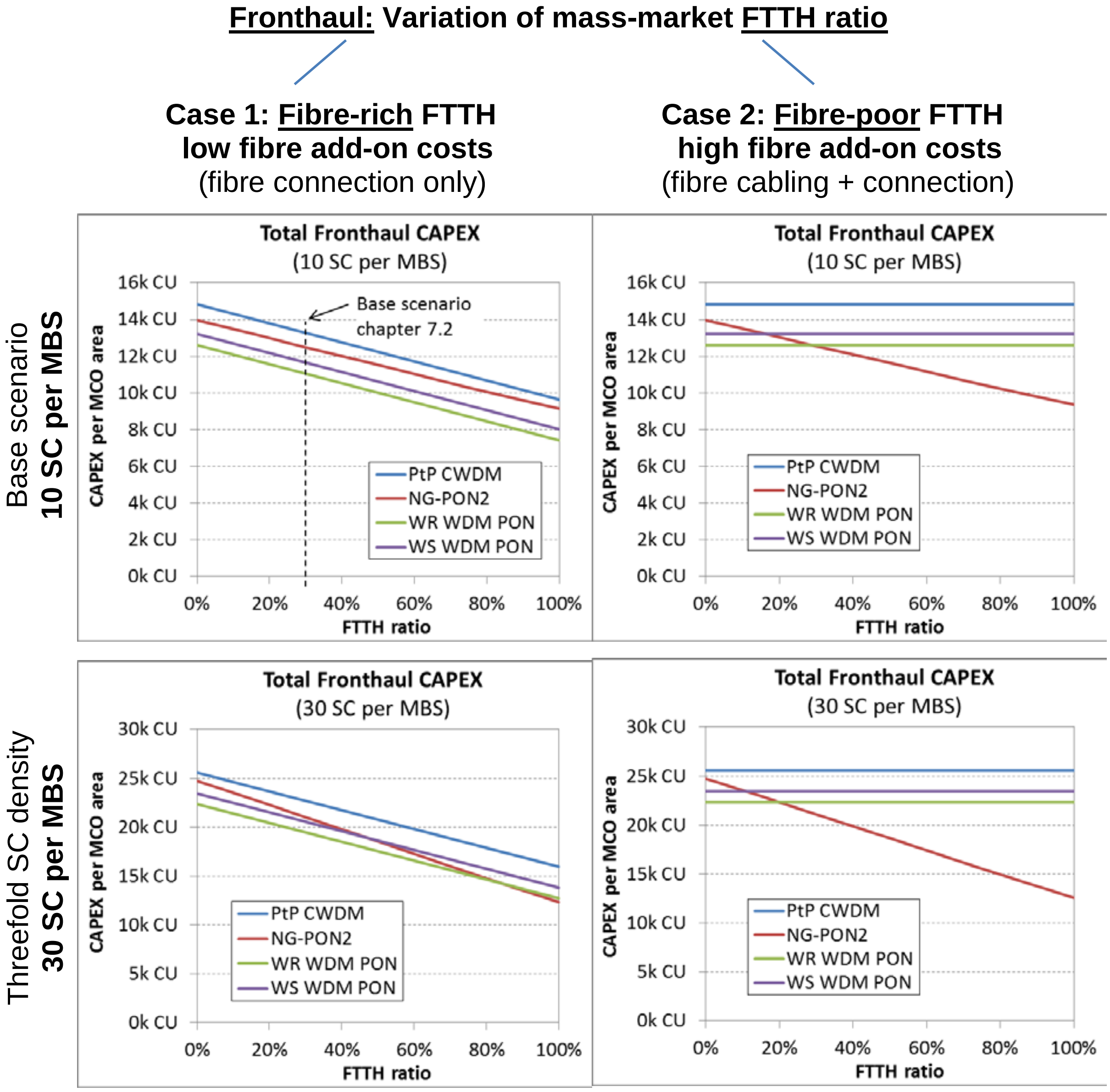


Figure 68: Fronthaul CapEx: Variation of mass-market FTTH ratio

7.3.2 Enhancement of Small Cell Radio Configuration

It is expected that future mobile traffic growths will mainly be served by small cells through small cell densification as well as enhancement of radio capacity. Since the parameter set used so far, with regard to the small cell radio capacity, is moderate, we therefore investigate an enhancement of the small cell radio configuration from 20 MHz and 2x2 MIMO to 40 MHz and 4x4 MIMO (Figure 7) exemplarily for a small cell density of 30 SC per MBS and 100% FTTH ratio, resulting in approximately a fourfold increase of the radio capacity.

This change in radio capacity requires 10 Gb/s interfaces (instead of 3 Gb/s) in the fronthaul case for small cells, but stays below the 3 Gb/s interface capacity in the backhaul case. Therefore, only the fronthaul case will be affected, as shown in Figure 69. However, in case of still higher radio capacities also the 3 Gb/s interface capacity in the backhaul case might be exceeded (for further study). With this variation, we can analyse, how flexible the different FMC solutions are regarding capacity enhancements.

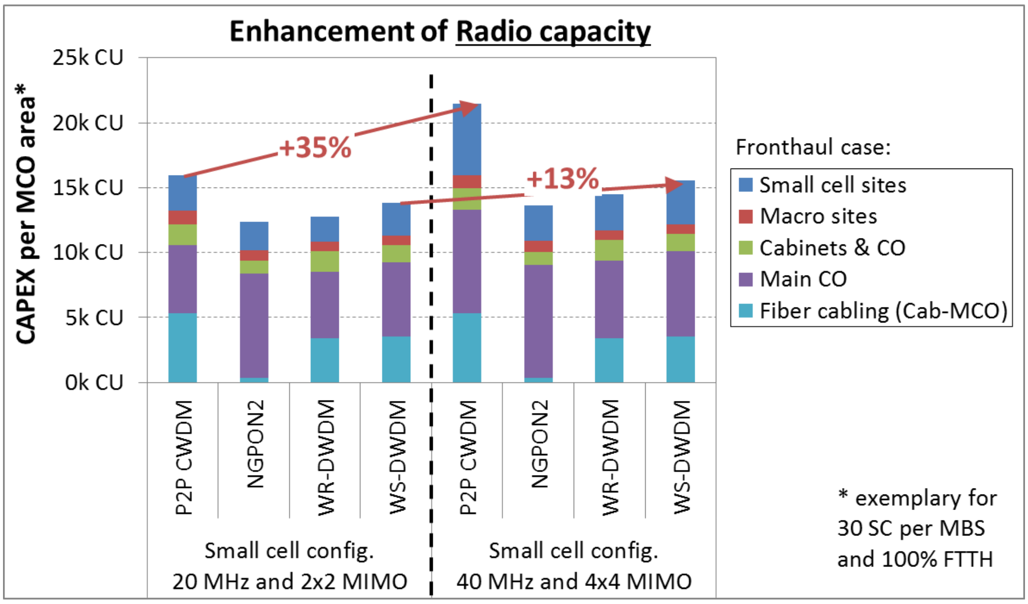


Figure 69: Variation of radio capacity (fronthaul CapEx)

The fourfold increase of radio capacity causes the highest increase of the total CapEx by about 35% for the PtP CWDM reference, driven by the high 10 Gb/s BiDi-CWDM interface cost. The changes in the relative difference in the total CapEx between the NG-PON2 and the WDM PON variants stay almost constant. The increase of total CapEx is in the range of 11-14% for these technologies. This means that that relatively low incremental transport costs are required for a significant enhancement of the radio capacity. CapEx changes occur only at the small cell sites and in the Main CO, because of the higher 10 Gb/s interface cost but unchanged splitting structures and number of interfaces. The number of amplifiers increases for the NG-PON2 due to the higher 10 Gb/s interface capacity and the resulting shorter reaches. However, the amplifier number increases only slightly, because in most cases also amplifiers are needed for 3 Gb/s interfaces (non-FEC for fronthaul) when considering convergence via a 1:128 power-splitter mass-market TWDM-PON in FTTH areas. A scaling of the radio side towards 5G requirements and the respective influence on the transport architecture will be studied in D3.4.

7.4 Conclusions of the Cost Assessment

This section summarises the key findings of the initial cost assessment and the analysis of the convergence potential for the FMC backhaul and fronthaul architecture as well as the considered technologies (P2P CWDM, NG-PON2, WR-WDM-PON and WS-WDM-PON).

Technology Comparison

The PtP CWDM reference is the most-expensive technology in all backhaul and fronthaul scenarios and all geo-type areas, which does not change with varying small cell density and FTTH ratio. This is mainly driven by the higher cost for the BiDi-

CWDM interfaces and the lower wavelength count on fibres. The stricter requirements (e.g., bandwidth/delay) of fronthaul causes a higher cost difference between PtP CWDM and the regarded next-generation technologies compared to backhaul.

When comparing the NG-PON2 with the WR/WS-WDM-PON technologies, especially the Main CO and fibre infrastructure costs make the difference, which is for instance caused by the higher port count AWGs of the WR/WS-WDM-PON technologies and the resulting lower production cost per AWG port and the higher wavelength count per fibre compared to the NG-PON2 WDM overlay. However, the slightly higher NG-PON2 system costs in the Main CO getting minor when the NG-PON2 exploits its full structural convergence potential on the fibre infrastructure layer as the dominant cost driver in the access network, which depends mainly on the mass-market FTTH ratio as well as the small cell density as stated below.

Backhaul vs. Fronthaul

As the initial cost assessment in D3.3 comprises only the transport cost excl. mobile equipment, a higher CapEx arise for fronthaul compared to backhaul. The fronthaul transport CapEx offset is in the range of 11-28%, depending on the technology, geotype and the ratio of small cell and MBS numbers. That means the expected fronthaul savings at the mobile cell sites would have to compensate this transport add-on cost as well as the cost for the BBUH in order to get beneficial (for further study).

A mixed variant with MBS backhaul and small cell fronthaul would require about 6% higher CapEx compared to the all-backhaul case, but reduces the CapEx of the all-fronthaul case by about 11%, while keeping the full baseband processing for small cells at a central location in the Main CO.

Infrastructure Influence

FTTH Areas:

The NG-PON2 gets the most cost-efficient technology for higher small cell densities (in our study for backhaul >12 SC per MBS and fronthaul >25 SC per MBS) in areas with a fibre-rich deployment in which the fibre add-on costs are low. In fibre-rich FTTH areas, the NG-PON2 savings reach up to 26% in case of backhaul and up to 11% in case of fronthaul for very high small cell densities. The main reason for this lies in the exploitation of the fibre infrastructure convergence potential through reuse of the FTTH mass-market infrastructure. The NG-PON2 convergence potential is even higher in FTTH areas with an assumed fibre-poor deployment, in which the NG-PON2 is the cheapest technology also for low small cell densities due to the high fibre add-on costs of the other technologies. In fibre-poor areas, the NG-PON2 savings reach up to 60% in case of backhaul and up to 50% in case of fronthaul for very high small cell densities.

If only looking at the pure system CapEx without fibre infrastructure, the WR-WDM-PON would be the cheapest technology for backhaul and fronthaul independent of the small cell density. However, from an operator point of view this case is artificial, because even in a fibre-rich FTTH mass-market deployment fibre add-on costs would arise at least for through-connecting the required fibres.

FTTC Areas:

The WR-WDM-PON is the most cost-efficient technology for backhaul and fronthaul, which does not change with variation of the small cell density. The main reasons for this are lower WR-WDM-PON system cost and higher wavelength count on the feeder fibres. When it comes to NG-PON2, it cannot exploit its fibre infrastructure potential in FTTC areas, because there is no underlying fibre technology for convergence on the fibre infrastructure layer.

In order to address also mixed FTTC/H deployments, a variation of the mass-market FTTH ratio has been evaluated as well.

Mixed FTTC/H Areas:

The fibre infrastructure convergence benefit of the NG-PON2 increases ever higher the mass-market FTTH ratio is, reaching the highest benefit in case of 100% FTTH deployment. In fibre-rich FTTH areas, the WR-WDM-PON is the cheapest technology independent of the FTTH ratio in case of a lower small cell density as, e.g., 10 SC per MBS. Whereas in case of an increased small cell density of, e.g., 30 SC per MBS, the NG-PON2 becomes the cheapest technology for FTTH ratios >50% in the backhaul case, the same is true in the fronthaul case only for FTTH ratios >85%. Under consideration of a fibre-poor FTTH deployment and a small cell density of 30 SC per MBS, the NG-PON2 gets already the cheapest technology for FTTH ratios >15% in the backhaul case and >20% in the fronthaul case.

Figure 70 shows which technology is most cost-efficient depending on the small cell density and FTTH ratio in a fibre-rich and a fibre-poor mass-market deployment. As obvious, the full-convergent NG-PON2 is more cost-efficient against the dedicated WR-WDM-PON in cases of higher small cell densities and FTTH ratios, especially in areas with fibre-poor deployments and thus high fibre add-on costs.

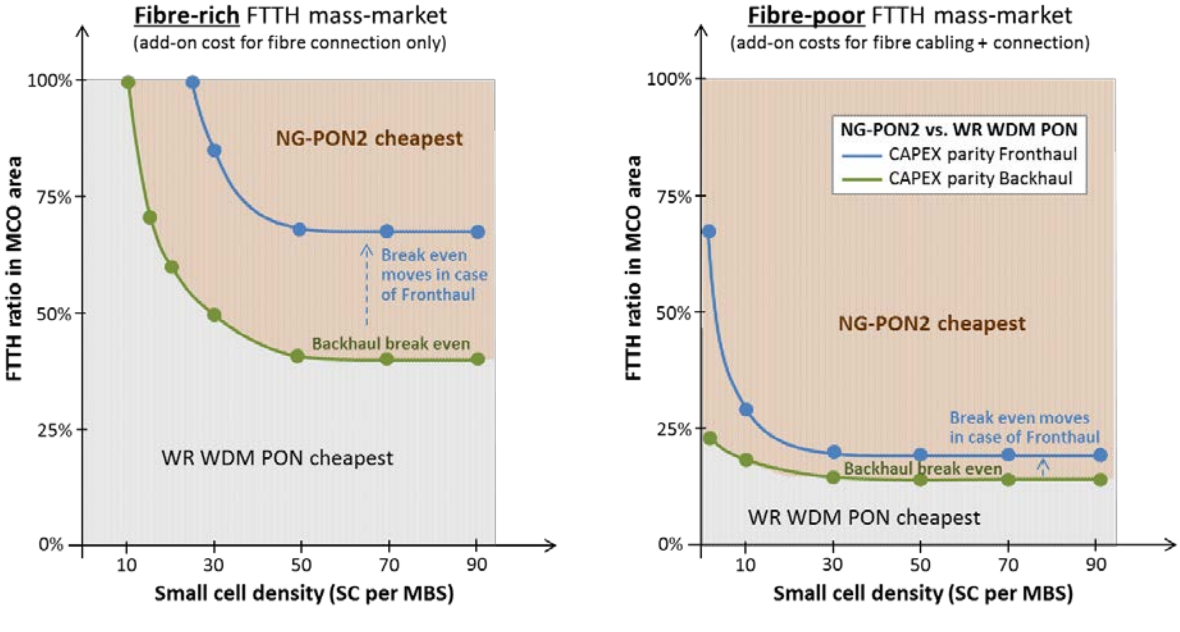


Figure 70: NG-PON2 vs. WR-WDM-PON cost-efficiency depending on SC density and FTTH ratio

Enhancement of Radio Capacity

It is expected that future mobile traffic growths will mainly be served by small cells through small cell densification as well as enhancement of radio capacity. In order to show the impact of the radio capacity on the network costs, an enhancement of the small cell radio configuration from 20 MHz and 2x2 MIMO to 40 MHz and 4x4 MIMO has been studied exemplarily for a small cell density of 30 SC per MBS and 100% FTTH ratio, resulting in approximately a fourfold increase of the radio capacity. The PtP CWDM reference causes the highest increase of the total CapEx by about 35%, mainly driven by the high 10 Gb/s BiDi-CWDM interface cost. The changes in the relative difference in the total CapEx between the NG-PON2 and the WDM PON variants stay almost constant. The increase of total CapEx is in the range of 11-14% for these technologies. This reveals that relatively low incremental transport costs are required for a significant enhancement of the radio capacity.

7.5 Development and Analysis of BBU Hotel Cost Models

Among the devices considered, the BBUH remains a challenge since its cost is not commercially available. Moreover, the cost of the BBUH depends on the implementation strategy. BBU hoteling can be implemented following different strategies, known as: (i) BBU stacking, (ii) BBU pooling, and (iii) Cloud-RAN BBUH. In this section, we describe these strategies exploiting building-block models which are then leveraged for cost modelling.

7.5.1 BBU Hoteling Strategies and Models

Before modelling the different BBUH strategies, we start by presenting the building blocks of the basic BBU model, as shown in Figure 71. We can differentiate baseline (or generic) building blocks and system-specific building blocks. As baseline blocks, we consider units for control, alarms, cooling or fans, and power supply with its DC-DC conversion. In principle, these blocks do not change significantly with the different BBU strategies. The system-specific units include all the necessary interfaces to exchange data (I/O), such as S1, X2, and fronthaul (generally using CPRI) interfaces, and two types of processing units. The first one is the BaseBand (BB) processing unit which is the computing element implementing Layer 1 (L1) and Layer 2 (L2) functionalities. The second processing unit is the general processing card which implements Layer 3 (L3) functionalities.

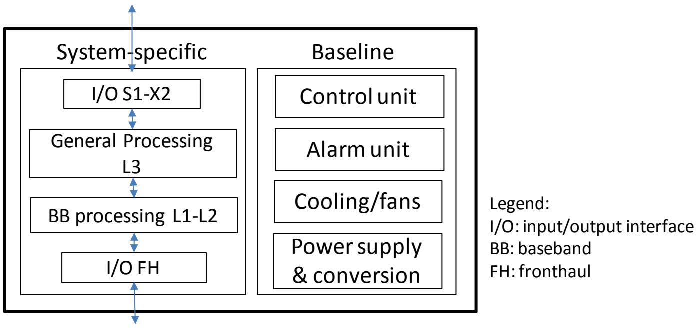


Figure 71: Basic building blocks of a BBU

This basic equipment is usually deployed locally at the base station (without hoteling). The cost model for such equipment mainly consists in summing up the cost of every block, as indicated in the following equation:

$$C_T = C_{IO,S_1-X_2} + rC_{IO,FH} + C_{BBproc} + C_{Gproc} + C_{Control} + C_{Alarm} + C_{fan} + C_{power} + \gamma(1)$$

where C_T is the total cost, $C_{IO,S1-S2}$ is the cost of a S1-X2 interface, $C_{IO,FH}$ is the cost of the fronthaul interface, and r is the number of fronthaul interfaces. The parameter r can take a value varying from 1 to 3, according to the number of cells that the base station is handling. C_{BBproc} is the cost of the BB processing unit and C_{Gproc} is the cost of the general processing unit. Note that BB processing and general processing units are logically separated but physically implemented in a single processing card. $C_{Control}$ represents the cost of the control unit, C_{Alarm} is the cost of the alarm unit, C_{fan} is the cost of the fan or cooling unit, and C_{power} is the cost of the power supply with its DC-DC conversion. We assume that all power supplies in our models include battery back-up. Finally, $\Upsilon(1)$ is a cost related to conditioning the area to support this equipment in one rack, including OpEx items such as floor space and power consumption. It is reasonable to assume that the cost of baseline blocks account for 40% of the cost, while the processing units account for 60% of the cost, apart from the cost of the interfaces and $\Upsilon(1)$.

