

Cable and Mobile Convergence

A Vision from the Cable Communities Around the World

A Technical Paper prepared for SCTE•ISBE by

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1. Introduction

After tremendous growth and success in video, data, and voice services, cellular wireless is the next frontier for cable. Quarter over quarter, the US cable mobile virtual network operator (MVNO) business continues to see mobile subscriber growth. As of the Q2, 2020, less than three years after the launch of the first MVNO by Comcast, the three US cable MVNOs combined have amassed 4.2 million customers [1]. This is shown in Figure 1.

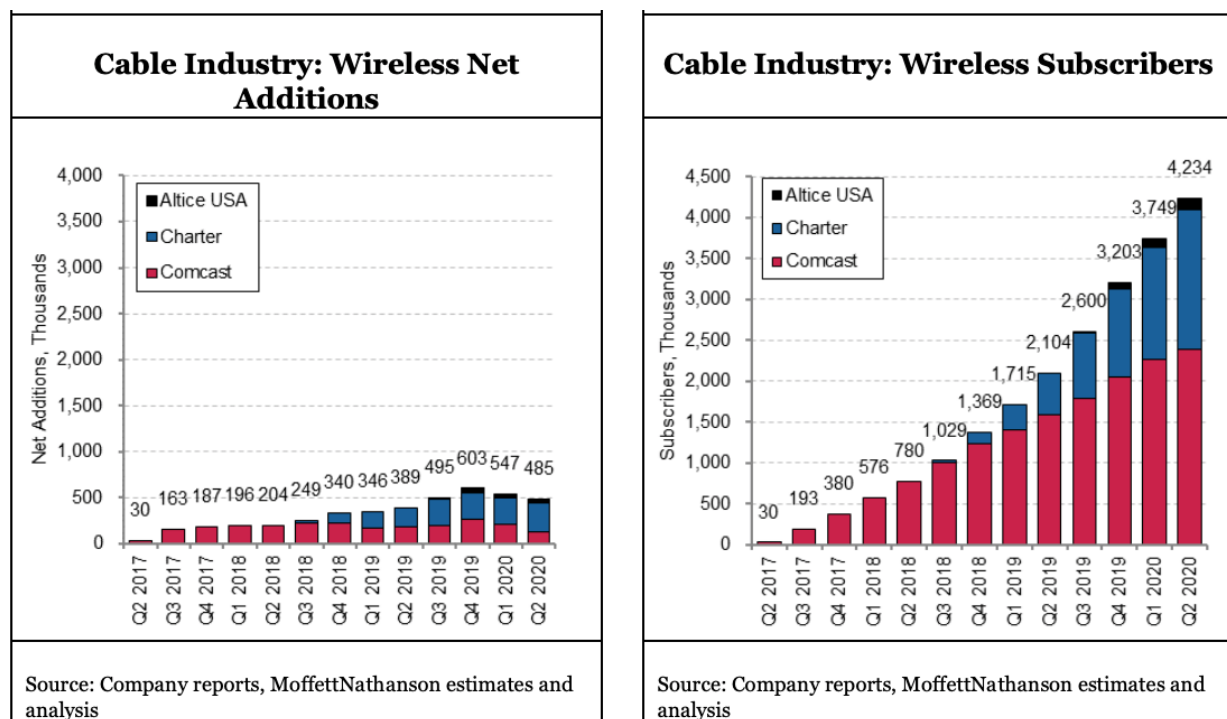


Figure 1 – Cable MVNO Customer Adds

While Comcast and Charter MVNO utilize Verizon as the mobile network operator (MNO), Altice USA has an agreement with Sprint (now T-Mobile). Recently, Cox Communication also demonstrated an interest in starting an MVNO.

The momentum is there. Consistently, executive leadership at cable companies has shown strong support for and interest in growing the wireless business.

The mobile customer growth is not restricted to the cable operators in the US. Cable operators in the neighboring north – Canada – are also reporting impressive number and innovative business model.

In contrast to the US, virtually all of Canada's largest cable and telco operators offer both wireline and mobile services on their own infrastructure. Rogers, Canada's largest cable and mobile operator, has been offering mobile services since 1985, with Vidéotron launching its wireless services in 2010, Shaw acquiring Wind Mobile in 2015, and Cogeco aiming to enter the Canadian wireless market through a Hybrid Mobile

Network Operator (HMNO) model. The Canadian market also faces strong competition from Canada's large incumbent Telco operators, which have invested heavily in fiber to the home, connecting more than 60% of their broadband homes directly to fiber, and leveraging a robust RAN sharing agreement to minimize their infrastructure costs.

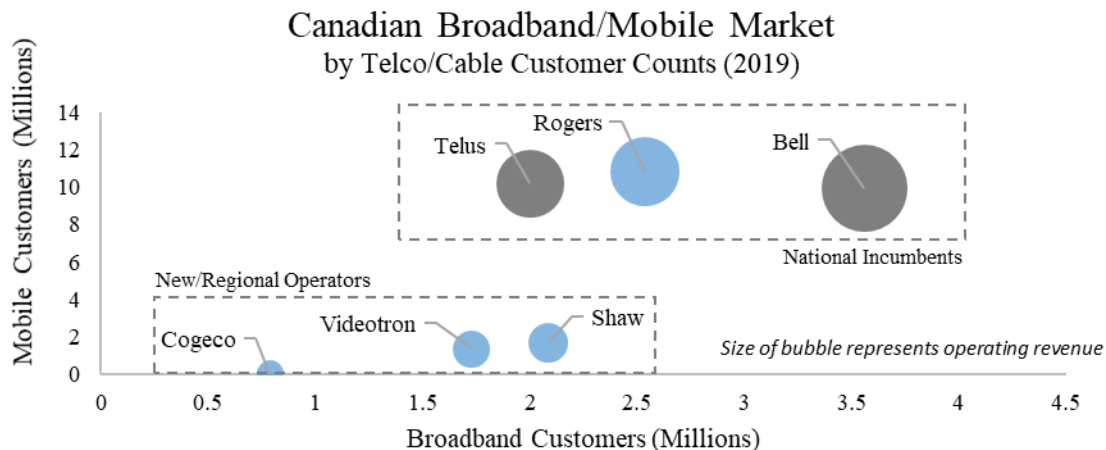


Figure 2 – Canadian Service Provider Market

In the South America market, Telecom is a leader in the Communication Service Provider (CSP) industry in Argentina. It is a merger of two companies – the former Telecom, incumbent telco, and former Cablevision, a cable operator. The merger of companies was approved in 2018, and the name TELECOM was kept as the name of the new company.

Telecom is the first CSP in Argentina to provide quad-play services: it serves 4 million fixed broadband subscribers, 18.8 million mobile subscribers, 3.5 million TV subscribers and 3 million fixed voice subscribers. It also provides business services. Telecom Argentina is a connectivity solutions and entertainment company transforming the digital experience of its customers, providing them a secure, flexible and dynamic service on all of their devices, with high speed mobile and fixed connections, and a live and on-demand contents platform which includes series, films, gaming, music and TV shows. It is also present in Paraguay, providing mobile service, and in Uruguay, with pay TV.

In Europe, the transformation of cable company to mobile company is mostly done. One of the biggest cable companies in Europe, and the world for that matter, is Vodafone. Vodafone acquired a variety of cable properties across Europe and now operates cable franchises in Germany, Spain, Czech Republic, Hungary, Romania, Albania.

The mobile journey of the cable companies will become an amazing success story. This white paper is intended to grab a snapshot of that story as it is coming together today. The paper will start with a framework for looking at different types of convergence which is also different ways of investing capital for different outcomes. The paper will then showcase six different cable operators with mobile plans, each of whom have common goals and technologies, but a unique point of view. Once the goals and objectives are understood, the paper will highlight technologies that are common to the solutions. These are some of the important technologies that we want the industry to focus on.

2. Four Stories of Convergence

There is a lot of buzz round convergence. What is convergence? Is it something in a 3GPP specification? Is it a product? Is it something in your architecture? Is it your customer's experience? Is it your experience? In this section, we would like to describe four stories of convergence. These are shown in Figure 3.

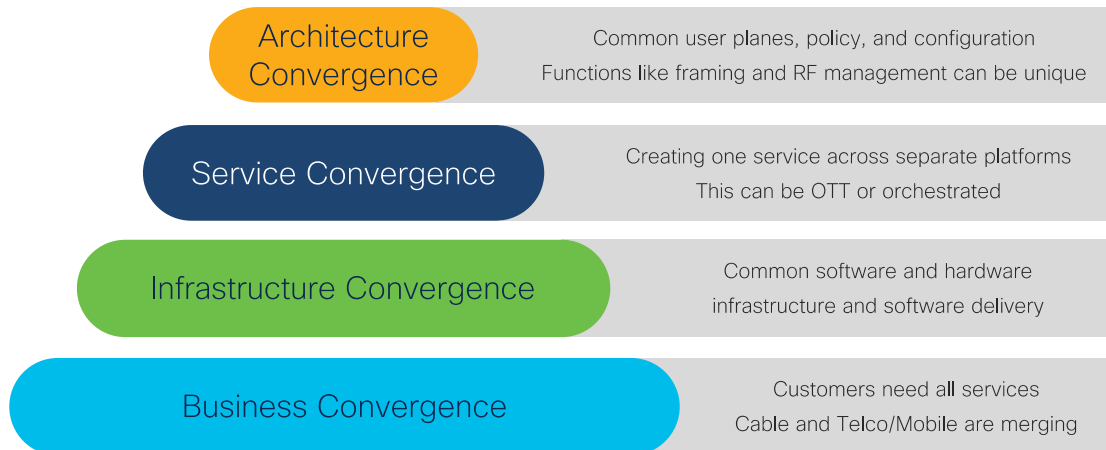


Figure 3 – The Four Stories of Convergence

2.1. Business Convergence

First things first. It does not make sense to converge technologies and architectures if there is not a business reason. As a stark example, it does not make sense to merge a DOCSIS and 5G system if your company is a pure mobile / telco company that does not have cable properties. Conversely, if you are just a cable operator with no mobile operations, does a 5G driven CMTS add profit to the bottom line? It doesn't.

So, the first step of business convergence is subscriber convergence. The same subscriber needs to pay for both cable broadband service and mobile service. This has already happened across the world. As you are reading this paper, you own a smart phone, a laptop, and have some kind of broadband service at home with either a legacy video service or some type of over the top video service, as does everyone in your family and so do your friends. Subscriber convergence is a done deal.

The second step in business convergence is convergence of cable and mobile operators. As shown in Table 1, this is currently happening around the world. Today's cable operators are tomorrow's mobile operators.

Table 1 – Operator Convergence

Region	Cable Operators	Status
USA	GCI	MNO
	Comcast, Charter, Cox, Altice	MVNO
Canada	Shaw, Rogers, Videotron, Eastlink	MNO
Latin America	Telecom Argentina, Claro Brazil, Liberty Latin America	MNO
Europe	Telenet (Belgium), SFR (France), Vodafone (Germany, Spain, Czech Republic, Hungary, Romania, Albania), NOS (Portugal), Telenor (Norway), TDC Net (Denmark), VodafoneZiggo (Netherlands), Telia (Norway/Finland), Tele2 (Sweden/Baltic), Virgin Media+Telefonica/O2 (UK)	MNO
	Virgin Media (UK), UPC Poland, UPC Switzerland	MVNO

Now, it would make sense that if you were to get both your cable broadband service and your mobile service from the same operator, that you would want to get a discount? What is that impact to the operator?

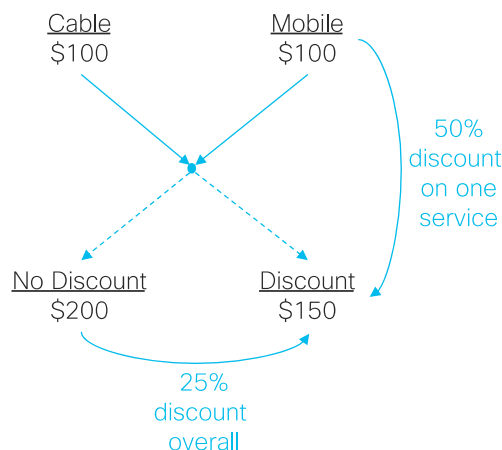


Figure 4 – Subscriber Convergence

Let's say you pay \$100 a month for broadband and a \$100 a month for mobile. If you combined your services with one operator, getting both services for \$150 would seem like a reasonable deal. This is shown in Figure 4. Now, as an operator who now owns both the mobile property and the cable property, this means less overall revenue for the same customer base. That means that either one of those operations – cable or mobile, needs to reduce its operating expenses by 50%, or both operations have to reduce their operations by 25%.

An important aspect of converging cable and mobile businesses together is organizational convergence. Otherwise, you just have two companies within one company, sometimes each with their own network. The challenge and importance of this is not to be underestimated and it often requires some sort of cultural convergence. There can no longer be a cable vs mobile competition within the new company. Everyone

must work together to make their subscribers happy with their services at the best cost operating model for the new company.

Subscriber convergence has already happened. Business convergence is happening now. Technology convergence is next [2]. And the outcome that overall convergence should strive for should be at least a 25% reduction in operating costs, if not more.

2.2. Infrastructure Convergence

If you could wear the same set of clothes every day and for everything you do, you would save a lot of money in clothing. Well, that may be impossible for most people, but what about converging the network that hosts a DOCSIS and mobile service? Could that save some money? There are many opportunities for infrastructure convergence. Here are a few examples.

2.2.1. Transport Network

Macrocells and small cells are typically connected using dedicated fiber. For new small cell locations, this might necessitate pulling fiber to a new location along with some copper for powering. This may prove cost prohibitive if a large number of fibers have to be pulled just to support a new service. Alternatively, the cable HFC plant is already composed of fiber and copper, each of which provide an opportunity for transport convergence.

The fiber portion of the HFC network currently uses an “analog” transport that is composed of modulated wavelengths. As the HFC plant gets upgraded to the new Distributed Access Architecture (DAA), that fiber will be converted to “digital” which refers to Ethernet over a wavelength. The analog lambdas are sensitive to noise and cannot coexist with digital lambdas.

As discussed in this paper, the HFC plant with DOCSIS as the transport layer is a great choice for mobile xhaul. So, just using HFC/DOCSIS as backhaul for mobile, even though DOCSIS and mobile might be two different services, is an example of transport convergence that has the potential to save a considerable amount of money by not having to deploy more fiber. By connecting the small cell to the coax side of the HFC plant, the fiber can be analog or digital.

While the HFC plant is still analog, analog services and digital services can use the same plant but must be on separate fibers. When the HFC plant is upgraded to DAA and the fiber becomes digital, then different services can be connected to the fiber, either through dense wave division multiplexing (DWDM), with one service per wavelength, or with an Ethernet switch located in the field that aggregates services on separate 10 or 25 Gbps links and then backhauls them all together on one 100 Gbps to 400 Gbps wavelength.

2.2.2. Open Source Code

Almost all products these days use open source. One of the nice things about open source software is that there are a lot of creative solutions and interesting choices. Open source can save considerable development time. One of the downsides of open source is support. Open source code goes in and out of style. If your system adopts some popular open source that suddenly becomes unpopular, you will lose the support of the community. This means it will be harder to add features and get bug fixes.

Another challenge for open source is that there are security holes and sometimes hundreds of them. Each release of open source needs to be properly vetted to close those security holes. And then there is personnel training. Each piece of software needs to be installed, supported, and upgraded by someone.

Wouldn't it make sense to use the same revision of open source across multiple systems? Would it not make sense to have a uniform code security policy? Wouldn't it make sense to use the same Kubernetes deployer for microservices?

To be fair, much of this open source is very transparent to the operator and is packaged internally by the vendor. There could be separate vendors for cable and mobile systems. Still, tracking open source issues is a real issue to consider.

2.2.3. Data Center

Software used to run in dedicated hardware boxes. Then in the mobile world, software was virtualized and placed onto servers. Now the software is being rewritten using cloud native technologies with microservices and containers intended for an SP edge (data center) environment.

This is cloud and edge ready software. Unfortunately, not all data centers environments are the same and cloud native technologies have been evolving at such a rapid pace recently, that it is currently an operational challenge to completely mix different applications from different vendors into a common cloud or data center deployment. But, it will happen, and this will help achieve a goal of operational simplicity where servers are installed in server farms and software does not much care where it lands.

Infrastructure convergence is happening and is a natural consequence of getting a product to market in an efficient manner. There is more work to be done, but it is a well understood problem that can be worked and optimized.

2.3. Service Convergence

A service is something a customer receives, experiences, and pays money for. It has a meaning and a feeling. The challenge is to identify those services that cross the mobile/cable boundary that can generate additional revenue, reduce operating expense, or both.

A converged service would imply that it should not matter where you are, or if you are connected by mobile, Wi-Fi, DOCSIS or PON -- you get the same service and experience.

