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# Enabling Technologies and Innovations for 5G-Oriented Optical Access Networks

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## ABSTRACT

In this invited paper, we discuss how optical fibers, the de-facto choice for last-mile connectivity of radio access network equipment, can rise to the challenges of 5G. We start by addressing technologies and trends for point-to-point connectivity, from fully passive to auto-tunable wavelength division multiplexing. Then, we assess niche solutions based on point-to-multipoint optical connectivity and possible scenarios allowing fixed-mobile convergent topologies. Finally, we briefly exploit the potential of abstraction of optical and radio access equipment through software defined networking for intelligent and multi-tenancy ready traffic management compliant with the constraints of mobile interfaces and hosting locations of cloud infrastructures.

**Keywords:** xhaul, backhaul, fronthaul, WDM, PON, SDN

## 1. INTRODUCTION

Since the start of the wireless technological revolution in the 1980's, we have been witnessing the breathtaking progress of services proposed by mobile operators and vendors. With a new generation about every 10 years, paradigms are broken and new ones are introduced. Most recently, the 4G marked a tremendous shift of philosophy in mobile communications as a whole, allowing an overwhelming domination of data-centric communications. The fifth mobile generation (5G) reinforces that trend. It pushes channel capacity beyond current limits and, most importantly, allows for unprecedented usages of the mobile network.

From sensor monitoring and robotic aided surgery to vehicle to everything (V2X) connectivity, just to mention a few use-cases, the main challenge of 5G resides in its wide set of requirements. These concern bandwidth, latency, jitter, availability, reliability, positioning precision and number of connected devices in conventional enhanced mobile broadband (eMBB) but also in new ultra-reliable low-latency communications (URLLC) and massive machine-type communications (mMTC). The diversified 5G requirements are only achievable with the introduction of new technologies and while those related to the 5G core network and air interface have been extensively discussed, the new paradigms affecting mobile equipment connectivity based on optical fiber systems are less known by the scientific community.

As commercial 5G deployments take place all over the world [1] and with the full 5G potential yet to be achieved, it is therefore crucial to raise awareness about the importance of optical fibers to ensure the needed transport channel capacities. It is also essential to understand the rationale behind the engineering, operation and management related to mobile equipment connectivity. Those, as we will discuss here, are affected by multiple opposing factors and can be very challenging to address. Finally, it is also important that future optical systems can adapt and comply with the many and heterogeneous end-to-end key performance indicators (KPI) of the different services in 5G.

These subjects are discussed in the remainder of this work, focusing on the optical access network that provides connectivity to the cell site equipment. Section 2 revolves essentially around 3GPP's technical specifications (TS) 22.261 [2] and 22.104 [3] and will provide the neophyte readers a first view of some of the main requirements and

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needed capabilities of 5G. In section 3, we concentrate on the new 5G radio access network (RAN) interfaces and section 4 discusses different options for fiber-based mobile site connectivity. In section 5, we discuss how the introduction of virtualization practices in the optical connectivity equipment could be beneficial to ensure the different needs of 5G services and finally, in section 6, we conclude our work.

## 2. 5G PERFORMANCE REQUIREMENTS AND CAPABILITIES

### 2.1 Performance Requirements

The first 5G requirements shown in Table 1 refer to the urban and rural wide-areas, for which experienced bit-rates of 50 and 25 Mbit/s/user are targeted in the downlink and uplink respectively. The total traffic per squared kilometer ranges from some few Gbit/s to several tens of Gbit/s depending on the density of active users. Offices, homes and residential deployments are represented by the indoor hotspot scenario, with bit-rates of up to 1 Gbit/s/user and a total traffic density that could reach up to 15 Tb/s/km<sup>2</sup> in the downlink. The crowd broadband scenario addresses massive gatherings such as in stadiums or concerts, where the high density of users sharing live content would put a higher constraint in the uplink bit-rates than in the downlink. Finally, the dense urban case targets city centers, offices, shopping malls and residential areas in densely populated zones.