7.5.1.1 BBU Stacking

The first BBU hoteling strategy is BBU stacking, in which the basic BBUs are simply placed remotely in a centralised location with very minimal changes on their implementation. Thanks to centralization, collateral systems, i.e., cabinets, racks, power supplying (voltage transformers, rectifiers, backup batteries), cooling (ventilation or air conditioning), backplanes, aggregation gateways, can be re-implemented to achieve relevant energy and costs savings. Figure 72 shows a possible implementation of BBU stacking where several BBUs are mounted on a rack and the power supply unit is shared among all the BBUs in the rack. Note that still it is required to have a power conversion unit in every shelf.

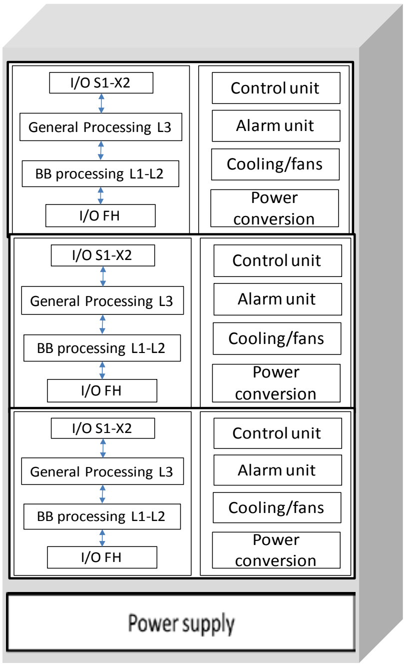


Figure 72: Building block model for BBU stacking

The formula for C_T in the stacking implementation is:

$$C_T = n\left(C_{IO,S_1-X_2} + rC_{IO,FH} + C_{BBproc} + C_{Gproc} + C_{Control} + C_{Alarm} + C_{fan} + C_{Pconv}\right) + kC_{PowerS} + \gamma(k)$$

where n is the number of shelves, C_{Pconv} is the cost of the power conversion unit, k is the number of required racks, and C_{PowerS} is the cost of the sole power supply unit.

The main savings compared to local BBUs are the shared power supply unit and the shared OpEx. In fact, in the basic case, for i separate BBUs, the OpEx-related term becomes i* Υ(1), while the same number of BBUs in the stacking case and s shelves per rack, would require Υ(i/s). A single location Υ(i/s) instead of i different locations of Υ(1), implies shared OpEx cost.

7.5.1.2 BBU Pooling

In this architecture, the BBUs placed at hotel sites are radically different from basic BBUs at cell sites. They can be implemented in several ways (for instance, maintaining a modular structure, or as monolithic devices), but the main feature is that they share some portion of their hardware resources. As it can be seen in Figure 73, one of the main differences is in the architecture of the multiple processing cards. Also, a low-latency switch is added to properly allocate resources to the interfaces, so that it is possible to allocate computational resources “on demand” for processing signals of different cells. In this way, to some extent, resource usage can be adapted to the load of each controlled cell, i.e., reserving more resources to high-loaded cells with respect to low-loaded ones. Considerable pooling gains are expected in this case, at the expense of more complex BBU hardware.

The whole BBU pooling unit presented in Figure 73 can also be mounted in a rack with a number of other similar units. Similarly to the model in Figure 72, all the BBU units can share a single power supply.

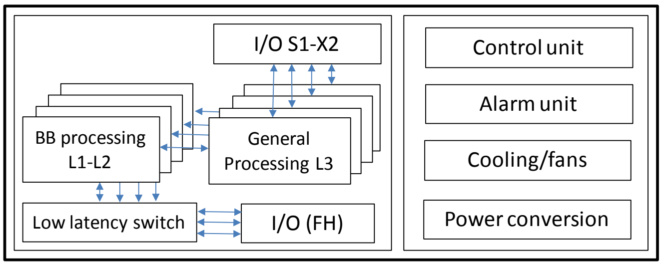


Figure 73: Model for BBU pooling strategy

The total cost C_T of this BBU hoteling strategy can be expressed as follows:

$$C_T = n\left(xC_{IO,S_1-X_2} + pC_{IO,FH} + bgC_{BBproc} + mgC_{Gproc} + C_{SW} + \alpha\left(C_{control} + C_{fan} + C_{Alarm} + C_{Pconv}\right)\right) + k\rho C_{PowerS} + \gamma(k)$$

where x is the number of S1-X2 interfaces, p is the number of fronthaul interfaces, b is the number of BB processing units, g is a pooling factor, m is the number of general processing units, C_{SW} is the cost of the low latency switch, α (α≥1) is the added complexity factor of baseline components when scaling their capacity, and ρ (ρ≥1) is the is the added complexity factor for the power supply unit. The parameter g (0<g≤1) is particularly important as it represents the multiplexing gain achieved by pooling processing units and interfaces (e.g., if g=0.7 then the number of required processing cards is 30% less than the required if there was no pooling gain). The value of g has a direct effect on the design of the shelf.

7.5.1.3 Cloud-RAN BBU Hotel

The Cloud-RAN BBUH strategy is implemented by using virtualization approaches at core/metro data centres. BBU virtualization is regarded as a way to further reduce RAN costs, since virtualized platforms can be built over general-purpose commodity equipment, instead of specialized hardware, potentially increasing the competition in the market and enabling multi-vendor interoperability. A Cloud RAN based on general purpose hardware also suffers penalties from decreased power and performance efficiency. Hence, BBU virtualization is still a pure research topic. Figure 74 presents a model inspired by the work in [38] for a future implementation of Cloud-RAN BBUH. A centralised RCC optimally allocates the load to processors and handles load migration. Load migration refers to the decision on when and how to migrate a load to other processor(s). Baseline elements such as alarm unit, cooling fans, control unit, and power conversion unit can be mounted per shelf, and the main power supply would be shared in a rack.

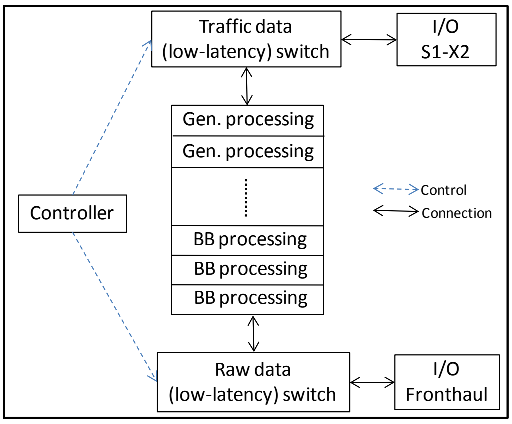


Figure 74: Model for the Cloud-RAN BBU hotel

The equation for total cost C_T becomes in this case:

$$C_T = k\left(xC_{IO,S_1-X_2} + pC_{IO,FH}\right) + \sigma kV\left(bC_{BBproc} + mC_{Gproc}\right) + \beta kC_{SW} + \omega kC_{SW} + kC_{Controller}$$
$$+ \eta s\left(C_{control} + C_{Alarm} + C_{fan} + C_{Pconv}\right) + \theta kC_{PowerS} + \gamma(k)$$

where V ($0<V\leq1$) represents the Cloud-RAN hotel pooling/virtualization factor. Note that the factor V also covers the processing inefficiencies related to the use of general-purpose processors. The parameter σ ($0<\sigma\leq1$) represents the cost reduction due to the fact that general-purpose processors are cheaper than system-specific processing cards, β and ω ($\beta\geq1$, $\omega\geq1$) are the added complexity factor for low-latency switch used to handle the raw data (from fronthaul) and the traffic data (to backhaul) respectively, $C_{Controller}$ is the cost of the main RCC unit, η ($\eta\geq1$) is the added complexity factor of baseline components when scaling their capacity in a Cloud-RAN hotel, s is the number of shelves where baseline cards are installed, and θ ($\theta\geq1$) is the added complexity factor for the power supply unit in the Cloud-RAN hotel.

Note that the requirement of low-latency is more important for the switch handling the raw data coming from the front-end than the switch handling the traffic at the back-end.

7.5.2 Comparison Analysis among the BBU Hotel Strategies

In this sub-section we aim at comparing the cost of the discussed BBUH strategies. The generic comparison scenario accounts a total of 100 eNBs, as an example. In this scenario, we consider a different number of locations for every type of BBUH to emphasize the different centralization degrees of the various strategies. We set the number of locations for basic BBUs as 100 (1 basic BBU per location), 6 for BBU stacking (e.g., at MBS), 4 for BBU pooling (e.g., at COs), and 1 for Cloud-RAN BBUH (e.g., at a Core CO). In what follows we present the technical assumptions for the BBU design, a rack/shelf design example for every BBU strategy case, the comparison results in terms on number of items, including a sensitivity analysis on the values of the pooling factors g and V, cost assumptions, and cost comparisons.

7.5.2.1 Assumptions

To perform the following comparisons we have defined the following assumptions:

- Relation number of fronthaul interfaces to number of processing cards is 1:1.
- Relation number of S1-X2 interfaces to number of processing cards is 1:6.
- Relation number of fronthaul interfaces to number of cells is 1:1.
- The pooling factor for BBU pooling is g=0.9, and the pooling/virtualization factor for the Cloud-RAN BBUH is V=0.6. Note that with a value of V=0.6 we are assuming the usage of hardware accelerators in the Cloud-RAN BBUH.
- Local BBU and BBUs in stacking hotel use a shelf of 2 rack units (U) out of the standard 44U rack.
- BBU pooling and Cloud-RAN BBUH use 11U shelves, with 20 generic slots each. The slots may be used to place processing cards and interface cards.

7.5.2.2 Rack/Shelf Design Example

According to these assumptions the design of every BBU strategy is as follows:

- BBU stacking: 18 shelves per rack, and remaining space used for the power supply unit.
- BBU pooling: 3 shelves per rack, and the remaining space used for the power supply. In each shelf, the generic slots may be used as follows: 9 fronthaul interfaces, 2 S1-X2 interfaces, and 9 processing cards. Note that the required processing cards in one shelf would be calculated as: 9 (fronthaul interfaces)*g (=0.9), which by rounding up give a total of 9. On the other hand, the number of S1-X2 interfaces required in this shelf is the number of processing cards/6, according to the assumptions presented.

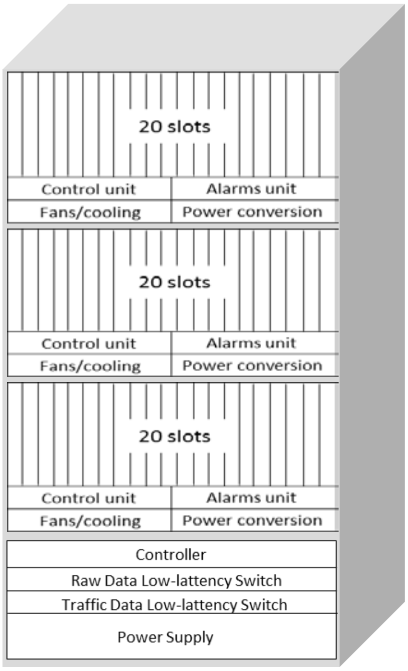


Figure 75: Rack design for a Cloud-RAN hotel

- Cloud-RAN BBUH: In Figure 75 we propose a rack design for Cloud-RAN BBUH. There we locate three 11U shelves with 20 generic slots each plus the baseline units, while the remaining space of the rack is used to install the low-latency switches, the RCC, and the main power supply. Keeping in mind the design in Figure 75, the rack may take a total of 35 fronthaul interfaces, 21 processing cards (35 fronthaul interfaces*V= 35*0.6), and 4 S1-X2 interfaces (21 processing cards/6). As seen, the number of required processing cards was calculated using the pooling factor g or V, accordingly. This is so, as V and g aid in the calculation of the resources that are really needed due to the pooling and virtualization gains. However, the design of the shelves may vary from one provider to another. Note that the factor V should also cover the processing inefficiencies related to the use of general-purpose processors.

7.5.2.3 Results and Analysis in terms of Number of Items

Following the assumptions and cost models described previously, Table 18 shows the results in terms of number of items, which is directly related to the total cost. Some items are of the same type but their capacity or complexity has increased, such is the case of the switches, power supply units, and the baseline units. Therefore they are multiplied by their respective parameters to indicate that the cost is increased by a factor. Firstly, we observe that BBU stacking enables relevant savings compared to local BBUs (no hoteling). The number of power supply units is reduced from 100 to 6. The cost and capacity of the main power supply in stacking are larger than the power supply with power conversion in the case without hoteling, however this lower number already implies a relative saving. The number of racks has also decreased from 100 to 6. This affects also the OpEx since there are now just 6 different locations: 100ϒ(1) in local BBUs vs. 6ϒ(1) in BBU stacking. Consolidation of BBUs in fewer locations implies that maintenance and conditioning are shared; hence, more efficient economically.

Important changes in terms of number of items are observed in BBU pooling and Cloud-RAN BBUH. The differences derive from co-location and pooling gains. Larger gains are obtained in Cloud-RAN as it is a much centralised option that is often associated with better pooling factors.

Table 18: Comparison results of comparing different BBU hotel strategies

Item	Local	Stacking	Pooling g=0.9	Cloud-RAN V=0.6
I/O FH	100	100	100	100
I/O S1-X2	100	100	23	11
Proc. cards	100	100	100	60σ
Control unit	100	100	12α	9η
Alarm unit	100	100	12α	9η
Fan/cooling	100	100	12α	9η
Full power unit	100	0	0	0
Power conv.	0	100	12α	9η
Power supply	0	6	4ρ	3θ
Switch	0	0	12	$3\beta + 3\omega$
Controller	0	0	0	3
Racks	100	6	4	3
Shelves	100	100	16	12
$\gamma(k)$	$100\gamma(1)$	$6\gamma(1)$	$4\gamma(1)$	$1\gamma(4)$

In [39], we have made a sensitivity analysis for the variations of g and V. We obtained that Cloud-RAN BBUH requires less number of processing cards and interfaces cards, under same conditions (i.e., g=V). If the pooling gains are the same in BBU pooling and Cloud-RAN BBUH, then the differences are mainly due to the shelf and rack design. While in BBU pooling the factor g is applied per shelf, in Cloud-RAN BBUH V is applied per rack. We observe that, while there are slightly less number of elements required in the Cloud-RAN case compared to BBU pooling, the Cloud-RAN BBUH would require two switches of higher cost per rack, and a RCC unit per rack.

7.5.2.4 Results in terms of Relative Cost

In this section we present the result of cost comparisons between the BBU strategies, in terms of CapEx and OpEx. The cost assumptions are explained and derived in [39]. We calculated the cost to the number of items presented in Table 18, and the results are presented in Figure 76. In the case of OpEx, we only considered the continued cost of the power consumption over 10 years. In the following, we use a generic cost unit, taken as relative cost whose reference is the cost of power consumption per MWh (=1 cost unit).

If the BBUH strategies can be sorted by the level of sharing resources, that is (1) BBU stacking, (2) BBU pooling, and (3) Cloud-RAN BBUH, then also the CapEx and OpEx are decreasing in the same order compared to the solution without hoteling (local BBUs). It is relevant to note that the OpEx cost, which only considers power consumption, can be comparable to the CapEx investment. Therein lies the importance of BBUH for green RAN deployment.

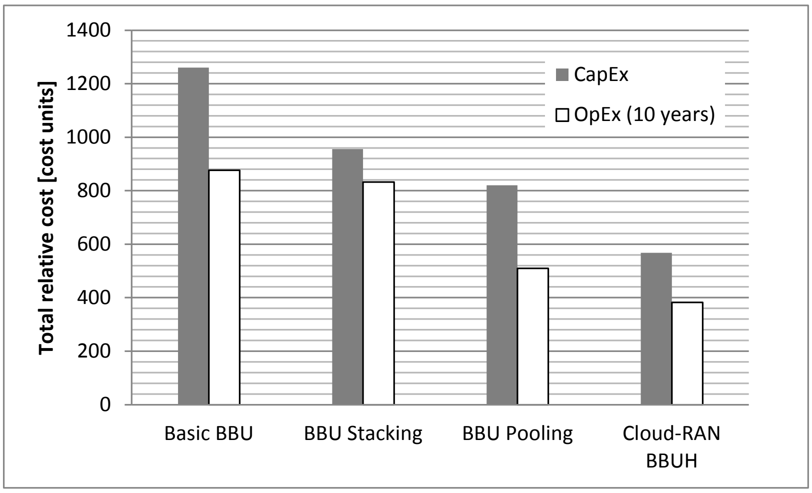


Figure 76: Cost comparison among different BBU strategies in terms of CapEx, and OpEx for a 10-year period [in relative cost units]

On the other hand, pooling BBU and Cloud-RAN BBUH reduce considerably the CapEx because more hardware is been shared. Based on our assumptions (using hardware accelerators), Cloud-RAN BBUH represents the best option in this scenario, mainly because of its low pooling/virtualization factor V, compared to g in BBU pooling. Also the savings in OpEx for Cloud-RAN BBUH is due to the fact that it needs to supply power to lower number of racks.

8 Network flexibility and Supervision

Previous chapters analyse the benefits and drawbacks of structural convergence between fixed access and mobile networks. Structural convergence enables increased sharing of resources between fixed access and mobile backhaul/fronthaul by providing a shared pool of infrastructure or system resources. To fully exploit resource pooling in dynamic scenarios (e.g., dynamic traffic patterns) requires flexibility in the network to dynamically reallocate resources based on demand. This has implications on the data plane which must include relevant flexibility and on the control/management planes which require coordination between different domains (Figure 77). The cost analysis in Chapter 7 compares architectures for shared versus dedicated systems for fixed access and mobile backhaul/fronthaul assuming static network deployments. The analysis does not account for the potential gains of dynamic resource pooling (exploiting dynamic traffic patterns) or for increased costs of frequent changes to the network which will be covered in D3.4.