Some examples of converged services that come up are the following:

Parental Controls: A parent can assign parental controls to a child's device and those controls work whether the device is on the cable broadband network or on the mobile network

Service Class Roaming: If you are a premium subscriber with a higher bit rate, you get the same service at your neighbors or the local coffee shop, even if those locations have lower service

Shared credentials on Mobile/WiFi: WiFi is often the extension of a DOCSIS network. This convergence would allow a single sign on and may even allow the network to direct which path to take based upon local mobile or cable network loading.

High Availability: If one of your transports such as cable access goes down, your services would transfer to the mobile access. This could occur transparently in the network or with some kind of blended service environment in the home.

It should be noted that mobile service today is per device – typically per cell phone and this per user. Cable broadband service is per home and the billing entity is per home which is per cable modem. There is a difference in device identification technologies. Cable modems do not use SIMs. Cell phones do.

One example of distinct separate networks but with a converged service is video conferencing where the video stream is sent over the broadband Internet, but the voice is sent over mobile as the mobile voice connection seems more reliable than the Internet connection. This convergence is simply achieved by the video using an IP address and the audio using a telephone number.

The key question is if the networks need to be converged to achieve these goals, or can dissimilar networks like mobile and DOCSIS just share common policy?

2.4. Architectural Convergence

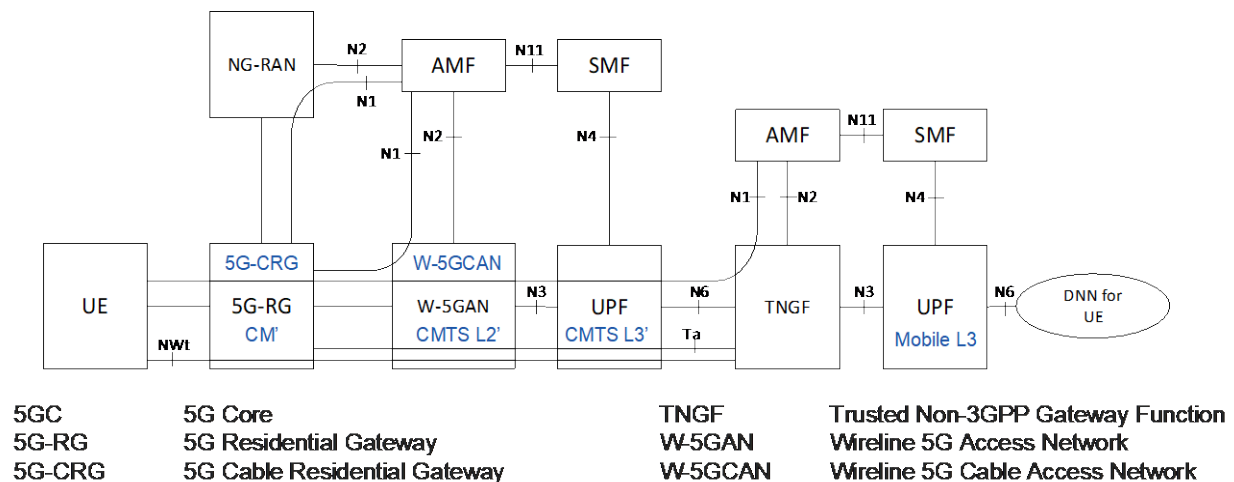


Figure 5 – Architectural Convergence

Architectural convergence is where the cable and mobile networks are truly converged. They share a common user plane and a common control plane. This convergence allows for different messaging over the RF interface. The classic example is the wireless and wireline convergence (WWC) work done in 3GPP [3][2]. This is shown in Figure 5, annotated with DOCSIS and mobile functionality. The groundwork for this architecture is partly based in joint CableLabs-Cisco whitepaper at a previous SCTE Expo [4].

Does this architectural convergence add simplicity or complexity? The DOCSIS system works fine and has worked fine for 25 years. Does drastically changing a 25-year old system add value or just add complexity?

What about software upgrades? Do the mobile and DOCSIS systems now have to be upgraded at the same time since that may be how they were tested? How does that impact the service velocity, which is the ability to roll out new services and bug fixes?

Does it reduce OPEX and CAPEX costs or does it add to those costs? Can you still mix and match vendors when the systems are highly interconnected? That may impact the operator's ability to buy best of breed. Can the entire DOCSIS CM provisioning system be replaced or augmented with a 5G provisioning system? Is there enough financial motivation for vendors to implement these changes?

These are important questions that are not fully answered yet, even though the early architectural pieces have been put into place. One thing is certain though, and that the work does not begin here, it ends here. Before architectural convergence takes place, there has to be business, infrastructure, and service convergence first.

3. Traffic Engineering

As the cable network adapts to the connectivity of small cells to fiber or HFC, it is instructive to know how many small cells are required to replace or supplement a macrocell installation. Those numbers are calculated in [5] and briefly summarized here.

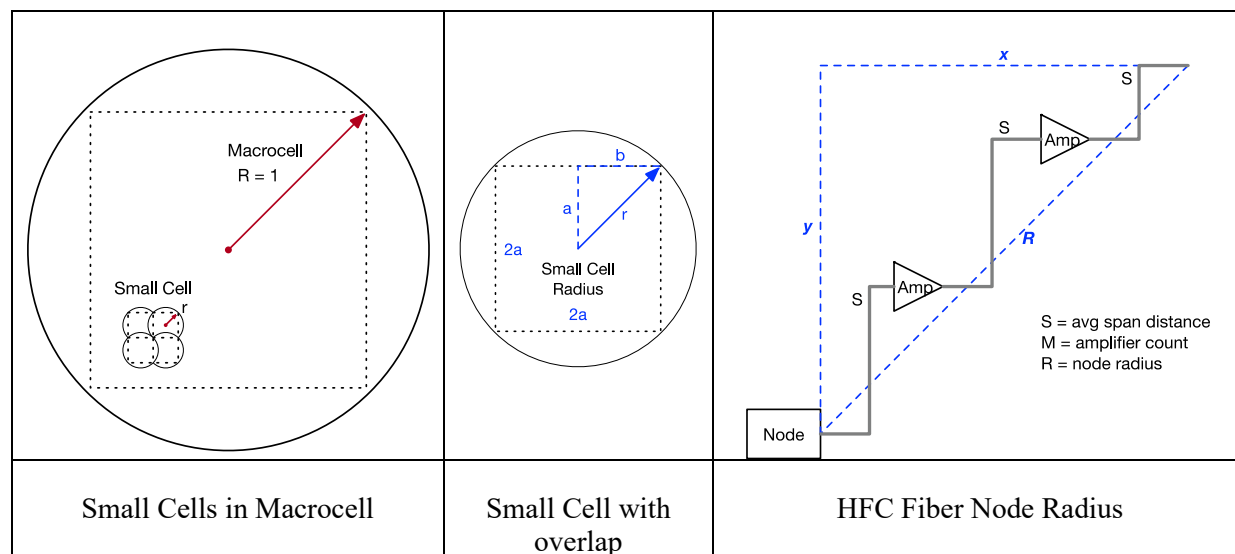


Figure 6 – Small Cell Traffic Engineering

An ideal overlap of one small cell radius to another is equivalent to placing a square in a circle and seeing how many small squares (for small cells) fit into a large square or circle (for macrocell). A similar calculation can be done by calculating the radius of the coax segment of an HFC plant. This is shown in Figure 6.

The number of small cells required depends upon the ratio of the service radius and is given by the formulas:

$$\#SC \text{ per MC} = \pi/2 (R/r)^2$$

$$\#SC \text{ per FN} = \pi/4 (S/r)^2 (M + 1)^2$$

where:

R = larger radius of macrocell or node

r = smaller radius of small cell

S = average coax span between actives

M = number of amplifiers in an $N+M$ cascade

The results of these formulas are shown in Table 2 and Table 3. The relative radius in Table 2 assume same power and same height. In reality, the small cells will be lower power and lower height, plus there will be RF blockage from tree, hill, and walls. As a result, actual deployed results may be higher. Likewise, if less than 100% coverage is needed, the numbers scale back down.

Table 2 – RF Cell Radius Comparison

Band	Service	Cell Type	Relative Radius	# Radios
700 MHz	LTE	MC	1.0	1
3.5 GHz	CBRS	SC	0.09	125 to 200
28 GHz	mmWave	SC	0.003	110,000 to 175,000

The first conclusion is that it can the number of radios for CBRS can be 100x that of an LTE macrocell, and for mmWave, the number of radios could be 100,000x that of an LTE macrocell. This dramatically impacts deployment economics and makes the existing HFC plant an interesting choice for mobile backhaul.

Table 3 – Small Cells per Fiber Node

		Small cell radius r:		500	1000	2000
M Amps	Total Span	Node Radius	Avg Span	# radios	# radios	# radios
0	1100	778	1100	4	1	1
1	2000	1414	1000	13	3	1
2	2850	2015	950	26	6	2
3	3700	2616	925	43	11	3
4	4600	3253	920	66	17	4
5	5460	3861	910	94	23	6
6	6300	4455	900	125	31	8

A second conclusion is that there is not just one small cell per fiber node on an HFC plant. It depends on the size of the coax segment the HFC plant. So, an N+0 plant may need one to four small cells, where as a N+5 plant may need 25 to 100.

4. A Survey of Mobile Deployment Plans by MSOs Around the World

Now that there is a framework and traffic engineering that show the need to connect small cells in an economical way, let's look at the goals and achievements of six prominent cable operators who are also MNO or MVNO as well.

4.1. Charter Communications

Since the merger earlier in the decade, Charter has been bullish on wireless and continues to invest significantly in research and development. Charter participation and leadership in industry forums and investments in startup ecosystem are a few obvious evidences of the long-term interest and strategy.

4.1.1. *Spectrum Mobile Data Offload*

In the second half of 2018, Charter launched a mobile service (Spectrum Mobile) via a Mobile Virtual Network Operator (MVNO) agreement with Verizon Wireless. All Spectrum Mobile voice and SMS traffic is transported over Verizon Wireless' cellular network. Spectrum Mobile data traffic is either transported over Verizon's cellular network or over Wi-Fi networks.

One of the core technologies enabling cable MVNO is wireless data offload. Charter has an extensive indoor and outdoor Wi-Fi network, which, in addition to providing broadband services, is used to offload the mobile data traffic away from Verizon's network. The contribution of Wi-Fi data-offload in making Spectrum Mobile a fast-growing and economical business can't be overstated.

However, there are limitations on where and how much Wi-Fi can be effectively used to offload cellular traffic. There are some well-known challenges with Wi-Fi data offload. For example,

- Some Spectrum Mobile customers manually switch off the Wi-Fi interface on the End-User Devices
- In congested networks, it isn't easy to manage the Quality of Experience (QoE) on Wi-Fi networks

As a result of these challenges with Wi-Fi, a decent size of the "off loadable" traffic is not offloaded from the Verizon network.

Operators are evaluating multiple solutions and tools to improve the offload numbers. One solution of particular interest is CBRS small cell, which could be used to complement Wi-Fi networks. Not only the CBRS 4G LTE networks could help with the offload, but also offer better QoS and mobility than incumbent Wi-Fi networks.

The CBRS RAN could target a range of indoor and outdoor deployment scenarios, such as outdoor, strand installations covering high demand areas and indoor, small and medium business (SMB), enterprise, residential femtocell deployments. These deployment scenarios are described in more detail later.

4.1.2. *Cellular Wireless – A New and Exciting Frontier*

The deployment of new wireless technologies from scratch is not without challenges. Cable companies have years of experience designing, deploying and managing Wi-Fi based networks both outdoors and indoors.

The 3GPP wireless technologies have unique requirements, which require attention of the cable operators and vendors alike. We talk about these unique requirements in the following sections to draw attention of the cable ecosystem and work together to conquer the wireless frontier at scale.

4.1.3. Possible Wireless Deployment Scenarios

4.1.3.1. Fixed Wireless Access (FWA)

FWA can target rural areas to extend the broadband service to unserved or underserved areas, and expand the footprint of the HFC network economically. FWA requires a transceiver outside the home. This use case can be realized by installing RAN equipment onto telecommunication towers and/or other suitable mounting locations, such as water towers.

4.1.3.2. Strand Mount (Aerial)

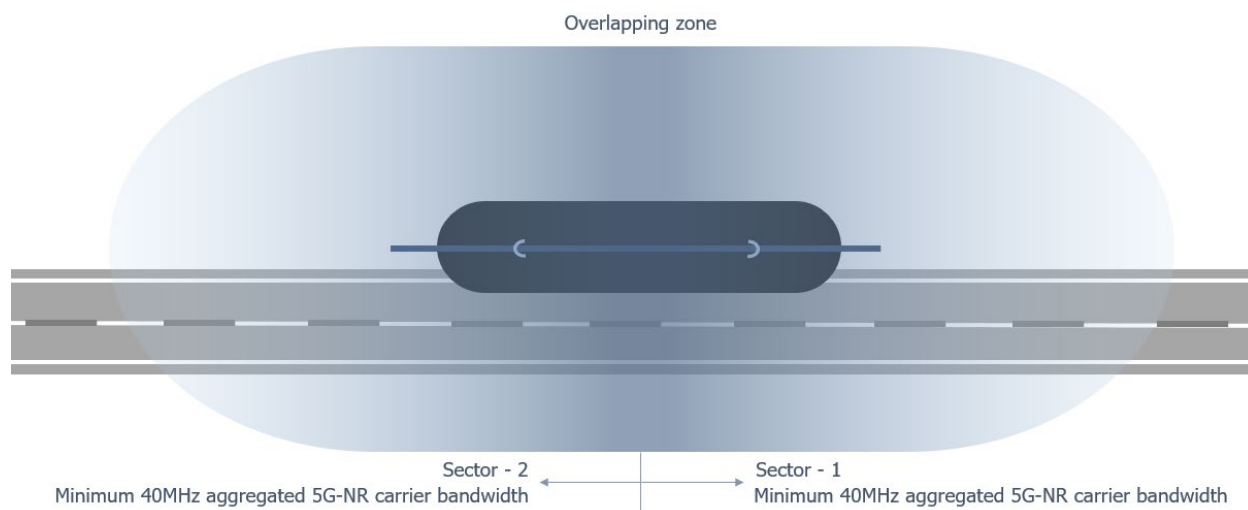


Figure 7 – An Example CBRS Strand Mount Deployment with Overlapping Macrocell

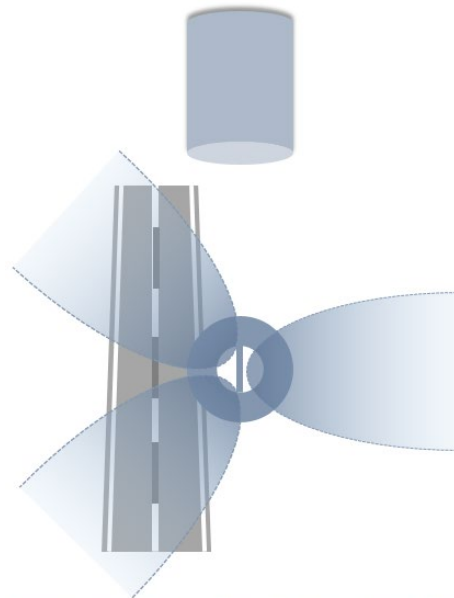
This is a one box solution that is mounted on the strand, where wireless radio is integrated with a DOCSIS 3.1 cable modem (CM). CBRS Category-B device types are planned with a quasi-omni and dual sector design.

Virtual RAN Deployment Model: operators are exploring technologies with split option 2 (shown later in Figure 58) for its vRAN based 5G CBRS wireless network deployment over DOCSIS because of its data transmission latency advantages. Since the DOCSIS network provides advanced latency reduction features such as the Bandwidth Report in the Low Latency Xhaul (LLX) technology [6], Charter may leverage such a feature to further ease CBRS wireless network deployment on cable strand. We will keep monitoring the latest advancements in vRAN field, and latest releases of 3GPP standards, together with O-RAN Alliance initiatives to fine tune our vRAN network deployment strategies.

Strand-mount appears to be the most cost-effective solution where aerial cable strand lines exist. The size and power of strand-mounted solutions are lower than attached mount (explained in a later section) CBRS device (CBSD), but their biggest limitation is power consumption from the HFC plant power supply. Another potential limitation of a strand unit is the mounting orientation – it has to be always along the strand and thus hotspot-targeted deployment in this case might be challenging. To mitigate this, engineers are evaluating quasi-omni strand design that has dual sectors with two sets of antennas covering NE and SW directions. Their height is always 18 feet and typically comes with 2 transmitters 2 receivers (2T2R)

multiple-input multiple-output (MIMO) capability. Utilizing existing assets to mount, connect to, maintain and operate may make these the most cost-efficient deployment type for outdoor Category-B CBSDs.

4.1.3.3. SMB Inside-Out



3 beams coverage from Integrated Directional Antenna
 Minimum 40MHz aggregated 5G-NR carrier bandwidth

Figure 8 – Tri-Star Configuration Product

“Inside-out” could provide outdoor / pedestrian street coverage utilizing its small and medium business customers’ locations. Charter has conducted tests in various SMB locations in New York and Los Angeles markets. Results show that the indoor low power Category-A CBSDs can provide blanket coverage when deployed every 400 – 500 ft.