Table 2 depicts some new verticals with very tight latency and reliability constraints. The end-to-end latencies depend on the delays of different network segments including the air interface, the processing within the RAN and core network protocol layers and, of course, within the optical transmission systems. Fiber propagation is not to be overlooked, especially in cases where high-accuracy positioning is necessary [5]. Despite their low bit-rates, the extremely low latency requirements of some services could impose a local approach to network planification. Edge networking could thus be envisaged with the added benefit of keeping sensitive data outside the public-domain. Table 2 also shows that interactions between physical and computational components in cyber-physical systems may require extremely high service availability. As a consequence, the mean time between failures cannot be neglected when searching for a suitable optical connectivity solution. In [6], we provide an in-depth assessment on this subject and show how optical systems could meet such tight latency and reliability constraints.

Finally, [2] also describes scenarios in which both extremely low latencies and high bit-rates are necessary. Audio-visual interaction use-cases such as augmented and virtual reality (AR/VR) are good examples where high video resolutions and appropriated motion-to-photon and motion-to-sound delays are essential for a good perception of the environment and proper interaction between users. For instance, VR content diffusion via a tethered headset would require end-to-end latencies between 5 and 10 ms and bit-rates from 100 Mbit/s to whooping 10 Gbit/s. These strict requirements would be needed to allow displacing complex computational procedures higher in the network, simplifying thus end-user devices.

Other scenarios such as satellite access and user equipment (UE) to network relaying are also detailed in [2] but are outside the scope of this work. The reader is referred to [7] and [8] for V2X and high-speed transportation use-cases. In [9], an assessment is provided on the use of a PtMP virtual RAN in a high-speed train scenario.

Table 1. Performance requirements for high data rate and high traffic density scenarios.

Scenario	Experienced bit-rate per user, downlink (uplink)	Area traffic capacity downlink (uplink)	Overall user density	Active user density
Urban	50 (25) Mbit/s	100 (50) Gbit/s/km <sup>2</sup>	10000/km <sup>2</sup>	2000/km <sup>2</sup>
Rural	50 (25) Mbit/s	1 (0.5) Gbit/s/km <sup>2</sup>	100/km <sup>2</sup>	20/km <sup>2</sup>
Indoor hotspot	1 (0.5) Gbit/s	15 (2) Tbit/s/km <sup>2</sup>	250000/km <sup>2</sup>	[4]
Crowd broadband	25 (50) Mbit/s	3,75 (7,5) Tbit/s/km <sup>2</sup>	500000/km <sup>2</sup>	150000/km <sup>2</sup>
Dense urban	300 (50) Mbit/s	750 (125) Gbit/s/km <sup>2</sup>	25000/km <sup>2</sup>	2500/km <sup>2</sup>

Table 2. Some verticals with low latency and high reliability requirements.

Vertical	Target availability (%)	Mean time between failures	End-to-end latency	Experienced bit-rate
Sensors for process and asset monitoring	99.99	$\geq 1$ week	$< 100$ ms	$\leq 2$ Mbit/s
Cooperative carrying of a large piece by robots	99.9999 to 99.999999	10 years	$< 2.5$ ms	2.5 Mbit/s
Robotic aided surgery with haptic feedback	$> 99.999999$	$> 10$ years	$< 2$ ms	2-16 Mbit/s
Robotic aided diagnosis with haptic feedback	$> 99.999$	$\gg 1$ month, $< 1$ year	$< 20$ ms	2-16 Mbit/s
Country-wide medical monitoring	$> 99.9999$	$\gg 1$ month, $< 1$ year	$< 100$ ms	$< 1$ Mbit/s

## 2.2 Capabilities

As one could expect, the numerous and heterogeneous requirements in 5G can hardly be met concurrently and the one-size-fits-all model of previous generations becomes increasingly obsolete. New capabilities are thus essential in answer to those needs. Here, we concentrate on the ones that could have an impact on future optical systems beyond classical network dimensioning issues, namely: slicing, closer to end-user cloud infrastructures and Ethernet based transport.