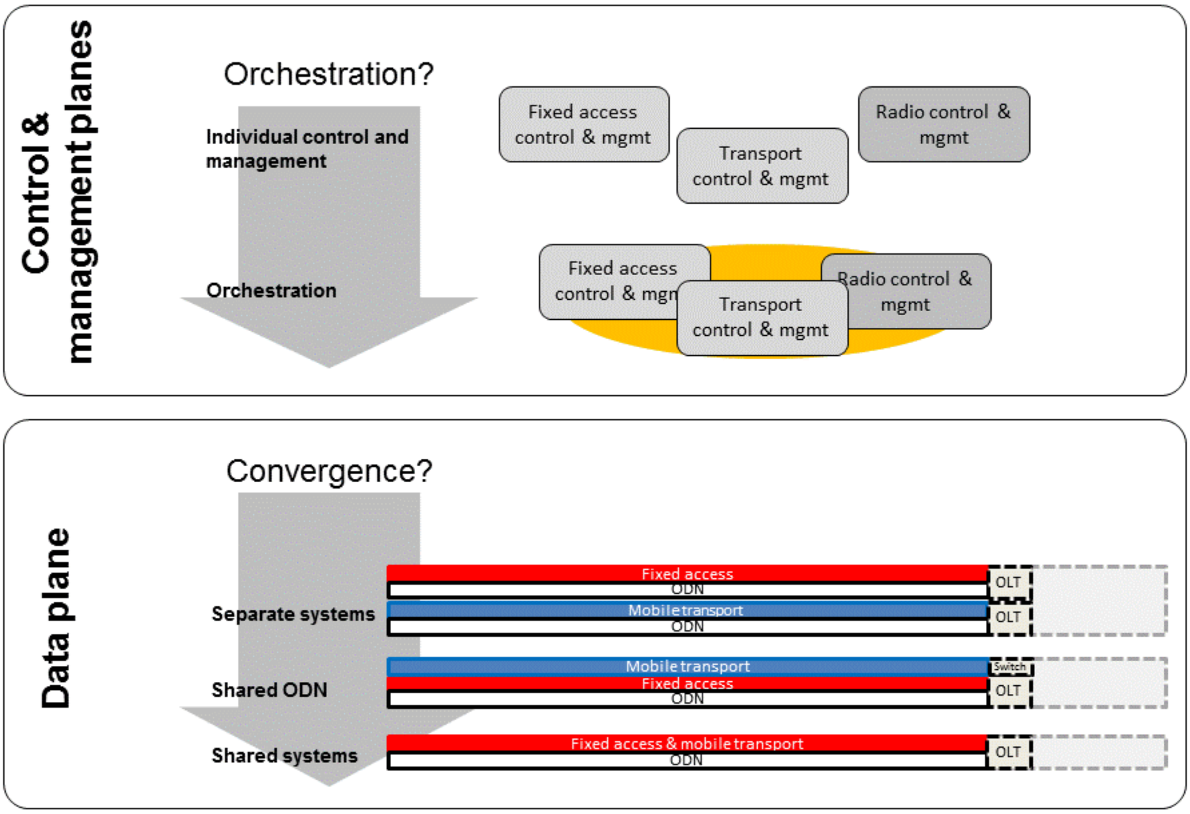


Figure 77: Increased structural convergence in the data plane opens up for optimization opportunities that can be fully exploited by coordination of the control and management across different domains such as radio, transport and fixed access

This chapter presents first work toward understanding the control and management architecture for the converged network and the benefits/drawbacks of coordinated control. Section 8.1 presents drivers for dynamicity in the network and use cases for network flexibility and RAN-transport interaction. Section 8.1 also presents a first overview of a control architecture that can enable joint optimization across different domains. Section 8.2 describes the implications on the data plane by presenting and analysing a number of system concepts which have been designed to provide an increased degree of flexibility compared to concepts in Chapter 6, in particular with focus on flexibility in the WDM-layer which is seen as a key technology for structural convergence. Furthermore, Section 8.3 presents concepts for performance monitoring in radio and transport, which are crucial building blocks of the control and management architecture.

8.1 Use Cases for Flexibility

With the rapid pace of change in industry, operational flexibility and scalability is becoming increasingly important for reducing time-to-market for deployment of new services. The network should facilitate new applications and services to be developed efficiently and deployed quickly. Automation and the ability to easily integrate network elements will be critical. The network should also support new models for network sharing in an increasingly complex landscape of actors in the Networked Society. Flexibility can also enable more efficient use of network resources, including transport resources as well as radio and IT resources. At the same, the access/aggregation is a cost sensitive part of the network and although flexibility may bring savings in terms of CapEx/OpEx, there may also be costs associated with a flexible architecture, and this will determine what type of flexibility will be available in the segment and e.g. how much of that flexibility will be in the optical/wavelength domain and how much will be in higher layer packet switching/routing.

Below is a non-exhaustive list of sources for dynamicity in the network:

- Adding/removing network resources/elements: connectivity, compute and storage resources
- Service deployment: deployment of new services, such as new end-user services or supporting services to service providers
- User dynamicity: dynamic traffic patterns from user movement/migration, variations in user activity
- Service dynamicity: dynamic service usage patterns with wide range of service requirements and impact of dynamic system behaviour
- Failures and service windows: rerouting traffic and minimizing impact
- Weather conditions: changing weather conditions impacting performance in the transport network (microwave, free-space opto)
- Moving network elements: moving cells

With 5G (Chapter 9) several of these factors are expected to be even more prominent with a wider range of requirements coming from end-users and devices, but also from new services yet to be developed by industries including vertical markets under digitalization (automotive, energy, transportation, agriculture, etc.). Densification of radio networks will bring larger traffic fluctuations between cells. It will also lead to a larger number of options for how and through which sites a client may connect via the radio access, possibly via several sites simultaneously (multi-site connectivity). Operational flexibility and ability to quickly roll out new services is expected to be increasingly important and with an increasing number of small cells automated and simplified procedures for deploying small cells and configuring resources will be required.

Hence, there will be larger incentives to build relevant flexibility into the network in order to cater for some of this dynamicity. The gains of network flexibility are scenario dependent. Some gains can be quantified (energy, costs, utilization of resources) given a set of assumptions, while other gains are more difficult to model (operational flexibility, simplified service provisioning, future-proofness, etc.). Much of the available system flexibility will be controlled/managed within each separate domain (radio, transport, fixed access). However, there will also be use cases for network flexibility that require coordination between the control and management of radio, transport and fixed access resources (RAN-transport interaction). These use case are particularly interesting as they determine the control plane architecture where relevant information needs to be shared between controllers of different domains.

Figure 78 illustrates the range of use cases for RAN-transport interaction, starting from different sources for dynamicity in the bottom layer, different degrees of flexibility in the radio and transport offered by different systems and deployment models, and different optimization goals (saving energy, increasing performance, handling bottlenecks, etc.) depending on what resource should be optimized in a given scenario. Combined these different factors provide a large range of possible use cases for flexible RAN-transport interaction.

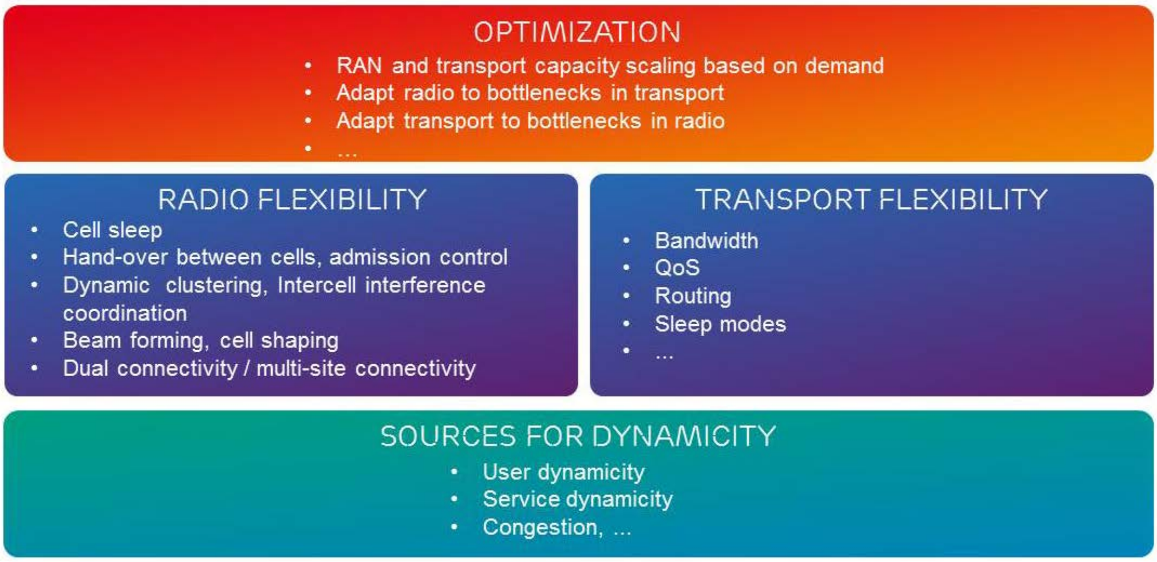


Figure 78: The range of use cases for flexible RAN-transport interaction

The remaining part of this section highlights a few of these use cases. A number of important use cases will be selected and analysed further in D3.4. In Section 8.2 flexible systems are designed for the COMBO context. In WP6, the structural convergence demo will also showcase selected use cases related to flexible RAN-transport interactions. A detailed description of the demonstration can be found in COMBO D6.2 [40].

Adding small cells: Simplified processes for configuring both radio and transport resources will be increasingly important. 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 is expected to change with densification through large numbers of small cells. For packet based backhaul this could involve provisioning connectivity with the correct QoS characteristics together with relevant radio resources. For fronthaul/backhaul deployment based on PtP WDM this involves provisioning of wavelength resources to connect between relevant radio resources. Automatic provisioning of such transport resources over a filtered ODN such as a wavelength routed (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 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 as well as splicing or patching in the field 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 79a 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 79b illustrates the case where host transceivers instead are pre-installed for each ODN attachment point. In a flexible ODN (Figure 79c) 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. Hence flexibility promises savings in either CapEx or OpEx. 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.). Within a few years' time (<2020) the cost ratio between a WSS and a tuneable transceiver is expected to be around 5-10. This gives an indication of the minimum reduction in number of host transceivers per WSS required for this type of flexible transport solution to be favourable.

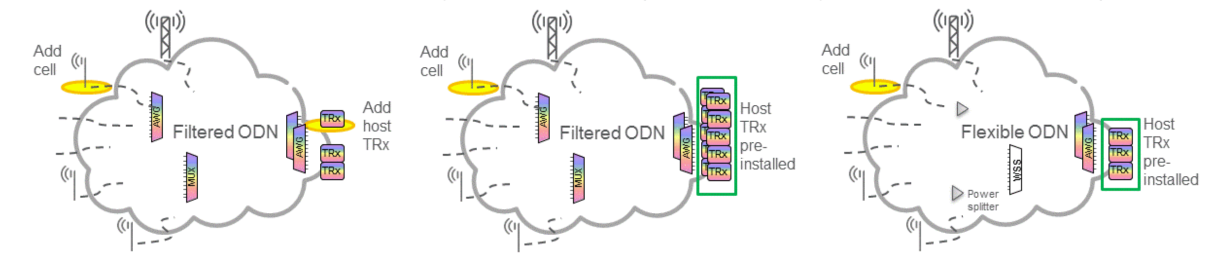


Figure 79: Service provisioning of transport resources for a new small cell for: a) filtered ODN with manual installation of host resources b) filtered ODN with pre-installation of host resources and c) flexible ODN with pre-installation of host resources (based on expected take rate) and flexible allocation of host resources.

Scaling of RAN-transport resources based on demand: Dynamic scaling of resources involves both the flexible allocation of shared resources and deactivation of unused resources. An example where such scaling could lead to large savings is for small cell deployment. Small cells are deployed to provide capacity and/or coverage for peak demand. Each small cell covers a smaller area with more fragmented utilization compared to Macro cells with larger coverage areas. Figure 84 illustrates what can be referred to as an elastic broadband service. In this scenario a number of RAN areas are connected to an aggregation point via an ODN. Traffic in the different RAN areas is expected to fluctuate with movement of users and dynamic service patterns. This dynamicity could be exploited for several purposes, such as improved utilization of centralised RAN resources through pooling, for a more lean dimensioning and utilization of transport resources by provisioning connectivity only to areas where needed, or for saving energy both in the radio and transport by powering off cells and transport interfaces that are not in use. The savings associated with such dynamicity would depend on the maximum fraction of cells that simultaneously would have to be active within an area. Savings would be significant for deployments with large numbers of cells but with low average traffic densities where only a fraction of the cells would need to be active simultaneously. The use case requires coordination between the RAN and transport/access.

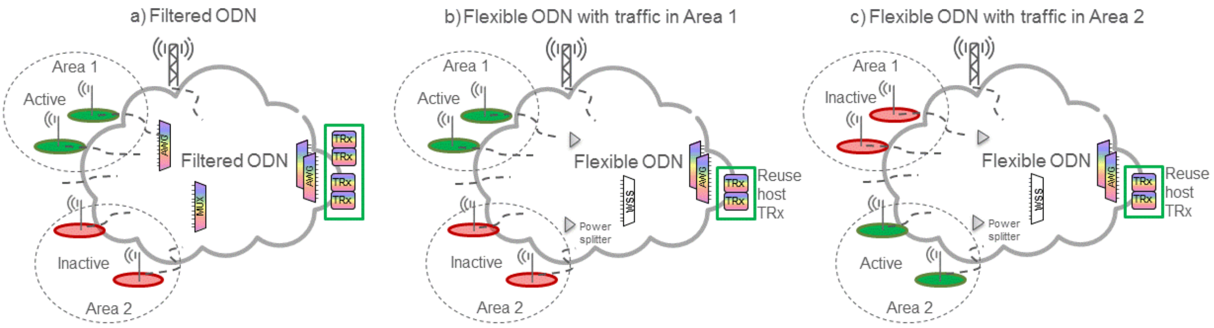


Figure 80: Illustration of a) the reference scenario for a static network and in b) and c) the use case where flexibility is exploited to reduce required network resources by shifting resources between areas 1 and 2 depending on where there is demand.

Load balancing exploiting flexibility in the RAN: There are several examples of how flexibility in the RAN could be exploited to enable more efficient use of resources in todays' networks. In 5G networks the degree of flexibility will be even greater. One example is beam forming, which has been proposed as a 5G technology. Beam forming could enable flexible allocation of radio resources to areas with high demand. Another example is multi-site connectivity with enables simultaneous connectivity of a mobile device via multiple radio cell sites.

The increased flexibility in the radio for connecting a device to the network could be exploited for various optimization use cases that involve other end-to-end resources such as transport. Figure 81 shows an example where flexibility in the radio is exploited to overcome bottlenecks in the transport. This is another use case that involves joint coordination between the radio and transport.

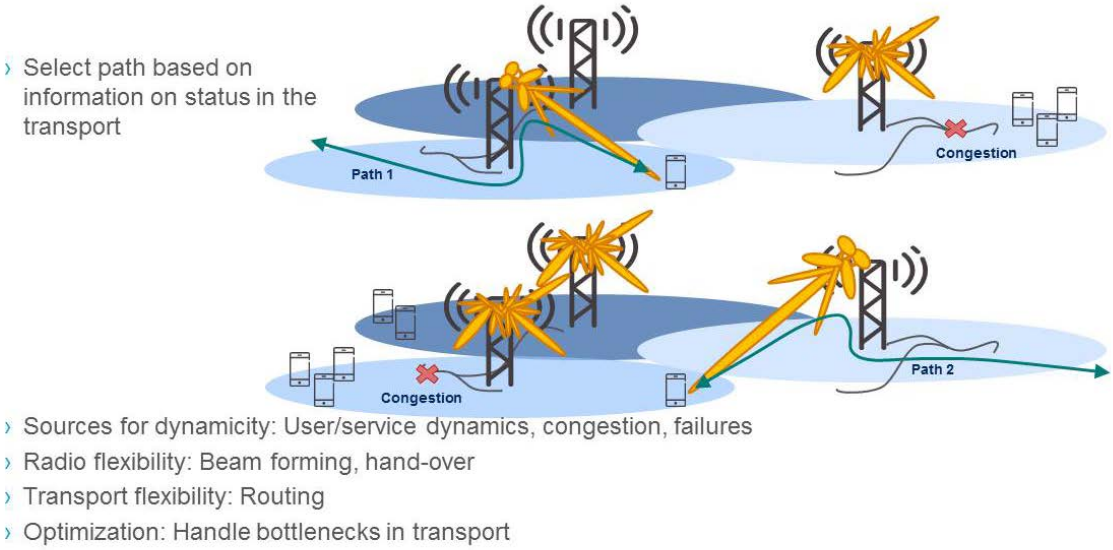


Figure 81: Flexibility in radio exploited to overcome bottlenecks in the transport

Dynamic coordination schemes: Another example of a use case for RAN-transport interaction is radio interference coordination between cell sites. Radio interference coordination is associated with stringent transport requirements. As illustrated in Figure 82 and Figure 83, there may be reasons to reconfigure the cell coordination clusters based on dynamic user and service patterns. Reconfiguring the coordination clusters requires flexible support not only from the radio but also from transport, irrespective of whether coordination is realized through a centralized RAN deployment or in a distributed deployment via X2. This use case also requires RAN-transport interaction as it is the RAN that can determine the desired cell clustering while it is the capabilities in the transport that determine which configurations are possible.

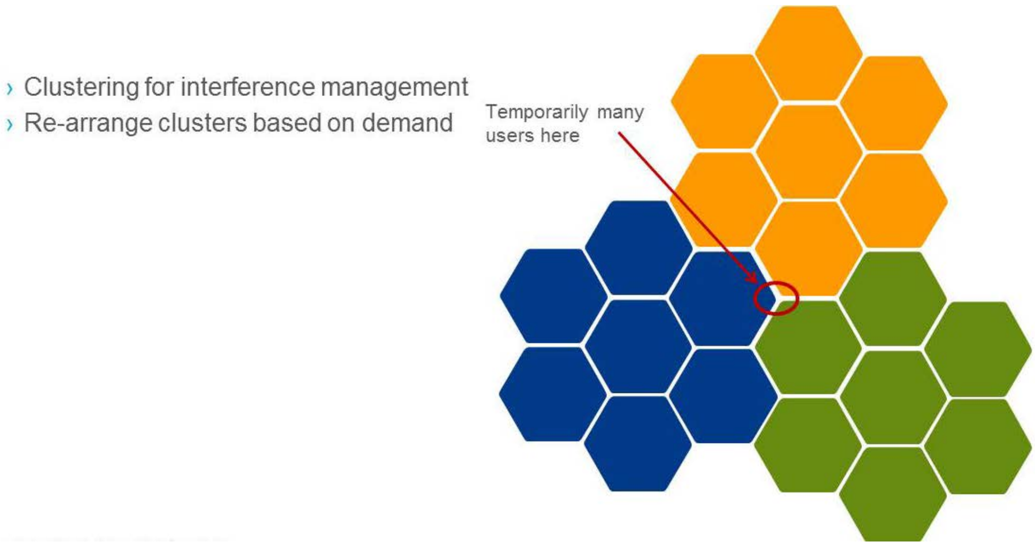


Figure 82: Three cell coordination clusters here consisting of seven cells each

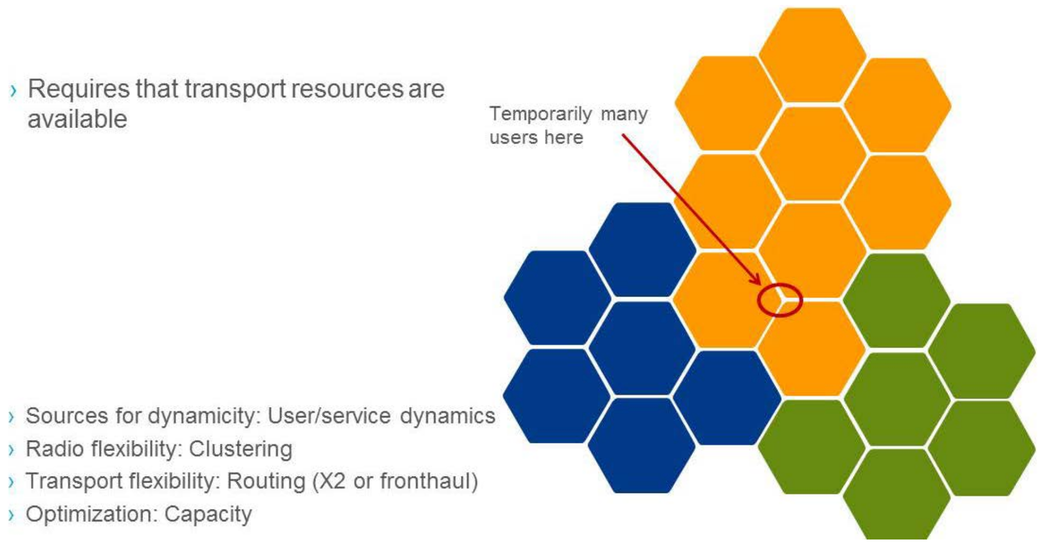


Figure 83: Temporary demands at the border between the coordination clusters may trigger a change in the clustering in order improve capacity locally

Efficient use of low granularity network resources: Another use case for flexibility is to improve utilization of resources that offer limited granularity/modularity. This includes resources within the transport itself as well as resources connected to the transport. Higher degree of integration, such as more ports per switch or more blades per rack, often leads to considerable savings. However, reduced granularity/modularity may also present an issue in deployments. One example from optical transport is related to multi-channel transceiver arrays, which are expected to reach market maturity in a few years' time. Multi-channel transceivers promise great savings in terms of cost, power consumption, and footprint through integration of multiple transceivers, allowing internal transceiver elements to be shared. However, decreased modularity where wavelength resources are installed in larger chunks compared to an approach based on individual transceivers, may also make it difficult to accurately deploy resources based on demand. Hence, despite savings per transceiver, decreased modularity may result in an over dimensioning of the number of transceivers. This problem could be alleviated with a flexible ODN where installed wavelength resources are utilized over a wider area compared to being confined to particular ODNs. Figure 89a illustrates the case of a static wavelength routed ODN exploiting multi-channel transceiver arrays. Note that this corresponds to the configuration discussed in Figure 84b but where the single host transceivers have been replaced by multi-channel transceiver arrays. The reduced modularity of the multichannel transceivers prohibits an approach depicted in Figure 84a where host transceivers are gradually installed based on demand. For low take rates this reduced modularity in the host transceivers leads to an over dimensioning of the number of transceivers. Figure 89b shows an alternative based on a flexible ODN where the number of host transceivers can be dimensioned based on expected demand, and decoupled from the dimensioning of the ODN. This approach could also be combined with centralization, and where transceiver resources are flexibly utilized over a larger area. Important factors for quantifying savings/costs are number of transceivers per array, number of attachment points that can be routed to the transceiver array, and typical take rates in the ODN. The concept of using flexibility to improve utilization of low granularity resources is not limited to optical transceivers. For other types of network resources such as baseband unit (BBU) resources, centralization and/or flexibility can be used as an avenue for reducing impact of limited granularity, where BBU resources through the flexibility of the transport can be exploited over a larger area and reducing the confinement of resources to particular branches in the network. This in turn also requires tight coordination between radio and transport resources.

