Fixed-Mobile Network Convergence
The Key Role of Fibre

A WHITE PAPER BY THE DEPLOYMENT & OPERATIONS COMMITTEE

Fibre to the Home Council Europe

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1. EXECUTIVE SUMMARY

For many years, people have dreamed of seamless communications where users receive the same customer experience regardless of their location or connection type.

Operators and service providers have been working towards this goal. The market has seen many mergers, acquisitions and investments designed to facilitate the convergence of fixed and mobile networks. This has led to the introduction of converged service offerings, as well as many forms of wholesale access and network infrastructure sharing.

At the same time, fixed broadband and mobile services have evolved at a very fast rate, enabled by technical advances such as 4G LTE in the wireless space and Fibre to the Home (FTTH) and Fibre to the Office (FTTO) in the wireline space. This evolution will doubtless continue, with imaginative and even more demanding applications being created to take advantage of enhanced service offers based on 5G and advanced broadband technologies. The concept of seamless, ubiquitous service delivery is now more desirable and closer to being achieved than ever before.

However, while the demand for enhanced networks and services is not in doubt, the business case for building and operating next-generation networks remains unconvincing in many cases. Hence, operators in many regions have been slow to invest in leading-edge access network technologies and have expressed doubt about the pace or scope of future investments in 5G networks.

The FTTH Council Europe believes that operators and associated stakeholders must consider alternative approaches to investment in their networks if they are to ensure the future availability of seamless service levels throughout their service portfolios.

Fibre is a fundamental, structural part of both 5G mobile and fixed access networks and there is a significant market opportunity to converge and share infrastructure. This is particularly important when you consider that the civil works to deploy fibre underground or overhead can be a substantial portion of the costs of deploying new mobile and fixed networks.

Consequently, it is obvious that any initiative that helps to reduce the global cost of deploying fibre, for example by reusing ducts or cables or consolidating operations, will have a significant positive impact on the business cases both for mobile 5G and fixed access networks.

To deliver this cost reduction, operators can take advantage of the fact that there will be significant overlap between the coverage and footprint requirements of 5G and fixed access networks – and thus the fibre deployment requirements of both will be similar. Consequently, consideration should be given to utilizing a common fibre infrastructure to build 5G and fixed access broadband networks.

By converging multiple fibre-based networks on to a single footprint, operators can make significant savings on capital and operational costs, which will greatly improve the business case for their investment, and improve their competitive position relative to rivals investing in dedicated, physically separate networks.

A quantitative study on the value of fixed-mobile network convergence has been prepared by the FTTH Council Global Alliance and is being presented at the FTTH Conference Europe in Amsterdam on 13-14 March 2019. This White Paper is complementary to that work and provides more detail about the assumptions, technologies and network architectures contained in the study.

2. TRENDS IN FIXED AND MOBILE NETWORKS

2.1. Trends in Mobile Networks

2.1.1. The vision of 5G technology

Unlike its predecessors, the fifth generation of mobile technology, 5G, will not only continue increasing the amount of bandwidth delivered to mobile terminals (eMBB - Enhanced mobile broadband), it will also allow billions of sensors to connect to the network (mMTC – massive Machine Type Communications) and deliver ultra-reliable services that can operate in real time (URLLC – Ultra-reliable and low-latency communications). These three scenarios are the most important use cases envisaged by the ITU Radiocommunications Group, ITU-R, that will enable a myriad of different 5G-enabled services, as illustrated in Figure 1.

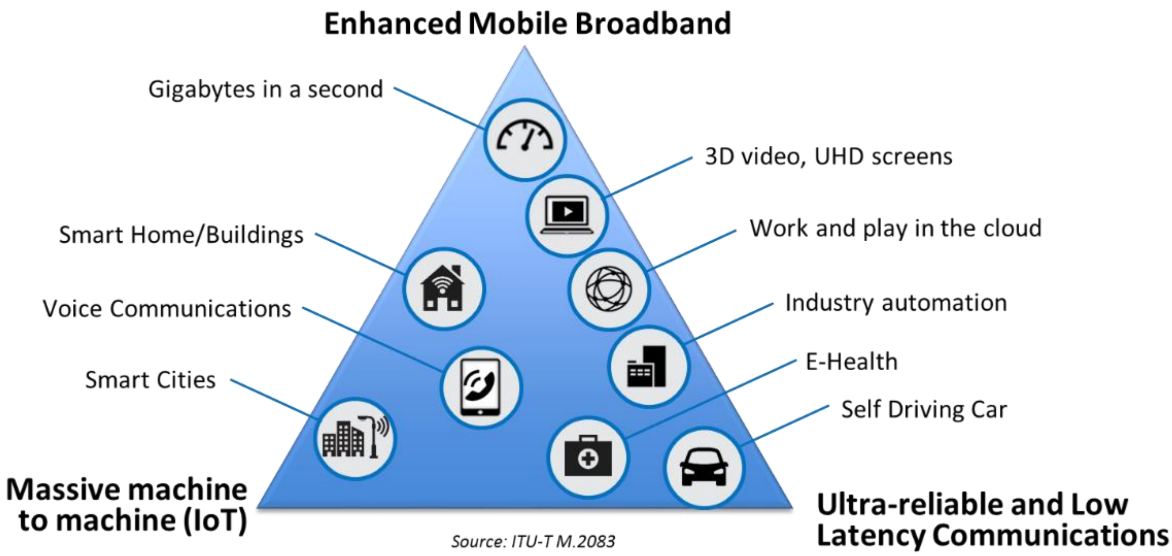

Figure 1: New usage and service scenarios enabled by 5G technology

Enhanced Mobile Broadband will offer increased transmission speeds compared to 4G, and the possibility of gigabit data rates in both the downlink and uplink. This will support high-definition video transmission, such as 8K displays, as well as the use of holograms and virtual/augmented reality, even when on the move. Ultra-reliable and Low Latency Communications aim to eliminate transmission error and decrease the round trip time – which is expected to be critical for scenarios such as self-driving cars and remote-controlled surgery. Massive machine-type communications (mMTC) will allow traditional machine-to-machine communication to multiply exponentially, by providing the infrastructure for all types of small sensors to connect to the Internet and send small bursts of data in what is called the massive Internet of Things (IoT).

Like any technology, 5G will need to be standardized before it can be widely deployed. Although the standardisation of 5G will not be finalized until later in 2019, with widespread capital investment expected to occur by 2021, mobile network operators are already preparing. Obviously, the scope of the change that mobile networks will have to undergo in order to support 5G technologies is profound and will affect many layers of the network.

At the infrastructure level, there will be three main changes to the network to enable 5G: the densification of the radio access network (RAN), the migration to centralized RAN architectures, and the need for Multi-Access Edge Computing (MEC).

2.1.2. Densification

One way to increase the bandwidth delivered by an existing macro cell to its connected subscribers – either because it is experiencing capacity constraints or simply to deliver higher bandwidth – is to 'densify' the area by deploying more cells, each covering a smaller area. However, reducing the site-to-site distance in the macro-network can only be implemented to a limited extent because finding new macro cell sites becomes increasingly difficult and can be expensive, especially in urban environments.

An alternative is to introduce low-power small cells to areas already covered by a macro cell, increasing capacity in spots with particularly high user demand. When combined, macro cells and small cells benefit from frequency reutilization – the small cells can transmit lower powers using the same frequencies as the macro cell, without creating interference. This allows the operator to reuse spectrum (an extremely expensive asset), instead of creating new cell sites that require the use of new frequencies.

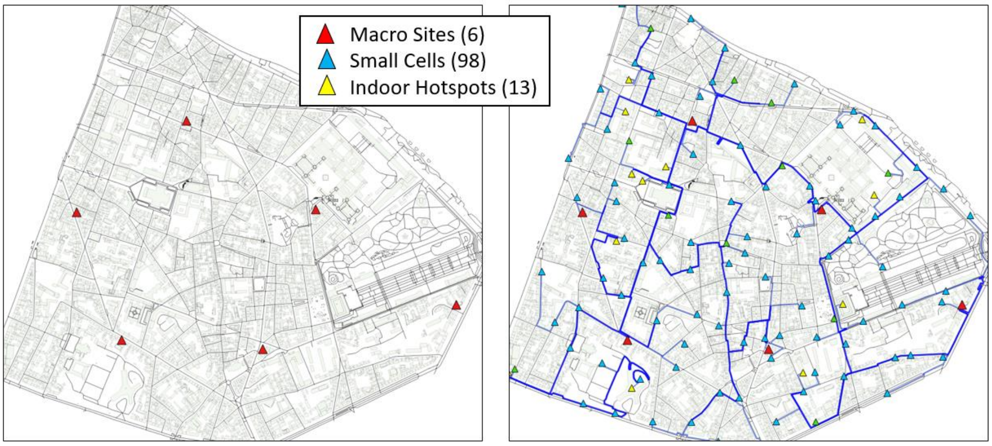

Figure 2: Illustration of mobile cell densification, from 6 (macro) sites to 117 sites (including small cells and indoor hotspots) in a dense urban area

The process of densification, whether it is accomplished by adding more macro cells, more small cells or both – to create a heterogeneous network or 'Het-Net' – reduces the inter-site distance between cells, as illustrated in the Figure above.