- Network slicing allows operators to provide compartmentalized and customized services. The slices may concern different needs in terms of functionality (priority, charging, policy control, security, mobility, ...), performance (latency, mobility, availability, reliability, bit-rates, ...) or even different tenants in the network. As an example, slicing could be required when a network access equipment supports different flavors of mobile traffic (fronthaul, backhaul, *cf.* section 3) and also different fixed services for home, enterprise passive optical LAN and etc. Slicing is enabled by automated and dynamic network operation, which has been increasingly easier thanks to functionalities such as vendor-agnostic equipment configuration and network abstraction brought by software defined networking (SDN). Naturally, the optical equipment must not block nor degrade the different 5G slices. Dynamic and intelligent adaptation of the optical transmission parameters and paths using SDN can enable an easier dialogue between mobile and optical network entities and, ideally, reduce capital expenditures coming from overprovisioned optical systems.
- In-network caching and service hosting closer to the end-users might be the only possible solutions for extreme URLLC use-cases in 5G. At the same time, some RAN and core protocol layer functionalities are now easily implementable by software. Cloud solutions enabled by continuous integration and continuous delivery (CI/CD) practices will thus play a major role in 5G allowing more frequent and reliable delivery of code for network function virtualization (NFV) and content hosting. Deployment of new computing infrastructures at different network segment levels (cloud, fog, edge) is to be expected and taking the optical network demarcation points as a reference seems nothing but natural.
- Ethernet has evolved from a local area network (LAN), collision-prone protocol to a carrier-class solution compatible with access and metro network quality standards. This was possible thanks to a series of technical specifications allowing different features such as VLAN tagging (IEEE 802.1Q), QinQ (IEEE 802.1ad), provider backbone bridges (IEEE 802.1ah) and connectivity fault management (IEEE 802.1ag). Today, Ethernet interfaces span across different systems and 5G takes advantage of such ubiquity. Different enhancements are already available to allow compatibility of Ethernet with the most challenging requirements in 5G. Deterministic latencies needed in time-critical 5G services can be ensured by time-sensitive network (TSN) policies

such as traffic shaping and frame preemption [10]. Moreover, Ethernet compatible cell-site frequency synchronization can be obtained through ITU-T’s synchronous Ethernet (syncE, G.8262, G.8262 and G.8264) and complemented with phase and time alignment provided by IEEE’s 1588v2 Precision Time Protocol (PtPv2).

### 3. 5G FUNCTIONAL SPLITS AND INTERFACES IN A NUTSHELL

The changes of strategy concerning mobile network deployment have been flagrant throughout the years, as depicted in Figure 1. Whereas 2G and 3G provided more centralized approaches with a segmented RAN, the first 4G systems went against this trend, pushing intelligence to the edges of the network. By concentrating the RAN stack into one single equipment (the eNB), this distributed RAN (D-RAN) topology constituted a simple and cost-effective way to put capacity exactly where it was needed. Later, a split of the eNB was proposed with an intelligent baseband unit (BBU) hosting most of the RAN protocol stack on one side and a remote radio head (RRH) hosting only lower physical layer (PHY) functionalities on the other. BBU and RRH were connected by a fronthaul interface, as opposed to the backhaul linking the RAN to the mobile core network.

Most 4G fronthaul deployments used the Common Public Radio Interface (CPRI) [11], a vendor-specific solution based on the quantization of the time-domain baseband samples of the mobile signals [12]. Interestingly, back then, the availability of low-cost, off-the-shelf optical transceivers used in metropolitan networks enabled once again the quest for centralized RAN (C-RAN) deployments, promoted by features such as reduced cell-site equipment footprint, improved performance at cell edges and easier to implement equipment security measures [13].

However, the enthusiasm aroused then by this full network centralization with BBU stacking/pooling capabilities did not last long [14]. CPRI is a spectrally inefficient solution needing fixed bit-rates independently of the actual cell-site traffic. Also, the required transport bit-rates scales with the signal bandwidth, number of mobile component carriers, sectors, radio access technologies (RAT) and antenna ports. Demonstrating the humongous optical access capacities that would be needed to comply with the 5G new radio (NR) is a straightforward exercise. Moreover, being associated to a functional split within the RAN PHY, it has very tight latency requirements which are directly related to the transmission time intervals (TTI) within the mobile stack. Last but not least, CPRI fronthaul does not provide features such as flexible manageability, support for quality of service (QoS) nor does it allow for statistical multiplexing. As such, it should be seen more as a network extension or "patch-cord" of sorts rather than an actual network interface.