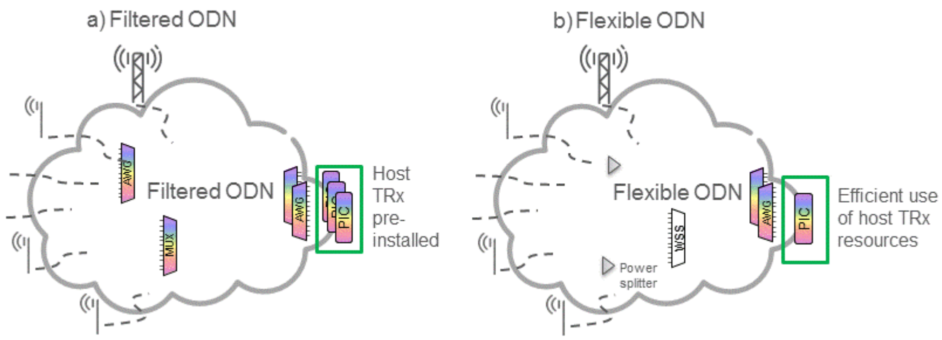


Figure 84: Illustration of a use case where flexibility is used to exploit multi-channel transceiver arrays for a) reference scenario with a filtered ODN and b) scenario with a flexible ODN

8.1.1 Control Architecture

The joint optimization of resources across different domains (radio, transport, IT, etc.) requires support from the control architecture. A major enabling technology to support dynamicity and programmability of the transport is SDN. Through SDN, the main intelligence of the network control is decoupled from the data-plane elements and placed into a logically centralised, remote controller. This allows a network operator to directly program customized control algorithms into the network controller. SDN enjoys the potential to provide higher degree of flexibility for transport control at a lower complexity, e.g., through abstraction of resources. Figure 85 presents one of several possible architecture options that will be further analysed in D3.4. Figure 85 shows a hierarchical control architecture where individual domain controllers responsible for RAN, transport, and IT resources provide an abstract view of resources to an orchestrator. The orchestrator in turn presents an abstract view of end-to-end resources to network applications on top of the orchestration layer. The architecture enables a unified orchestration and control of network, storage and processing, through exposing a programmatic transport API that can be used by network services and applications.

One key question is defining the abstraction between the controllers and the orchestrator. For a transport network, resources could for example be exposed through the big switch or virtual link models. The abstraction defines which optimization opportunities will be available between the domains (i.e., which use cases will be supported), but also the complexity and scalability of the control plane.

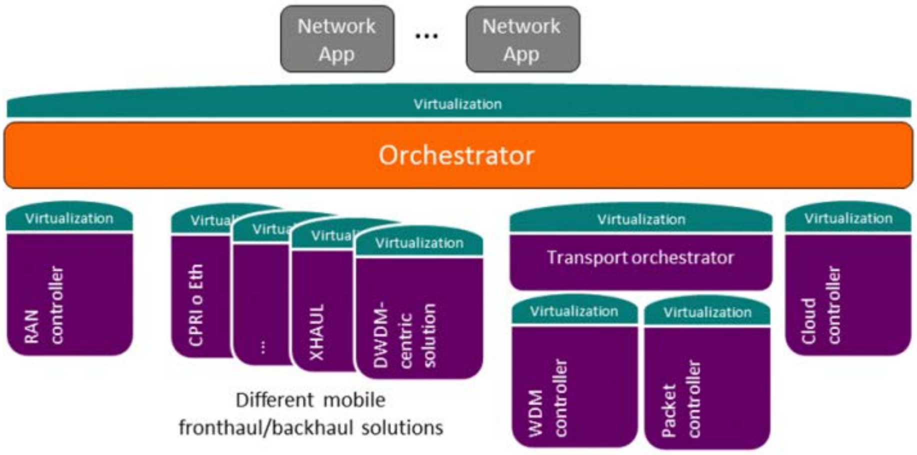


Figure 85: Hierarchical control architecture to enable joint orchestration of resources across different domains

8.2 Flexible System Concepts

Some of the use cases in section 8.1 rely on flexibility in the transport/access, some rely on flexibility in the radio and some rely on flexibility in both. This section analyses the degree of flexibility that can be provided in the transport/access for the different Combo scenarios. For each system scenario described in Chapter 6, there is either some degree of flexibility that can be exploited or a flexible system counterpart can be designed. Here, we design and present flexible variants for previously considered convergence scenarios for the urban geotype. Compared to static wavelength routed variants, flexibility comes at an additional cost in terms more costly components (such as WSSs) and increased insertion loss that may need to be compensated for by reach extenders.

NG-PON2 with PtP WDM PON (Shared Spectrum): Figure 86 shows a solution for flexible WDM-PtP overlay in NG-PON2. The advantage of this architecture compared to static variants is that WDM-PtP 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 86, 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 WDM-PtP. This limits the number of ODNs that can be attached to the same WSS. As a consequence, low fan-out WSSs are used leading to a large number of required WSSs. The number of WSSs is, therefore, rather driven by the total number WDM-PtP wavelengths in the deployment than the number of ODNs that require WDM-PtP services. If the spectrum for WDM-PtP services could be extended resulting in more WDM-PtP 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 86is 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.

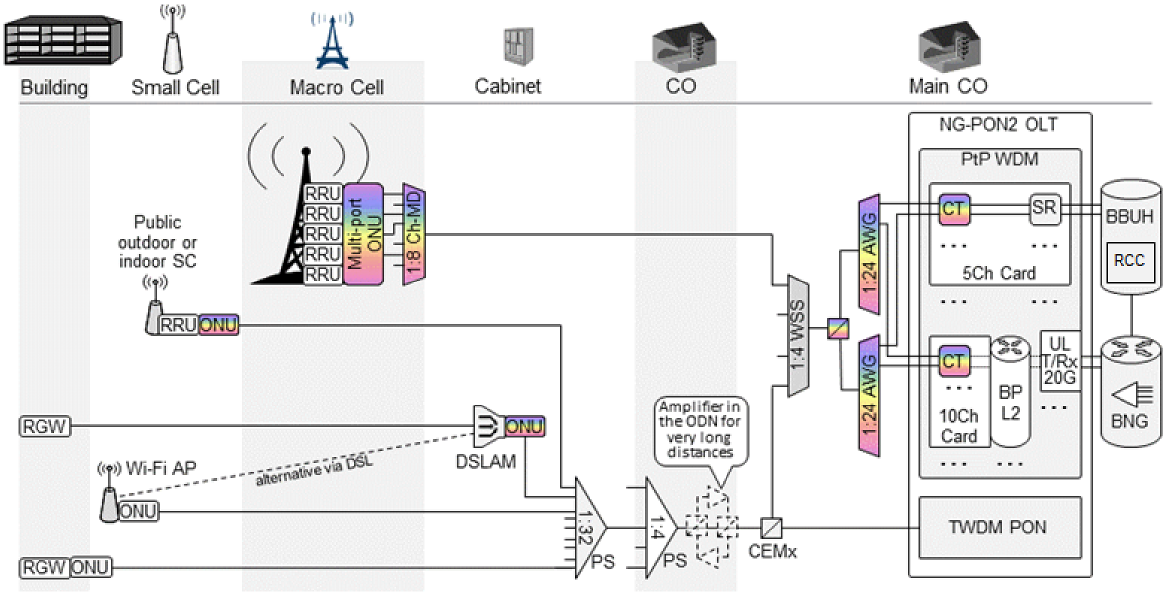


Figure 86: NG-PON2 (shared spectrum) with flexible WDM-PtP wavelength allocation

DWDM-PON (Expanded Spectrum NG-PON2): Figure 87 and Figure 88 show two different variants of a flexible DWDM-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. The WS-WDM-PON based on a power splitter-based ODN described in Section 6.4 exhibits a high degree of flexibility. The main challenge for this solution is reach. A large number of amplifiers and/or reduced splitting ratio may be needed to provide the required reach capabilities. Figure 87 shows a hybrid variant where one of the power splitter stages is replaced by a band filter. This make the ODN partially filtered, improving reach at the cost of slightly reduced flexibility. Figure 88 shows a variant where one of the power splitter stages has been replaced by a large fan-out WSS. This improves reach at the cost of a more costly WSS-based ODN. A possibility not shown is to replace the 1:8 power splitters by filters (e.g., AWG) in Figure 88 for clients with more static connectivity needs. This improves reach and reduces cost (no tuneable Tx/Rx filters) for static clients.

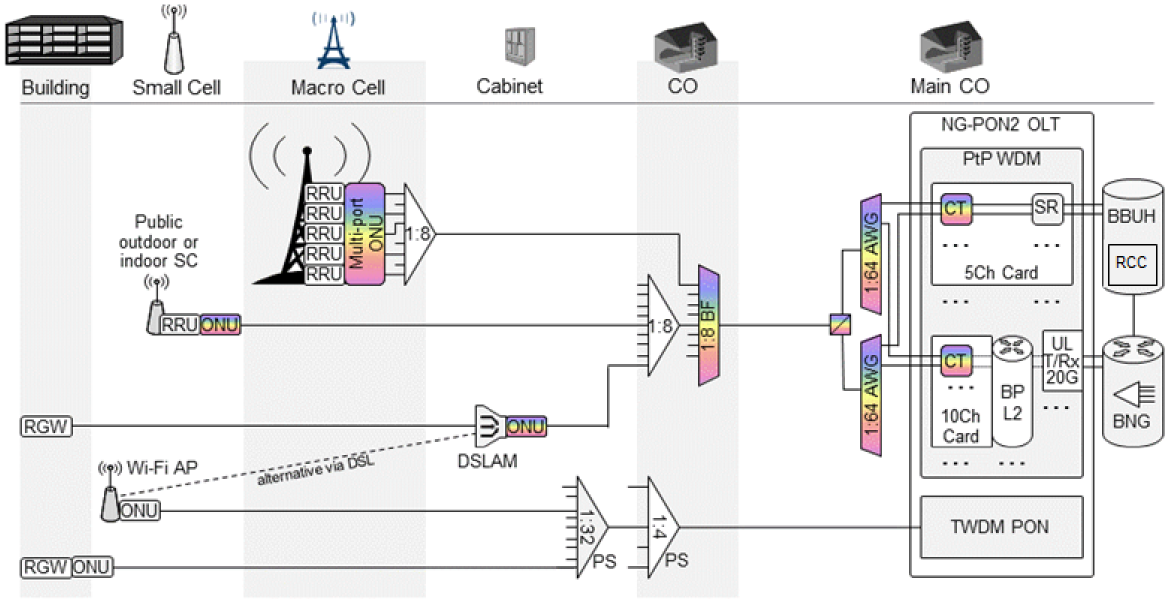


Figure 87: Hybrid PON with partially filtered ODN allowing for some degree of flexibility

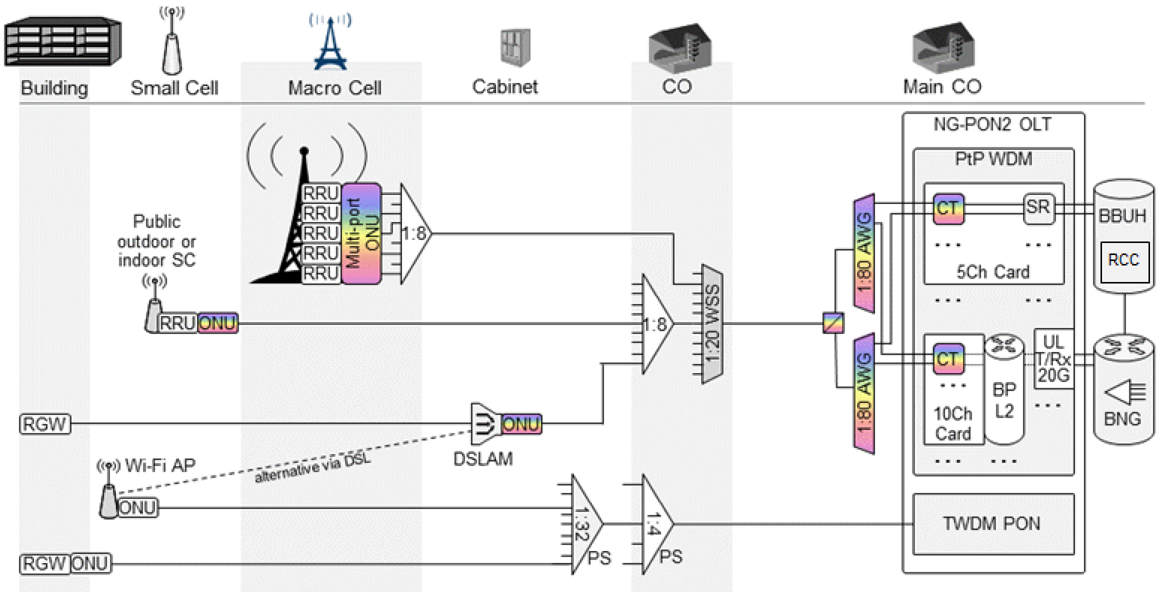


Figure 88: Flexible DWDM-centric access network based on WSSs

DWDM-Centric Aggregation: Figure 89 and Figure 90 show flexible variants of the DWDM-centric aggregation network where DSLAMs, Ethernet switches or GPON OLTs are backhauled by a DWDM-centric network. The static variants were discussed in Section 6.6 for alternative starting scenarios. The system shown in both figures is similar to the system in Figure 88. The main difference is the number of clients and amount of traffic served by the network as the solution also backhauls all of the fixed access traffic. Figure 89 and Figure 90 show examples for tree-like fibre infrastructure. These scenarios could be extended to other topologies like rings in order to provide improved resiliency.

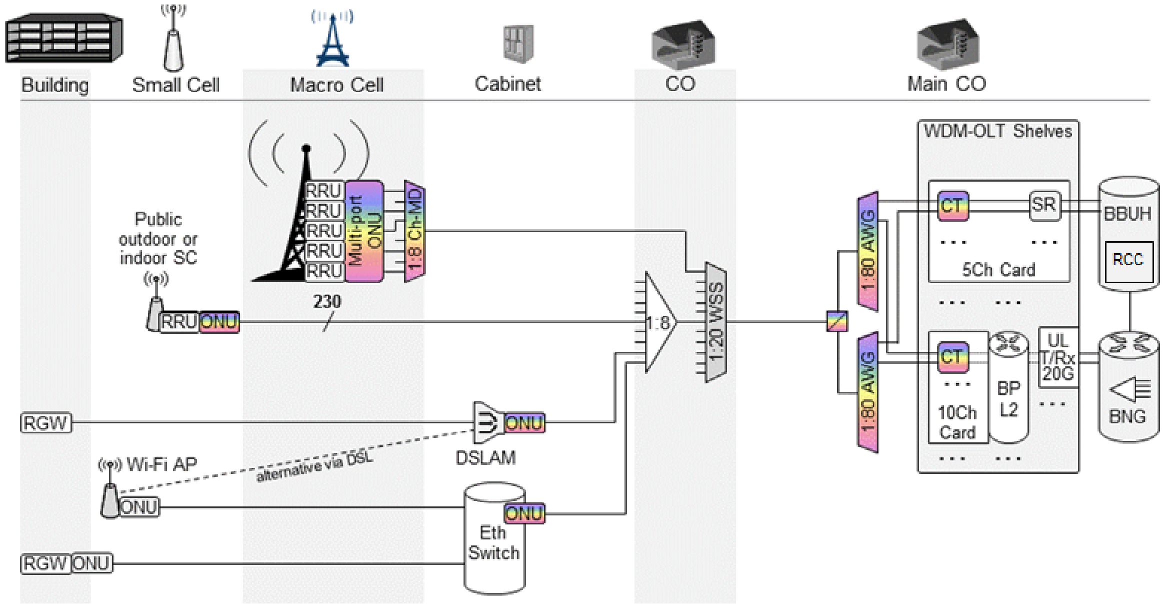


Figure 89: Flexible DWDM-centric access/aggregation network serving mobile as well as remote fixed access nodes

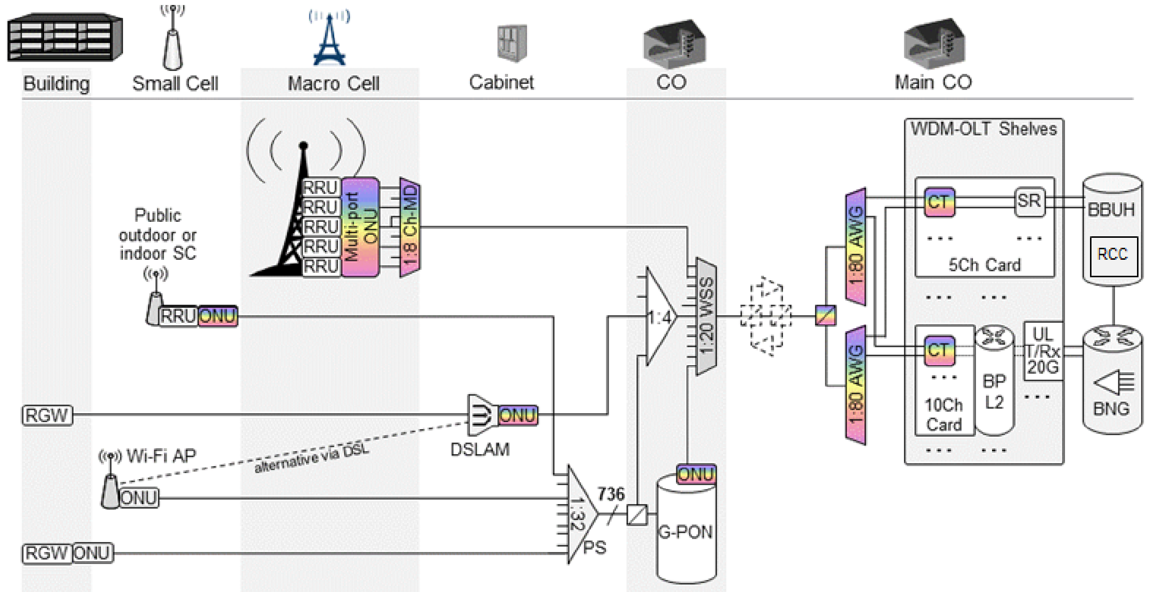


Figure 90: Flexible DWDM-centric access/aggregation network serving mobile as well as GPON backhaul and reusing the GPON ODN

In order to compare some of the costs of the considered flexibility, Table 19 presents dimensioning results for four considered convergence scenarios for the urban geotype and for fronthaul deployment, where flexibility on a wavelength level may be more critical. Note that the benefits of flexibility are not captured in these results as it requires more careful modelling of dynamicity related to relevant use cases presented in the previous section. The outcome of the dimensioning is merely the presentation of configurations that are feasible in terms of reach/performance whilst minimizing required infrastructure resources. Flexible configurations are found feasible for urban and dense urban scenarios while suburban and rural scenarios require extensive use of amplifiers. The configurations should be compared to their more static counterparts in Chapter 6 rather than to each other, as some of them are based on different starting scenarios.