A strand or attach mount usually compliments SMB coverage by serving as an umbrella cell and fill in any coverage holes. A Tri-Star configuration which adds a third sector to cover indoor and two sectors pointing outside the stores from behind a glass window is being evaluated. Operators can make use of this deployment type where applicable to form a uniform layer of CBRS coverage targeting an areas of interest (AOI) and have run trials confirming seamless connectivity and performance between them.

4.1.3.4. Attached Mount

In high demand markets such as New York, operators may leverage locations where it has wireless rights on the buildings to deploy high power Category-B CBSDs for outdoor mini-macro type deployment. Attached mount nodes can be installed more strategically than strand mount or SMB to clear obstructions or point to a targeted hotspot with required down-tilts like other two types (strand, SMB) of deployment. Attached mount deployment use case brings possibility to deploy most advanced antenna features such as MIMO and antenna beamforming to support 5G technology deployment and provide high end user performance speeds. This type of deployment provides larger coverage and capacity than strand and SMB scenarios.

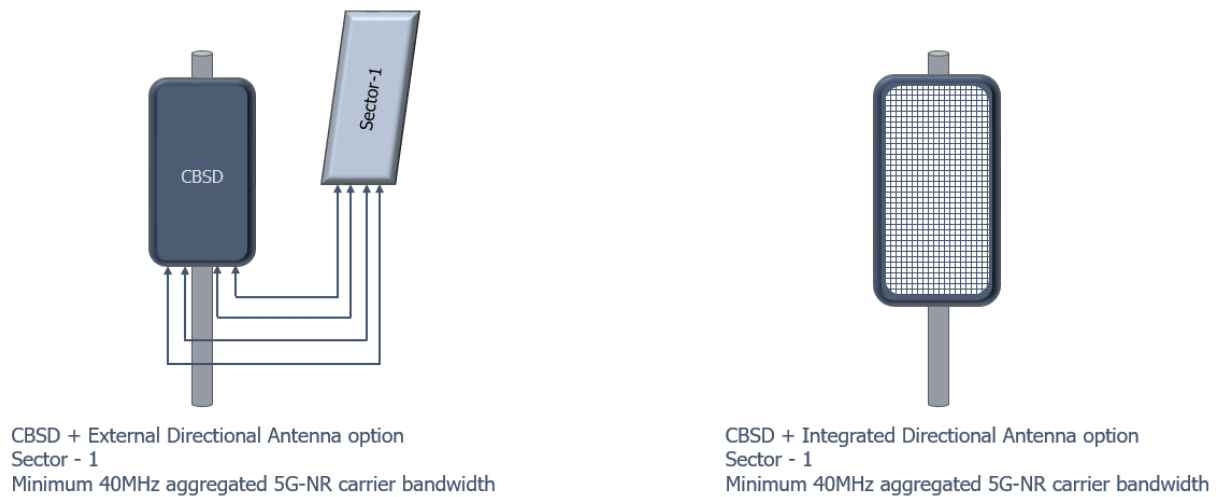


Figure 9 – Attached Mount Mini-Macro

4.1.3.5. Indoor Enterprise

This scenario covers indoor deployment of CBSDs into large enterprises, multi-dwelling units (MDU) and indoor venues. Charter has done indoor enterprise trials in its Spectrum Plaza office building with 50 indoor Category-A type CBSDs with 4G CBRS service.



Figure 10 – Example Cat-A CBSD

4.1.3.6. Residential Femtocell

For a typical residence, a femtocell shall provide comprehensive coverage inside and around the house.

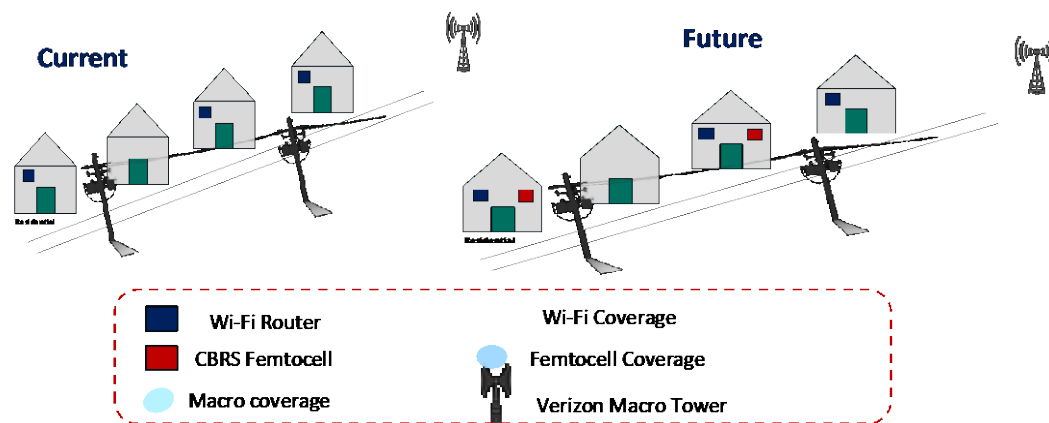


Figure 11 – Residential Femtocell Deployment

Key Features of Residential Femtocell scenario are as follows:

- Deployment Type: Indoor
- CBSD Class: CAT A
- EIRP: 30 dBm
- Antenna: Integrated Omni
- Backhaul: Ethernet/DOCSIS
- Power: AC

4.1.3.7. Residential Femtocell and In-home Connectivity

MSOs have a range of options for standalone femtocell connectivity in the home, which are depicted in Figure 12. Each option has its advantages and disadvantages. Option #3 in Figure 12 is intuitive and used by a couple of MNOs in the USA, but can it support TDD LTE timing and synchronization requirements without requiring hardware upgrade on the Wi-Fi router? Option #1 will require the addition of new LAN ports on the CM. Option #2 will put the femtocell in the path of all the broadband traffic in the home, which may not be optimum.

The solution the industry selects for timing and synchronization will be one of the primary factors in deciding the in-home connectivity model. The timing and synchronization topics are covered in Section 5.3 of this paper.

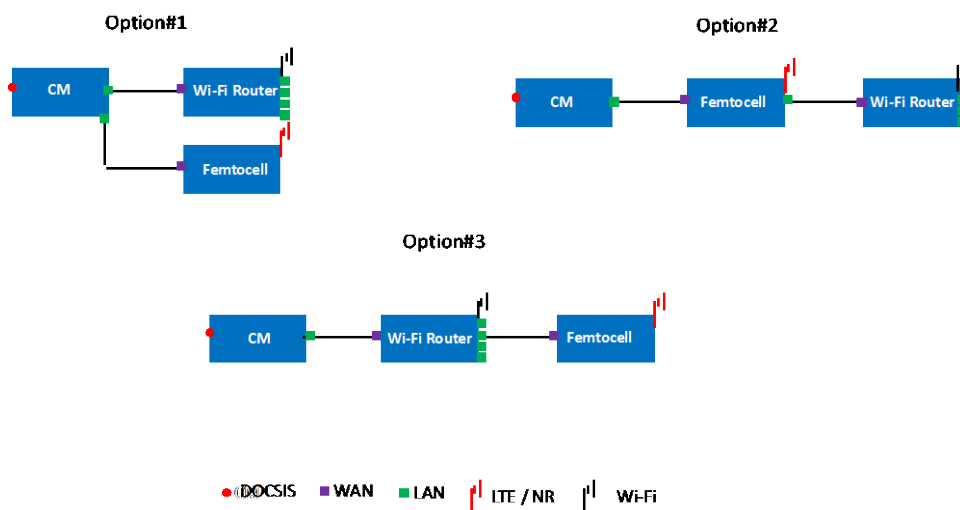


Figure 12 – Residential Small Cell Gateway Options

4.1.4. Backhaul

The near-ubiquitous availability of cable and DOCSIS assets in urban and suburban areas may be one of the key enablers for the industry to deploy small cells at scale economically.

There are, however, some preparation and planning around bandwidth, latency, QoS, and timing that operators need to make.

4.1.4.1. Bandwidth

Depending on the wireless node capabilities, configuration, and network architecture, the peak and average bandwidth demands on the DOCSIS backhaul will vary.

For example, a 20 MHz TDD LTE small cell will demand much less peak bandwidth than a 40 or 100 MHz 5G NR small cell. Similarly, an integrated small cell architecture will require less average bandwidth per node for control plane traffic than a vRAN based architecture.

4.1.4.2. Latency

Latency is a critical factor in determining the quality of experience for the end-users. High end-to-end latency for user plane traffic can deteriorate user experience enough to render some applications unusable. Additionally, high latency for the control plane traffic may break important cellular features such as seamless handover.

MSOs are evaluating the application of CableLabs' Low Latency Xhaul (LLX) [6] technology in reducing latency through mobile and DOCSIS scheduler pipelining.

4.1.4.3. Quality of Service (QoS)

The HFC plant is a shared medium used by many customers and applications simultaneously in the time and frequency domain. Luckily, DOCSIS offers an extensive set of tools (e.g., service flows and classifier) to logically separate and treat traffic differently for different applications.

Layer 2 and layer 3 traffic tagging capabilities to allow the cable modem to apply operator provisioned classifiers and ultimately customized QoS for all traffic originating from and terminating at the small cell.

4.1.4.4. Timing and Synchronization

Unlike Wi-Fi, 4G LTE and 5G NR require stringent synchronization (frequency and phase) of wireless transmissions to avoid interference between uplink and downlink. Since the CBRS spectrum is a shared band, the clock synchronization across base stations of both the same and different operators is critical for full realization of the spectrum and to avoid unwanted interference.

As laid out in Table 4, the timing and synchronization requirements for TDD LTE and 5G NR are especially stringent.

Table 4 – Timing and Sync Requirements of LTE and 5G

	Frequency	Phase
4G LTE TDD	± 50 ppb	± 1.5 μ s
5G TDD	± 50 ppb	± 1.5 μ s

These synchronization requirements are documented in 3GPP specifications TS 36.133, TS 36.922, and TS 38.104.

The acquisition of accurate phase and frequency for outdoor small cell deployment is rather straightforward using GPS.

On the other hand, the acquisition of accurate phase and frequency for indoor wireless deployment is much more complex and requires evaluation of multiple options.

As highlighted in the table below, there several options for timing and synchronization. For outdoor deployments, GPS is the most widely used timing source. However, for indoor applications such as femtocell, the combination of precision time protocol (PTP) and DOCSIS Time Protocol (DTP) ranks higher on the list and is being carefully studied and tested.

Table 5 – Options to Provide Timing and Sync

	Advantages	Disadvantages
DOCSIS Time Protocol (DTP) with PTP	<p>Supports LTE TDD and 5G timing precision requirements</p> <p>Timing from operator-owned and operated network</p> <p>CableLabs standard promoted by cable vendors</p>	<p>Requires significant changes to DOCSIS infrastructure, including hardware upgrade to CM</p> <p>Grand Master clocks in each headend</p> <p>Regular network calibrations MAY be required</p>
Global Positioning System (GPS) *With and without network assist	<p>No upgrades to DOCSIS network required</p> <p>Supports LTE TDD timing precision requirements</p>	<p>Receive challenges indoors, susceptible to jamming</p> <p>Placement not in the control of the operator</p> <p>Installation and operation cost external antennas</p>
Network Listen/Macro Sniffing (e.g., synchronization signals from Macro cells)	<p>No upgrades to DOCSIS network required</p>	<p>Reliance on macro network for timing, availability everywhere could be an issue</p> <p>Out-of-band listen requires dedicated radio – additional cost & more space</p>
PTP over-the-top	<p>No upgrades to DOCSIS network required</p>	<p>Timing synchronization not precise enough for TDD LTE even with DOCSIS QoS. (5-10 millisecond range)</p> <p>Performance is negatively impacted with network loading and uplink packet delay variation (uplink bandwidth limited)</p>
Network Time Protocol (NTP) over-the-top	<p>No upgrades to DOCSIS network required</p>	<p>Timing synchronization not precise enough (100 millisecond) even with dedicated QoS on DOCSIS</p>
TV Broadcast Listen	<p>No upgrades to DOCSIS network required</p>	<p>Need a receiver for TV broadcast</p> <p>Femtocell must know its own location & TV tower</p>

4.1.5. Dual-SIM

4.1.5.1. What is DSDS

Dual SIM dual standby or DSDS is a device that has 2 SIMs installed into it. Both SIMs are active only when not in a call but when the user places a call, the other SIM is placed in standby. In the case where a service provider (SP) wants to use one SIM subscription for voice and text and the other SIM subscription for data, updates to the device firmware are required for the reconfiguration.

4.1.5.2. Charter Use Case

MSOs are typically in a MVNO relationship with an MNO. Charter wants to improve the MVNO economics. Since Charter is not providing voice or text on its RAN networks, at this time, Charter requires the device to scan and connect to both networks at the same time or switch back and forth as needed. This requires two subscriptions which entails the need for two SIMs.

4.1.5.3. How Does DSDS Work

DSDS is a derivate hybrid between dual SIM single standby (DSS) and dual SIM dual active (DSDA). In DSDS, both SIMs are in standby mode as long as neither is in a call nor actively listens for paging messages from both networks while idle. However, once a call is received on one of them, the other SIM becomes inactive and is unable to receive calls or messaging. When incoming calls come in for the inactive SIM they are simply routed to voicemail and SMS messages are held until the active SIM goes idle.

Table 6 – Comparison of Three Dual-SIM Technologies

	Dual SIM Dual Standby	Dual SIM Single Standby (Passive)	Dual SIM Dual Active
Overview	A hybrid between Dual SIM Standby and Dual SIM Dual Active	Worst implementation of Dual SIM technology, and affordable phones commonly use it	It can also receive calls on either of the two SIM cards, at the same time
Technology	<p>Smartphone have two active SIM cards, and they both use only one radio transceiver. However, they are both active only as long as they are not used, hence the name of Dual Standby.</p> <p>As long as the SIM cards are both in Standby mode, calls can be made and received on any of them. However, once a call on one SIM card is taken, the other becomes inactive and the first card is no longer actively used.</p>	<p>Capable of using two different SIM cards, but only one of them can be active at any time, hence when one SIM card works, the other is unreachable.</p> <p>To use the second SIM card, it needs to be manually activated and the first SIM deactivates</p>	<p>Both the SIM cards are permanently active. During a conversation on one of them, the other still works and receives calls, messages or data.</p> <p>The disadvantage of Dual SIM Dual Active phones is that the devices have two radio transceivers, one for each SIM card, hence consuming more battery than regular Single SIM smartphones</p>

Usage	Most popular implementation	Used in older mobile phones (not smartphones) and lower priced phones	High battery consumption and more expensive to manufacture, leading to a higher device price
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4.1.5.4. How Switching Decisions Are Made

In normal DSDS, the device will not switch on an active data session until it is no longer able to maintain connection to the network. Charter has worked with the original equipment manufacturers (OEMs) to switch based on several factors. Signal strength and signal quality are used to determine the need for the device to switch networks. When a device is out of coverage of operator's CBRS network, it maintains data, voice and text on the MNO's network. This allows the user to maintain their experience at all times.

When a device enters a geographic local, geo-fenced area, the device enables the second SIM and the device begins to actively search for a suitable network. Once the user equipment (UE) determines that the level, quality and hysteresis timer has elapsed, it will then preform an attach request to the network. The UE will maintain normal mobile operations with the one exception that it continues to listen to the first network for incoming pages for text and voice calls.

When the device receives a voice call from the MNO network, it then answers this request and reattaches to the data network of the MNO so the user may continue to use data. This is done due to the fact that the UE can still only have one active network on a DSDS device. When the call ends, the device again searches for the MSO network and, if available and criteria met, reattaches the data stream.

As the device begins to leave the MSO coverage area, signal quality and strength reduce. Rather than allowing it to lapse into a radio link failure (RLF), the device moves back to the MNO network if available, based on predetermined exit levels of strength and quality.

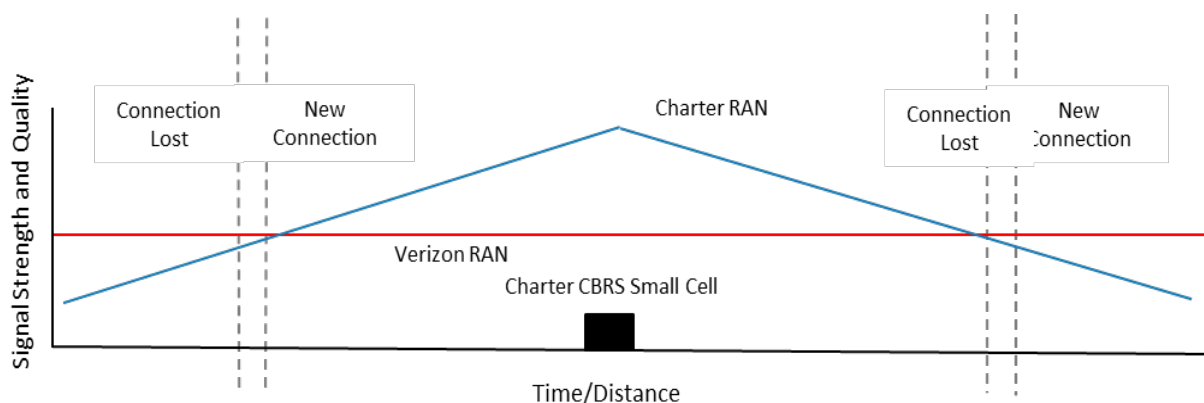


Figure 13 – How a DSDS Device Moves Across Networks

4.1.5.5. Dual eSIM

Embedded-SIM or eSIM is an embedded universal integrated circuit card that allows a user to store a cellular profile without the need for a physical chip that needs to be inserted into the device. It allows for the storage of multiple SIM profiles to be stored, but at this time only one can be used at a time and the user

has to manually switch between each profile to use it. New features will need to be developed to allow two eSIM's to function as the current physical SIM (pSIM) and eSIM.