In search for some sort of conciliation between centralized and distributed RAN deployment strategies, new functional splits have been proposed in 5G . Apart from the backhaul, high and low layer functional splits (HLS and LLS respectively) have been defined with the latter still referred to as fronthaul and the former commonly called midhaul\*. Those allow for a separation of the RAN equipment into a central unit (CU), with layer 3 and higher layer 2 functionalities, a distributed unit (DU) with lower layer 2 and higher layer 1 and finally a radio unit (RU), with lower layer 1, as depicted in Figure 2 (left). While the 3GPP has standardized the HLS interface between the CU and DU [15], evolved CPRI (eCPRI) [16] and O-RAN’s open and interoperable interface [17]

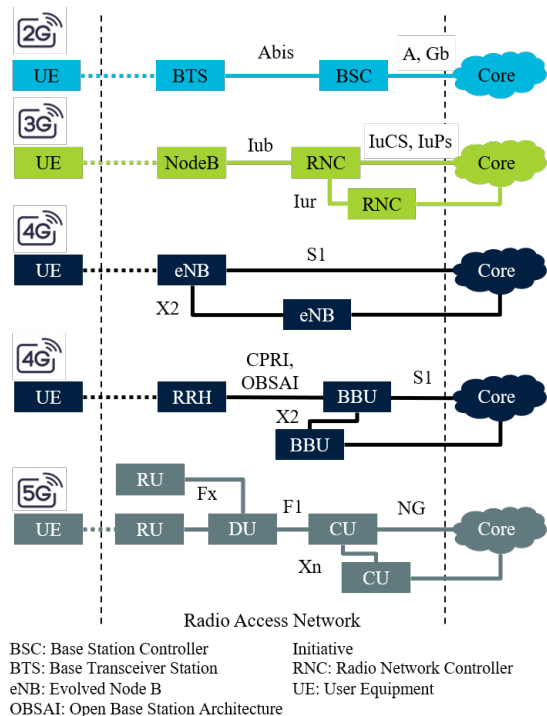


Figure 1. Evolution of mobile interfaces and topological approaches.

\*The "midhaul" term here is not to be confused with the X2 interface connecting eNBs.

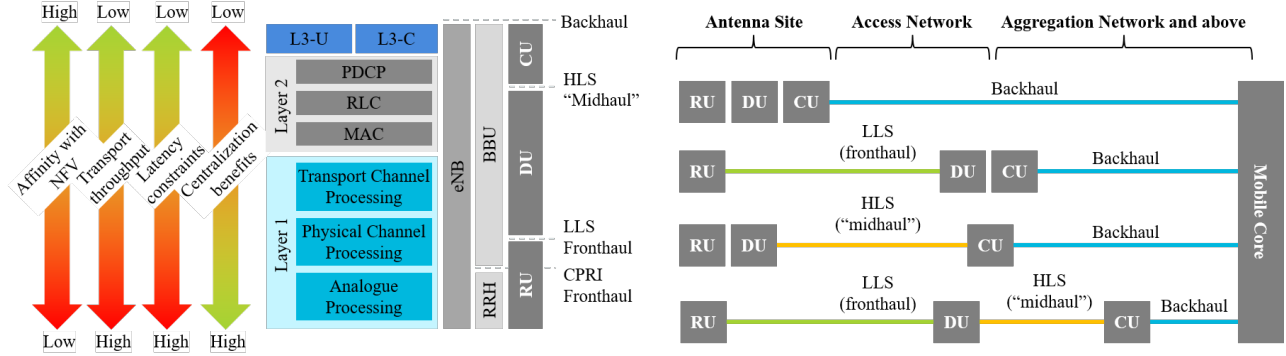


Figure 2. (Left) 5G functional splits separation and how they compare with 4G RAN blocks. (Right) Possible locations of 5G RAN equipment in the network.

stand as potential candidates for the new fronthaul links between the DU and the RU. The reader is referred to [18] for a detailed survey of the functional splits proposed for 5G and to [19] for a summary of their features.

The reader should note that the functional splits in 5G go way beyond a simple mechanism to allow different deployment strategies as shown in Figure 2 (right). Indeed, since all interfaces are based on Ethernet and can be complemented by TSN strategies and advanced synchronization approaches based on syncE and PtPv2, a fully-fledged networking experience can be provided at different RAN levels with features such as QoS, statistical multiplexing, traffic balancing, wholesale models for the optical links and so on. Moreover, since the RAN can now be divided into different functional blocks, software implementations in NFV can separately target protocol layers that have less adherence to dedicated hardware, such as those in the CU [20] <sup>†</sup>.