Regardless of whether it is a macro or a small cell, the amount of data these cells are carrying is on the rise, especially with 5G technology promising user data rates of 100 Mbps and beyond. Hence, to connect cell sites it makes sense to consider a future-proof solution with virtually unlimited bandwidth like optical fibre, instead of microwave links or traditional copper T1/E1 connections.

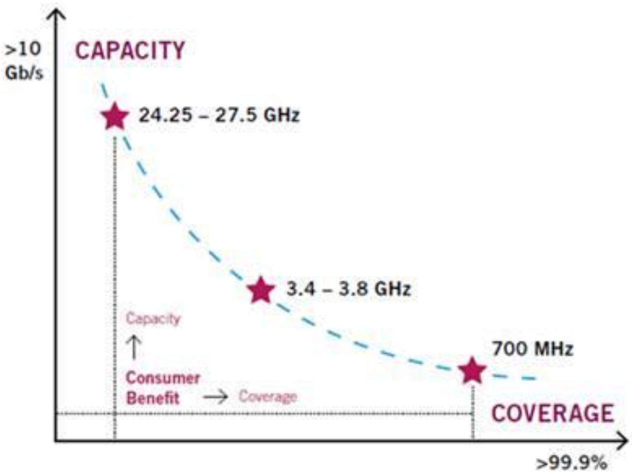

Figure 3: Densification requires more optical fibre. Source: www.theiet.org

2.1.3. Centralization of the radio access network

With the same idea of better reutilizing the frequency spectrum and also trying to reduce power consumption in access networks, operators are looking into virtualization, which at the infrastructure level can be achieved by migrating into centralized RAN architectures.

In a traditional RAN architecture, a Baseband Unit (BBU) connected to its Remote Radio Heads (RRHs) and their antennas are all co-located at the cell site. The BBU processes user and control data, while the RRHs generate the radio signals transmitted over the airwaves via the antennas. In this configuration, the link connecting the BBU at the cell site back to the Mobile Switching Telephone Office (MTSO) is referred to as backhaul.

In a centralized RAN architecture (C-RAN), all BBUs from the same local area are relocated from their cell sites to a common aggregation point. This is the simplest form of centralized RAN; in more evolved versions like Cloud-RAN, BBUs are no longer hardware units but virtual ones running on generic servers. Now, the proximity of BBUs to each other allows dynamic allocation of the BBU resources among the RRHs, to provide load balancing of the mobile traffic and tighter coordination of interference for more efficient use of the frequency spectrum.

There are many benefits of centralized architectures for the operator in the form of capital and operational cost reduction. Energy savings of between 40% and 50% can be achieved with such architectures on support equipment such as air conditioning [1]. Aggregating BBUs in a few central locations also simplifies management and operations; and lighter and simpler equipment left at the cell site translates to easier installation and less need to visit the cell site for maintenance.

In C-RAN architectures where the BBU is relocated to a central location, the segment connecting the BBU and the RRH that was originally at the cell site extends to backhaul-like distances. This link between the BBU and RRH is now called fronthaul.

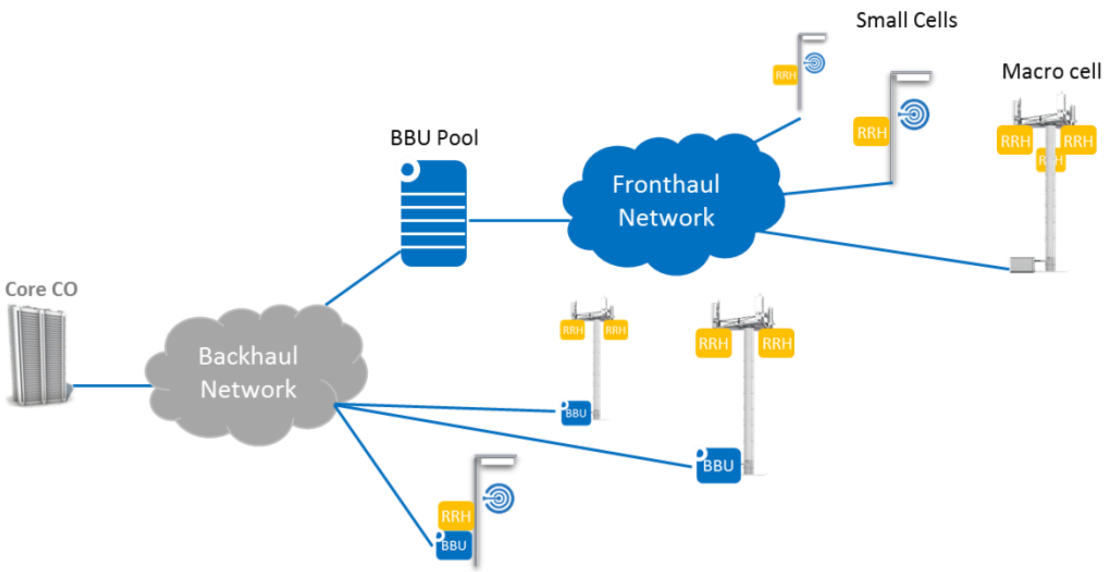

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Figure 4: Fronthaul is the segment that connects the RRH to the BBU, whereas backhaul accounts for the segment between the core network and the BBUs.

Whether at the cell site or through a fronthaul link in a centralized architecture, the BBU and RRH communicate using digital baseband interfaces. The most common specification is CPRI (Common Public Radio Interface), which can be carried over tens of kilometres and is compatible with common transceiver formats e.g. SFP/SFP+ pluggable optics for Ethernet and Fibre Channel.

The CPRI specification supports data rates of 2.458 Gbps, 3.072 Gbps, 4.915 Gbps, 6.144 Gbps, and 9.830 Gbps. Later releases add new CPRI line rates up to 24.3 Gbps (CPRI Rate 10). These rates are relatively high compared to the bandwidth handled by backhaul links because CPRI is the digitized version of an analogue radio signal – the optical signal is directly modulated by a radio signal before being transmitted over the fibre. This allows radio signals to be optically distributed to cell sites directly at the carrier frequencies and converted from the optical to electrical domain at the cell site before being amplified and radiated by an antenna. This implementation is simple and cost-effective as no frequency conversion is needed at the cell site, but translates to much higher bandwidth requirements in the fronthaul link, for example a 4G sector typically needs a 10 Gbps CPRI link. This high bandwidth combined with very low latency requirements (typically 200-400µs [2]) are the reasons why fronthaul connections and centralized RAN architectures need to be implemented in an all-fibre topology.

2.1.4. Multi-Access Edge Computing

Edge computing, as an evolution of cloud computing, will bring application hosting from centralized data centres out to the edge of the network, where it is closer to consumers and the data generated by applications. Edge computing will be one of the key pillars to meet 5G Key Performance Indicators, particularly the demanding targets for low latency and bandwidth. The network edge encompasses multiple access technologies; hence the term Multi-access Edge Computing (MEC). Through MEC, operators will be able to place processing and storage capabilities closer to users and terminals, enabling the deployment of versatile service platforms.

The Multi-access Edge Computing (MEC) initiative is an Industry Specification Group (ISG) within the European Telecommunications Standards Institute (ETSI). The purpose of the group is to create a standardized open environment that allows the efficient and seamless integration of the solutions provided by service providers, vendors and platform suppliers. The ISG has more than 80 member companies from across the value chain working together to define architecture, application areas, deployment scenarios and interfaces.

The MEC ISG has already published Phase 1 specifications, focusing on the management and orchestration (MANO) of MEC applications and the various types of application programming interfaces (APIs). The MANO system will enable the service environments in edge data centres, while the service APIs expose information about the underlying network capabilities to the applications, and the user equipment APIs allow the client applications to interact with the MEC system for the management of the applications lifecycle.