4.1.5.6. *Is DSDS Good Enough*

With the modifications to the operating systems and the chipset enhancements that have occurred over the last year, DSDS functionality is very good. As it stands to date, the user would generally not realize as the device moves between the networks. Working with the chipset vendors and the device manufacturers, there may be some room for improvement. Regardless, the technology today will satisfy many needs for private network owners who wish to connect or offload data to their network. This allows them to control the access to their network with increase security and still allow calls and messages to be received without having to set up their own voice and data network.

4.1.6. *Virtualized RAN Architecture*

Charter's medium to long-term network vision is to transition from standalone RAN to a vRAN architecture where baseband functionality is centralized and virtualized, and supports standard open interfaces. Ultimately, Charter is driving for flexible hardware and software implementations affording scalable, cost-effective network deployments.

The transition to a vRAN based architecture is being evaluated for all the mobile-offload deployment scenarios described earlier in the paper. For emphasis, the use of vRAN is not only being evaluated for outdoor deployments but also for indoor residential deployment using femtocells.

For the near-term deployments, an operator's focus can be on the integrated solution, which includes both the Radio Unit (RU) and baseband unit (BBU) functionality in a box at the edge.

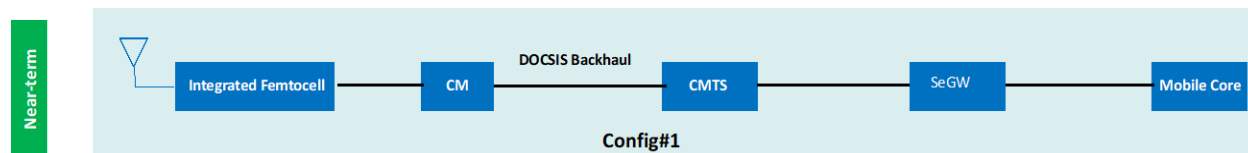


Figure 14 – vRAN Architecture – Backhaul

The long-term RAN architecture aims to centralize and virtualize the Centralized Units (CU) functionality, leaving the RU, and Distributed Units (DU) features at the edge of the RAN. Operators also want the flexibility to dynamically allocate DU functionality either at the edge of the RAN or centrally depending upon the backhaul option available.

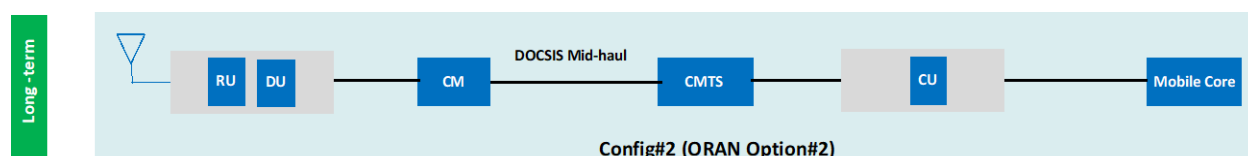


Figure 15 – vRAN Architecture – Midhaul

When fiber backhaul is available, operators can consider two options: collocating the DU/RU to align with the DOCSIS deployment scenarios or to move the DU to a centralized location.

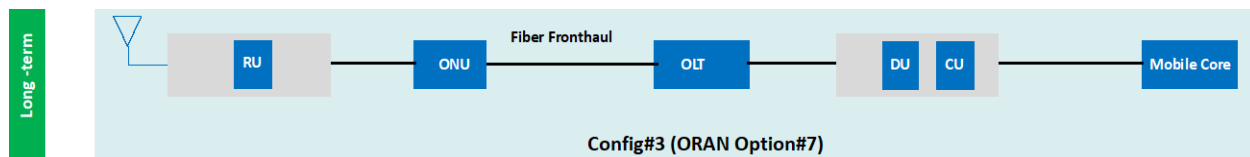


Figure 16 – vRAN Architecture – Fronthaul

The mobile community envisions improved RAN performance with vRAN architecture compared to a traditional, integrated RAN. For example, the performance enhancements would be realized by utilizing better interference management and improved mobility. In the long run, there are opportunities to reduce total cost of ownership (TCO) from baseband pooling.

4.1.7. Fixed-Mobile Convergence

Charter has years of experience designing, deploying, and managing Wi-Fi networks both outdoors and indoors, leveraging Charter's extensive DOCSIS and PON networks. Charter will expand its wireless networks with the deployment of 5G NR small cells. Charter's availability of DOCSIS and PON assets in urban and suburban areas is one of the key enablers allowing Charter to deploy 5G NR small cells at scale economically.

However, fixed mobile convergence is more than network convergence, it is about customer experience. Fixed mobile convergence allows Charter to provide a single cohesive experience to its customers. Convergence at the service level consolidates subscriber management and policy enforcement allowing customers to enjoy their services as they move between access networks. A parent can assign parental controls to a child's device and those controls work whether the device is on the cable broadband network or on the mobile network. A premium subscriber would get the same service at the neighbor's house or the local coffee shop, even if those locations have lower service. With a converged service, the network would be able to identify and enforce network policies on customer devices no matter where they are and give them the same service and experience.

Charter's vision for fixed mobile convergence is to deliver ubiquitous wired-wireless connectivity to our customers anywhere and on any device. Customers would carry their services, policies, and identity with them wherever they go. Through Charter's unique broadband and wireless assets, this can be delivered through the deployment of high capacity and low latency networks.

4.1.8. Automation

Charter envisions a new automation tool in its production network for its commercial network for applications such as network automation intelligence and workflow orchestration, network integration and network management. The tool enables end-to-end automated network life-cycle management for a large-scale network rollout and also enables automated reporting and provides a high level of customization. The tool's customizable dashboards and dynamic widgets provide end-to-end project visibility for seamless status tracking of network elements, work orders and tasks. It's a real-time, technology-agnostic single platform for live network analytics by leveraging data points from multiple sources for an enablement of valuable insight about network's health.

The tool is closely integrated with different network elements for an end-to-end network visualization, configuration management, performance management, fault management, change management features. It enables not only proactive network diagnostics but also provide remediation for performance enhancement. It is scalable platform with fully developed infrastructure to handle massive data volumes and transactions,

allowing an operator to handle continuous growth in user data due to high bandwidth speeds and an increase in number of mobile devices.

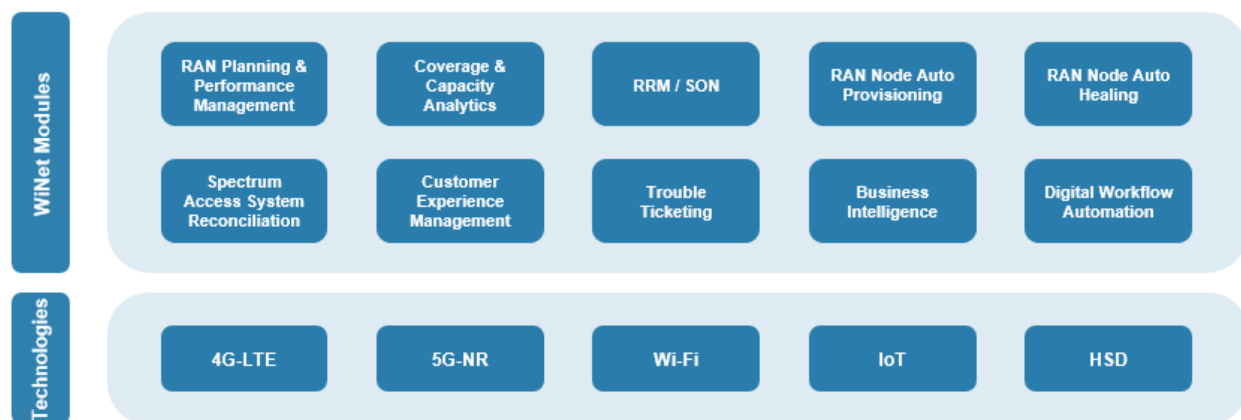


Figure 17 – Charter Wireless Automation Framework

4.2. Cox Communications

Convergence with wireless is currently centered around leveraging our fiber and HFC plant to provide services to the MNO's that include: Fiber To The Macro Cell Site (FTTX), strand mount small cells on our aerial HFC plant that incorporated AC power and DOCSIS backhaul transport, and offering CRAN (Centralized Radio Access Network) facilities space and fiber transport to upgrade the MNO's architecture as they move toward cloud native RAN.

Cox believes the market is becoming more attractive for us to enter the wireless space and we are exploring it more aggressively now but have not announced any specific plans.

As Cox looks forward to evaluating the current wireless segment, we look back to take the lessons learned from our earlier wireless attempts of both an MVNO and MNO solution. The challenge 10 years ago was in understanding the customer demographics with the then recently launched iconic smartphone device that limited our differentiation, as well as having wholesale metered voice, text and data on a much slower and costlier 3G network from our MVNO provider. With the trial markets we built in our cable franchised footprint, we wanted to provide ubiquitous service and our subscriber penetration rates couldn't support the cost of the wireless infrastructure as well as having to work roaming agreements without the scale of a large MNO. We are more optimistic with today's wireless environment as other cable operators have successfully launched MVNO's using high speed LTE networks and having driven their wireless offload tonnage by Wi-Fi both in the home and metro systems as well as evaluating other solutions such as small cells to drive the wholesale usage costs down.

As we look to the future, there are several fronts we see opportunity that include: driving Low Latency Xhaul (LLX) that enables low latency 5G wireless backhaul, looking at fixed wireless access that extends the edge of our HFC and fiber plant to add incremental households as well as enabling the opportunity to support rural broadband deployments, deploying Wi-Fi 6E in our wireless gateways that we can drive higher data throughput experience to our customers over our broadband network, and finally as we explore opportunities with retail wireless.

4.3. Shaw Communications

Shaw Communications is a Canadian cable and mobile operator that provides both wireline services to over four million homes and businesses in western Canada, as well as mobile services to customers in British Columbia, Alberta and Ontario. Shaw has offered broadband services in Canada since 1996 and became a mobile operator in 2015 with the purchase of Wind Mobile, which it has since rebranded to Freedom Mobile. In July 2020, Shaw launched the Shaw Mobile brand to provide a new wireless service that leverages Shaw's Fast LTE and HFC/DOCSIS networks to provide Shaw Internet customers with an innovative wireless experience.

Over the past five years, Shaw has invested heavily in its wireless network, adding macro sites and purchasing new spectrum in order to improve the performance and reach of its rapidly growing wireless service. Since its entry into wireless, Shaw has focused significant effort on leveraging synergies between its established wireline business, and its new and growing wireless division. Indeed, access to Canada's largest public Wi-Fi network (Shaw Go WiFi), fiber backhaul, critical facilities, buildings, operational teams, retail, as well as many other opportunities proved to be of significant value early on. However, the ongoing exponential growth in wireless traffic and the impending arrival of 5G has put network and service convergence as a key focus area.

Seamless connectivity is the foundation for our future economy, but this future will require extremely close interplay between mobile and fixed technologies. The deployment of the 5G vision will require an unprecedented level of network connectivity and densification, as well as previously unseen levels of collaboration between wireline and wireless technologies [7].

In order to deliver both 5G as well as 10G (multi-gig fixed broadband), converged Canadian operators like Shaw will need to find ways to leverage their key strategic advantages to compete with their well-funded and converged Canadian Telco competitors. The top three strategic opportunities are:

- **Hybrid-Fiber Coax Infrastructure** – Already deployed to virtually every house and business in the country, HFC infrastructure makes an ideal solution for the densification of wireless networks. Able to transport multi-gigabit traffic today, it can also transport power, greatly reducing the time and cost of small cell deployments.
- **Hub Site Facilities** – Cable's historic hub-site topology, gives operators access to significant spare power and cooling, just a few miles from the customer. Thanks to the new "Distributed Access Architecture", these new facilities will soon be vacated, giving cable operators access to a network of distributed mini-datacenters, which can then be leveraged to provide ultra-low latency virtual/cloud RAN services, which are likely to be a key component of 5G roll outs.
- **Core/Service Convergence** – Both wireless and wireline networks leverage virtually the same architecture, leveraging a "wireless core" or "CMTS" to control the flow of wireless or wireline traffic. The convergence of these two cores will ultimately enable a truly seamless and differentiated experience for customers, increasing security, flexibility and control.

The opportunities described above are indeed highly strategic to virtually all cable operators globally. However, in order for them to be realized, several key challenges must be addressed as an industry. These challenges include:

- **Latency Reduction** – 5G as well as new mid/fronthaul solutions will require ultra-low latency, which cannot be easily met by today's consumer focused shared access networks like DOCSIS and PON. Improvements in new DOCSIS technologies, such as Low Latency Xhaul (LLX) [6], will be required

in order to reduce latency to sub 1ms level, making HFC virtually indistinguishable from dedicated fiber for 5G and mid/fronthaul purposes.

- **Timing Distribution** – Delivery of highly accurate timing to small cells is challenging using today’s DOCSIS protocol. However, innovations such as the DOCSIS Time Protocol (DTP) [19] will solve this challenge, eliminating the need for costly GPS integration, and greatly improving the flexibility and efficiency of small cell installs.
- **Xhaul Over HFC** – Today’s fronthaul protocols are extremely demanding and designed for dedicated fiber use. In order to enable the ultra-dense and demanding wireless networks of the future, new “xhaul” techniques must be developed that will allow operators to leverage the efficiencies of fronthaul while using shared access topologies such as HFC and PON.
- **Core Convergence** – While similar, wireless and wireline core technologies differ in numerous ways. Converging these technologies to enable a host of benefits for consumers will require development and integration across a diverse vendor ecosystem.

While challenging, the issues outlined above are certainly possible to overcome, and the industry is already making progress to address these. Recent models built at Shaw, indicate that a cable operator could reduce its build cost by up to 99% and build time by up to 95% by leveraging existing HFC infrastructure, rather than extending fiber to feed small cell densification [8]. The promises of cloud RAN and core convergence also carry similar promises of greatly reduced costs and improved customer services. However, operators will need to rally behind these new technologies and drive their development in order to see the benefits realized.

Ultimately, we believe that both cable and wireless technologies are evolving in lock step, and our industry is exceptionally well positioned to realize the incredible synergies between two of our most important assets. As shown in Figure 18 below, today’s exponential growth in broadband is necessitating densification of our networks, accomplished through distributed access architecture (DAA) in wireline and small cell deployment (ideally enabled through DOCSIS) in wireless. That densification is also an enabler for multi-gigabit symmetrical services, enabled through DOCSIS 4.0 in wireline, and 5G in wireless.

In the future, competitive and efficiency drivers will require operators to embrace cloud and virtual network infrastructure, enabled by virtualized CCAP (vCCAP) in wireline and vRAN/vEPC in wireless. Shaw believes all of these steps will happen in very close timing, which will lead to the ultimate convergence of both network infrastructures. The final converged state will enable a myriad of new opportunities and efficiencies, such as the unified edge cloud, universal nodes, end-to-end network slicing and orchestration, converged wireless/wireline cores, new services and much more.