All in all, future optical systems used for mobile site connectivity might have to deal with different types of Ethernet interfaces (backhaul, midhaul and fronthaul) [21] and their respective constraints in terms of bit-rate and latency. The "sidehaul", i.e., the links between CUs should also be considered with caution, especially in view of the different stand-alone (SA) and non stand-alone (NSA) deployment scenarios targeted in 5G [22].

## 4. MOBILE SITE CONNECTIVITY

### 4.1 Point-to-point Solutions

Point-to-point (PtP) is the de-facto choice for connectivity of mobile equipment in the access network today. Optical links generally rely on dual fiber pluggable transceivers to ensure upstream and downstream transmission but single-fiber "bidir" modules have been increasingly used to facilitate installation and reduce the number of needed optical fibers. In most cases, however, no specific standard is followed for cell-site connectivity deployments. This means that no interoperability between the optical transceivers is ensured whatsoever, which complicates the engineering rules and possible migration paths in what concerns reach, optical power budgets, wavelengths and even pluggable form factor types used in the optical links. This is the reason why many operators are currently backing up ongoing standards by the IEEE and the ITU on 10, 25 and 50 Gb/s bidirectional PtP (ITU-T G.9806 and IEEE 802.2cp) and expectations are that both standardization organisms can align their PHY layer requirements [23]. Besides interoperability, the standardized interfaces would enable interesting features such as management and monitoring of the optical links.

As discussed in the previous section, the requirements of the optical access transport layer depends on the deployed RAN topology and thanks to the new 5G functional splits, the choices are varied. More centralized architectures have stringent requirements in terms of bandwidth and latency, which are associated to the fronthaul interface. More distributed architectures can benefit from the relaxed latency and bandwidth requirements of the midhaul or backhaul interfaces. We also saw that the extreme needs of some 5G use-cases will probably push the RAN and associated mobile cloud infrastructure even further to the edges of the network. Figure 3 (a)

<sup>†</sup>We refer to this implementation as a virtual CU (vCU) here.

shows an example of a centralized 5G topology in a fiber-rich zone, where multiple fibers are used to connect the DU to the RUs and a LLS interface is transmitted at both antenna site and access network segments. Figure 3 (b) depicts another example, this time with a more distributed and multi-RAT compatible deployment (4G and 5G). Notice that in this case, the LLS interface is limited to the cell-site whereas the optical access can transport midhaul, backhaul and sidehaul interfaces.

In zones where fiber is scarce, PtP systems can be enriched by some sort of wavelength division multiplexing (WDM) approach to increase capacity. Figure 3 shows three of them where LLS interfaces would justify the needs for higher throughput. Coarse WDM (CWDM), as depicted in Figure 3 (c), is a passive solution that has been used for fronthaul connectivity for some years now. It allows small footprints and full compatibility with temperature variation requirements. Subdivisions of the CWDM grid have already been proposed to increase spectral efficiency and MWDM solutions seem to be gaining some momentum in China. By taking the six lowest wavelength channels of the CWDM grid and separating each of them into two, MWDM takes advantage of lesser effects of chromatic dispersion in the O and lower E bands to increase the bit-rate per (sub) channel. LAN WDM (LWDM) is another technology based on a similar principle packing 12 channels between 1269 to 1332 nm. It provides an intermediary solution between CWDM and dense WDM (DWDM), with an 800 GHz wavelength grid. The main challenge of fixed wavelength WDM solutions, however, from an operational point of view, is the management of the different "colors" of the optical transceivers of the mobile site.