In the second phase of work, the scope of MEC has expanded to include key industry segments, such as Vehicle to Everything (V2x) and industrial automation; key use cases such as Network Slicing; and the definitive evolution of the architecture from mobile to multi-access scenarios, including Wi-Fi, Li-Fi and Fixed Wireless Access (FWA).

2.1.5. Summary of mobile trends

The trends of cellular densification, RAN centralization, and edge computing will provide the increased capacity, low latencies, simplified operations and reduced costs that future (and even present) generations of mobile technology will need. Depending on its legacy network, each operator will have to decide whether each of these strategies is necessary and when it is the right time to implement them. Yet, while each business case will be different, it is clear that only optical fibre can deliver a network that is fully prepared to deliver 5G requirements, and sooner or later more fibre will be needed. The question operators must consider is whether there is any opportunity to optimize the incremental cost of fibre deployments by integrating the mobile build-out into the current rapid deployments of FTTH.

2.2. Other Trends

2.2.1. Legislative and policy view

The need for high-speed broadband and ultimately fibre networks is understood by policy makers in Europe as the following examples show:

- In 2016 The European Commission published a policy paper: “Connectivity for a Competitive Digital Single Market – Towards a European Gigabit Society”. The vision for this Gigabit Society “… is operationalized through three strategic objectives for 2025: for Europe's growth and jobs, Gigabit connectivity for places driving socio-economic developments; for Europe's competitiveness, 5G coverage for all urban areas and all major terrestrial transport paths; for Europe's cohesion, access for all European households to Internet connectivity offering at least 100 Mbps”.
- The Government of Sweden was even more ambitious in its broadband strategy, setting goals “… that 98 percent of the population should have access to broadband at a minimum capacity of 1 Gbit/s at home, as well as in the workplace, the remaining 1.9 percent at a minimum capacity of 100 Mbit/s, and 0.1 percent at a minimum capacity of 30 Mbit/s, no later than the year 2025.”
- In the UK, where the Government outlined the target for every home to have access to a “full fibre” broadband by 2033, the Institute of Directors has asked for these plans to be accelerated, calling upon the Government to provide a firm date to switch off the UK's copper network in favour of faster fibre connections. It suggested a target of "as soon as possible" after 2025, according to a report from BBC News in August 2018.

These reports suggest that 2025 will be the year when the ‘Gigabit Society’ becomes a reality.

2.2.2. Industry view

The manufacturing industry seems to have chosen 5G as their vehicle to realize Industry 4.0 environments on their campus networks. In Germany for example, more than a dozen players on the DAX (the 30 major German stocks) as well as the smaller companies showed interest in spectrum in the context of the country’s planned 5G auction.

The same is true for many municipalities. Cities with an existing fibre footprint are thinking about opting for local spectrum to enrich their smart city infrastructure.

Finally, the major telecom service providers are planning to combine their FTTH and 5G rollouts to gain benefits from using the same infrastructure (ducts, cables and fibres). The importance of 5G to their plans is illustrated by the 5G spectrum auction in Italy in October 2018, which exceeded expectations, raising €6.55 billion or 164% more than the initial offers.

2.2.3. Consumer view

The CES 2019 show provided an insight about what’s coming next in terms of more bandwidth-hungry consumer electronics devices like 8K TVs and virtual/augmented reality headsets, especially for the gaming sector, which will fuel the need for more bandwidth and lower latency.

From a convergence point of view, services like the Apple TV app are a good example, showing how different types of content are spread over various end devices.

2.2.4. Technical view

The speeds available to users at the edge of the network keep increasing. In addition to the constant development of WiFi, ‘Light Fidelity’ or LiFi uses visible light for short-range data transmission. The first pilots launched last year mainly focus on high-end office illumination. However, developers are considering installing LiFi in streetlights, vehicle headlights, museums and other locations – it's worth keeping an eye on this technology.

The speeds provided by optical access equipment are similarly increasing. Published in 2015, the NG-PON2 standard for passive optical networks (PON) delivers 4 x 10 Gbps symmetric bandwidth using four wavelength pairs. This technology is an attractive vehicle to carry both fixed and mobile traffic over a common physical network. In the scenario depicted below, the fixed network operator could use one or more wavelength sets (one for consumers, another for business customers), while the mobile operator uses another pair for fronthaul or backhaul.

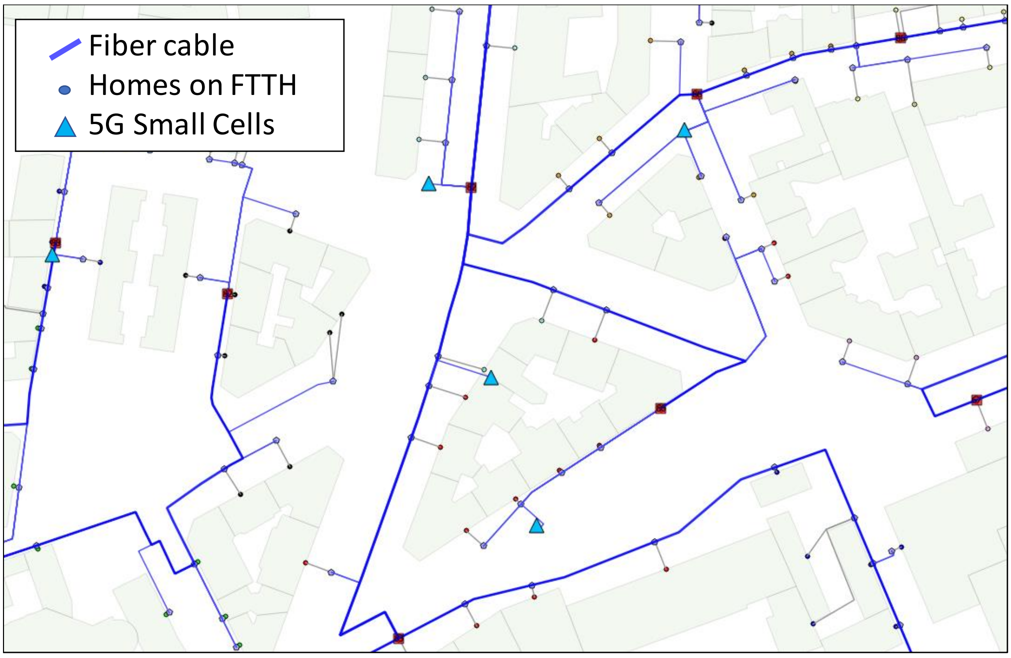

Figure 5: Cable view of an FTTH and 5G antenna area.
A real example of shared fiber infrastructure

Both IEEE and ITU-T Study Group 15 have started work on the next generation of PON standards, 25G-PON, which will support 25G transmission per wavelength, expected to be an important data rate for 5G fronthaul (see §2.1.3).

The fact that NG-PON2 or future 25G-PON may be used in combination with existing GPON equipment adds even more options to this converged scenario. From the duct and cable point of view, the antenna is simply another 'demand point' in the fibre footprint; the additional capex to connect the antenna is relatively low and probably much lower than the effort to connect the small cell to a standalone mobile network.

For an integrated operator, the benefits of building a single, converged network are obvious. For fixed line operators, this approach opens up an additional revenue stream from the mobile operator, while the mobile operator should benefit from reduced cost to connect the small cells.

Service providers are currently investigating virtualization in the access network. Leading these efforts, the Open Network Foundation (ONF) is a non-profit operator-led consortium, which serves as the umbrella for a number of projects aiming to transform carrier network infrastructure and business models. These projects leverage network disaggregation, white box economics, open source software and software-defined standards.

The ONF, which started the software defined networking (SDN) movement, has had a number of notable successes, not least of which is CORD (Central Office Re-architected as a Datacenter) which blends in Cloud and Network Function Virtualization (NFV) technologies to create what is now the leading solution for transforming operator edge networks.

The edge of the network – the Central Office for telcos and the head-end for cable operators – is where operators connect to their customers. The CORD project is intent on transforming this edge into an open and agile service delivery platform enabling the operator to provide the best end-user experience along with innovative next-generation services.

US operator AT&T, for example, in late 2017 piloted various optical line terminal (OLT) virtualizations using Open Source Access Manager Hardware Abstraction (OSAM-HA) software in their data centres in Atlanta and Dallas. OSAM-HA is a further development of the Virtual OLT Hardware (VOLTHA) abstraction layer project by ONF.