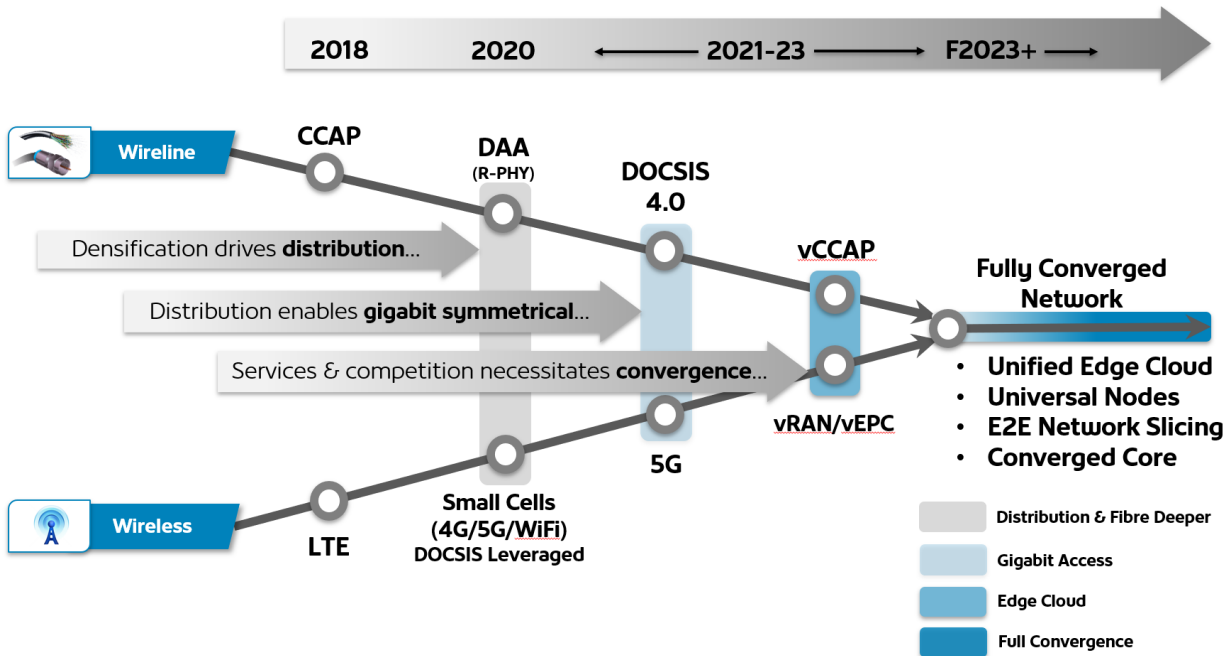


Figure 18 – Wireline and Wireless Convergence Roadmap

In addition to new technology changes, Shaw strongly believes that several other industry challenges must be overcome in order to ensure Canadians have access to world leading wireless services and 5G. These include inter-operator handover, access network convergence, and Wi-Fi interoperability, and will be discussed in more detail in the sections below.

4.3.1. Inter-Operator Handover

Existing regional MNOs, like Shaw, typically rely on domestic roaming agreements to provide coverage outside of their home network footprint. With traditional roaming interfaces, however, subscribers often experience network problems such as dropped calls or interrupted downloads/uploads as they move between the home network and the roaming partner's visited network. This negatively impacts customers' perceptions of network quality and brand, which undermine a regional operator's ability to effectively compete and grow in a new market. This will also be the case for MSOs planning to deploy CBRS, where the initial coverage areas will typically be more localized.

Fortunately, the 3GPP Home Routing (HR) specification provides a standards-based approach for supporting seamless inter-operator handover between the operator's home network and its roaming/MVNO partner's visited network. With HR, the data plane traffic is routed back to the home network, giving the home network operator control over the subscriber's traffic and its IP context. This allows subscribers to roam between the home and visited networks without service interruptions. Figure 19 shows the network architecture for HR.

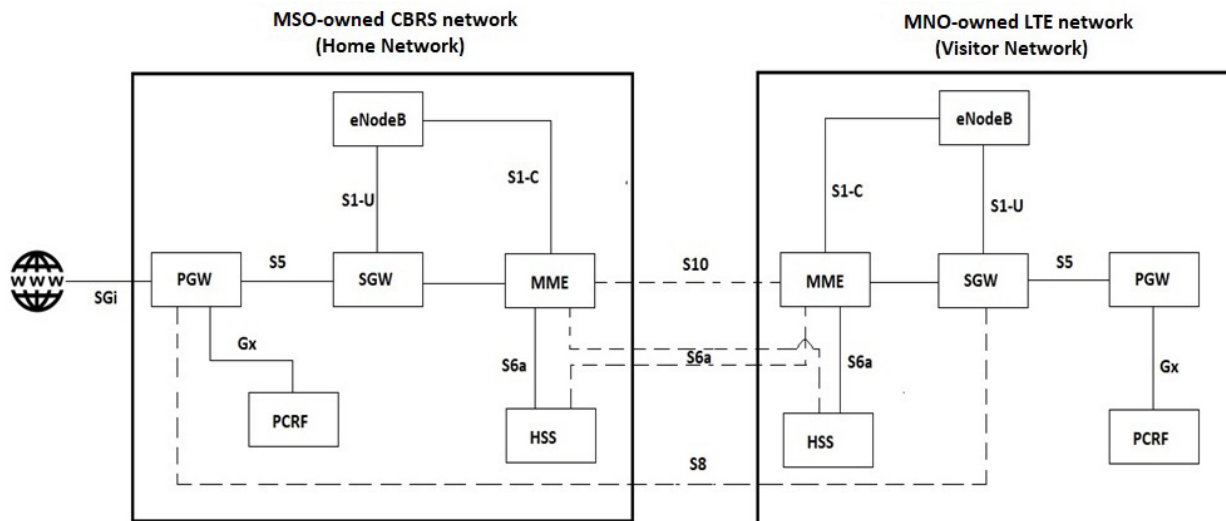


Figure 19 – Home Routed (HR) Network Architecture

To implement the HR model, the home and visited networks are required to share three interfaces: S6a, S8, and S10. These are described briefly below.

- S6a—is an interface between the Mobility Management Entity (MME) and the Home Subscriber Server (HSS) of both networks that enables the transfer of subscriptions for authenticating and authorizing user access to the network.
- S8—is an interface between the Serving Gateway (SGW) of the visited network and the Packet Gateway (PGW) of the home network, acting as an inter-Public Land Mobile Network (PLMN) reference point to transfer user traffic back to the home network. S8 allows the home network to control a subscriber's traffic even when the subscriber is roaming on the visited network.
- S10—is an interface between two MMEs used for bearer modification with MME relocation and MME-to-MME information transfer. S10 enables seamless data session transfer in connected mode. In addition to sharing roaming interfaces, HR implementation requires each network to be configured with mobility parameters that utilize connected- and idle-mode triggers.

The HR implementation is ideal for operators that have a roaming/MVNO agreement with an MNO that allows sharing of the roaming interfaces (i.e., S6a, S8, and S10) and control over mobility configuration. In addition to establishing the roaming interfaces, both operators also need to exchange cell site information to update their neighbor relations tables that identify the other operator's adjacent cell sites to which handovers occur.

Inter-operator mobility allows regional operators/MNOs to provide high quality services to their subscribers on par with the national wireless carriers as they expand their networks into new markets. Adopting inter-operator mobility would also promote competition, investment, and network deployments by regional operators, particularly in rural and remote areas. With inter-operator mobility, regional operators will have the ability (and incentive) to expand into smaller communities and rural areas more quickly and compete with the incumbents more effectively because they can ensure high quality service to their customers as they build out their network footprint.

4.3.2. Access Network Convergence

5G deployments will drive a dramatic increase in network density through small cell deployments. Although dark fiber has been used extensively in the past to support 3G/4G macro site deployments, unprecedented levels of new fiber builds would be required to support the roll-out of 5G. Fortunately, MSOs have already been deployed HFC/DOCSIS access networks down virtually every street and to almost every building on the continent to the point where today it reaches 93% of American households. And with the recent release of the DOCSIS 4.0 standard, HFC networks will soon be able to deliver multi-gigabit capacity.

As such, MSOs are uniquely positioned to create ultra-dense 5G small cell deployments by leveraging their existing hybrid fiber coax (HFC) networks and emerging technologies such as DOCSIS 4.0, DAA, LLX, and multi-access edge computing. The main advantages of HFC/DOCSIS networks relative to other alternative networking technologies (e.g., dark fiber) are its low cost, scalability, access to power, and ease of deployment. For the past couple of years, Shaw has utilized its aerial HFC plant to deploy LTE small cells for additional capacity and/or coverage in targeted areas. Deploying small cells on aerial plant addresses three major challenges with outdoor small cell deployments: site access, backhaul and power. That is, site access is usually already covered by existing pole-line attachment agreements and both backhaul and power are provided over the coaxial cable plant.

Figure 20 shows an example of a converged access network architecture with several options for transporting 5G small cell traffic over the HFC/DOCSIS network.

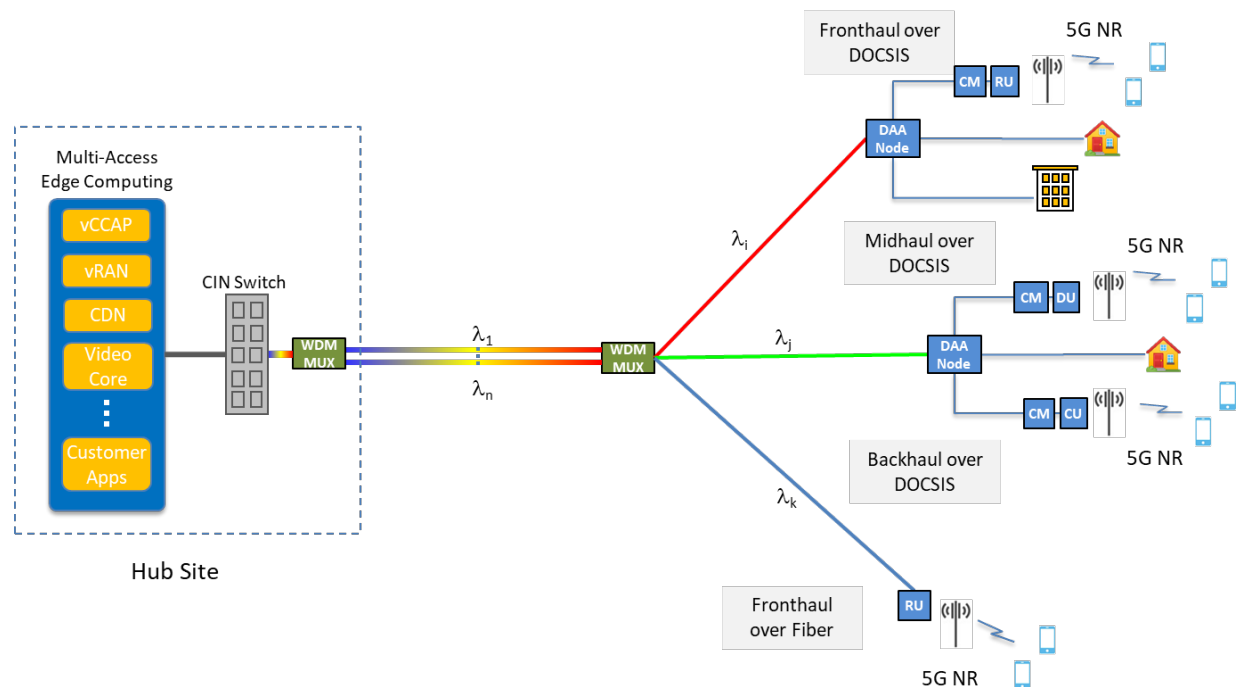


Figure 20 – Converged Access Network Architecture

As shown in the figure above, 5G fronthaul, midhaul and backhaul can be viably transported over DOCSIS using the technologies mentioned earlier (e.g., LLX, DTP). With fronthaul, the 5G remote unit (RU), which implements basic RF functions (e.g., filtering, amplification), is located at the cell site and the other radio functional blocks are implemented within the virtualized RAN (vRAN) at the hub site. Fronthaul offers the

highest performance and efficiency but has the most stringent latency and throughput requirements. Midhaul and backhaul implement different functional splits, at what are known respectively as the distributed unit (DU) and centralized unit (CU). These splits have less demanding transport requirements but provide lower performance and efficiency compared with fronthaul.

In cases where the small cell is already near existing fiber plant, fronthaul can also be carried over fiber by assigning a dedicated wavelength to the small cell and sharing the common wavelength division multiplexing (WDM) link between the hub site and a remote WDM multiplexer (MUX). The preferred transport option depends on several factors such as the latency requirements of the end user applications, the available 5G spectrum (and hence capacity) the radio site, and the cost of deployment.

The other opportunity for access network convergence is at the hub site (or headend). Both the virtualized CCAP (vCCAP) and vRAN can be implemented on multi-access edge computing platforms in which compute and storage resources are shared across multiple applications. CableLabs and other standards bodies are developing architectures and specifications to realize this important opportunity.

With the fundamental technologies (e.g., DOCSIS 4.0, DAA, LLX, DTP, multi-access edge computing) needed for wireless/wireline access network convergence still at relatively early stage of development, broad support is needed across the industry to make them a commercial reality.

4.3.3. Wi-Fi Interoperability

Although 5G mobile networks will be deployed extensively throughout the world, Wi-Fi will continue to carry the bulk of Internet traffic well into the future. According to Cisco's latest Annual Internet Report [9], public Wi-Fi hotspots are expected to grow four-fold from 2018 to 2023. As such, public Wi-Fi networks represent an important opportunity for MSOs to offload mobile data traffic from their own mobile networks or those of their MVNO partners to reduce network build and/or roaming costs.

Over the past decade, Shaw has built Canada's most extensive service provider Wi-Fi network, Shaw Go WiFi, with over 100,000 public access points deployed to date. Shaw Go WiFi extends our Internet customer's broadband experience beyond the home as a value-add to our customer's wireline network experience. Over 3.6 million devices have authenticated on the Shaw Go WiFi network, which is used by our customers in coffee shops, restaurants, gyms, malls, public transit and other public spaces from British Columbia to Ontario.

Freedom Mobile and, more recently, Shaw Mobile customers are also able access to the Shaw Go WiFi network along with over 300,000 home hotspots deployed in our Internet subscribers' homes across the country. Our mobile customers' devices automatically connect and authenticate to our public and home hotspots via Hotspot 2.0 (aka Wi-Fi Certified Passpoint) using their wireless credentials stored on the SIM. This provides mobile customers with extended network coverage and offloads a significant proportion of traffic from the mobile network.

With the introduction of Wi-Fi 6 (IEEE 802.11ax), dramatic improvements are expected in Wi-Fi capacity, efficiency, and reliability in the coming years. The Cisco Annual Internet Report predicts that Wi-Fi 6 hotspots will grow 13-fold from 2020 to 2023 and represent 11% of all public Wi-Fi hotspots by 2023. The recent allocation of 1.2 GHz of unlicensed spectrum in the 6 GHz band in the U.S. also has huge potential for Wi-Fi and will enable the Wi-Fi 6 evolution by alleviating congestion in the existing 2.4 GHz and 5 GHz unlicensed bands. The first wave of unlicensed devices capable of leveraging 6 GHz is expected in the U.S. in the final quarter of 2020 and 60% of devices are anticipated to be Wi-Fi 6 capable by 2022.

3GPP Release 16 also promises to further enhance mobile/Wi-Fi network convergence through Access Traffic Steering, Switching and Splitting (ATSSS). Based on Multipath TCP (MPTCP), ATSSS allows separate 5G NR and Wi-Fi traffic flows to be simultaneously established between an ATSSS-capable mobile device and the core network, providing highly available and robust services. At present, ATSSS is an optional feature for user devices and the 5G core network so operator support is vital to its success.

4.4. Vidéotron

4.4.1. Who is Vidéotron?

Vidéotron (www.videotron.com), a wholly owned subsidiary of Quebecor Media Inc., is an integrated communications company engaged in cable television, entertainment, Internet access, cable telephone and mobile telephone services. Vidéotron is a leader in new technologies with its Helix home entertainment and management platform. As of June 30, 2020, Vidéotron was serving 1,497,300 cable television customers, and 472,200 subscribers to its Club illico video streaming service.

Vidéotron is also the Québec leader in high-speed Internet access with 1,753,100 subscribers to its cable service as of June 30, 2020. As of the same date, Vidéotron had 1,404,900 subscriber connections to its mobile telephone service and was providing cable telephone service to 979,600 Québec households and organizations. Vidéotron has been recognized as one of Montréal's popular employers.

In 2010, Vidéotron built and launched its own 3G (AWS) network and upgraded it to LTE in 2014.

In 2018, Vidéotron Launched Fizz Mobile, 100% digital mobile service brand¹. This virtualized service provider model is based on Digital Business Platform utilizing TM Forum's Open Digital Framework, which includes business process and information frameworks and Open APIs.

Vidéotron is currently preparing the upgrade of the wireless network to serve Vidéotron and Fizz customers with LTE-Advanced and 5G evolutions.

4.4.2. 5G Opens a Very Wide Range of Applications

5G opens the way to many new opportunities. One of the challenges for operators is to select the right markets to address first with this technology.

There are so many applications that can benefit from 5G, operator will have to expand and consolidate some of their "natural skills". For example, those related to entertainment and content distribution that may evolve to massive contents distribution VR/AR or telepresence, to provide a full set of immersive experiences. An example of the 5G set of services is shown in Figure 21.

IoT is an unmissable opportunity but it has such a wide field of applications that service providers will have to build a strong strategy to select the profitable and strategic markets and serve them with the right IoT technologies and services.

Then many new fields are now being opened to operators with 5G used for example in the "intelligence" field or "autonomy". That creates room for new businesses innovations but also require operators to change their way to do business to be able to propose solutions adapted to this new market in their portfolio.

In this new environment of constantly emerging innovations, operators must consider more than just 5G Radio Access Network and core and include all their network elements in a converged solution to provide a wide range of features to address different markets and services with the right solution.