Table 19: Dimensioning for different convergence scenarios with a flexible WDM for fronthaul in urban areas

Urban, Fronthaul			NG-PON2 w flexible WDM-PtP	Hybrid WS/WR PON	WSS-PON	DWDM-centric aggr. FTTC	DWDM-centric aggr. GPON
System	**OLT shelves**		**4.9**	**4.9**	**5.3**	**6.9**	**5.0**
	OLT T-TRX	3G	561	561	561	846	561
		10G	69	69	69	69	75
	OLT↔BBUH TRX pair grey	3G	2 x 46	2 x 46	2 x 46	2 x 46	2 x 46
		10G	2 x 69	2 x 69	2 x 69	2 x 69	2 x 69
	Pluggable ONU tuneable TRX	3G	515	515	515	800	515
		10G	0	0	0	0	6
	Multiport ONU T-TRX + grey TRX pair	3G	3 x 46	3 x 46	3 x 46	3 x 46	3 x 46
		10G	3 x 92	3 x 92	3 x 92	3 x 92	3 x 92
	Amplifiers (bi-directional)		**72**	**2**	**7**	**12**	**8**
	AWGs, Band Filters, WSSs		**122**	**33**	**24**	**59**	**47**
Fibre	FTTC/H area (70% DSL, 30% FTTH) FTTH fibre excluded	Cab↔CO	TWDM	285	285	800	285
		Macro↔CO	23	23	23	23	23
		CO↔MCO	23+TWDM	11	8	12	8

8.3 Supervision of Antenna Sites and Fronthaul Links

When building a network, it is essential to consider the Operation Administration and Maintenance aspects. In particular, links and sites must be monitored in order to detect any kind of problem including faults and performance degradation. Integrating backhaul and fronthaul segments into fixed access infrastructure can thus raise specific challenges for network operation. Monitoring elements are natively provided by Ethernet in the backhaul network, but no such elements are provided by the CPRI: this is why new monitoring solutions need to be developed for the fronthaul segment so as to ensure its ultimate integration with fixed access infrastructure.

In the Centralised-RAN architecture the antenna sites and the BBUHs are under the mobile operator's responsibility, whereas the fronthaul link is under the fixed operator's (fibre provider's) responsibility. There must be precise demarcation points in order to separate the responsibilities. Thus, a monitoring system must be implemented in such a way that each entity receives alarms about the network segment for which it is responsible. These demarcation points must be outdoor compliant and as simple as possible, preferably without a need for a power supply to reduce expenses and breakdowns. The need for a separation of responsibilities is even more important in wholesale offers where the client requires SLAs (Service level Agreements) from the infrastructure provider. A first SLA level is the optical link monitoring. Higher SLA levels would address performance monitoring; it could include KPIs such as throughput, frame loss rate, latency, jitter and availability.

This section describes technical solutions for supervision of antenna sites and monitoring of optical access links, and analyses how they can be applied to fronthaul monitoring.

8.3.1 Antenna Site Monitoring

Antenna site monitoring allows the mobile operator to supervise equipment at antenna sites which are under its responsibility. The antenna site alarms are collected by a robot located in the energy cabinet at the antenna site. This robot is connected to the network via IP, which allows remote monitoring of antenna site alarms and remote control of the antenna site power supply. Note that a management channel for transport of these monitoring and control signals has to be provided to the mobile operator by the fixed operator, in addition to the data channels. This management channel is multiplexed /demultiplexed at both ends with appropriate equipment, as depicted in Figure 91 for the fronthaul case.

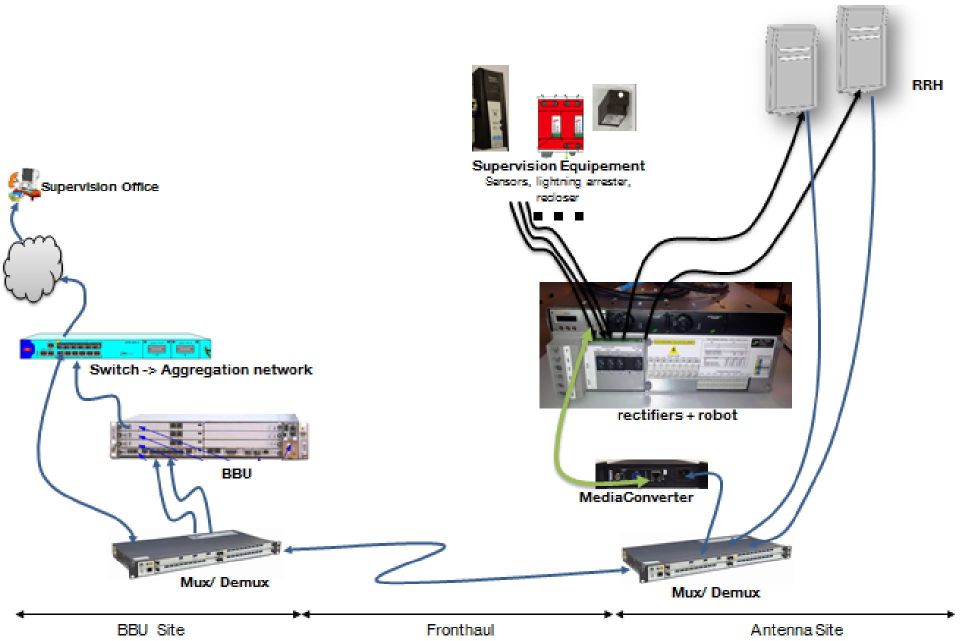


Figure 91: Antenna site monitoring in the fronthaul case

Specifically, linking supervision equipment (sensors, lightning arrester, reclosing device, etc.) to the robot enables the supervision of the antenna sites as presented in Figure 91. In fact, the process takes place in 2 steps. First, three types of alarms can be generated by the robot in case a sensor triggers: Major alarm, minor alarm, lack of power. These alarms are sent to the supervision office via two RRHs in order to secure the process. Second step, once the supervisor is warned, he/she can connect remotely to the robot using this time the wavelength channel dedicated to the antenna site monitoring. He/she can have details about the occurring problem and resolve it remotely if possible.

8.3.2 Access Link Monitoring

Problems for monitoring links in the access part of a network result from the fact that the monitoring itself must not lead to significant added cost, and from the requirement that it must not interfere with the (payload) data signals. If the data signals must be transported fully transparently (as is the case, e.g., for CPRI), then any inbuilt OAM functions of the data signal (e.g., Ethernet OAM functions) cannot be used or accessed. In that case, additional low-cost, non-intrusive OAM means must be added.

A first possibility for access link monitoring uses optical reflectometry (OTDR). In order not to interfere with any payload data signals, OTDRs in PONs (and also elsewhere) typically use the L-band around 1650 nm. Then, simple blocking filters for the OTDR signals can be implemented to protect the data-signal transceivers. An implementation of OTDR monitoring in a WDM-PON is shown in Figure 92.

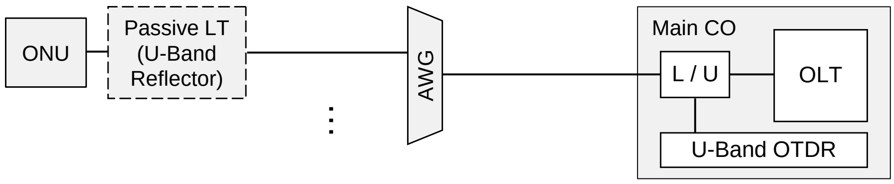


Figure 92: U-band OTDR monitoring in WDM PON

In the OLT, the OTDR signals are coupled onto the respective feeder fibres by means of simple U-band/L-band filters. In WR-ODN, the signals are filtered and routed in the ODN. This means that a tuneable OTDR must be used which works in a cyclic order of the AWG in the monitoring band (U-band). Then, unambiguous monitoring of the outgoing distribution fibres is possible (which is a potential advantage of WR-ODN over WS-ODN). In WS-ODN, due to the broadcast characteristic, all distribution fibres cause reflections, which then overlap on the way back toward the OLT. This can cause ambiguous results (i.e., OTDR signals which cannot discriminate between certain distribution fibres anymore). This problem can partially be compensated by using special passive line terminations in the form of partial reflectors which are coded with unambiguous signatures. Then, signals can be discriminated even in WS-ODN, unless any two (or more) distribution fibres have exactly the same length.

In a large MCO, the OTDR can be switched across all feeder fibres in order to reduce the per-fibre cost of the monitoring. Further cost reduction is possible with line monitoring which always uses (U-band) reflectors and thus allows a simplified monitoring unit where several reflectometry parameters can be relaxed (and thus made cheaper). This setup allows monitoring the integrity of the respective link, down to the reflector. It is shown in Figure 93.

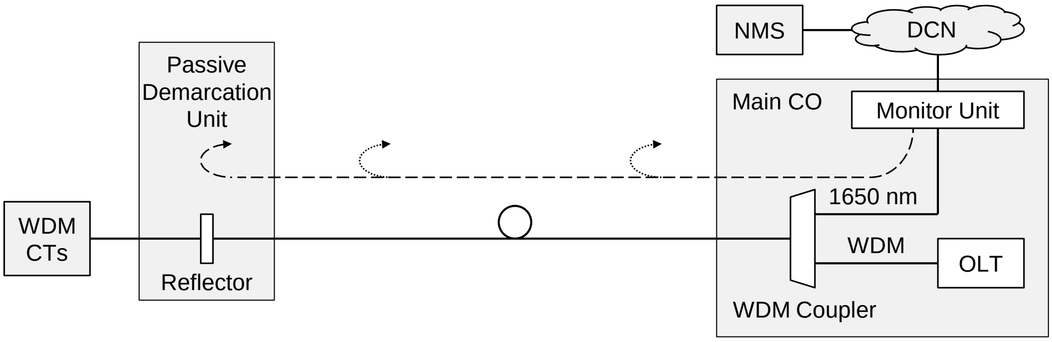


Figure 93: U-band access-link monitoring

One monitoring unit (placed here in the MCO) can serve several outgoing feeder fibres. In order to support monitoring behind a WDM filter in the ODN, tuneability of the monitoring unit would be required. Whether the simplified access-link monitoring scheme is suitable for WS-ODN (with differently coded reflectors, as mentioned before) is subject to ongoing research.

So far, fibre monitoring down to a passive demarcation point was shown. Problems can occur in WDM scenarios where several Channel Termination points have to be discriminated. In addition, obviously, no digital (performance) monitoring is possible. For the latter, per-channel monitoring channels (in-band, out-band) are required. Since in general, the payload data signal is not allowed to be accessed for monitoring, means for monitoring must be added. This leads to dedicated, per-channel (OAM) signalling channels. These channels must be added to the data signals without interfering with them. This can be done, e.g., by adding the signalling channel as an RF pilot tone, or via sufficiently slow baseband amplitude overmodulation. These implementations are currently discussed in ITU-T G.989.2 for the NG-PON2 AMCC for PtP WDM PON (also refer to Section 6.2.1). The principle is shown in Figure 94.

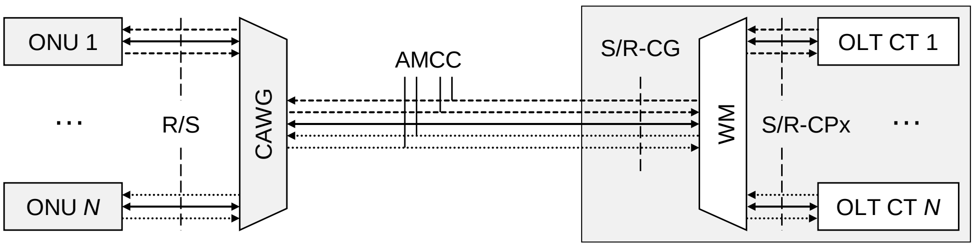


Figure 94: AMCC in (PtP WDM) NG-PON2

The AMCC allows per-channel, per-direction OAM signalling. Thus, the remote ONUs can be fully monitored, independent from the payload, and including performance and status monitoring. The ONU may also be connected to its client equipment (DSLAMs, BBUs, RRUs) such that the client OAM information can be transmitted. The latter is not possible in cases where the ONU collapses into a pluggable (SFP+, this is true since now no dedicated OAM interface is available anymore). However, it is still possible to access the Digital Diagnostics Interface of the remote end and thus have at least full visibility of the remote pluggable. Figure 95 shows a possible AMCC implementation for remote Channel Terminations which can be integrated into pluggables.

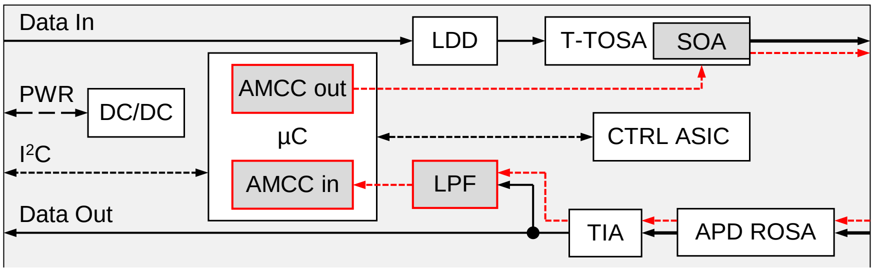


Figure 95: Possible AMCC implementation in a pluggable Channel Termination

AMCC performance data currently discussed in FSAN and SG15-Q.2 include AMCC bit rates of up to 150 kb/s. Such bit rates are seen sufficient for OAM tasks.

8.3.3 Specificities of Fronthaul Link Monitoring

Fronthaul link monitoring allows the fixed operator to supervise the fixed infrastructure which transports CPRI traffic between BBUs and RRUs, and which is under its responsibility. Specificities of link monitoring for fronthaul are discussed in this sub-section. Two solutions are possible to carry out fronthaul monitoring:

- Out of band monitoring using a dedicated management channel (different from the antenna site management channel)
- In band monitoring within the overhead of protocols such as Ethernet, OTN, light-weight CPRI framing, or PON.

8.3.3.1 Out of Band Monitoring

In the radio access network, fronthaul transport can be achieved by means of passive multiplexing and de-multiplexing of the CPRI links. The link supervision can then be realized with an active device located only at the BBUH. This solution is shown in Figure 96 in the case of a dual fibre CWDM fronthaul transport system, where one fibre is dedicated to downlink and another fibre is dedicated to uplink.

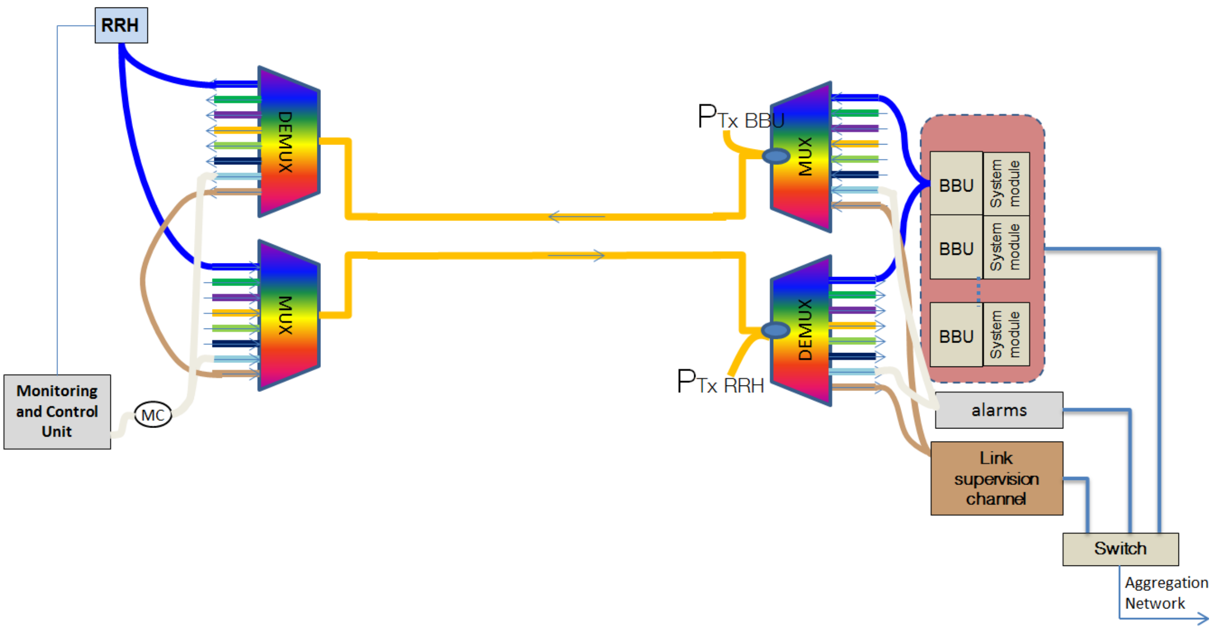


Figure 96: Dual-fibre CWDM fronthaul monitoring

Using CWDM Multiplexers allows having a total of 16 channels with 20nm channel spacing. One channel is dedicated to the fronthaul link supervision and another channel is dedicated to the antenna site monitoring. These channels are then connected to the aggregation network switch, using the appropriate VLAN, in order to be sent to the supervision office via the system.