Further, ONF is working on Software Enabled Broadband Access (SEBA), a lightweight platform based on a variant of R-CORD (residential CORD). SEBA supports a multitude of virtualized access technologies at the edge of the carrier network, including PON and G.Fast, and eventually DOCSIS and other access technologies. SEBA supports both residential access and wireless backhaul and is optimized such that traffic can run a 'fastpath' straight through to the backbone without requiring Virtual Network Function (VNF) processing on a server.

The ONF recently started a new project on COnverged Multi-Access And Core – COMAC, which aims to bring convergence to operators' mobile and broadband access and core networks. It will build upon a suite of ONF projects that are part of the CORD project umbrella. By leveraging and unifying both access and core projects, COMAC aims to enable greater infrastructure efficiencies as well as common subscriber authentication and service delivery capabilities so users can roam seamlessly between mobile and fixed environments while experiencing a unified experience.

Optimized for 5G deployments, the COMAC Exemplar Platform will leverage SDN and cloud principles to disaggregate elements and will be built on a microservices architecture, so operators can dynamically place elements where they best serve their needs. Access, edge, core or public clouds work together in a centralized and coordinated way to deliver exceptional user experience while leveraging common infrastructure and public cloud economics.

Being still in a pre-industrial stage, these concepts and resulting projects show a concrete way how access, aggregation and edge devices might be software-managed in the future and mainly over fibre infrastructure, except for the last few metres which can use different fixed, wireless and mobile technologies.

2.2.5. A fixed-mobile convergence

Fixed and mobile networks have until now mostly developed independently of each other with limited joint usage of infrastructure and resources. This has led to an enormous level of investment that becomes unsustainable when considering the higher fibre requirements of both FTTH, FTTO and next-generation mobile networks. The alternative is to unify the optical access to allow both fixed and mobile network to share resources in what is called a converged network.

The term was first coined in 2004 by the Fixed-Mobile Convergence Alliance (FMCA) which defined convergence as "a transition point in the telecommunications industry that will finally remove the distinctions between fixed and mobile networks, providing a superior experience to customers by creating seamless services using a combination of fixed broadband and local access wireless technologies to meet their needs in homes, offices, other buildings and on the go". In this definition 'fixed broadband' means a wired connection to the internet, such as FTTH, DSL, cable or T1, while 'local access wireless' means Wi-Fi or any cellular radio technology (macro or small cells).

In 2013 a European Union FP7 ICT integrated project called COMBO (COnvergence of fixed and Mobile BrOadband access/aggregation networks) started studying the implications of convergence.

The three-year project was built with the contributions of 16 partners (including Telefonica, Deutsche Telecom, Ericsson or ADVA, among others) who identified that fixed and mobile convergence was already being mainly implemented at the application and service level [3] with all-IP services and the IP Multimedia Subsystem (IMS). This convergence had already started to blur the boundaries between fixed and mobile access with users connecting their mobile devices to fixed access points and laptops connecting to the mobile broadband network.

The project also identified two deeper forms of carrier-based convergence [4]:

- **Functional convergence** is defined as the implementation of a generic network function to realize similar goals in different network types (fixed, mobile, Wi-Fi).
- **Structural convergence** is defined as the pooling/sharing of network and infrastructure resources (cable plant, cabinets, buildings, sites, equipment, and technologies) for several network types (fixed, mobile, Wi-Fi).

2.3. Is Structural Convergence Possible?

Structural convergence appears to have a lot of advantages, but firstly, is it possible?

Backbone networks are already shared networks in some sense, at least for an operator with multiple services or customer types. Dual- or triple-play service offerings (broadband, phone and TV) are simple examples of one infrastructure with many services on it. Renting (or with Indefeasible Rights of Use - IRU) of ducts, dark fibres or even wavelengths are already common offers on terrestrial backbone networks and on submarine cables.

Furthermore such arrangements are not new to either the wireless or fixed networking industries. Mobile operators have successfully shared their existing networks for many years. The concept of wholesale fixed network access is also well established, enabling sharing in that arena.

Once operators agree to the concept of establishing a converged fibre infrastructure, it is clear that sharing can provide further financial efficiencies to those operators. In many cases, an operator's core network is already a common fibre infrastructure used for fixed and mobile services, for residential customers as well as businesses.

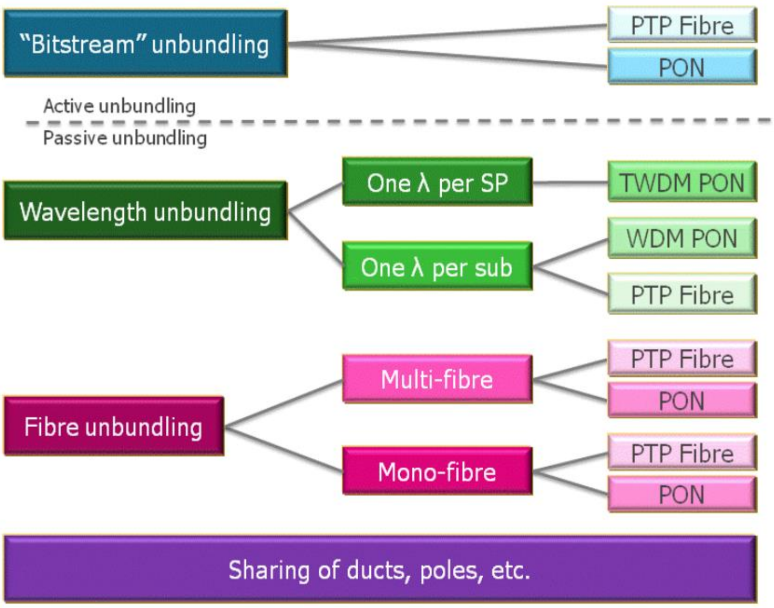

Figure 6: Different levels of structural convergence

2.4. Constraints and Challenges

Getting operators to agree to share networks is not necessarily straightforward. With some operators wishing to retain their proprietary, closed infrastructure in order to preserve their competitive advantages against challengers, convergence may not come about without intervention from the regulatory authorities.

Shared infrastructure has to support many services and possibly many operators. When different services are supported, with different service level agreements (SLAs), then structural convergence should be designed to answer customers' specific needs such as low latency, intervention and repairs, and should also permit various architectures on same network.

In the next section §3, we investigate which geographical and technical levels of the network can be shared, along with the associated constraints and challenges.

2.5. Summary: The Benefits of Convergence

Out of the two types of convergence (functional and structural), structural convergence will have greater impact on the short-term evolution of optical networks, allowing converged operators to benefit from the lower costs of deploying and operating a unified network infrastructure. With structural convergence, operators can offer multiple services on a unique infrastructure, whether those services are fixed or mobile, and delivered to residential, business, or wholesale customers. In addition on a middle term perspective functional convergence will also revolutionize the way we deal with networks deployment and operations.

Thus, the main reason to promote structural convergence can be summarized as "the effective sharing of infrastructure costs by multiple competing operators". This could accelerate network deployment and provide better coverage with lower total costs. However, such an approach implies new forms of relationships between all actors, including those who may be competitors, which may require some form of intervention from the regulatory authorities. For details, we invite the reader to review 'Chapter 5: Infrastructure Sharing' in the FTTH Handbook [0].

More specifically structural convergence could lead to:

- Lower total cost of deploying and operating the converged network.
- Increased competitiveness against rivals operating on a non-converged network.
- Enhanced coverage, even in the more rural area, for the same level of investment.
- The development of an efficient European ecosystem connecting everybody and everything, everywhere with an efficient, cost-effective, fibre network.
- A standardized telecom network system in Europe where it will provide a simpler, faster and reliable means to connect everybody and everything, everywhere, dynamically.

In conclusion, the mobile trends of centralization, densification and virtualization lead unequivocally to the requirement for more optical fibre connections. In addition, many other trends in fixed access networks, including new use cases like IoT, and the ambition for fast and efficient FTTH coverage across Europe, lead to the need for "a converged fibre infrastructure as the structural network for the EU Gigabit Society".

3. STRUCTURAL CONVERGENCE

This chapter provides a description of the many levels of structural convergence, from trenching operations up to virtualization techniques. The reader is referred to the FTTH Handbook [0] for more precise information on civil works and ducts.

3.1. Civil Works and Ducts

How can an operator increase the telecom network density? More than one technique may be used in the same network, depending on the circumstances of the network build. As a significant part of the cost of a fibre network build is related to civil works, operators are advised to evaluate all their options to permit a higher density of ducts to be installed, with new civil works as trenching operation or by adding subducts to existing ducts.