¹ "Vidéotron's disruptive all-digital brand, Fizz, goes from concept to launch in 10 months," by John C. Tanner, Contributing Editor, TM Forum, September, 2019. <https://inform.tmforum.org/casestudy/videotrons-disruptive-all-digital-brand-fizz-goes-from-concept-to-launch-in-10-months/>

Wireless access convergence, fiber network convergence and virtualization are some of the main elements that operators will have to integrate in order to be able to actively participate to this new network panorama.

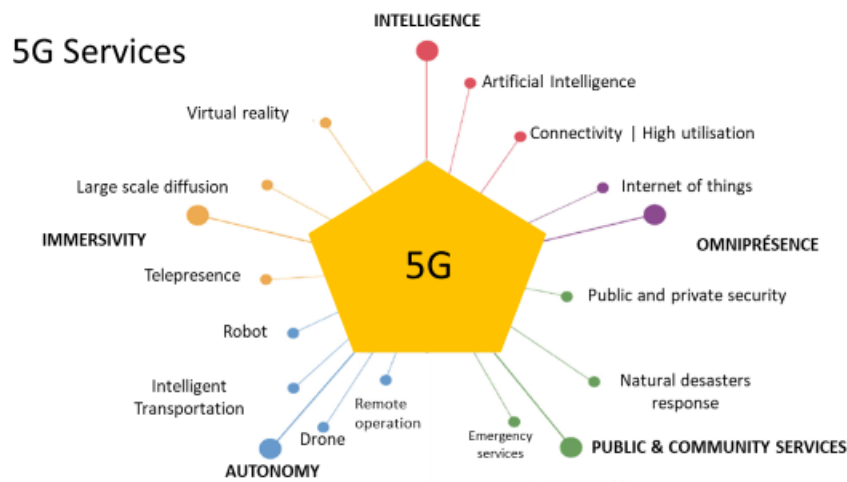


Figure 21 – 5G Diversity of Services and Applications

4.4.3. Wireless Access Convergence – Building on Wi-Fi Assets

Access to a wireless network coverage is now a fundamental service and all consumers are expecting a good connection at all time for their mobile devices.

But building a mobile network providing a full coverage in any point is a challenge, especially for indoor locations. For LTE networks and for future 5G networks, many solutions exist to improve coverage at any point. For example, small cells to address a specific location that could require better coverage or higher capacity, as well as low band frequencies for long range and better penetration in buildings.

Mobile Network Operators (MNO) are using those tools in the design of their networks, but Wi-Fi is another element that can be very beneficial to wireless coverage, in addition to lowering the cost for MNO and the end user. Indeed, Wi-Fi is now widely deployed in homes, building and many public spaces.

Recent developments in the wireless technologies allow a much greater performance and transparency for users when it is time to decide to connect to traditional wireless network (LTE, or 5G networks normalized by 3GPP) or Wi-Fi Network. Those developments also improve the transition from 3GPP networks to Wi-Fi access point (AP) when the user is moving.

With a strong convergence between 3GPP access and Wi-Fi, it is possible to offer new services or to improve existing services for example:

- Access to a large free Wi-Fi coverage and create a community of users.
- Better customer experience is provided by an automated and seamless connection to the best network available.
- Allow customers to save on their data plans.

- Allow operators to minimize costs as Wi-Fi can be deployed with a lower cost in \$/Bits. This is valid for MNO as they can save on deployment CAPEX & Network OPEX.
- Those technologies also allow agreements between operators for access to Wi-Fi network, including international roaming solutions in order to improve the connectivity for travelers.
- The improved customer satisfaction through the ease of use of Wi-Fi will result in increased customer satisfaction and thus will reduce the level of churn for the operators.

Among all the technologies that enable the convergence between Wi-Fi and 3GPP access network, are:

Hotspot 2.0 or Wi-Fi Certified Passpoint (based upon the IEEE 802.11u protocols) now allows the mobile device to connect and authenticate without the need for the user to manually select a network with a very high level of security. This is an essential tool in order to allow the users to connect automatically to the Wi-Fi network (on which they are authorized to access). Hotspot 2.0 thus provides a much easier access to Wi-Fi networks. A single login is required to set the system up and then the system does the rest: searching for accessible networks and gaining entry.

Access Traffic Steering, Switching and Splitting (ATSSS) is a feature included in 3GPP Rel-16 to enable high level of convergence between 5G and Wi-Fi networks. This feature that can be hosted in the User Equipment (UE) and the 5G Core (5GC) to provide 3 essential features for convergence:

- Steering: ensure the best network selection between 5G and Wi-Fi
- Switching: allows seamless handover between 5G and Wi-Fi
- Splitting: enables network aggregation to combine capacity of both 5G network and Wi-Fi

ATSSS allows this advanced management of connection independently for data link and voice service.

Intelligent Wireless Network Steering (iWiNS²) developed by CableLabs is complementary with ATSSS as it enhances mobile steering and switching between LTE, Wi-Fi and CBRS nodes. iWiNS also has the granularity to apply per-dataflow steering policies by multi-users and multi-networks feedback. This solution requires an application to be installed on the UE and can be improved if the app is integrated into the Operating System (OS) of the device. It can take decisions depending of the state and traffic of the networks (Wi-Fi and LTE/5G) to optimize the communication on a real time basis.

These powerful tools used in conjunction with Wi-Fi 6, the most advanced version of Wi-Fi, will enable wireless access convergence and provide a better connectivity to customers at all times and all places.

² See “iWiNS Architecture – An aware approach to mobile traffic steering”, Mario Di Dio, Rich Terpstra, CableLabs, August 2019.

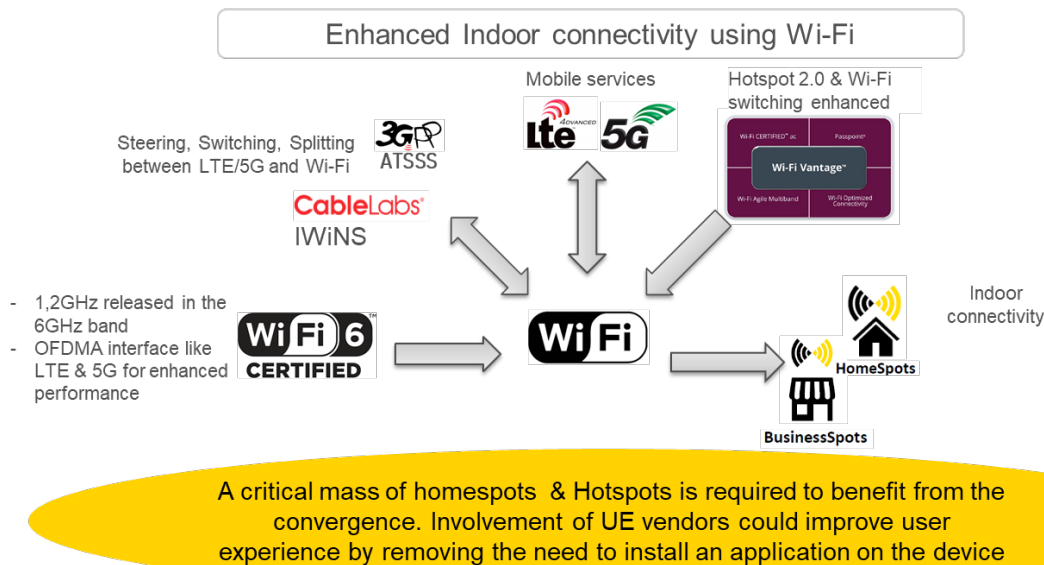


Figure 22 – Wireless Access Convergence

4.4.4. Network Convergence – All-in-One Fiber Network

With the arrival of Distributed Access Architecture (DAA), network operators will soon extend their Ethernet network outside of headend and indoor sites to build a new digital network outside plant rather than the current analog amplitude modulation used to transport the digital services (DOCSIS and digital video).

In the next generation of HFC network, operators will deploy DAA and the new nodes will integrate the DOCSIS Physical layer (R-PHY) or the DOCSIS Physical and MAC layers (FMA, Flexible MAC Architecture). In both cases those nodes will be interconnected through an Ethernet digital fiber optics link, sometime called Converged Interconnect Network (CIN).

Coax is not the only medium fed by this CIN, some operators will also choose to evolve a part of their network to Fiber To The Home (FTTH) solutions.

Some operators, especially those who already own an HFC network may be attracted by the opportunity to build a PON network (for example 10G EPON) matching the topology of the HFC network. This is now possible using a “remote OLT” (R-OLT) installed in the field and built in a “clamshell” housing like a legacy HFC node or a new DAA node. The position of DAA nodes and PON nodes will then be similar and the topology of digital fiber network (or CIN) used to interconnect DAA nodes and R-OLT will be equivalent.

This CIN being an Ethernet network (typically 10GE), it is possible to aggregate multiple channels (or wavelength) on the same link using DWDM aggregation. In addition to HFC DAA nodes and PON R-OLT, this CIN can also connect some wireless sites (LTE, 5G, Wi-Fi, small cells, macro-sites, hotspots) and some business customers.

As this converged DWDM network will serve a higher number of customers but also a wide variety of services including some with high reliability requirements (for example wireless macro-sites, or business

customers), a redundancy can be deployed. Using a backup path and LACP for management of the traffic the critical nodes or sites can be fed with the second link in addition to the first one in order to prevent service interruption in case of fiber break on the common part of the link.

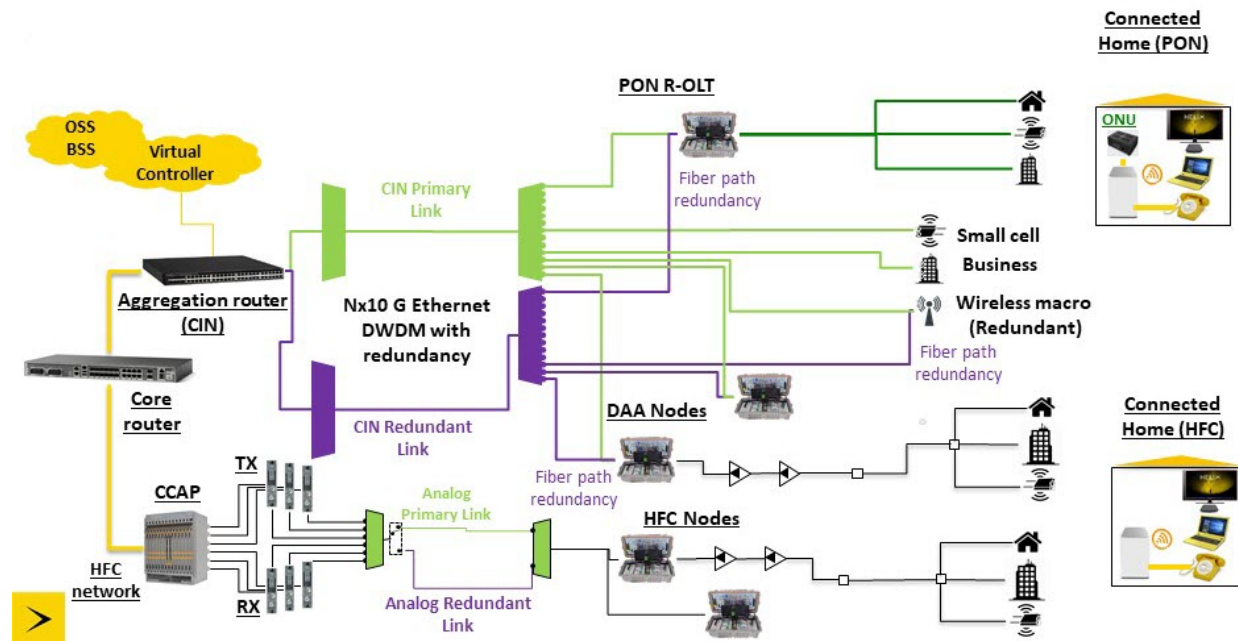


Figure 23 – Fiber Network Convergence with DWDM Ethernet Aggregation

In a next evolution step, this converged network will evolve to a more efficient architecture. Indeed, the DWDM aggregation allows to improve fiber utilization. On the other end, this method of aggregation is very static and does not allow to manage traffic from one node to another. The physical link is shared but the logic association is still a point to point (P2P) connection from the CIN router to each node.

A next step will be to replace this DWDM aggregated link by a high capacity link. 100 Gbps and more will soon be available for the access network as coherent optics can now be used for transport on the shorter ranges required for access network.

In this context, an aggregation node with coherent termination device (ANCTD) could be used as a transition between 100 Gbps P2P link and the lower capacity ports of the converged nodes (Typically connected with 10GE or 25GE links).

This ANCTD may take different aspects depending on operator's preference and target architecture:

- Layer 1 muxponder
- Layer 2 switch
- Layer 3 router

A Layer 3 routers would support very well a ring architecture for redundancy and allow a more advanced traffic management. In that case, the performance and metrics (capacity, QoS, latency) can be adapted depending on the requirements of the nodes or the services provided through those nodes.

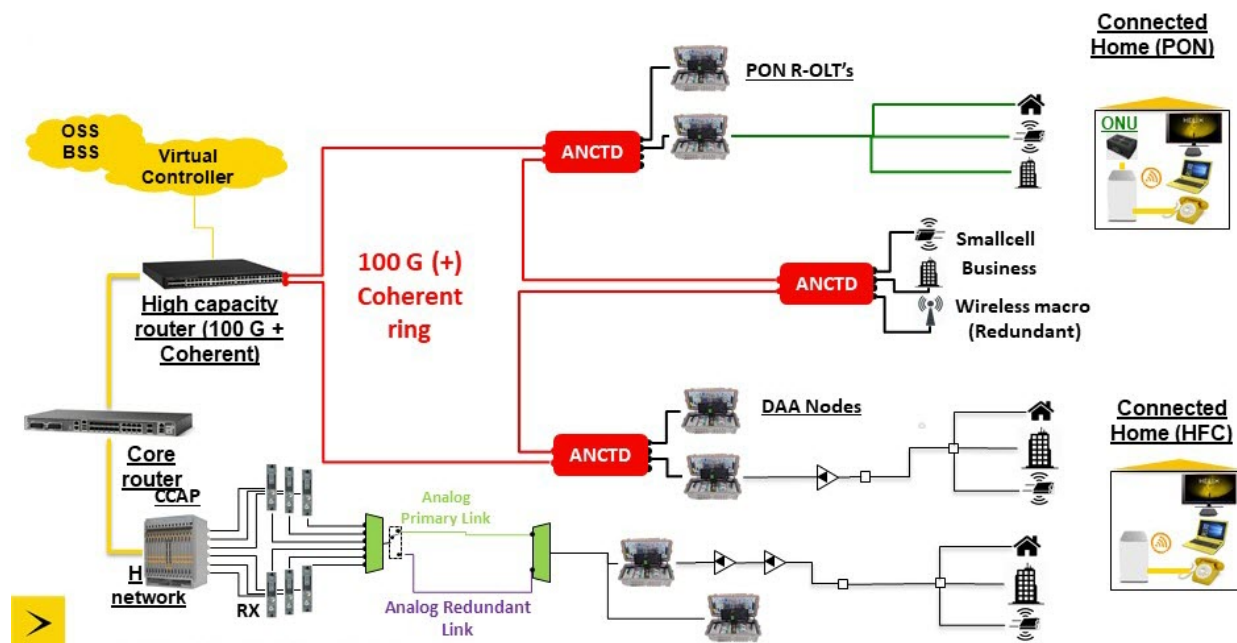


Figure 24 – Fiber Network Convergence with High-Capacity Coherent Ring

4.4.5. Virtualization – A Core Ready for All Opportunities

Our vision about the virtualization is to create an open ecosystem in which our internal developers and our external partners will be able to integrate their solution. Our foundation uses different sets of technology and hardware based on different standard: ETSI, TM Forum and MEC. We strongly believe that each virtualization technology will benefit Videotron to implement new services and facilitate and support our innovation process.

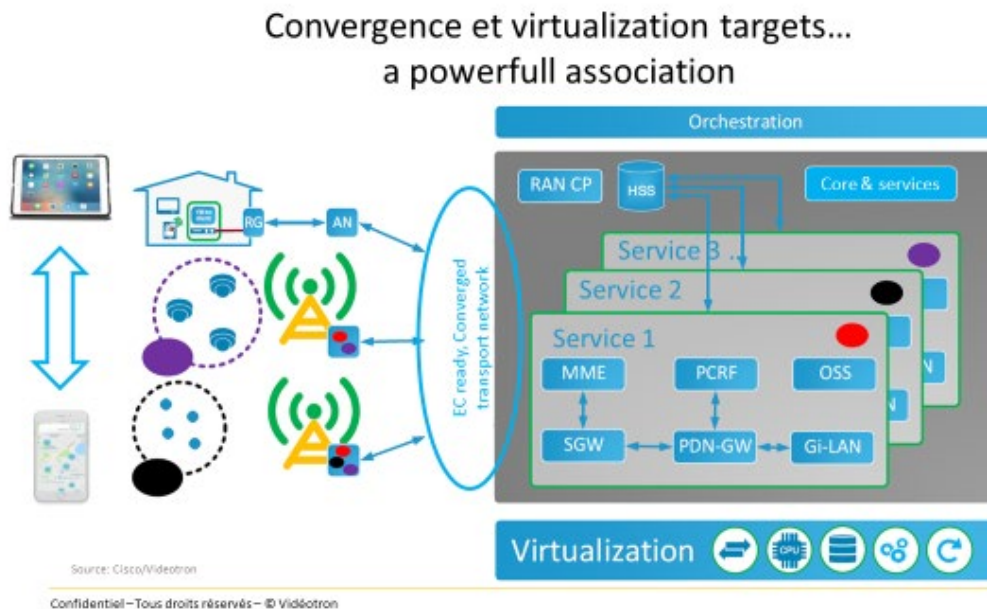
Hybrid cloud strategy allows deployment of a new business support systems (BSS) system in the public cloud as well as the 5G RAN components in private cloud. The success of the OSS 5G RAN deployment in less than a week has proved that having the right technology in place has improve time to market. Next achievement is to make sure private cloud is up to run network function virtualization (NFV) virtual RAN for the 5G radio. In fact, the 5G is the main telco application that will benefit from the virtualization technology and the automation & orchestration framework we are deploying.