The fronthaul link supervision is accomplished by comparing the inserted optical power in the dedicated channel and the received one, after having introduced a loop back on the RRH side. This solution is simple to implement, reliable and outdoor compliant, but is not compatible with expected evolution to single-fibre architecture (e.g., WDM PON).

Indeed, thanks to the emergence of bidirectional transceivers, it will be possible to achieve single-fibre CWDM for the fronthaul transport as shown in Figure 97.

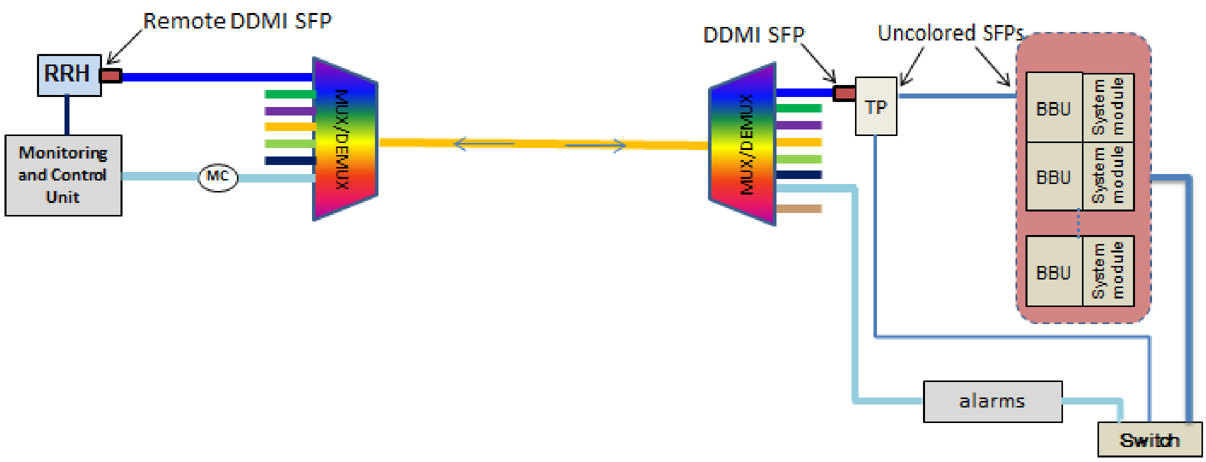


Figure 97: Single-fibre CWDM fronthaul monitoring

Different solutions permit the transition to the single fibre architecture; the most performant one is CSC (Cooled Single Channel) SFP consisting in dividing each CWDM channel in two sub-channels used for transmission and reception.

In order to supervise the fronthaul link, a first solution is to use a mirror at the end of the dedicated channel and measure the reflected power at the reception which allows the detection of fibre failures.

A more sophisticated solution is to use the Digital Diagnostics Monitoring Interface (DDMI) to achieve the monitoring. As a matter of fact, this interface is common for SFPs, it provides information about temperature, supply voltage, transmit bias current, transmit power and receive power. The innovative part would be to use this interface remotely.

The idea is to send the information provided by the DDMI of the RRH’s SFP to the BBU’s SFP using, e.g., a pilot tone or an over modulation. Using a transponder just before the BBUH, the fixed operator can retrieve the monitoring signal to send it in the aggregation network using the appropriate VLAN, allowing the transmission to the fixed operator supervision network. Uncoloured SFPs are then used to link the transponders to the BBUs. This solution provides a higher SLA level including supervision of each wavelength channel.

Besides the reduction of the CapEx, using the single-fibre solution together with remote DDMI will permit to better leverage on the existing fibre infrastructure between antenna sites and central offices. It is thus an essential step towards full integration of backhaul and fronthaul with fixed access infrastructure.

Finally, it is important to clarify that the proposed solution for both antenna sites and fronthaul monitoring is totally compatible with other WDM approaches such as WX WDM-PON solutions. DWDM assumes an equivalent technology to CWDM with several physical differences, such as channel spacing and laser sources. However, dedicated wavelength channels and pilot tones are concepts that are currently under study in order to implement the control and management system, hence, could also be addressed for DWDM monitoring.

8.3.3.2 In-band Monitoring

8.3.3.2.1 CPRI over Ethernet

Encapsulating CPRI in Ethernet frames provides native OAM. In fact, Ethernet allows link and performance monitoring. According to IEEE 802.1ag; Continuity Check Messages (CCM) are sent periodically at regular intervals. If no CCM is received within a specified interval, loss of continuity is detected, which implies that a link failure occurred.

ITU-T Y.1731 completes IEEE 802.1ag with mechanisms allowing the following KPIs measurements: Throughput, Frame loss, Frame delay, and jitter.

Ethernet is very practical because of its large availability and the fact that it provides natively high levels of SLAs. Nevertheless, encapsulating CPRI over Ethernet is not mature yet, it causes delay and jitter which not tolerated by the CPRI.

8.3.3.2.2 CPRI over OTN

OTN (Optical Transport Network) provides also native OAM. It allows link and end-to-end performance monitoring thanks to the TCM (Tandem Connection monitoring) overhead.

However, OTN mapping/demapping could affect the performances (latency, jitter, synchronization) needed for CPRI.

8.3.3.2.3 Light-Weight CPRI Framing

The physical layer of the CPRI interface is designed in such a way that a very low bit error ratio can be achieved. This is partly achieved by employing appropriate line coding. For example, for CPRI line rate options 1 to 7, once the Layer 2 CPRI frame is handed over to the physical layer, using the 8B/10B line coding, for every 8 bits of the frame 2 bits are added to guarantee bounded data transition rate to achieve DC balance and sufficient clocking information for clock recovery. Obviously, such a line code incurs huge overhead, e.g., 25% overhead for the 8B/10B coding, to the overall data rate of the interface. Unlike OTN links, which are specified to connect optical nodes over long distances and also support advanced multiplexing hierarchy and complex protection mechanisms, CPRI links are used to transport data over short distances (low tens of kilometres) over point-to-point connections. In the proposed light-weight framing scheme, instead of encoding the CPRI frame using 8B/10B line coding, a scrambling code, similar to the ones used in OTN frames, is used to guarantee the necessary data transitions and clock information. Since this scrambling code does not incur any overhead penalty, the salvaged capacity can be reused to create a light-weight framing by mapping CPRI Layer 2 client frames over DWDM channels. Depending on the CPRI bit rate, the light-weight framing structure will be able to support different framing features including FEC codes to protect the payload and the overhead, Bit Interleaved Parity (BIP) bits to be able to detect and correct errors, a generic communication channel and an in-band signalling or OAM channel to support basic OAM functions over the link. And this can be achieved without changing the bit rate for line rate of the CPRI interface.

8.3.3.2.4 CPRI over PON

Native OAM is provided with OMCI (ONT Management and Control interface) in PON systems according to ITU-T G.984.x, G.987.x and G.989.x. So far, the necessary encapsulation of the CPRI frames impacts the latency and synchronization requirements. With TWDM NG-PON2 and fixed bandwidth allocation, it might become possible to transport CPRI, but significant challenges are to be solved to meet the CPRI performance requirements [55].

Another solution within NG-PON2 is to use transparent PtP WDM PON (or general transparent WDM-PON). In this case, monitoring can be provided via the PtP WDM PON AMCC, the per-wavelength signalling channel.

8.4 Conclusions

The cost analysis in Chapter 7 considers static network deployments. This chapter introduced the concept of network flexibility. A key question is what type of coordination will be required/beneficial between the control/management of different network domains (radio, transport, fixed access, IT, etc.) in different convergence scenarios.

- Use cases for flexible RAN-transport interaction are presented. Four use cases of potential importance are outlined. These serve as a starting point for modelling the benefits of coordinated control in D3.4.
- Flexible system variants based on flexibility in the WDM layer are designed for key scenarios in Chapter 6 to demonstrate the degree of flexibility that is feasible. Flexible system concepts are feasible for urban and ultra-dense urban scenarios while sub-urban and rural scenarios would require extensive use of optical amplifiers.
- Supervision schemes for different technology components used for the system design in Chapter 6 are presented.

9 An Outlook of the Impact of Current 5G Requirements on COMBO

Aside new stringent capacity, delay, and delay variation requirements, 5G carries with it some quite new expectations from the underlying transport networks connecting the projected densely interconnected sites. To name a few of these expectations: highly flexible flow and connectivity handling in-between sites and for each user terminal; major challenges for fronthaul solutions due to the very high capacities expected from the 5G antenna-carriers and leading to new ways of virtualizing parts of the 5G RAN; major synchronization challenges; the potentials of re-prioritizing network mechanisms end-to-end in favour of dominant traffic types of tomorrow, not least media/video and Internet of Things (IoT); and last but not least, the convergence of radio access and wireless backhauling with its potentially huge impact on structural convergence.

9.1 A Sneak Peek of What is coming with 5G

The vision of 5G is commonly presented as part of the 2020 network vision, 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 extreme capacity mobile broadband, massive machine type communication, and ultra-reliable ("critical") machine-type communication. 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. In general also, 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 indeed has proven to be a very robust technology, and 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. What we could expect is an evolution of mobile technology along the LTE track, primarily in existing spectrum, paralleled by new RATs, or variations of existing ones to meet specific demands of tomorrow, e.g., extremely energy efficient machine-type applications. It is understood that the variety of requirements on 5G will be quite substantial, but in order to provide a flavour of challenges ahead, also for transport, the following list referred to by many is presented in the FP7 METIS project [41]:

- 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
- 10 times longer battery life for low power Massive Machine Communication (MMC) devices
- 5 times reduced end-to-end latency

We should further expect enhanced variants of this list in the future, as research findings emerge, e.g., of lower latency opportunities and requirements. Already today, multi-RAT support in user terminals is considered important, and this way of mixing radio accesses to fulfil a fluid traffic need of individual terminals is likely to continue. We see it today with LTE's License Assisted Access (LAA), or the emerging 3GPP dual connectivity to master/slave cells (see, e.g., 3GPP TR 36.842), and with multipath appliance of LTE/Wi-Fi, and we are likely to see it tomorrow with LTE and the new 5G RATs. In addition, we need to bear in mind that new bands expected for 5G, from sub-GHz to centimetre and millimetre waves, will fulfil different needs. As already apparent in today's networks, different bands will apply to different layers, and as a further complication, bands serving a specific terminal will not necessarily terminate on the same radio network access point. As with multi-radio access examples of above, we can expect multi-radio connectivity (i.e., multiple user planes) as well as split control and user planes. For example, a terminal may establish a control plane relation with a macro layer and user planes with the macro-associated small cells and Wi-Fi APs. In order for this model to work, not least in order to scale with the great amount of small cells expected, flexible network bookending of control and user plane flows will need to be supported in the transport domain somehow. And this whilst meeting very high expectations on sustainability and affordability.

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. Although we expect great improvements in the fronthauling technologies, e.g., benefiting even more from Ethernet technology and infrastructure reuse [42], projects such as METIS predict that other types of splits will dominate, in order to lower capacity and latency requirements. In some cases, this might challenge existing fronthauling solutions (e.g., LTE), in case multi-RAT solutions need to be supported (e.g., control plane over LTE, user plane over both LTE and 5G). 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 [44].

As for synchronization and timing, the 5G landscape is likely to multiply the importance and criticality of an accurate and reliable timing throughout the network. This aside, there are in addition a number of "networked society" applications in various parts of the network that will require very robust timing. Related issue are the strict latency requirements that may benefit from distributing a common sync reference.

In addition to the advances in radio discussed earlier, 5G is many times used to motivate new paradigms in areas such as core and OSS/BSS. One such paradigm which might have a considerable impact on the COMBO structural convergence is Information Centric Networking (ICN) [45], in which the traditional host based model embodied by the current internet is challenged by a "named data" paradigm. Here the use of the Internet Protocol itself is abandoned for a new set of protocols, and the entire structure of the network is re-optimized in order to focus on efficient handling of massive media distribution (not least video!) including massive IoT. One key aspect here is also to make content caching an inherent part of the network, as opposed to today's overlay solutions.

9.2 Potential Structural Impact from 5G "Outside-In"

A potentially major structural impact from 5G heterogeneous networks, not least in dense urban areas, is the combination, on the one-hand, of 5G technology enablers such as massive beamforming, very high capacities by means of new bands including above 10 GHz, multi-RAT connectivity etc., with on the other hand Fixed Wireless Terminal (FWT) technologies currently gaining momentum as a complement to fixed broadband access [42], and also gaining momentum as a consequence from the convergence of radio access and wireless backhauling [47].
Extrapolating on this, one should not exclude the relevance in many cases of entirely new structural convergence approaches, e.g., using 5G FWT to redirect the heterogeneous network mobile/wireless 5G radio capacity, from outdoor users to indoor-located fixed wireless terminals in homes (as the busy hours shift from daytime outdoor to evening indoor), thus outright obsoleting fixed broadband access plants in some instances. Under the right circumstances, such solutions could provide very high sustainable and peak capacities to residential users, at marginal costs compared to the expected regular network capacity expansion and densification towards 5G.

As an example, let us consider a European dense urban scenario where we assume that 5G is being rolled out, primarily through reuse of macro sites with complementary site densification where needed. In the NGMN [34] estimates, the use case category of "broadband access in dense areas" corresponds to a user traffic density of 750 Gb/s/km^2 in the downlink (and 150 Gb/s/km^2 in the uplink). Let us assume that a 5G (densified) macro network supports this NGMN use case.

We model our population density roughly on Paris, i.e., 20,000 persons/km^2 [63]. With a 100% service penetration and a 60% market share the operator we study the needs to serve 12,000 5G subscribers. However, during the evening, media consumption of most of these subscribers has moved to inside their homes. The question is then how we could leverage on our deployed 5G network to also provision services to these residential users. One approach is of course to try to penetrate to the devices (e.g., 4K TV sets) directly, but this is increasingly challenging with modern building practices, particularly when combined with higher frequency bands envisaged for 5G. Instead, we assume the deployment of fixed-wireless terminals to those homes, each equipped with a CPE with external antenna.

In hybrid access solutions, e.g., as being deployed by Deutsche Telekom [46], this wireless link is of course bundled with a DSL fixed link – in our exercise let's assume we only use the 5G FWT for backhauling. Inside the home the CPE could be devised as a "5G relay" (assuming such relay will be standardized in 3GPP, based on the LTE relaying concepts), or it could terminate the 5G backhauling link and provide any type of radio access inside the home: 5G/LTE over both licensed and unlicensed bands, Wi-Fi, etc.

Based on statistics from Eurostat [64], we assume 2 persons/households and in most cases looking at the same 4K enabled device. We further assume that all households will exhibit an "indoor media busy hour" in the evening, during which they are watching video content of 4K quality with an average rate of 15 Mb/s [65]. This results in a traffic density of 90 Gb/s/km^2. If we assume that we have the equivalence of 12 sectors per base station thanks to beamforming and other technology advances, and 200 MHz/sector (including new bands for 5G) providing 3b/s/Hz, then each base station provides up to 7.2 Gb/s. To provide 90 Gb/s/km^2 we then need 13 base stations/km^2, which we for reasons of simplicity turn to 16 base stations/km^2, resulting in an inter-site distance of 250 meters, with each site serving over 350 homes during evening hours. The business case for this deployment is of course not necessarily simple to make, if the base stations are deployed for the sole purpose of our example. However, as an add-on to an existing 5G network providing the capacities envisaged by NGMN, the challenge does not seem daunting. Also note that since the scenario assumes 5G to FWT, this is likely to happen sooner than will be the case for 5G all the way to end users, particularly in higher frequencies for regulatory reasons. The peak cell rate that could be provided to individual homes would easily reach beyond Gb/s and, hence, be very well positioned from a commercial perspective to compete with HFC, DSL and PON broadband access networks. Similarly to HFC/PON, the 5G based broadband access solution could also scale well in providing efficient support for broadcasting, e.g., of popular live content.

10 Conclusion

This deliverable addresses one central question regarding convergence: Assuming there is a widespread residential fixed fibre infrastructure in 2020, can it be reused for/shared with mobile small cell and macro cell deployments? Or do operators need to deploy a dedicated network for mobile traffic?

To answer this question and to reach the objective of the deliverable, COMBO has developed FMC architecture options (in line with Specific Objective SO1.4) by considering the requirements given by the expected RAN evolution in terms of transport latency and data rate. These are given by the restrictions of placement of BBU and RCC in a centralized and decentralized flavour considering backhaul and fronthaul RAN architectures as well as MBS and small cell deployment. Several infrastructure studies have shown that due to the LTE HARQ latency restriction well below 1 ms, a BBU or RCC needs to be placed at the Main CO level or even closer to the antenna site.

The focus of this deliverable is on the following fixed and mobile converged architectures:

- Backhaul with RCC centralised at Main CO
- Fronthaul with both RCC and BBU Hotel centralised at Main CO

As a reference for the technical and economical assessment in 2020, SFSW CWDM as a natural evolution path was assumed for these architectures. As convergence solutions WS/WR-WDM-PON and NG-PON2 have been analysed against the reference. The target in all scenarios was to combine as much as possible all backhaul (fixed and mobile) and/or fronthaul clients on the same transport technology and fibre infrastructure. NG-PON2 is the only transport technology enabling fibre infrastructure- and technology-level convergence. All other solutions require separate fibre infrastructure for fixed residential and mobile fronthaul/backhaul services, allowing “only” technology-level convergence. The benefit of TWDM- (i.e., NG-PON2) compared to WDM-based transport for mass market fixed access has already been evaluated in FP7 project OASE [67], but only from the fixed network point of view. OASE showed that as long as the guaranteed constant available data rate for residential access is below 500 Mb/s, a shared medium access in the first mile is more economically beneficial than delivering a whole WDM wavelength with WR or WS-WDM-PON to each residential customer.

The backhaul and fronthaul architectures have been dimensioned and assessed with respect to cost for different deployment scenarios between 0% FTTH (100% FTTC) and 100% FTTH (0% FTTC), number of supported small cells, and radio capacity. The key findings from the current investigations on converged transport are:

- The reference PtP CWDM solution, with limited convergence potential, is in all cases the most expensive solution.
- In an FTTC deployment scenario, WR-WDM-PON is always the cheapest solution independent of fibre cost.