Semi-active solutions (Figure 3 (d)) allow overcoming this disadvantage, at least partially, thanks to a multiplexer. This equipment multiplexes data coming from different black and white transceivers and forwards them to a colored link all the way to the RU. Auto-tunable DWDM solutions, which were primarily intended for metro applications in ITU-T's G.698.4, are also an option. Using a lower-bit rate pilot tone, this solution allows for seamless integration and easy maintenance of colored optical transceivers [24]. Optical transport network (OTN) is another metro network solution that has been considered for optical site connectivity. OTN is compatible with a plethora of packet oriented protocols (ITU-T G.709) and integrates the optical wavelength transport over different topologies (ITU-T G.872) with advanced operation, administration and maintenance (OAM) features. The inherently somewhat strict tributary timing procedures and consequent inability to comply with statistical multiplexing have been limiting its dissemination in favor of Ethernet/IP based solutions though.

Finally, Figure 3 (e) shows a final example of WDM based transport, this time using a passive optical network (PON). This option would allow for some sort of watered down fixed-mobile convergence approach that would take advantage of the currently deployed fixed fiber-to-the-premises (FTTx) infrastructure and would benefit from interoperability and optical interface monitoring features obtained thanks to the ITU standards. Two possible PtP architectures could be envisaged in this case. In the first one, a dedicated PtP optical distribution network (ODN) would be deployed for the mobile site, allowing thus the sharing only of the optical line terminal (OLT) with fixed-access users. In the second approach, known as PON overlay, the PtP WDM PON link (ITU-T G.989.2, annexes A and C) would also share the ODN with the fixed users, allowing higher fixed-mobile convergence than in the first case. A first disadvantage of this second approach is that the PtP link would have to comply with the FTTx ODN optical budgets needed for point-to-multipoint (PtMP) connectivity. A second drawback comes from the degraded availability coming from a shared fiber infrastructure and which could have significant impacts on certain 5G services (*cf.* 4.2).

## 4.2 On the Suitability of Point-to-multipoint for RAN Connectivity

5G will be the first mobile generation in history to be deployed with a large park of optical fibers already available in the access network. It is only natural that operators, vendors and researchers address the question on the whether it would be possible to reuse deployed PtMP FTTx infrastructure for mobile connectivity. Even if significant advances have been made to allow reduced PON latencies by means of new fixed and dynamic bandwidth allocation algorithms (FBA, DBA), some practical deployment issues still deserve attention.

Gigabit-capable PON (G-PON) is the most deployed technology and 10 Gigabit Symmetrical (XGS-PON) is ramping up. The following PON generation, the High Speed PON (HS-PON), targets 50 Gbit/s but is still under discussion within the standardization bodies. As such, it is not yet mature. The first main challenge of a full fixed-mobile convergence concerns thus bit-rate and the misalignment in time between PON and 5G roadmaps. Considering the needed requirements of the LLS interfaces seen in section 3 and comparing them with the current