3.1.1. Sharing the trenching

In a trenching with multiple ducts laying, fibre networks are not physically shared; nevertheless such a common planned and conducted operation can significantly reduce the total cost compared to networks deployed in parallel in different trenching and laying down operations.

Figure 7: Trenching machine and duct containing multiple subducts

3.1.2. Many cables in a same duct

Because a fibre cable is much smaller than a copper cable, it is often possible to deploy new fibre cables in an occupied duct, with or without adding sub-duct.

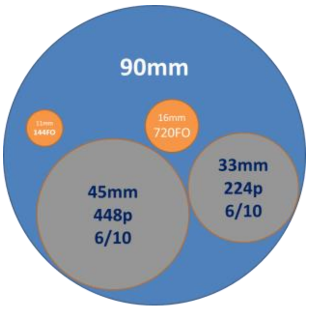

Figure 8: Relative sizes of fibre and copper cables

3.1.3. Microduct and micro-cables

A conventional duct infrastructure can be constructed in a more efficient way by using one of several duct and microduct products: tight bundles, loose bundles, or flat bundles.

Since micro-cables offer about 50 percent reduction in size and 70 percent reduction in weight compared with standard cables, the duct size has also been reduced over the years.

Figure 9: Some examples of microducts

There is a complete range of accessories available on the market for microduct networks, which are designed to help the operator maximize the use of existing ducts.

Figure 10: Some examples of microduct accessories

3.1.4. Micro-ducts installed by air blowing

The best known and efficient technique to install microducts into existing sub-ducts is by jetting / blowing. This is an effective and fast installation process.

Figure 11: Air blowing operations

To optimize the existing network capacity, it is also possible to install several micro-ducts or a second cable in a duct already occupied by an existing cable using this technique.

3.1.5. Many ducts and microducts by direct burial

It is also possible to take advantage of existing equipment for trenching to install several ducts and microducts simultaneously. Nowadays with the miniaturization of the telecommunication infrastructure it is possible to use low-impact micro-trenching techniques, which are less invasive in terms of time and space.

3.2. Cables and Cable Management

There are a wide variety of standard fibre optic cables that can be used.

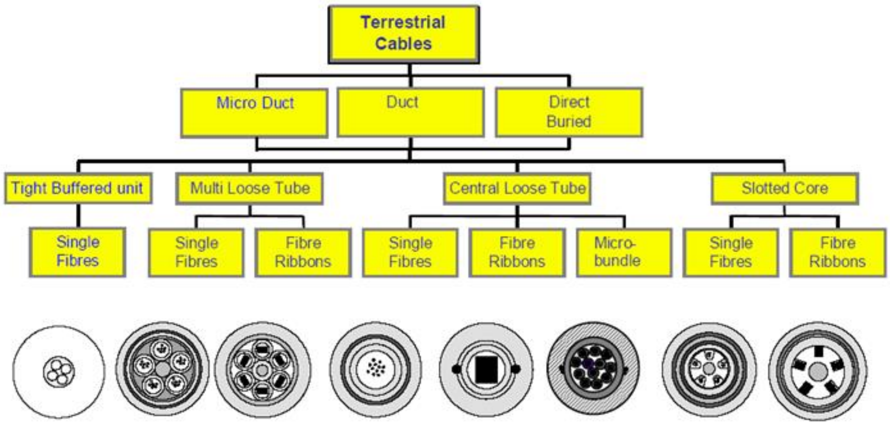

Figure 12: Types of fibre optic cable

One of the operational advantages of a cable blown in a small duct (one duct, one cable) is that any installed cable can easily be removed and replaced by another cable of different capacity, size or technology, or an identical cable in the case of a repair. Thus, a crew of two people is sufficient to process the repair on the network and/or replacement of the cable.

Where different customer cables occupy the same duct, it is important to consider how this will affect operations; for example, how could a repair time of four hours be guaranteed for specific customers? Additionally, how could different architectures like point-to-point (P2P) and point-to-multipoint (PON) be supported on the same physical network?

One simple approach is to take advantage of the fact that fibres in a cable can be gathered into bundles (in groups of 12 fibres, for example) and have different operations, architecture or security measures associated with each bundle number. Also, there are many access points and equipment in the local loop – such as manholes/access chambers, street cabinets, and boxes/closure storage – which can be used in practice to provide so points of flexibility.

For example, with multiple fibre bundles in a cable, it is possible to manage these bundles differently inside closure storages and in cabinets in order to define various topologies and operational requirements. Different parts in the same cabinet could be assigned to different bundles, each for a different service provider and some with specific security measures. For sensitive customer links, the operator would then be able to identify the corresponding bundles and intervene inside the closure to repair them first.

Figure 13: Underground fibre distribution with closures

3.3. Hardware Collocation

Until now, fibre access network deployment has emphasized optimisation of the outside plant (OSP) by finding the most cost-effective method for connecting the Central Office with myriad subscribers in residential, manufacturing or multi-dwelling environments.

In contrast, in the mobile world, the outside fibre plant has comparatively few cell towers and rooftop installations compared to end points in fixed networks. With the increase in mobile cell count from additional macro and small cell infrastructure to enable high speed and low latency applications, operators will be challenged to deploy the necessary fibre infrastructure. Especially challenging is the urban environment, where the number of potential sites and the associated required real estate (outdoor cabinets, space on masts, manholes etc…) is already severely limited.

Mobile fronthaul network architectures comprising interconnected small cell antenna sites are inherently different from traditional mobile antenna systems. Whilst dark fibre rental or indeed dedicated fibre connectivity is normal in current mobile infrastructure deployment, the new challenge will be to network multiple new cell sites in locations not previously under consideration – such as street lighting masts, traffic light intersections, building walls, or bus waiting zones.

This will require new fibre routes to sites which until now have not been a focus for fibre distribution in either the fixed or mobile OSP architectures. In turn, this will necessitate new collocation and flexibility points in the OSP architecture where multiple operators can share the fibre infrastructure, often with completely different structural and planning aspects in mind.

Immediately, four types of 'sharing' architecture models come to mind:

1. Collocation of shared fibre infrastructure in a single outdoor cabinet or underground chamber;
2. Site collocation by adding more outdoor cabinets placed next to each other;
3. Physically segregated collocation space in an outdoor cabinet with barrier-free entry for each operator;
4. Collocation of shared fibre infrastructure at a single terminal at the individual fibre level with common connection interface.

In sharing model 1, several operators place their fibre infrastructure in a single, large outdoor cabinet or underground chamber. However, this inevitably leads to network security and maintenance issues as several operators will share physical access to the cabinet locking system. The maintenance team of operator A will have access to the fibres of operators B and C, which means it is essential to identify which operator owns which splicing cassette, and there is an increased risk of interruption in service due to maintenance from several operator's teams.

Figure 14: FTTx fibre distribution cabinets often have limited space available

Additionally, existing outdoor cabinets are often located in high-density geographies, with many fibres and micro-ducts converging on an environment with limited space. Adding the new fibre plant for a growing 5G cellular infrastructure may not be straightforward given the sheer quantity of additional fibres currently anticipated.

In model 2, placing outdoor cabinets adjacent to each other requires costly additional real estate, often unavailable due to local site restrictions such as space constraints, limited access or for aesthetic historical and architectural reasons. It may be a favourable move in rural areas, but in urban environments this may not be a real option.

Model 3 is a new collocation option, where operators physically share the fibre infrastructure in a 'discrimination-free' outdoor cabinet with clearly separated fibre spaces for each operator. Operator A, who originally sourced the site and placed the outdoor cabinet, must consent to having additional units stacked on top of his own cabinet, as shown below. The advantages for operators B and C to colocate with the original outdoor cabinet are lower site investment costs, bundled with the advantages that they do not require additional site permits or costly street level excavations. Operator A is able to lease the available space to operators B and C, resulting in more favourable economics compared to developing the site purely for its own use. Barriers to entry for site development for services other than fixed networks are therefore greatly diminished.

Figure 15: Outdoor cabinet with spatial infrastructure separation for multiple operators

In the case of model 4, a terminal is installed to provide the connection point for the drop cable feeding individual homes or wireless end points. This terminal can be shared between operators, by allocating specific ports to specific functions. To facilitate quick and easy interconnection between individual operators or services, these drops are often connectorized using a common optical interfaces, either standard indoor connectors mounted inside conventional closures, or external environmentally hardened connector interfaces.