- Even in an FTTH area where one could re-use the mass market fibre infrastructure for NG-PON2 deployment, convergence is not always the most cost efficient.
    - Particularly for a fibre-rich FTTH roll-out with low assumed cost for using deployed fibres, WR and WS-WDM-PON could be more cost efficient for low number of small cells in the order of 12 or 25 small cells per MBS for backhaul and fronthaul, respectively. Conversely, in a dense RAN deployment situation where the number of small cells per MBS is high, NG-PON2 becomes the most cost efficient transport solution.
    - In a fibre-poor FTTH deployment with high assumed cost for additional fibre, NG-PON2 is the most economical solution, independent of the number of deployed small cells.
- For low number of deployed small cells NG-PON2 suffers from the bad utilization of PtP WDM hardware such as AWGs, due to pre-defined mass market splitting structure. Typically, on a 1:128 mass market PON branch, 16 wavelengths can be used over this infrastructure for PtP WDM, but some deployment situations may lead to a lower number of PtP WDM channels effectively used per PON branch. As an illustration, with the assumptions made in Chapter 6 for an urban or ultra-dense urban area with 30% FTTH and 10 small cells per MBS, the possible number of PtP WDM channels would in fact allow backhauling of up to 20 small cells per MBS. This drawback of NG-PON2 can be further mitigated by adapting the design of the system architecture, which will be further analysed in D3.4.
- Considering only system CapEx without fibre cost, WR-WDM-PON is always the cheapest solution, independent of backhaul/fronthaul architecture, or the amount of deployed small cells.
- Figure 98 shows in which region WR-WDM-PON on a separate infrastructure or NG-PON2 on a converged residential infrastructure is most beneficial. Moderate RAN densities give an advantage to WR-WDM-PON in fibre-rich context, even at high FTTH/FTTC ratios, and especially in the fronthaul case. The figure also strengthens NG-PON2 converged architecture as the cheapest solution when both the FTTH/FTTC ratio and the RAN density increase, which makes structural convergence a future-proof concept in the perspective of 5G.

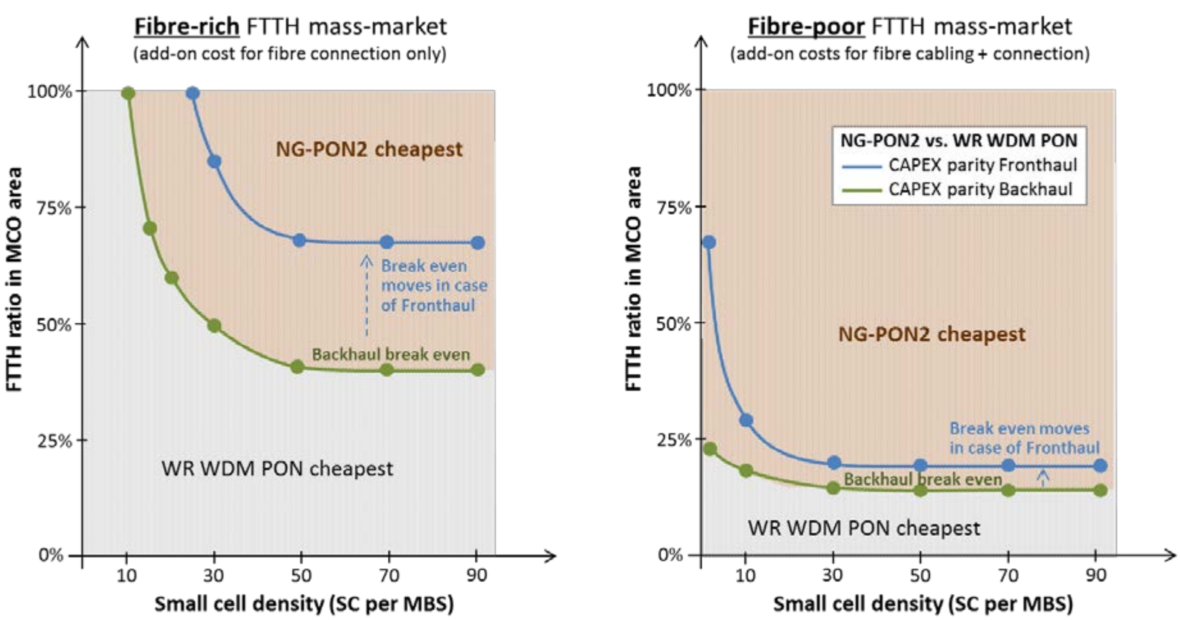


Figure 98: NG-PON2 vs. WR-WDM-PON cost-efficiency depending on SC density and FTTH ratio

Given the importance of the centralized RAN architecture, additional studies have been performed focusing on the placement and deployment strategies for BBUHs. As for placement, in case Main COs are equipped with switching equipment supporting also optical bypass, numerical simulations show that fronthaul traffic can be transported over the existing aggregation network, resulting in a more aggressive scenario where BBU hotels are allowed to be located at higher levels than Main COs.

As for BBUH deployment strategies, novel cost models have been proposed together with a preliminary analysis of the effects of these BBUH strategies. It was found that costs savings are more pronounced in more centralized options, and this strongly depends on the pooling gain that can be offered.

A key question for the control/management is what type of coordination will be required/beneficial between different domains (radio, transport, fixed access, IT, etc.) in different convergence scenarios. Several use cases for flexible RAN-transport interaction are found in Chapter 8 and serve as a starting point for modelling the benefits of coordinated control in D3.4.

Flexible system variants based on flexibility in the WDM layer are designed for key COMBO scenarios to demonstrate the degree of flexibility that is feasible. Flexible WDM systems are feasible for urban and ultra-dense urban scenarios while sub-urban and rural scenarios require extensive use of optical amplifiers.

Integrating backhaul and fronthaul segments into fixed access infrastructure raises specific challenges for network operation. Monitoring elements are natively provided by Ethernet in the backhaul network, but no such elements are provided by the CPRI in the fronthaul case. AMCC implementation is proposed for NG-PON2-based fronthaul segment monitoring, whether PtP WDM or WDM-PON, including in the case of pluggable ONUs. Remote use of DDMI interface in case of pluggable ONUs is also proposed as a practical solution in the case of pluggable ONUs. Alternatively, a light-weight CPRI framing method is analysed as an interesting future solution for fronthaul segment monitoring.

Future Work

As for the continuation of the project, the work in this deliverable provides good indications on further investigations that will be presented in Task 3.3's second and final deliverable D3.4. For example, D3.4 will take into account the requirements from 5G, including the requirements on the 5G control architecture (Chapter 8), and assess their impact on the convergence of access and aggregation networks (Section 9.2). The benefits of coordinated control will also be modelled in D3.4 based on the use cases for flexible RAN-transport interaction (Chapter 8). Furthermore, D3.4 will investigate the decentralised architecture options where the small cells are directly connected to the MBS, either via backhaul or via fronthaul (Chapter 4); the impact of intermediate solutions between backhaul and fronthaul, allowed by different functional splits in the RAN (Section 3.2); the impact of PICs that may significantly reduce the difference of the number of physical interfaces between backhaul and fronthaul (Section 6.3.4). When it comes to the cost assessment, it will be linked to other ongoing work items, including the integration of the BBU cost models (Section 7.4) and other architectural options under investigations (e.g., mixed backhaul-fronthaul approaches). Moreover, there will be a sensitivity study on the most significant parameters influencing the costs.

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A APPENDIX

A.1 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 20: 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

A.2 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 the 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. The 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 21: 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

A.3 The OLT Model

Figure 99 illustrates the OLT model used for the dimensioning and techno-economic studies. This 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”), which defines a shelf of 11 rack units (approximately 22 cm) composed of 20 slots per shelf for line cards of multiple technologies, a switch and the power supply. The upper part inside the WDM-PON OLT shelf represents a card with 10 cages supporting 5 CPRI channel terminations, whereas the bottom part represents a card with 10 cages supporting 10 channel terminations connected to the L2 switch.

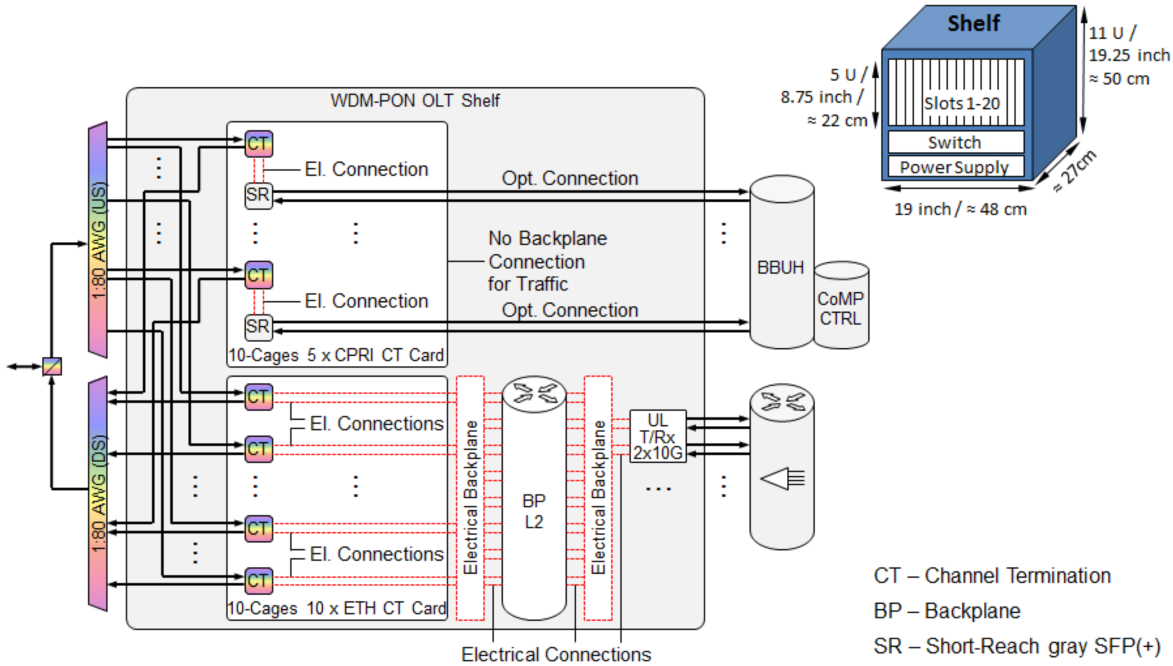

Figure 99: OLT shelf model

Future Outlook

The OLT model used in Chapter 6 is based on technologies that are foreseen in the near future. 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 100 where each PON is served by a multi-channel transceiver array. A cross-point switch, which provides protocol agnostic switching, enables provisioning of different services onto different wavelength channels in the PON.

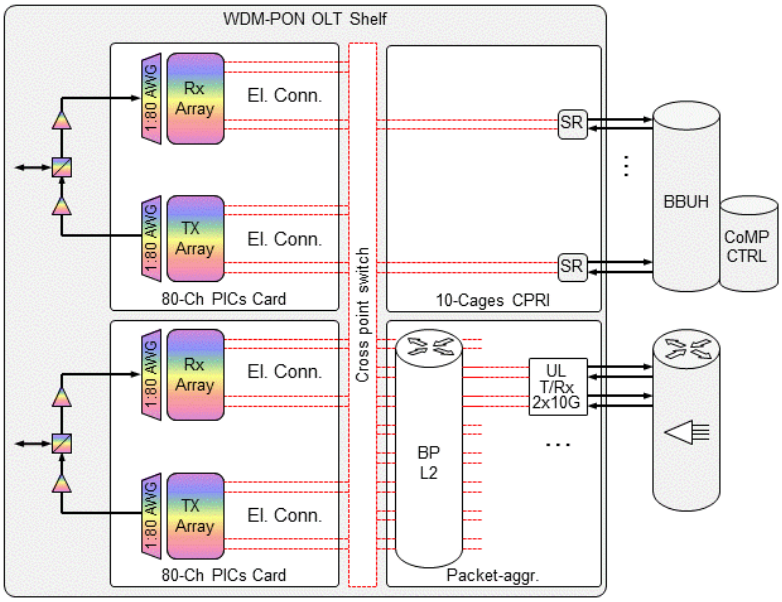

Figure 100: Alternative OLT shelf based on multichannel transceiver arrays

A.4 NG-PON2 Deployment in FTTC Areas

A different NG-PON2 deployment is considered in FTTC areas for comparison reasons with the other technologies, using only the PtP WDM overlay part (i.e., no TWDM) and a single-stage power splitter in the CO, as shown Figure 101. This gives the opportunity for a later integration of convergence in case of a subsequent mass-market TWDM-PON rollout in those areas via adding CEMx and an additional power splitting stage, depending on the operator needs. The fronthaul FTTC area implementation of the NG-PON2 looks similar with the exception that the MBSs stay fronthauled via the NG-PON2 PtP (WR) WDM PON option also in FTTC areas, in contrast to the backhaul case.

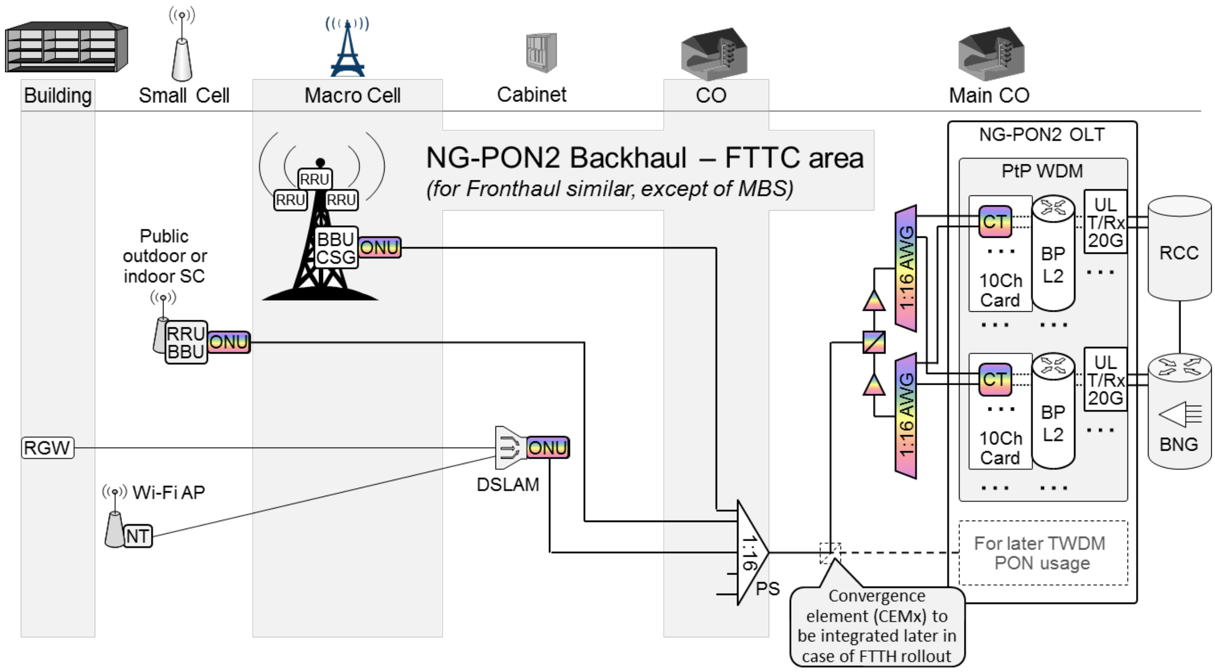

Figure 101: NG-PON2 backhaul architecture in FTTC areas

A.5 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 Section 5.1. These results were used for the comparison between the 2020 reference architecture and the converged architecture options in Chapter 6, and Chapter 7 for the cost analysis.

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.

Table 22 and Table 23 contain the dimensioning results for the 2020 reference network with mobile backhaul and fronthaul respectively, described in Chapter 5.

Table 24 and Table 25 show the dimensioning results for NG-PON2 with mobile backhaul and fronthaul respectively, described in Section 6.1.

Table 26, Table 27, Table 28 and Table 29 contain the dimensioning results for WS- and WR-WDM-PON with mobile backhaul and fronthaul respectively, described in Section 6.4.

Table 30, Table 31 and Table 32 detail the dimensioning results for the alternative starting scenarios described in Section 6.6.

Table 22: Dimensioning result for the 2020 reference network with mobile backhaul

2020 reference architecture Backhaul numbers	**Ultra-Dense Urban (2 km^2)**	**Urban (15 km^2)**	**Sub-Urban (142 km^2)**	**Rural** (no small cells) **(615 km^2)**

System elements per service area	**OLT shelves**		**0**	**0**	**0**	**0**
	Main CO BiDi CWDM TRx	3 Gb/s coloured	188	538	699	356
	Remote BiDi CWDM TRx	3 Gb/s coloured	188	538	699	356
	Remote grey TRx	3 Gb/s	0	0	0	0
	Amplifiers		**0**	**0**	**0**	**0**
	CWDM mux/demux 1:16		**26**	**68**	**88**	**46**
	System specifics		Coloured TRx add high complexity to the operation			
Fibres per service area	Counts	BS ↔ Cab	88 (13 km)	253 (114 km)	319 (239 km)	31 (33 km)
		Cab ↔ CO	188 (66 km)	538 (565 km)	699 (1223 km)	356 (872 km)
		CO ↔ MCO	-	34 (65 km)	44 (260 km)	23 (359 km)
	Total length	**BS ↔ MCO**	**79 km**	**743 km**	**1722 km**	**1264 km**

* 30% FTTH with no converged usage of existing TWDM PON fibres; in rural 0% FTTH

Table 23: Dimensioning result for the 2020 reference network with mobile fronthaul

2020 reference architecture Fronthaul numbers			**Ultra-Dense Urban (2 km²)**	**Urban (15 km²)**	**Sub-Urban (142 km²)**	**Rural** (no small cells) **(615 km²)**
System elements per service area	**OLT shelves**		**0**	**0**	**0**	**0**
	Main CO BiDi CWDM TRx	3 Gb/s coloured	196	561	728	387
		10 Gb/s coloured	24	69	87	93
	Remote BiDi CWDM TRx	3 Gb/s coloured	196	561	728	387
		10 Gb/s coloured	24	69	87	93
	Remote grey TRx at MBS (Multiport NT↔RRU)	3 Gb/s pair grey	2 x 16	2 x 46	2 x 58	2 x 62
		10 Gb/s pair grey	2 x 24	2 x 69	2 x 87	2 x 93
	Amplifiers		**0**	**0**	**0**	**0**
	CWDM mux/demux 1:8/1:16		**40**	**112**	**144**	**104**
	System specifics		Coloured transceivers add high complexity to the operation			
Fibres per service area	Counts	BS ↔ Cab	88 (13 km)	253 (114 km)	319 (239 km)	31 (33 km)
		Cab ↔ CO	188 (66 km)	538 (565 km)	699 (1223 km)	356 (872 km)
		CO ↔ MCO	-	56	72	52

				(106 km)	(425 km)	(811 km)
	Total length	**BS ↔ MCO**	**79 km**	**785 km**	**1887 km**	**1716 km**

* 30% FTTH with no converged usage of existing TWDM PON fibres; in rural 0% FTTH

Table 24: Dimensioning result for NG-PON2 with mobile backhaul

NG-PON2 Backhaul numbers			**Ultra-Dense ($2\ km^2$)**	**Urban ($15\ km^2$)**	**Sub-Urban ($142\ km^2$)**	**Rural** (no small cells) **($615\ km^2$)**
System elements per service area	**OLT shelves**		**1**	**3**	**4**	**2**
	OLT TRx	3 Gb/s tuneable	188	538	699	356
	Pluggable ONU TRx	3 Gb/s tuneable	180	515	670	325
	MBS ONU TRx	3 Gb/s tuneable	8	23	29	31
		3 Gb/s pair grey (incl. CSG TRx)	2 x 8	2 x 23	2 x 29	2 x 31
	Amplifiers (bi-directional)		**0**	**1**	**7**	**2**
	AWG / CEMx		**53**	**148**	**184**	**45**
	New PS (FTTC area)		**9**	**24**	**31**	**23**
	System specifics		colourless optics; additional tuneable DWDM TRx ONU filter (narrow band 22nm); FEC			
Fibres per service area	Counts	BS ↔ Cab	88 (13 km)	253 (114 km)	319 (239 km)	31 (33 km)
		Cab ↔ CO	134 (47 km)	384 (403 km)	498 (872 km)	356 (872 km)
		CO ↔ MCO	-	24 (46 km)	31 (183 km)	23 (359 km)
	Total length	**BS ↔ MCO**	**60 km**	**562 km**	**1294 km**	**1264 km**