Through our automation and orchestration knowledge and process, we are targeting the creation of new values for our customers. The idea is to provide the right technological foundation for any new digital services. Any new digital services will require a specific part of the network and a specific location deployment (fog, edge, data center, public cloud). With network slicing, specific resources will have to be delivered for a specific B2B customer, and specific applications will be deployed near the customer to improve real-time experience. These use cases require a virtualized infrastructure and an automation & orchestration framework as shown in Figure 25.

One of the most challenging aspects is related to the maturity of the different virtual network function (VNF) partners to adequately run their VNF in an open virtualized ecosystem. They provide an entire virtualized stack that meet any operators needs in term of performance, scalability and service availability, but they require more investments than expected. Based on Gartner analysis and the open standard of the

industry (ETSI, TM Forum), we concluded that we need to limit the implication of such vendors in the value chain and spend more investments and time in the automation & orchestration area. The idea is to integrate properly any NFV stack at the OSS (our ecosystem for automation, orchestration, resource inventory, security tools and monitoring) level. That way, we let the NFV vendors be good at what they are good at, and we integrate their NFV stack to our OSS & BSS catalogue.

All the efforts done so far has created a new digital culture across the engineering team. The industry and our IT team has provided the right framework, knowledge and process to proceed to our NFV deployment. The future is to make sure our foundation will evolve the right way to host the 5G core, to enable new digital services area such as 5G network slicing and cloud gaming.



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Figure 25 – Convergence and Virtualization

4.5. Telecom Argentina

4.5.1. Introduction

Telecom is the result of merging two former companies, one a mobile operator and one a cable operator. It has four main access network technologies that were evolving in different ways and then came together. The question is, how should Telecom evolve these networks in order to meet the capabilities and services that they will have in the future, while trying to choose the best of these different technologies, reusing the infrastructure, evolving the future access services, increasing the customer experience and avoiding duplicating investment due to the overlapping of different access network technologies in a same area.

Figure 26 shows Telecom's four access technologies, overlapping each other, in the same area: HFC (DOCSIS), fiber to the cabinet (FTTC) supporting xDSL, fiber to the home (FTTH) and 4G.

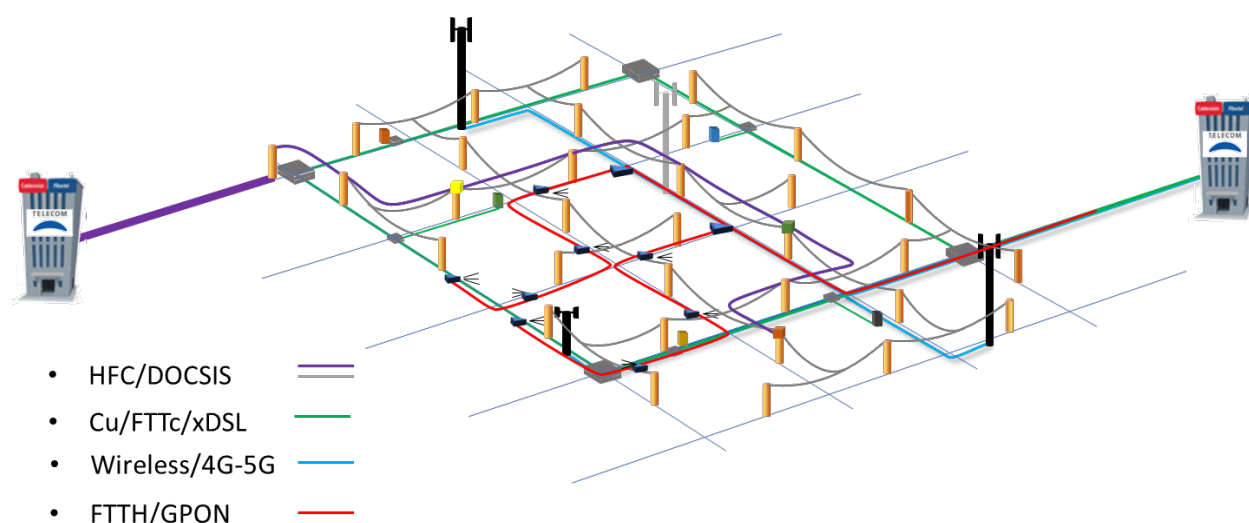


Figure 26 – Telecom Access Network

Figure 27 shows the deployment topology for each access in a cleaner fashion. Each of these networks has different capacities, characteristics and connection flexibility. For example, the HFC network reaches an area of 1,000 households with a couple of fiber optics (FO) from the hub to the fiber node, while the FTTC network reaches an area of 400 households with one FO. Even when the first one can provide more and better services, the second one provides very valuable growth potential for example with its underground wiring.

On the other hand, the 4G/5G wireless access network actually uses technology that could provide not only mobile services but also fixed services (especially on 5G). It also has a mobile backhaul over dark fiber to reach the base station from the central office. Finally, during the last few years, a new FTTH-based network has been implemented in certain areas and will be our target access network in long term.

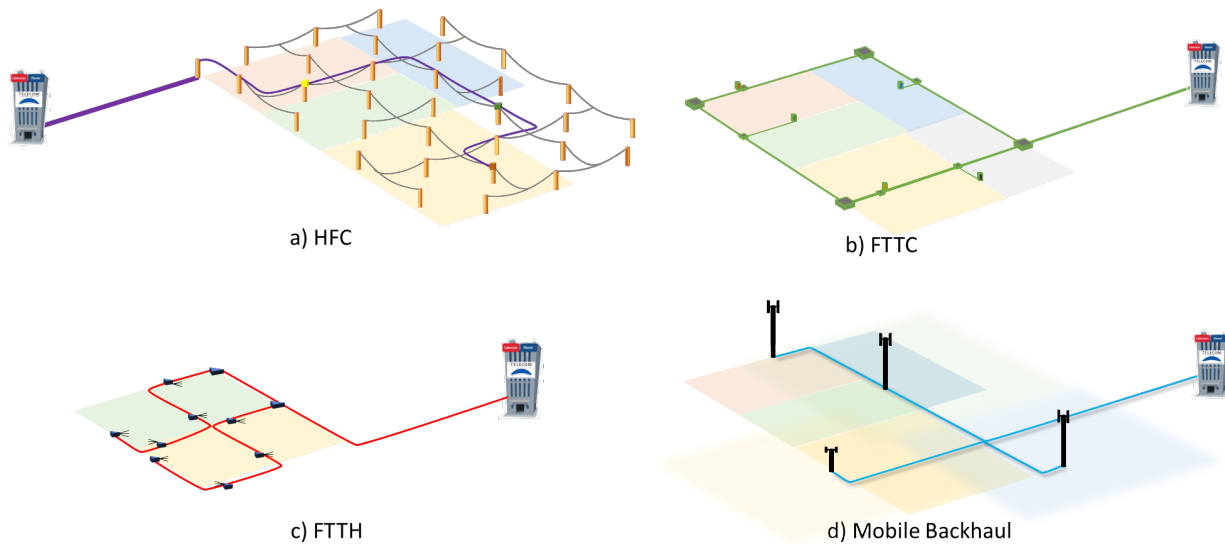


Figure 27 – Telecom Access Technologies

The goal must be to find a **target access network** to provide the capacity and attributes for the future services, as well as a **converged access transport** to distribute and connect each access with the different core services in the data centers (those being national, regional, or even at the edges of the network).

Figure 28 shows the complete picture of the four access technologies combining the access distribution, access transport network and the services that could be provided locally from the hub or central office (CO) or it could extend through different data centers (DC), like 4G in the national DC.

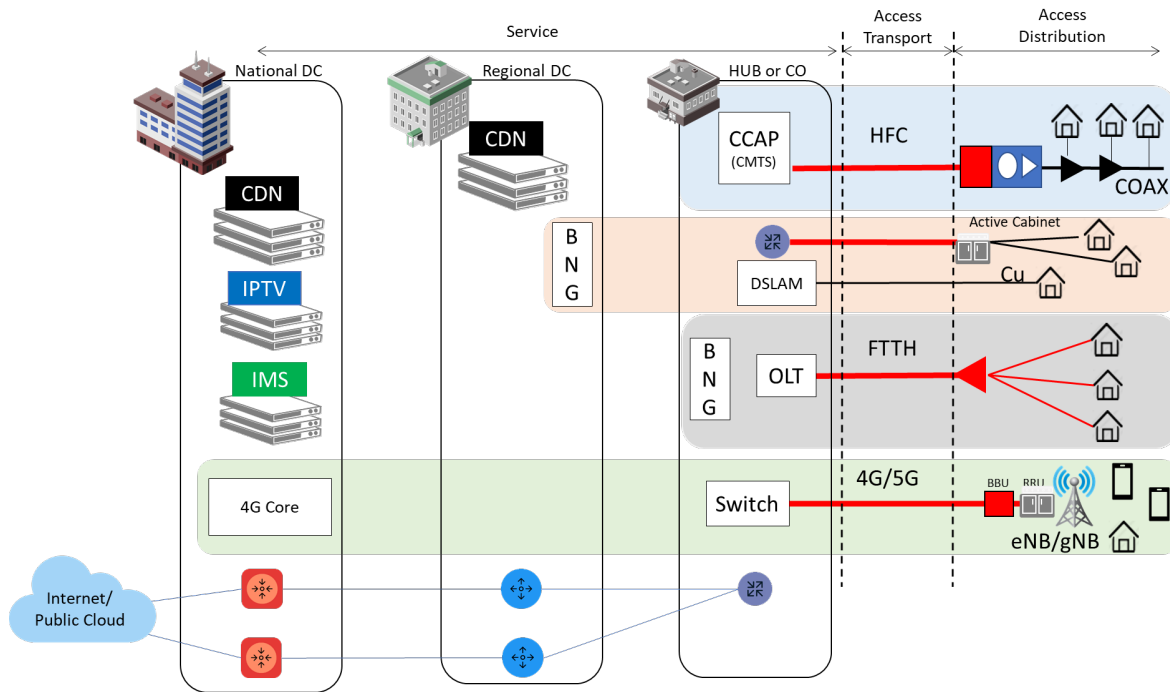


Figure 28 – Telecom Access Network Prior to Convergence

4.5.2. Convergence Access Network and Convergence Access Infrastructure

After several studies that Telecom did during 2019, based on different requests for information (RFIs), consultancy processes, and internal analysis, we found different approaches for Distribution Access Networks and Transport Access Networks. Figure 29 shows the new picture with convergence access network and transport infrastructure.

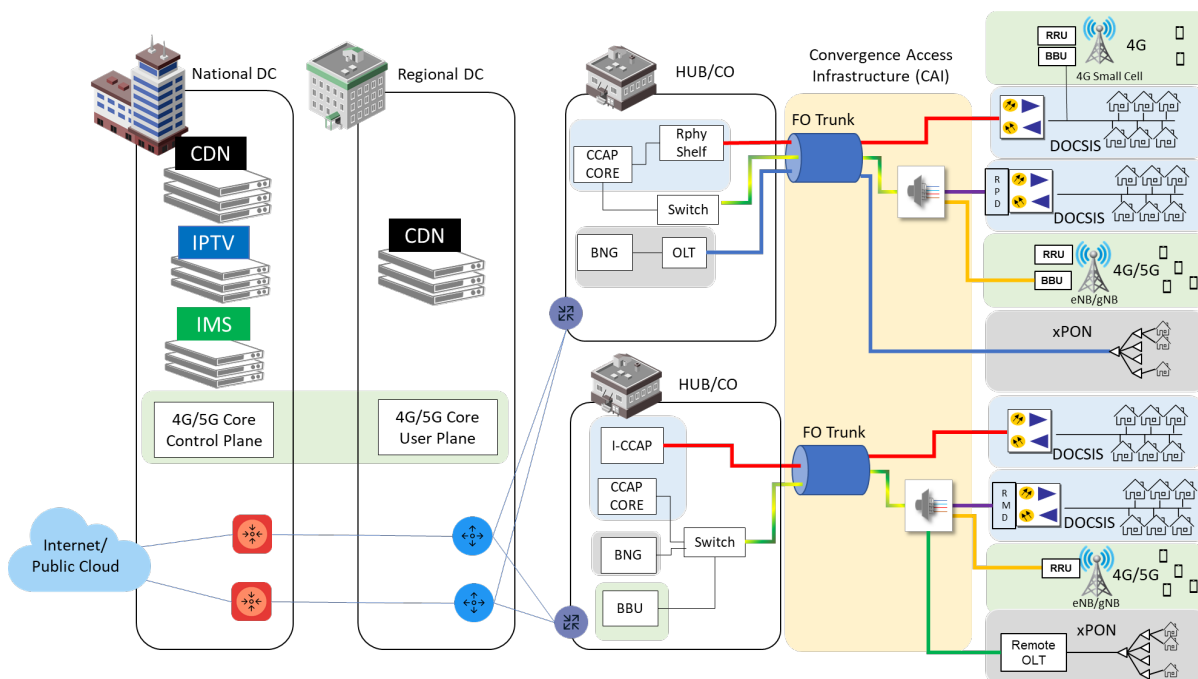


Figure 29 – Access Convergence

4.5.3. Fixed Access Network

For fixed access services, there is not just one recipe. Depending on the homes passed density of the area, take rates, product roadmap, and existing technologies deployed in those areas, there are different criteria on how to evolve the access network.

For instance, in areas where there are more than 50 homes passed per block, and take rates that are greater than 25%, and if the area has DOCSIS and DSL technologies, the analysis shows that the fixed access technologies evolution will first evolve on HFC capacity up to DOCSIS 3.1 on 1 GHz or 1.2 GHz spectrum and will then evolve towards FTTH overlay (GPON and XGSPON).

That means that Telecom will leverage the existing HFC/FTTC infrastructure to build an overlay network and it will smoothly move DOCSIS subscribers to xPON technologies. It doesn't mean that we are going to shut down the HFC network. Even in 10 years we are going to have our HFC network.

FTTH overlay doesn't mean a FULL FTTH migration. What the strategy of FTTH overlay means is that the target fixed access network should be FTTH at the end of the road. In our case, the period of analysis was 10 years, and just a percentage of the customers will be migrated to GPON and this will be a function of different factors such as product tier, churn, competition, and DOCSIS offload necessities. That strategy shows a smaller TCO compared to keeping HFC technology while evolving it towards DOCSIS 4.0. Two key points for that are:

- Leverage the existing fiber infrastructure from both former companies using a converged access transport network. Most of the HFC plant has aerial fiber and it could be extended if needed for optical distribution network (ODN), and there are underground fibers and/or fiber ducts from the former FTTC network. This strategy should lead us to an underground fiber trunk – whenever possible – towards field nodes, even active or passive.

- Home network services must be completely an IP environment. CMs must be replaced by optical network termination (ONTs) in case of DOCSIS to xPON customer migration. Home services must be the same for residential gateway (RGW) features, Wi-Fi capabilities, and monitoring. The most important thing is to protect the investment in set-top boxes (STBs). TV services are based on IPTV in the home network, which is something that Telecom already started to deploy (Telecom have analog clients, and the analog reclamation will be based on IPTV directly, so most of the home will be prepared to be migrated towards xPON during next years).

In areas with DOCSIS and digital subscriber line (DSL) technologies, but with lower households passed density and/or take rate, we found that the FTTH overlay was not so cost-effective in terms of total cost of ownership (TCO). However, DOCSIS evolution could support future demands, so we defined an option called HFC Target which moves xDSL customers towards DOCSIS. The risk of this option relies in ultra-high tier requirements driven by competition.

There are some older areas where the network is just asynchronous DSL (ADSL) technology or one-way HFC. These are in general suburban or rural regions with even lower households passed (HHP) density. Here, fixed wireless access (FWA) service was analyzed as the best choice to provide triple-play services.

The finding was that the best combination is to start the deployment with FWA, and then after some years, move to FTTH (assuming aerial fiber), and then reuse the FWA deployed capacity for mobile services. This alternative de-risked the investment of building a fixed network in areas where the take rate could not be properly estimated.