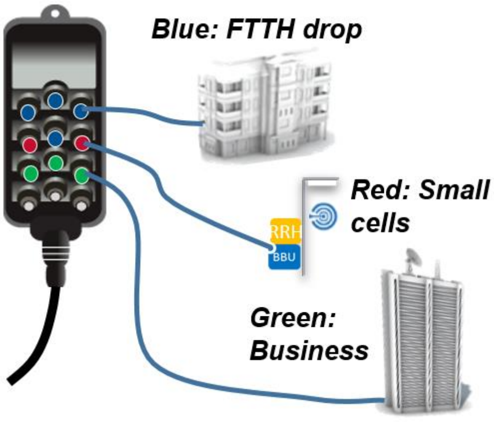

Figure 16: Drop cable terminal interconnect

Other low-level sharing arrangements are also possible or even desirable. Operators can share floor space in central offices in addition to cabinets; they could share electricity supplies, air-conditioning equipment, building and cable surveillance, and even the same active equipment – modern equipment can connect P2P, PON or even DSL with just one uplink to the network.

3.4. Fibre Sharing

Passive optical network (PON) architectures already provide forms of fibre sharing between many end customers. All the flavours of PON are detailed in the FTTH Handbook [0].

Older generations of PON are based on time-division multiplexing (TDM), where user terminals take turns to transmit data. Wavelength-division multiplexing (WDM) provides another degree of freedom for sharing a single 'pipe', with different signals on different wavelengths. We will briefly detail some new combinations of TDM-PON and WDM, for example in NG-PON2.

3.4.1. General WDM approaches

WDM is a method of combining or separating multiple wavelengths of light in or out of a single strand of fibre with each wavelength of light carrying a different signal. WDM filters reflect a certain range of wavelengths and let another range of wavelengths pass through.

Most FTTH networks today are using just two or three wavelengths – one for GPON downstream, one for GPON upstream, and one for RF video. The vast spectrum of coarse or dense WDM (C/DWDM) wavelengths remains unused, and hence offers a path for growth and evolution. These new wavelengths can be marketed as 'virtual dark fibre' or wavelength services and would be far less costly yet faster to deploy than laying P2P dark fibre.

One option is to use the same fibre strand but keep cell site traffic and residential GPON traffic on different wavelengths. Passive C/DWDM filters are put at both ends of the fibre to combine and separate the different wavelengths. Alternatively, traffic could be allocated to separate fibre strands, and connectivity at the hubs and closures designed to appropriately route the traffic.

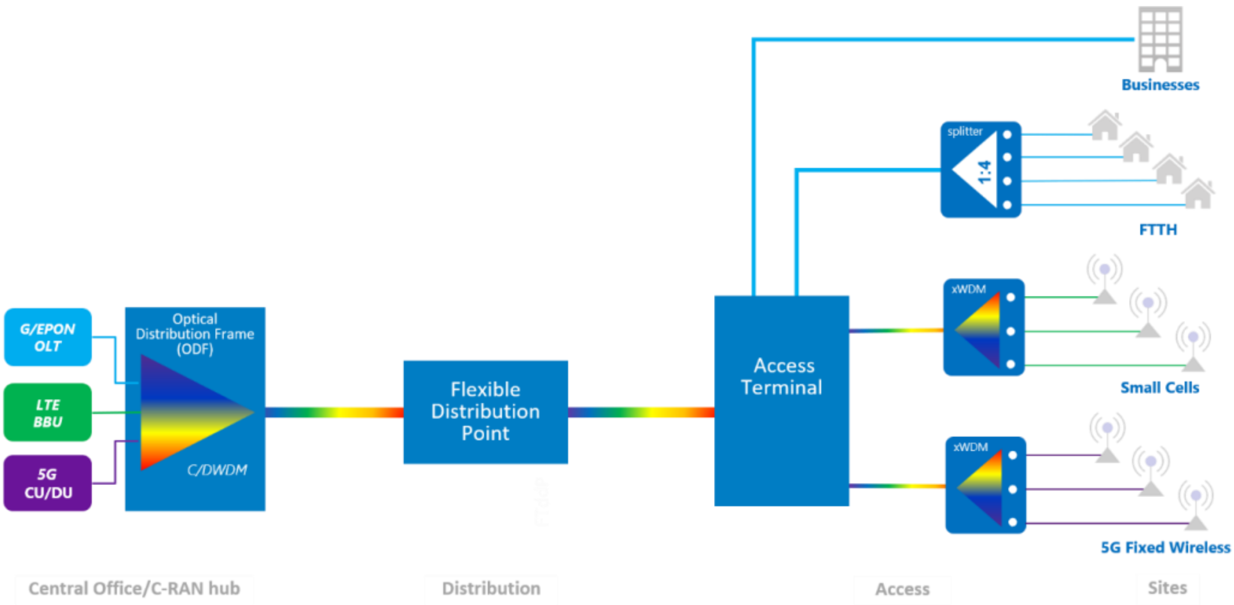

Figure 17: A WDM approach applied to the access network

Incumbent service providers usually have both wireline and wireless operations, so converging both onto a single network and maximizing asset utilization makes excellent business sense. Real-life examples have occurred where an FTTH network was built, and several months later, the same construction crew dug up the same street to lay fibre for a cell site – wasteful and disruptive.

For small telcos, utilities, and municipalities – who don't have deep pockets – addressing multiple market segments, adding revenue streams, and de-risking the business case may be the way to get their FTTH project approved. A city may have a project to fibre up schools and government offices, another for traffic lights and security cameras, one for Wi-Fi in the city centre and one for residential high-speed internet. By converging multiple applications onto a single fibre network, this project now has more stakeholders, more sources of funding and greater economies of scale.

Obtaining dark fibre for this application can often be a lengthy and costly process. With cell densification accelerating and 5G on the horizon, the availability of fibre becomes a potential bottleneck whilst the demand for fibre-based backhaul and fronthaul continues to increase.

A converged access and aggregation network will require architectures capable of delivering all services simultaneously (FTTH, FTTO, backhauling DSLAMs, Wi-Fi access points, backhauling macro and small cells, and fronthaul applications). With structural convergence in mind, the COMBO project (see §2.2.5) analysed two main architectural options:

1. DWDM
2. NG-PON2 with P2P WDM overlay

The conclusions are presented in the following sections.

3.4.2. DWDM

DWDM proves to be the most suitable architecture for areas where aggregation points in access networks are distributed (like OLTs in central office location and Ethernet switches or DSLAMs in cabinets or buildings). The flexible DWDM layer allows flexible wavelength allocation for fronthaul and backhaul applications, including DSLAM backhaul. Flexibility in the aggregation segment may be feasible as higher equipment costs, such as reconfigurable optical add-drop multiplexers (ROADMs) are shared over a larger number of clients.

3.4.3. NG-PON2 with P2P WDM Overlay

In areas where a common PON-based infrastructure is being deployed and access nodes are being centralized in main central offices, this option maximizes the reutilization of existing network resources. It shares power splitter-based optical distribution networks for all services except for fronthaul links, which are implemented with dedicated WDM overlay fibre to provision for its higher bandwidth requirements. In this solution, cells sites as well as fixed access mass-market lines are connected by a fully converged access network which combines P2P WDM overlay channels with a TWDM-PON, through a convergence element (CEMx) in the main central office.

3.4.4. Summary of WDM options

Based on the results from COMBO project, GPON architectures are the best option for a converged network for areas where common FTTH PON infrastructure is being built, which is the majority of scenarios. This has been confirmed by operators like Telefonica Spain, which plans to deploy XGS-PON with the aim of bringing faster broadband speeds to its customers but also help pave the way for 5G rollout, as the technology can be used for mobile backhaul as well as the aggregation of remote access node traffic [5].