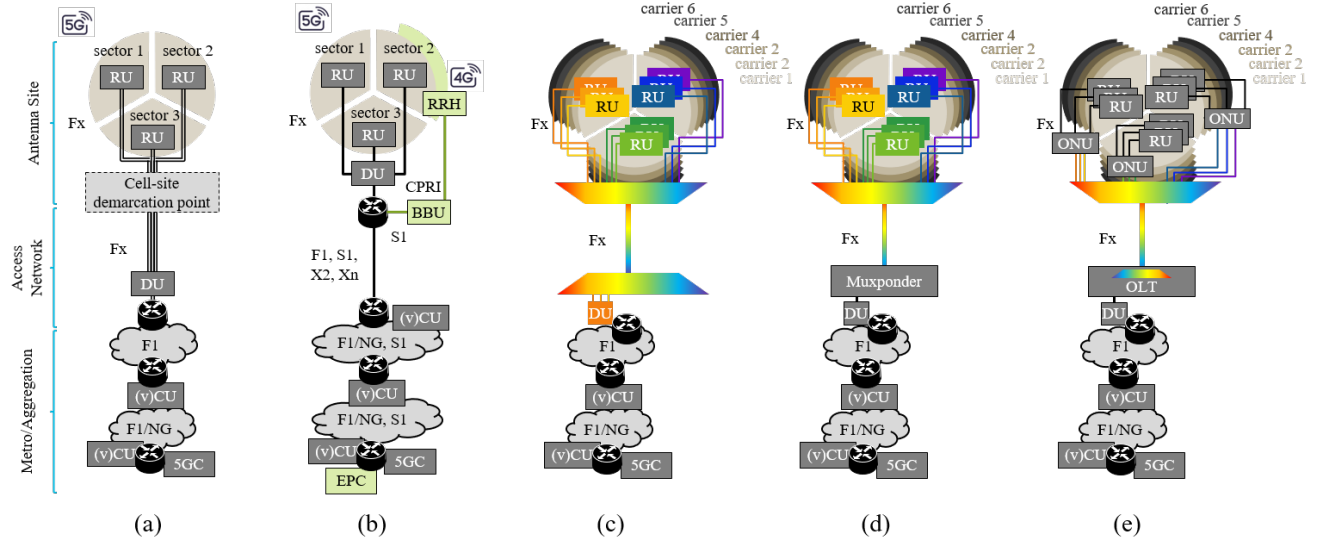


Figure 3. Different possible point-to-point connectivity options. (a) Multi-fiber C-RAN, (b) Multi-fiber, multi-RAT D-RAN, (c) C-RAN with Passive WDM, (d) C-RAN with semi-active solution, (e) C-RAN with active WDM PON (new ODN or PON overlaid).

capabilities of commercially available PtMP systems in terms of throughput and latency, we can consider that PON technologies would not be a good fit. A HLS with its relaxed throughput and latency requirements, would thus be the only compatible interface with PON today. A typical 10 Gbit/s HLS throughput needed by 5G macro cell sites in distributed RAN would thus require the use of XGS-PON. Nevertheless, the policies allowing fair traffic separation between mobile and FTTH users sharing one same PON ODN is yet another challenge that still needs to be addressed.

Another possibility would be to consider a dedicated PON to collect several HLS interfaces of different cell sites. In order to circumvent the bit-rate limitations of current PON, we could imagine that the optical infrastructure would serve a lower mobile traffic load, below the dense scenario requirements in Table 1<sup>‡</sup>, say from small cells. If we take now the dense scenario equivalent for a typical PON deployment shown in Table 3, our best hope in terms of infrastructure sharing would be to have only about 4 small-cells per fiber cabinet and yet, they would be very close to each other. Compared to a PtP architecture, the deployment cost reduction obtained using a shared PtMP infrastructure in this case would be hardly justified in view of the limitations imposed by the optical system to mobile bit-rate and latency. The third challenge of a full fixed-mobile convergence concerns thus the synergy between currently deployed FTTH and mobile-site topologies and nodes.

Finally, the last challenge of a full fixed-mobile convergence concerns the needed availability of certain 5G services, as discussed in section 2. Local regulators may impose a deployment model based on sharing of the PON infrastructure between several operators. This enables technological neutrality, increase competition and eventually allows reduction of the costs of the FTTH plans offered to the final users. In other words, operators that do not own infrastructure may simply rent it in some cases. As such, network nodes such as fiber cabinets may be shared and submitted to technical interventions of different operators without any prior consultation or agreement on the maintenance practices. Table 3 also shows some availability figures for the OLT but also for shared and private fiber cabinets. It is clear that 5G services with the most strict availability constraints are not adapted to PtMP networks today.

Not everything is lost for the cause of PtMP transmission of mobile interfaces though. Traffic offloading of low priority services to PtMP links in shared fixed/mobile ODNs is an use-case that could be exploited to allow relieving the constraints of high priority services in nearby macro-sites. Using PtMP connections as temporary backup links for mobile sites in private networks is also another interesting use-case. Both examples

<sup>‡</sup>The actual transport bit-rate would be higher than that due to the overheads of high layer RAN functions.



Table 3. Key-figures of a typical PtMP PON deployment in France, 2020.

Scenario	PON split ratio	ODNs per cabinet	Users per cabinet	Down(up)-stream bit-rate per ODN	Mean cabinet density	Availability (%)		
						OLT	Cabinet	
							Shared	Private
Urban and rural	1:64	15	960	10(10) Gbit/s	1 every 37 km <sup>2</sup>	99.999	99.99	99.997
Dense urban		5	320					

can be efficiently implemented by means of dynamic and intelligent configuration of the optical access nodes. This feature is possible using network configuration automation and abstraction provided by SDN, which is the subject of the following section. The reader is referred to [23] and [25] for an in-depth assessment of both PtP and PtMP optical access solutions for mobile connectivity.