* MBS via dedicated fibre Cab ↔ CO; 30% FTTH with converged fibre usage; in rural 0% FTTH

Table 25: Dimensioning result for NG-PON2 with mobile fronthaul

NG-PON2 Fronthaul numbers			**Ultra-Dense ($2\ km^2$)**	**Urban ($15\ km^2$)**	**Sub-Urban ($142\ km^2$)**	**Rural** (no small cells) **($615\ km^2$)**
System elements per service area	**OLT shelves**		**2**	**6**	**8**	**4**
	OLT TRx (incl. BBUH grey TRx)	3 Gb/s tuneable	196	561	728	387
		10 Gb/s tuneable	24	69	87	93
		3 Gb/s pair grey	2 x 88	2 x 276	2 x 348	2 x 62
		10 Gb/s pair grey	2 x 24	2 x 69	2 x 87	2 x 93
	Pluggable ONU TRx	3 Gb/s tuneable	180	515	670	325
	Multiport	3 Gb/s tuneable	16	46	58	62

	ONU TRx at MBS (incl. RRU grey TRx)	10 Gb/s tuneable	24	69	87	93
		3 Gb/s pair grey	2 x 16	2 x 46	2 x 58	2 x 62
		10 Gb/s pair grey	2 x 24	2 x 69	2 x 87	2 x 93
	Amplifiers (bi-directional)		**1**	**20**	**30**	**4**
	AWG / BF / CEMx		**64**	**183**	**229**	**105**
	New PS (FTTC area)		**8**	**23**	**30**	**21**
	System specifics		colourless optics; additional tuneable DWDM TRx ONU filter (narrow band 22nm)			
Fibres per service area	Counts	BS ↔ Cab	88 (13 km)	253 (114 km)	319 (239 km)	31 (33 km)
		Cab ↔ CO	134 (47 km)	384 (403 km)	498 (872 km)	356 (872 km)
		CO ↔ MCO	-	29 (55 km)	38 (224 km)	32 (499 km)
	Total length	**BS ↔ MCO**	**60 km**	**572 km**	**1335 km**	**1404 km**

* MBS via dedicated fibre Cab ↔ CO; 30% FTTH with converged fibre usage; in rural 0% FTTH

Table 26: Dimensioning result for WR-WDM-PON with mobile backhaul

WR-WDM-PON Backhaul numbers			**Ultra-Dense ($2\ km^2$)**	**Urban ($15\ km^2$)**	**Sub-Urban ($142\ km^2$)**	**Rural** (no small cells) **($615\ km^2$)**
System elements per service area	**OLT Shelves**		**1**	**3**	**4**	**2**
	OLT TRx	3 Gb/s tuneable	188	538	699	356
	Pluggable ONU TRx	3 Gb/s tuneable	180	515	670	325
	MBS ONU TRx	3 Gb/s tuneable	8	23	29	31
		3 Gb/s pair grey (incl. CSG TRx)	2 x 8	2 x 23	2 x 29	2 x 31
	Amplifiers (bi-directional)		**0**	**0**	**1**	**2**
	AWGs and Band Filters		**33**	**89**	**89**	**60**
	System specifics		Of the 89 filters, 14 are full-band AWGs in OLTs			
Fibres per service area	Counts	BS ↔ Cab	88 (13 km)	253 (114 km)	319 (239 km)	31 (33 km)
		Cab ↔ CO	188 (66 km)	538 (565 km)	699 (1223 km)	356 (872 km)
		CO ↔ MCO	-	7 (13 km)	9 (53 km)	5 (78 km)
	Total length	**BS ↔ MCO**	**79 km**	**692 km**	**1516 km**	**983 km**

Table 27: Dimensioning result for WS-WDM-PON with mobile backhaul

WS-WDM-PON Backhaul numbers	**Ultra-Dense**	**Urban**	**Sub-Urban**	**Rural** (no

			(2 km^2)	**(15 km^2)**	**(142 km^2)**	small cells) **(615 km^2)**
System elements per service area	**OLT Shelves**		**2**	**4**	**5**	**2**
	OLT TRx	3 Gb/s tuneable	188	538	699	356
	Pluggable ONU TRx	3 Gb/s tuneable	180	515	670	325
	MBS ONU TRx	3 Gb/s tuneable	8	23	29	31
		3 Gb/s pair grey (incl. CSG TRx)	2 x 8	2 x 23	2 x 29	2 x 31
	Amplifiers (bi-directional)		**3**	**9**	**11 (12)**	**6**
	AWGs (MCO only)		**6**	**18**	**22**	**12**
	Power Splitters		**35**	**100**	**128**	**82**
	System specifics		Of the 89 filters, 14 are full-band AWGs in OLTs			
Fibres per service area	Counts	BS ↔ Cab	88 (13 km)	253 (114 km)	319 (239 km)	31 (33 km)
		Cab ↔ CO	188 (66 km)	538 (565 km)	699 (1223 km)	356 (872 km)
		CO ↔ MCO	-	9 (17 km)	11 (65 km)	6 (94 km)
	Total length	**BS ↔ MCO**	**79 km**	**696 km**	**1527 km**	**998 km**

Table 28: Dimensioning result for WR-WDM-PON with mobile fronthaul

WR-WDM-PON Fronthaul numbers			**Ultra-Dense (2 km^2)**	**Urban (15 km^2)**	**Sub-Urban (142 km^2)**	**Rural** (no small cells) **(615 km^2)**
System elements per service area	**OLT shelves**		**2**	**5**	**7**	**4**
	OLT TRx (incl. BBUH grey TRx)	3 Gb/s tuneable	196	561	728	387
		10 Gb/s tuneable	24	69	87	93
		3 Gb/s pair grey	2 x 96	2 x 276	2 x 348	2 x 62
		10 Gb/s pair grey	2 x 24	2 x 69	2 x 87	2 x 93
	Pluggable ONU TRX	3G tuneable	180	515	670	325
	Multiport ONU TRx at MBS (incl. RRU grey TRx)	3 Gb/s tuneable	16	46	58	62
		10 Gb/s tuneable	24	69	87	93
		3 Gb/s pair grey	2 x 16	2 x 46	2 x 58	2 x 62
		10 Gb/s pair grey	2 x 24	2 x 69	2 x 87	2 x 93
	Amplifiers (bi-directional)		**0**	**0**	**1**	**3**
	AWGs and Band Filters		**43**	**115**	**149**	**96**
	System specifics		Out of the filters, 18 are full-band AWGs in OLTs			
Fibres per service	Counts	BS ↔ Cab	88 (13 km)	253 (114 km)	319 (239 km)	31 (33 km)
		Cab ↔ CO	188	538	699	356

area			(66 km)	(565 km)	(1223 km)	(872 km)
		CO ↔ MCO	-	9 (17 km)	12 (71 km)	8 (125 km)
	Total length	**BS ↔ MCO**	**79 km**	**696 km**	**1533 km**	**1030 km**

Table 29: Dimensioning result for WS-WDM-PON with mobile fronthaul

WS-WDM-PON Fronthaul numbers			**Ultra-Dense (2 km^2)**	**Urban (15 km^2)**	**Sub-Urban (142 km^2)**	**Rural** (no small cells) **(615 km^2)**
System elements per service area	**OLT shelves**		**2**	**6**	**7**	**4**
	OLT TRx (incl. BBUH grey TRx)	3 Gb/s tuneable	196	561	728	387
		10 Gb/s tuneable	24	69	87	93
		3 Gb/s pair grey	2 x 96	2 x 276	2 x 348	2 x 62
		10 Gb/s pair grey	2 x 24	2 x 69	2 x 87	2 x 93
	Pluggable ONU TRX	3G tuneable	180	515	670	325
	Multiport ONU TRx at MBS (incl. RRU grey TRx)	3 Gb/s tuneable	16	46	58	62
		10 Gb/s tuneable	24	69	87	93
		3 Gb/s pair grey	2 x 16	2 x 46	2 x 58	2 x 62
		10 Gb/s pair grey	2 x 24	2 x 69	2 x 87	2 x 93
	Amplifiers (bi-directional)		**4**	**11 (12)**	**15 (16)**	**9**
	AWGs (MCO only)		**8**	**22**	**30**	**18**
	Power Splitters		**35**	**99**	**128**	**81**
	System specifics					
Fibres per service area	Counts	BS ↔ Cab	88 (13 km)	253 (114 km)	319 (239 km)	31 (33 km)
		Cab ↔ CO	188 (66 km)	538 (565 km)	699 (1223 km)	356 (872 km)
		CO ↔ MCO	-	11 (21 km)	15 (89 km)	9 (140 km)
	Total length	**BS ↔ MCO**	**79 km**	**700 km**	**1551 km**	**1045 km**

Table 30: Dimensioning results for a GPON starting scenario for different RAN deployments (urban geotype)

GPON with WR-WDM-PON starting scenario (urban)			**Fronthaul**	**Backhaul (via WDM-PtP)**	**Backhaul (via G-PON)**
System elements per service area	**OLT shelves**		**5.0**	**2.7**	**1.6**
	OLT T-TRX	3 Gb/s	561	538	308
		10 Gb/s	75	6	6
	OLT↔BBUH TRX pair grey	3 Gb/s	2 x 276	0	0
		10 Gb/s	2 x 69	0	0
	Pluggable ONU	3 Gb/s	515	515	285

	tuneable TRX	10 Gb/s	6	6	6
	Single-port ONU T-TRX + grey TRX pair	3 Gb/s	0	3 x 23	3 x 23
		10 Gb/s	0	0	0
	Multiport ONU T-TRX + grey TRX pair	3 Gb/s	3 x 46	0	0
		10 Gb/s	3 x 69	0	0
	Amplifiers (bi-directional)		**9**	**7**	**4**
	AWGs and Band Filters		**87**	**61**	**12**
Fibre per service area	FTTC/H area (70% DSL, 30% G-PON) GPON fibre excluded	SC ↔ Cab	G-PON	G-PON	G-PON
		Cab ↔ CO	285	285	285
		Macro ↔ CO	23	23	23
		CO ↔ MCO	9	7	4

Table 31: Dimensioning results for a starting scenario with active remote nodes in the cabinet for different RAN deployments (urban geotype)

FTTC with WR-WDM-PON starting scenario (urban)			**Fronthaul**	**Backhaul**
System elements per service area	**OLT shelves**		**6.3**	**3.0**
	OLT T-TRX	3 Gb/s	846	593
		10 Gb/s	69	0
	OLT↔BBUH TRX pair grey	3 Gb/s	2 x 276	0
		10 Gb/s	2 x 69	0
	Pluggable ONU tuneable TRX	3 Gb/s	800	570
		10 Gb/s	0	0
	Single-port ONU T-TRX + grey TRX pair	3 Gb/s	0	3 x 23
		10 Gb/s	0	0
	Multiport ONU T-TRX + grey TRX pair	3 Gb/s	3 x 46	0
		10 Gb/s	3 x 69	0
	Amplifiers (bi-directional)		**0**	**0**
	AWGs and Band Filters		**162**	**24**
Fibre per service area	FTTC/H area (70% DSL, 30% PtP fibre) PtP fibre excluded	SC ↔ Cab	PtP fibre	PtP fibre
		Cab ↔ CO	570	570
		Macro ↔ CO	23	23
		CO ↔ MCO	13	8

Table 32: Dimensioning results for a GPON plus dedicated small cell transport starting scenario for different RAN deployments (urban geotype)

GPON/DSL with dedicated SC transport starting scenario (urban)			**Fronthaul**	**Backhaul**
System elements per	**OLT shelves**		**2.8**	**1.6**
	OLT T-TRX	3 Gb/s	331	285
		10 Gb/s	98	29

service area	OLT↔BBUH TRX pair grey	3 Gb/s	2 x 46	0
		10 Gb/s	2 x 69	0
	Pluggable ONU tuneable TRX	3 Gb/s	285	285
		10 Gb/s	6	6
	Single-port ONU T-TRX + grey TRX pair	3 Gb/s	0	3 x 23
		10 Gb/s	0	0
	Multiport ONU T-TRX + grey TRX pair	3 Gb/s	3 x 46	0
		10 Gb/s	3 x 92	0
	Amplifiers (bi-directional)		**0**	**0**
	AWGs and Band Filters		**78**	**12**
Fibre per service area	FTTC/H area (70% DSL, 30% G-PON) GPON fibre excluded	Cab ↔ CO	285	285
		Macro ↔ CO	23	23
		CO ↔ MCO	6	4

A.6 The Relation between the DISCUS Architecture and COMBO

Besides intensified links to other active or terminated projects, such as FP7 OASE and FP7 METIS, COMBO investigated the proposal of the FP7 DISCUS project. COMBO initiated discussions with the DISCUS project in order to develop a deeper understanding of their vision, and decide whether the DISCUS network architecture provides an attractive solution to COMBO requirements. The following paragraphs summarize our view.

In the **COMBO FMC vision**, we are targeting structural convergence, i.e., a converged network infrastructure that supports fixed residential mass-market network, Wi-Fi backhaul, and mobile backhaul and fronthaul network services.

Fulfilling the requirements of 4G while keeping in mind the requirements from future 5G, the mobile backhaul / fronthaul network is expected to support sophisticated CoMP features and/or fronthaul requirements. Among others, **latency** becomes a critical requirement with CoMP and fronthauling macro base stations and small cells.

These are fundamental design principles for the converged FMC network architecture in the vision of COMBO. In a simplified interpretation, a converged FMC architecture has to meet the technical requirements of CoMP and/or fronthaul; and the economic constraints of mass-market fixed access.

After a deeper investigation of the **DISCUS architecture**, and after two bilateral meetings with the DISCUS project consortium, we have found a significant difference in the requirements and motivations of the DISCUS and the COMBO FMC network architecture options: DISCUS is working on the components and system design of a high capacity (up to 1:1024 split), Long Reach (LR) (up to 100 km) TWDM PON access network, which supports aggressive node consolidation, and a flat aggregation network architecture.

From COMBO's perspective, the FMC network has different types of "clients":

- Fixed residential and business access: the DISCUS architecture is a promising solution for that application, both from technical and economic perspective;
- Backhauling mobile base stations and small cells: as long as CoMP scenarios with tight delay requirements are not considered, the DISCUS architecture is an appropriate solution;
- Backhaul with CoMP: the high RTT delay (ms range only for fibre propagation) over the 100 km access network span is not compatible with very tight radio coordination which is considered in COMBO requirements, as explained in Chapter 3;
- In addition, the bandwidth requirements of mobile fronthaul in the range of 1-10 Gb/s per client also exceeds the scope of a 10 Gb/s TDM or TWDM PON solution, even with the 40 Gb/s extensions.

Therefore, at least in areas where CoMP or fronthauling is expected, even in the longer future (with the advent of 5G), we do not see the DISCUS LR-PON concept a future-proof solution as an FMC architecture (even if it supports fixed access service). In sparsely populated, rural environments, where fronthaul and CoMP are not foreseen, the DISCUS architecture may be an attractive solution – however, not as a real FMC scenario.

In COMBO, the support of CoMP and fronthaul is a fundamental network design principle, making the FMC network investment future proof. Therefore, we came to the decision not to treat the DISCUS LR-PON solution as a potential FMC solution in COMBO.

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Distribution List

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PMC	Public deliverable (will be made available through COMBO website)	
SC		
Other		

Glossary

Acronym / Abbreviations	Brief description
3GPP	3rd Generation Partnership Project
AMCC	Auxiliary Management and Communications Channel
AP	Access Point
AWG	Arrayed Waveguide Grating
BS	Base Station
BBU	Baseband Unit
BBUH	BBU Hotel
BNG	Broadband Network Gateway
BRAS	Broadband Remote Access Server
CapEx	Capital Expenditure
CAWG	Cyclic AWG
CDM	Code Division Multiplexing
CEMx	Coexistence Element
CO	Central Office
CoMP	Coordinated Multi-Point
CPRI	Common Public Radio Interface
C-RAN	Centralised RAN
CSG	Cell Site Gateway
CT	Coloured Transceiver
CWDM	Coarse Wavelength Division Multiplexing
DFB	Distributed Feedback
DBR	Distributed Bragg Reflector
DDMI	Digital Diagnostics Monitoring Interface
D-RAN	Distributed RAN
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DWDM	Dense Wavelength Division Multiplexing
EPC	Evolved Packet Core
eICIC	enhanced Inter-Cell Interference Coordination
FEC	Forward Error Correction
FMC	Fixed-Mobile Convergence
FTTB	Fibre to the Building
FTTC	Fibre to the Cabinet
FTTdp	Fibre to the distribution point
FTTEx	Fibre to the Exchange
FTTH	Fibre to the Home
FSAN	Full Service Access Network
FWT	Fixed Wireless Terminal
GPON	Gigabit Passive Optical Network
HARQ	Hybrid Automatic Retransmit reQuest
HFC	Hybrid Fibre Coaxial
ICN	Information Centric Networking
IoT	Internet of Things
IPoE	Internet Protocol over Ethernet

Acronym / Abbreviations	Brief description
ITU-T	The ITU Telecommunication Standardization Sector
KPI	Key Performance Indicator
L2VPN	Layer 2 Virtual Private Network
L3VPN	Layer 3 Virtual Private Network
LAA	License Assisted Access
LTE	Long Term Evolution
LTE-A	LTE-Advanced
MASG	Mobile Aggregation Site Gateway
MBS	Macro Base Station
MEF	Metro Ethernet Forum
MIMO	Multiple Input, Multiple Output
MPLS	Multiprotocol Label Switching
NFV	Network Function Virtualisation
NGMN	Next Generation Mobile Networks
NG-PON2	Next Generation Passive Optical Network version 2
OADM	Optical Add/Drop Multiplexer
OAM	Operations, Administration and Management
OBSAI	Open Base Station Architecture Initiative
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Termination
OMCI	ONT Management and Control interface
ONT	Optical Network Termination
ONU	Optical Network Unit
OpEx	Operational Expenditure
OTDR	Optical Time-Domain Reflectometry
OTN	Optical Transport Network
PON	Passive Optical Network
PtP	Point-to-Point
PTP	Precision Time Protocol
QoS	Quality of Service
RAN	Radio Access Network
RBS	Radio Base Station
RCC	Radio Coordination Controller
RE	Reach Extender
RN	Remote Node
ROADM	Reconfigurable OADM
RRU	Remote Radio Unit
RTT	Round Trip Time
SDN	Software Defined Network
SFSW	Single Fibre Single Wavelength
SMSR	Side-Mode Suppression Ration
TDM	Time-Division Multiplexing
TWDM	Time and Wavelength Division Multiplexed
UC	Use Case
UMTS	Universal Mobile Telecommunications Service
VDSL	Very high bit rate Digital Subscriber Line
WDM	Wavelength Division Multiplexing

Acronym / Abbreviations	Brief description
WP	Work Package
WR	Wavelength-Routed
WS	Wavelength-Selective

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