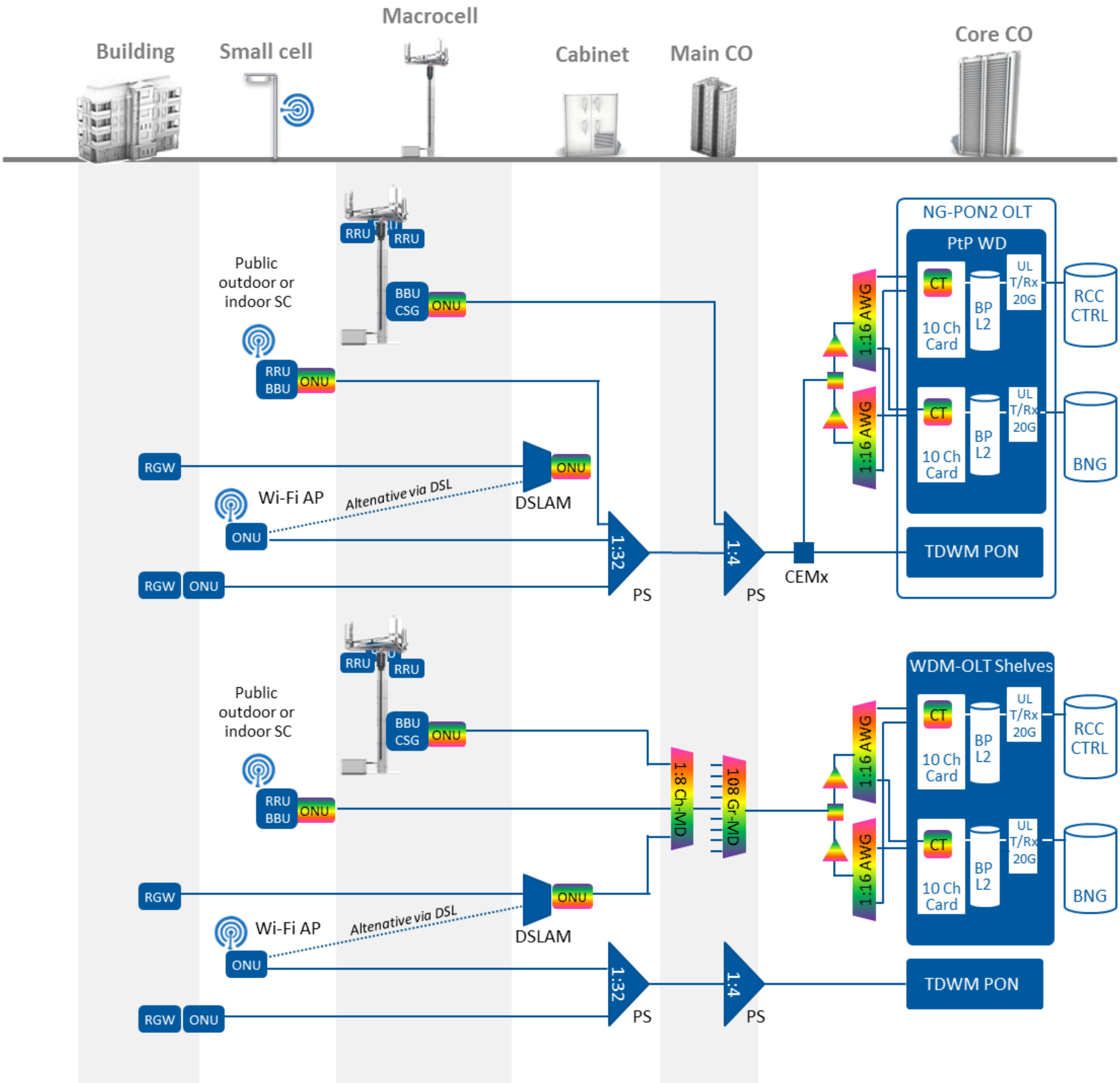

Figure 18: Two different convergence architectures analyzed by COMBO

3.5. IP Level and Virtualization

Two other major trends will impact networks as the industry moves forward, enabling further efficiencies in network construction and operations.

3.5.1. Network virtualization

The first is network virtualization, a trend whereby more and more network functions are virtualized with the ambition to drive efficiency through automation and pooling of resources [6].

Virtualization means traditional dedicated networking devices will be replaced by software running on standardized servers, which means both wireless and wireline networks will rely on these resources to be present throughout the network. It is an excellent opportunity to share these compute resources, as virtual machines and container technology allows for complete separation of the distinct functions.

While the industry focus has been on virtualization of core network functions to date, it is clear that 5G mobile networks will seek to virtualize baseband equipment in Cloud-RAN architectures from the outset. The same is happening in fixed networks, where concepts as virtual OLTs and CORD architectures (see §2.2.4) have been receiving broad industry support.

3.5.2. Multi-Access Edge Compute

The second trend is Multi-Access Edge Compute (MEC), which seeks to deploy computing power deeper in the network, in order to deliver low latency services, or simply avoid congestion of the core network by keeping the handling of large data volumes near the edge.

While it is yet unclear at what scale and at what location compute power will have to be deployed in the network, it is clear that making these resources available at points in the network where they are accessible for both mobile and fixed data connections will generate significant synergies for operators. The actual deployment of the MEC infrastructure will aim to reuse existing physical infrastructure, for example by deploying a number of racks in an existing central office, or by deploying a cabinet or small container at a wireless cell site location, in order to reuse the available real estate, power and connectivity these locations have to offer.

3.6. Planning

To move forward, operators must address a number of questions. How should an operator 'size' the various parts of a fibre or mobile network to be able to evolve and deal with structural convergence, to accommodate new fixed and mobile services and usages, and prepare for a near future with unknown services?

3.6.1. Back to basics

5G is definitely coming but is not here yet: technical standards have to be finalized, spectrum must be released and allocated, and new devices supporting 5G are still under development. There is no doubt that the launch of 5G is imminent, however the applications and the ecosystem will become more concrete over the coming years. From our perspective in 2019, this gives operators time to focus on the planning of current fibre networks and consider how to integrate 5G requirements into them.

First, while there are indeed many uncertainties, there are also some cornerstones that are sufficiently solid to serve as a basis for developing a strategy for FTTH and 5G infrastructure sharing and convergence:

- Fibre is essential for both fixed and mobile superfast connectivity. There is currently no other way to handle the increasing volumes of data consumed by actual users, and there is more to come when autonomous cars and other machines become connected.
- Radio access network densification is unavoidable: More cell sites and antennas will be needed, cf. §2.1.2.
- Fibre is going very deep: Antennas will have to get fibre connections, cf. §2.1.3.
- FTTH and 5G networks will be in place for at least a decade and probably longer. The passive infrastructure will continue to be available and used, even though transmission technologies and mobile radio standards will be changing over the long term.

Second, current 4G networks are already implementing concepts and techniques that serve as foundations for 5G networks (e.g. C-RAN, MIMO), and these techniques are going to be pushed further in order to achieve very high throughputs and very low latencies. Fibre will play a major part, whether for the radio access network or the fixed access:

- In most cases, the FTTH network is going to be rolled out first, and 4G and 5G cell sites can be integrated into the design to be connected by fibre.
- Conversely, plans to increase the coverage of 4G and 5G networks may also lead operators to consider the converging needs of fixed and mobile networks, and prepare fibre coverage in the same area.

Bringing the fibre needs for the fixed access and fronthaul/backhaul networks into one optimized fibre network design offers a significant cost-saving opportunity (for example trenching only once to install fibres for both use cases), but at the same time means a significant increase in complexity for the design, due to mixing different requirements into one network, for example:

- FTTH network could potentially use GPON splitters on fibres for consumer users, while fibres for front/backhaul might be P2P. Thus there is a need, as explained in §3.2, to design and obtain different fibre topologies on a same shared fibre network.
- Some fibre termination points may require redundant connections (rings) while others can be star topologies. This redundancy may also be required for business customers; thus the need for different topologies on a shared fibre network, as detailed in §3.2 and §3.3.
- Infrastructure sharing can happen on different levels as described above (trench, duct, cable or even on the level of fibres with separate wavelengths per application), each with their own impact on rollout and on operations.

3.6.2. Devise a future-proof strategy

An operator's strategy for deploying 5G-ready FTTH networks should take into account the characteristics and the needs of the rollout area.

3.6.2.1. Dense urban areas

If building new infrastructure is known to be difficult in specific urban areas – for example because the underground is saturated, making it difficult to dig new trenches, or collocation facilities would require too large a footprint, or obtaining permits is not easy and takes time – then there could be a real opportunity for shared infrastructure to be provided and managed by a neutral wholesale operator who will need to plan and build a fibre network with capacity for multiple types of networks and multiple operators.

3.6.2.2. Low-density urban and suburban areas

In low-density urban areas, the objective reasons for more infrastructure sharing are related to the higher costs of rolling out a 5G network in these geographies. Operators may be inclined to cooperate with third-party infrastructure providers to achieve rollouts in areas where it would be too expensive to have parallel networks or where cost reduction is more important than providing cutting-edge services exploiting the special features of 5G like ultra-low latency or massive IoT.

3.6.2.3. Rural areas

Rural areas are probably not at the forefront of operators' plans to make their investment in 5G profitable, but the presence of an FTTH network to share costs frames the equation differently. Primary roads, village centres and other places of interest (transportation hubs, shopping centres, tourist sites) can be of great interest to operators who need to 'quickly' extend their coverage within the framework of rules imposed by regulators and governments. It is expected that the incremental investment to support 5G in the future will not be significant compared to the other costs of deploying the FTTH network.