## 5. TOWARDS MORE INTELLIGENT ACCESS NODES

We have seen how both NFV, empowered by the new 5G functional splits, and closer to end-users cloud infrastructures could play an important role in 5G. We have also seen that the extremely heterogeneous needs of different 5G use-cases beg for a slicing approach, where different services can be isolated and treated according to their requirements. Slowly but surely, the trends around virtualization are also reaching the optical access systems. SDN solutions are already being deployed by major operators all around the world seeking at a first movement, vendor-agnostic network configuration tools and eventually enabling solutions fully compatible with multi-service and multi-tenant capabilities. The objective of this short section is to give some examples on the use of virtualization approaches based on our recent works with the hope that they could make some sense to the reader that is not familiarized with the subject.

In [26], we experimentally evaluate a scenario where low-priority mobile services are offloaded to a 5G-capable XGS-PON customer premises equipment (CPE). Virtual entities corresponding to different RAN and core network blocks are implemented on a generic server, on top of an Openstack virtualization environment. We investigate the impacts of DBA in the uplink transmission of a HLS interface and assess the robustness of the mobile interface to packet jitter.

In [27], we extend O-RAN’s Cooperative Transport Interface (CTI) concept so that congestion issues at the OLT backplane is also taken into account. Our solution allows for end-to-end traffic flow prioritization, from the ONUs all the way up the OLT backplane. The experimental setup is enabled by a smart SFP+/OLT transceiver allowing any generic switch or router port to be converted into a PtMP OLT port. YANG model-driven abstraction of the OLT (switch + smart SFP+/OLT + conventional PtP transceivers) provides proper dynamic network configuration and interfacing between Netconf and Python application program interfaces (API) at the south of the SDN controller and a Restconf interface at the north.

In [28], we use the same smart SFP+/OLT modules, PON abstraction of [27] and vRAN/vEPC interfaces [26] but this time connected to a generic server. We consider a scenario where the server would host multi-access edge computing (MEC) and vRAN functionalities. Simultaneous PtP and PtMP connectivities are also considered and the server interfaces are bound to data plane development kit (DPDK), which enables fast packet processing and forwarding by circumventing the operating system kernel.

Whereas different flavors of the offloading scenarios have been investigated in the works above, in [29] we experimentally investigate a more unorthodox application of SDN in the optical access. A Restconf/YANG solution is used for the creation of different slices associated to different PHY layer parameters in a distributed antenna system (DAS) analogue radio-over-fiber (A-RoF) link. This interface is used to ensure connectivity of different services and RAN interfaces to active phased array massive multiple input, multiple output (mMIMO) antennas in which beam forming/steering is performed with electrical or optical phase shifters. This work was later extended in [30] to integrate, on top of the SDN controller, an orchestration intelligence responsible for dynamically managing different slices through the optimization of the transmission parameters based on indicators such as traffic demand, network load and etc.

## 6. FINAL CONSIDERATIONS

Contrary to its predecessors, 5G must provide optimized communications for a colorful palette of services, situations, traffic volumes and end-user devices. Network slicing and cloud solutions allowing closer to end-user caching and hosting are some of the capabilities enabling to meet these needs. In view of such challenging and heterogeneous requirements, it is very important to raise awareness about the importance of optical fiber connectivity beyond typical link dimensioning questions. We have seen that different functional splits of the RAN protocol layer allow for a vast range of choices in terms of RAN architectures and that the optical links must be prepared to face varied requirements in terms of bit-rate, latency and jitter of different Ethernet interfaces, namely the backhaul, the midhaul, the fronthaul and the sidehaul.

We have also seen that PtP remains the de-facto choice for optical access connectivity today and that different choices based on WDM exist allowing to increase capacity with more or less work in terms of the optical transceivers manageability. We have evaluated different levels of fixed-mobile convergence and taken into account issues related to practical deployments of a fully-convergent PtMP based solution. Finally, we have given some examples showing how SDN optical network abstraction could provide full abstraction of underlying optical infrastructure, enabling isolated and clustered multi-service and multi-tenant scenarios in line with the end-to-end requirements of 5G. Considering all these factors, we expect that the optical connectivity is bound to a more important role, if not as important as the RAN and core themselves, in future mobile deployments. Let the 6G come!

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