3.6.2.4. *Special needs for dedicated applications*

The specific use cases, for which 5G has been specially designed, deserve more attention. Transportation, mobility, and industrial factories will be the subject of specific applications that are not defined at the moment. Even 'private' 5G networks (for the industry) could drive very specific needs that are not possible to assess in a general way.

To talk more about the technique and address the topic of materials to be dimensioned, one should note that 5G networks will have special requirements with regard to typical FTTH architectures. In some ways, these requirements are, however, quite close to those that enterprise customers on a fibre network (FTTO) may already have:

- **Low latency**: Less important in the backhaul, latency will be critical in fronthaul connections. Carriers could consider providing dedicated fibres to allow other operators to use their protocols and not stack layers. Indeed, standards such as CPRI are popular in 4G networks but will not scale well for 5G. Standards and architectures are evolving (eCPRI) to make the use of Ethernet and/or WDM practical so that a pair of fibres, per operator, towards a cell site should be enough.
- **Strict SLAs**: Consider segregating fibres – or better cables – to improve fault detection and isolation, and to enable shorter repair times.
- **Protection**: Connections in the backhaul and sometimes the fronthaul will generally require ring topologies to provide multiple redundant paths in case of failure. This also reduces the number of fibres needed in comparison to point-to-point links on a star topology. Thus operators will provide, when possible, different paths for backhaul and even fronthaul links for increased service availability in the event of a failure in the transport network.
- **High security**: Securing access to cabinets, manholes, etc. should be considered when mission-critical services are being carried by the 5G network.

3.6.2.5. *Planning for the rollout of cell sites operating at higher frequency*

5G comes with different options for frequency bands. One popular option will be cells operating around 3.5 GHz. These cell sites will operate in a frequency band that is roughly twice as high as the current 4G deployments. 5G cell sites will also reuse actual 4G sites, and there will be a gap in-between that could be filled with new 5G cells. This expected densification and the current layout of macro cells can broadly guide the design of extra fibre capacity requirements.

Planning for the rollout of small cells designed to operate in the millimetre wave bands (above 26 GHz) will be another challenge. The exact location of the equipment (base station and antenna collocated) will depend on many factors due to wave propagation that only a specialized study will reveal, but best practices will also emerge over time. So, it could be of interest to pre-empt locations where structures to support antennas are available, or at least have the fibre run nearby: for instance, lamp posts, bus stops, etc. Creating a manhole or handhole and ensuring that access to the electricity grid is available would be a relatively future-proof approach.

3.6.3. Time frames are crucial

If there are plans for a 5G network and the locations for cell sites are already known, then planning a converged FTTH-5G network is complex but achievable, even though the technical details for the implementation of 5G networks are still evolving and could still change over time.

In many real-life cases, however, it is likely that a fibre network is being deployed for FTTH today, while the final decisions on the future 5G network are not yet fixed. In that case, planning for a future-proof fibre network becomes particularly challenging, as the fibre network also needs to be flexible to accommodate the unknown needs of the future 5G network.

Thus, time frames are crucial and it is important to understand the time-related implications of the progress of 5G technology in different markets:

3.6.3.1. Spectrum allocation

Frequencies are being assigned, but the schedule to free the spectrum assigned to 5G may spread over many years and beyond 2025. Moreover, spectrum allocation is a national issue for each market, for example 5G deployments in Europe presently focus on the 3.7 GHz band. The expected RAN densification is thus limited by the availability of spectrum; this can be taken into account in fibre network projects.

3.6.3.2. Availability of devices

Terminals for 5G are not yet commercially available, but this issue will be resolved soon – as the first 5G handsets are expected to be available by 2020.

Millimetre wave bands (26-28 GHz) have also been identified to provide 5G connections with very high throughput, with fixed wireless access being a likely application, but operators are not going to start massively rolling out the corresponding small cells, at least not in Europe. FTTH network promoters therefore have a little time to consider this option and define their plans. Thus, providing extra capacity in the FTTH network in the shape of empty ducts is generally a better option than installing massively oversized cables.

3.6.4. Evaluate and mitigate risks

The large number of uncertainties and the need to build a 5G-specific business model around the deployment of the FTTH involve risks that it is important to assess in advance. An operator will be better prepared if they know precisely how to quantify the incremental cost induced by the 5G network needs compared to the FTTH network, and test different scenarios with different levels of investment and different time assumptions. For example, extra capacity for 5G links could be added later in existing ducts, or by implementing WDM.

Other examples of risks include:

- In an urban area, fibre needs are expected to be high but operators may only be interested in certain routes and not in extra capacity for the whole area, because they may already have enough capacity in place locally. It is therefore better to plan an intensive deployment in partnership with other operators, rather than take the risk of overinvestment.
- In low-density areas (rural, suburban) where rolling out a dedicated 5G fibre infrastructure is deemed to be costly, it is likely that 5G operators will accept a shared network infrastructure, but this cannot be relied upon. It is thus very important to validate the pricing and the interest for the services or capacities offered, especially from a technical perspective, to make sure they match the needs of the 5G operators.
- Creating an infrastructure that is open to multiple 5G operators could increase the risk of accident, improper intervention, or damage to shared facilities, which could adversely impact the FTTH service. Therefore, particular attention should be given to the separation of services.

4. A 'CONVERGED' FUTURE

The need for more fibre in mobile networks is about to reshape the way the industry deploys both mobile and fibre networks. For decades fixed and mobile networks have been deployed separately in an expensive race to deliver higher broadband services. However, the future network will converge on a unified infrastructure capable of supporting any service, from FTTH to cell sites with fronthaul connectivity, promising important capital and operational cost savings to operators.

To accelerate the rollout of FTTH, network sharing has been employed as a remedy to reduce the build cost, often in response to regulatory intervention. This has proven to be successful in many cases and has resulted in a proliferation of methods of network sharing both at a structural and functional level. Fixed-mobile network convergence adds another dimension to this complex challenge, which blurs the conventional boundaries of the operations of fixed and mobile network operators.

From the convergence of applications and services at upper layers to the more intimate sharing of the optical spectrum, the possibilities of network convergence are yet to be completely explored. One thing is certain, however: PON architectures strongly resonate as the technology of choice. In areas where a common PON-based infrastructure is already in place, PON technology allows access fibres to be shared between all types of services, to make the most cost-effective use of main central offices, host OLTs, BBUs in centralized RAN architectures, and other radio elements in a fully converged access network.

Much of the opportunity for cost saving from converged networks lies in the optimization of geography and optical connectivity. Installed fibre stays in the ground for decades whereas the dynamic nature of mobile network capacity places severe demands on network agility. The network architect is planning for the unknown. However, it is clear that there is a strong synergy between FTTH deployment and the provision of optical connectivity for the expected proliferation of mobile cell sites, which the advent of 5G will demand.

The FTTH Council Global Alliance has explored the quantitative financial aspects of structural convergence in the study presented at the FTTH Conference in Amsterdam on 12-14March 2019.

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Table of figures

Glossary

APIs	Application Programming Interfaces
BBU	Baseband Unit
CPRI	Common Public Radio Interface
C-RAN	Centralized Radio Access Network
CWDM/DWDM	Coarse / Dense Wavelength Division Multiplexing
eMBB	Enhanced Mobile Broadband
FMC - FMCA	Fixed Mobile Convergence - Fixed Mobile Convergence Alliance
FTTH	Fibre to the Home
FTTO	Fibre to the Office
Het-Net	Heterogeneous Network
IMS	IP Multimedia Subsystem
IoT / mIoT	Internet of Things / massive Internet of Things
IRU	Indefeasible Rights of Use
mMTC	massive Machine Type Communication
MEC	Multi-Access Edge Computing
MIMO	Multiple-Input Multiple-Output
MTSOs	Mobile Switching Telephone Offices
NFV	Network Function Virtualization
ONF	Open Network Foundation
OSAM-HA	Open Source Access Manager Hardware Abstraction
OSP	Outside plant
P2P	Point to point
PON	Passive Optical Network
RAN	Radio Access Networks
ROADMs	Reconfigurable Optical Add-Drop Multiplexers
RRH (or RRU)	Remote Radio Head (also called Remote Radio Unit)
SDN	Software Defined Networking
SLA	Service level agreement
URLLC	Ultra-reliable and low-latency communications
V2x	Vehicle to Everything
VOLTHA	Virtual OLT Hardware Abstraction layer
WDM	Wavelength Division Multiplexing

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