4.5.4. Small Cell Backhaul over DOCSIS

As depicted in Figure 29, there are small cell deployments over DOCSIS. The main use case here is to deploy pico-cells over HFC to improve the coverage service and provide better service quality to small, mid-size and large enterprises mainly inside offices, rooms, basements or to cover particular public indoor spaces (like shopping malls). The service must provide 4G and 3G connectivity.

Figure 30 shows a simplified architecture that provides 4G services over DOCSIS backhaul. The HeNB (Home eNodeB is the name used in 3GPP to refer to small cells in 4G) is connected to the 4G EPC using DOCSIS as backhaul. The BBU is connected through a CM and establishes a secure connection with IPsec tunnel, that goes through the CMTS, the IP backbone (IPBB), and it is then terminated at the SeGW (Security Gateway).

Optionally, the architecture considers adding a HeBGW (Home eNodeB Gateway) that works as a concentrator of S1-U (i.e., user plane) and S1-MME (i.e., control plane) interface when there is a big amount of HeNB in order to avoid overload, especially in the MME. Finally, the HeMS (Home eNodeB Management) is the component that is in charge of the management of HeNB.

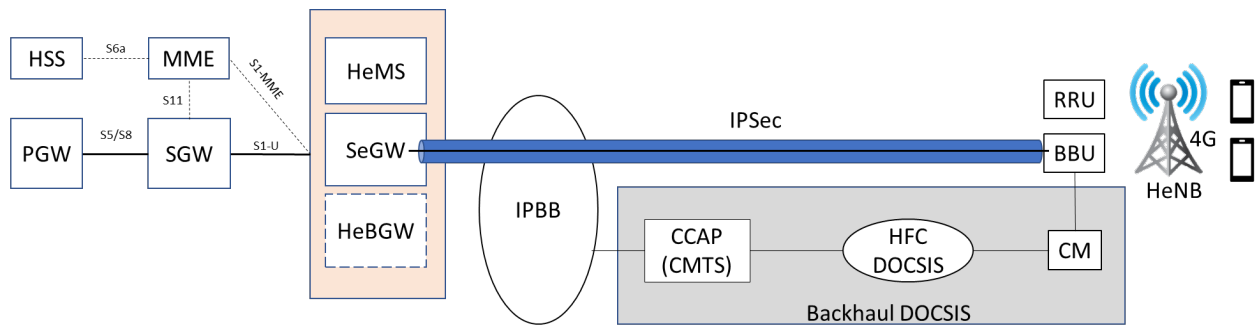


Figure 30 – 4G Small Cells Backhaul over DOCSIS Architecture

The following graphs show the distribution of average and peak throughput of LTE microcells for 2T2R³ microcells during the peak hour, for downlink (DL) and uplink (UL).

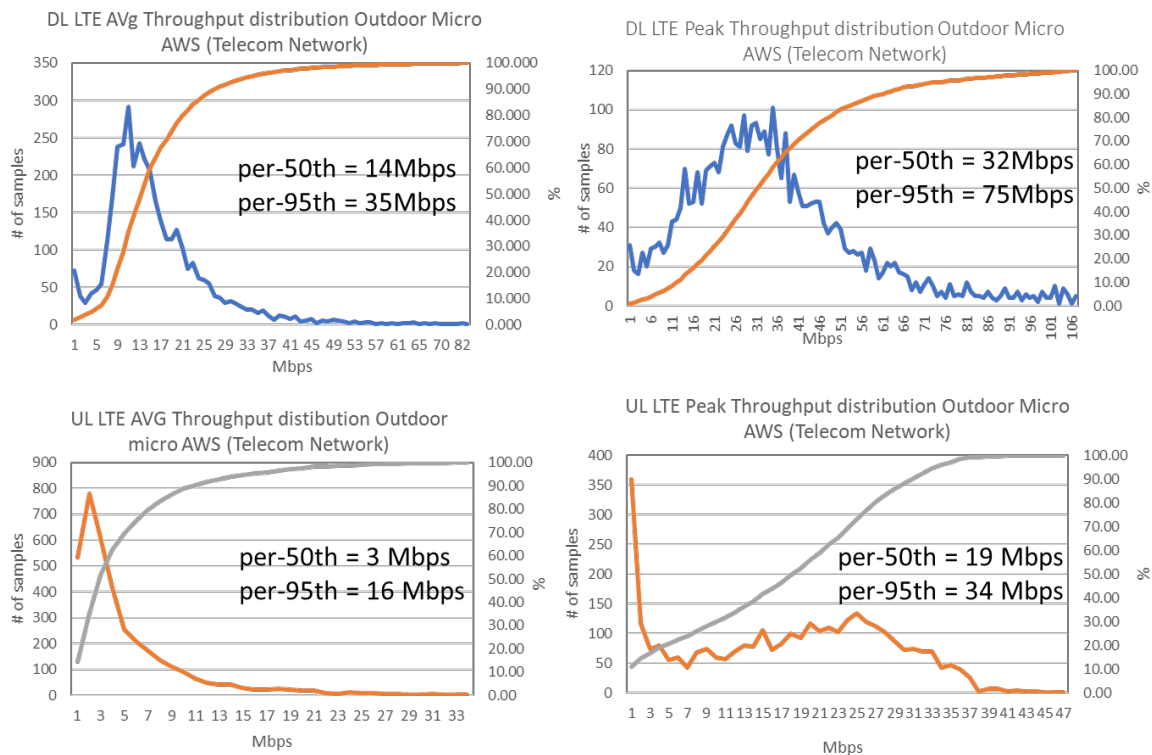


Figure 31 – LTE outdoor microcells Throughput

For DL direction, LTE backhaul over DOCSIS is not a big concern in terms of peak traffic. Nowadays we have products of 100 Mbps in downstream (DS) for residential subscribers, then a small cell could be considered as another CM in the DOCSIS DS service group (SG). However, a small cell requires an average DS throughput of 35 Mbps, while a regular residential subscriber requires an average throughput of at least 10 times lower than that of a small cell. Therefore, sharing the DS SG between small cell deployment and residential subscribers must be done in a planned way.

³ Measurements were taken in June 2018 – 2T2R Bandwidth = 15 MHz at AWS band.

From the upstream (US) point of view, assuming 70% utilization for capacity planning, 42 MHz split HFC networks provide approximately 47 Mbps (three 6.4 MHz channels with 64 QAM @70%) or 76 Mbps (four 6.4 MHz channels @ 64QAM @70%). On the other hand, the graph above shows that meeting the 95% of the times with the needs of UL LTE peak traffic demands a DOCSIS US SG capacity of at least 34 Mbps. Then in this configuration, it could be a challenge to use DOCSIS as backhaul sharing the resources with other residential CMs in the same service group. Hence, is highly recommended move the US split to the mid-split of 85 MHz and deploy D3.1 in US for more capacity, if the small cell is to share the same SG with residential subscribers.

Regarding 5G, in terms of capacity, if DOCSIS is considered as a backhaul solution, then mid-split and DOCSIS 3.1 in the DOCSIS US is a must, whilst in DS SG, the number of SC-QAM/OFDM blocks should be increased. Tests conducted in Telecom Lab with 5G gNodeB (gNB) showed DL peak rates of 1.5 Gbps and 130 Mbps in UL.

Another point to consider in backhaul over DOCSIS is the latency added to the end-to-end service. Round trip time (RTT) latency values that were obtained during the trials were in the range of 30 to 50 msec. In order to improve those values, the Low Latency Xhaul (LLX) over DOCSIS technology [6] is required (see Section 5.2).

4.5.5. Evolution Towards 5G

Deploying previous generations of mobile technologies, i.e., 2G, 3G, and 4G, involved abrupt changes, where, in addition to radio access, a complete change of the core was required to support the next generation. In stark contrast, 5G supports deployment alternatives that can leverage part of the 4G infrastructure, thus easing the inception of this technology.

The 3GPP defines a set of standard deployment options as shown in Figure 32. Regarding the evolution of mobile services from 4G to 5G, the first step is to deploy a 5G non-standalone (NSA) option 3x architecture [10]. Option 3x is one of the NSA options where an improved 4G EPC (EPC+) can be used to connect the RAN, which is composed of eNBs as master nodes as well as gNBs. Option 3x architecture gives Telecom a fast time-to-market and the possibility to provide enhanced mobile broadband (eMBB) services (for instance for FWA) in certain areas, as a complement to other fixed-wired services as well as 5G mobile services. For that, new gNBs are collocated next to the 4G's eNBs in areas where the service is required.

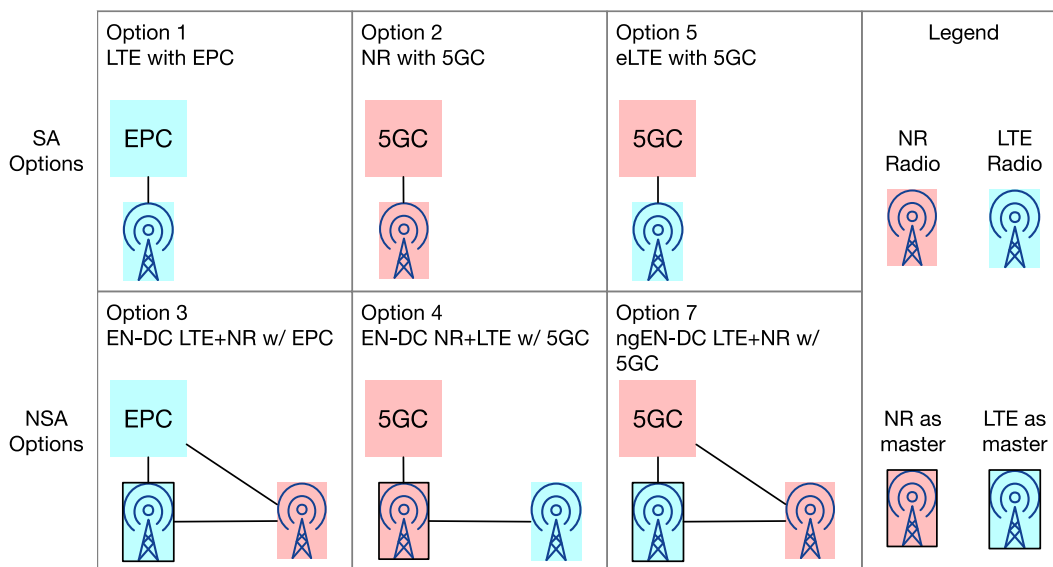


Figure 32 – 3GPP Deployment Options

Some upgrades are needed in the core to evolve the 4G EPC (EPC+) in order to support the NSA capabilities. At the same time, to improve the capacity and improve the traffic distribution, control/user plane separation (CUPS) architecture is implemented that splits the control plane in the national DC and user plane in the regional DC.

This will be followed by a coverage strategy that will be given depending on the commercial demand that we have, but also on the spectrum available. Here, there are several options. For example, using the spectrum in 3.5 GHz which requires regulation definitions in Argentina. Other options may be to make use of the existing bands (“refarming”). The problem is that it would take capacity out from 4G services.

However, a technique called Dynamic Spectrum Sharing (DSS) began to be developed. DSS allows dynamic use of the spectrum by arranging resources for 4G and 5G terminals at different portions of time and frequency subcarriers. It’s like doing an on-demand refarming. This is not really going to generate much more capacity than what we have today for 4G, because, at the end of the day, the amount of bandwidth is still the limit, but it will give the possibility that 5G terminals can camp into a 5G service area. Figure 33 shows a potential roadmap, from the initial state in LTE Advanced Pro, then 5G NSA core plus new generation radio deployment and coverage expansion.

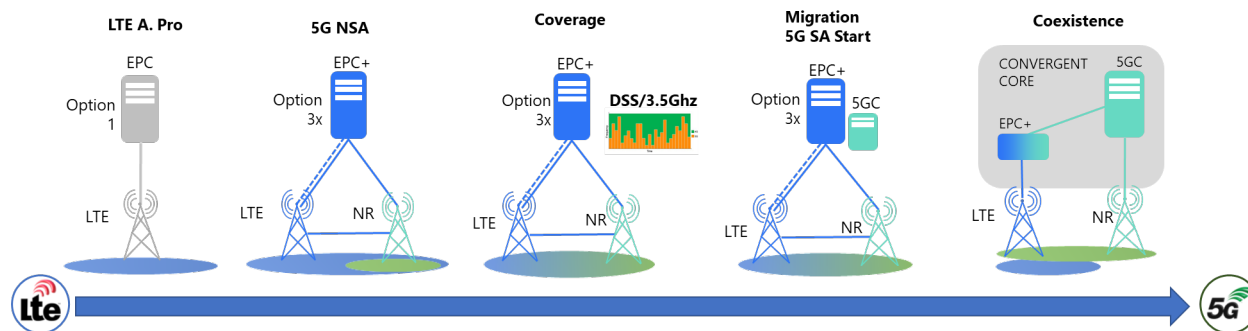


Figure 33 – Possible Evolution Toward 5G

To offer the other 5G attributes, aka ultra-reliable and low-latency communications (URLLC) and massive machine type communications services, a new generation of radios (NR) are necessary but not enough. A full fledged 5G core using a service-based architecture is mandatory. This means beginning a process of core evolution and integration to include the new 5G standalone (SA) components in place.

Finally, we will have a converged 5G core with embedded capabilities that support 4G services since 4G will remain for many years still in our mobile access network. The first step is moving from LTE to option 3X NSA. The next step is to introduce 5G SA. In the industry, there are not much interest in option 7 or option 4. In theory, an operator could simply introduce a new 5G SA option 2 to connect new 5G UEs, then to operate 2 different cores, the “legacy” 4G and 5G NSA and the new one 5G SA.

However, while we introduce a 5G SA, we must guarantee the service continuity between LTE, 5G NSA option 3x and 5G SA option 2. Use 5G SA option 2 to connect 4G UE is another challenge because this migration strategy would require upgrading the eNB to gNB, while also would likely need to acquire new licenses in the new 5G SA option 2 to include the legacies 4G UE. This migration strategy requires more cost without any extra benefit.

What Figure 34 depicts is a combination where we keep the components of 5G NSA supporting 4G UE and 5G UE that works in option 3x, combined with 5G-SA components that connects the UE in option 2.

What we have is an evolution of our today 4G core including LTE+5GNSA 3x capabilities and finally we add 5G SA core components but all in the same “convergent core” solution. That allows us to keep the investment that we did for 4G and 5G NSA, to introduce the 5G SA, providing service continuity and giving the benefit to operate just one “platform.”

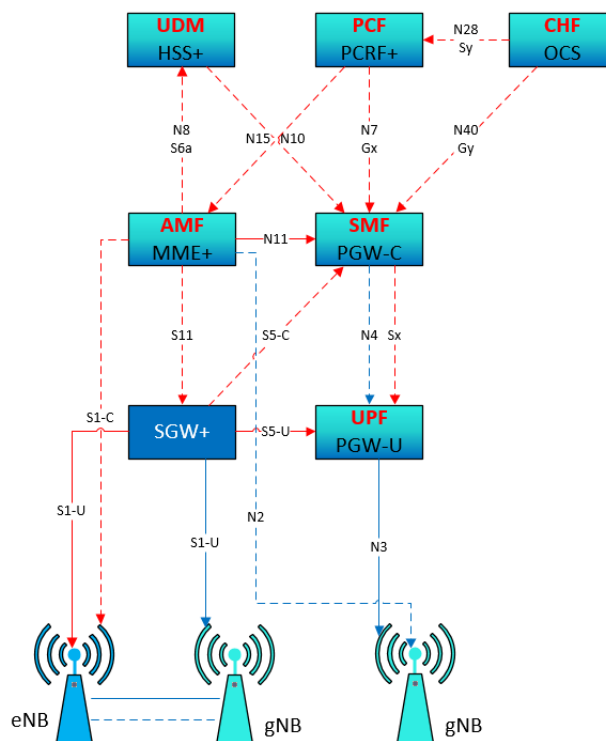


Figure 34 – Convergent 5G Core

4.5.6. Convergence Access Infrastructure

Figure 29 showed access distribution areas that are connected towards the hub and CO with a Convergence Access Infrastructure (CAI). That means that the same fiber trunks are used to support different services such as RPD, RMD, R-OLT, eNB, SMB CPEs, and to connect the access distribution area.

One option is to carry those services directly on dark fiber from the hub or CO to RPD, RMD, R-OLT, eNB, etc. In this scenario, each service uses one or two dark FO.

Another option could be multiplexing several services in one fiber and field devices to demultiplex or disaggregate the services. There are different techniques in this case: with passive architecture using wavelength division multiplexing (WDM), or with active architecture with Ethernet aggregation switches, and/or xPON technologies.

In Figure 35, (a) and (b) show passive WDM transport architecture. They could be distributed or centralized architectures respectively. In these cases, the field devices are passive optical filter and the services (RPD, R-OLT, eNB, etc.) requires a colored small form-factor pluggable (SFP). Figure 35 (c) and (d) depict an active Ethernet aggregation switch in the field, where (c) shows distributed architecture, and (d) shows centralized architecture.

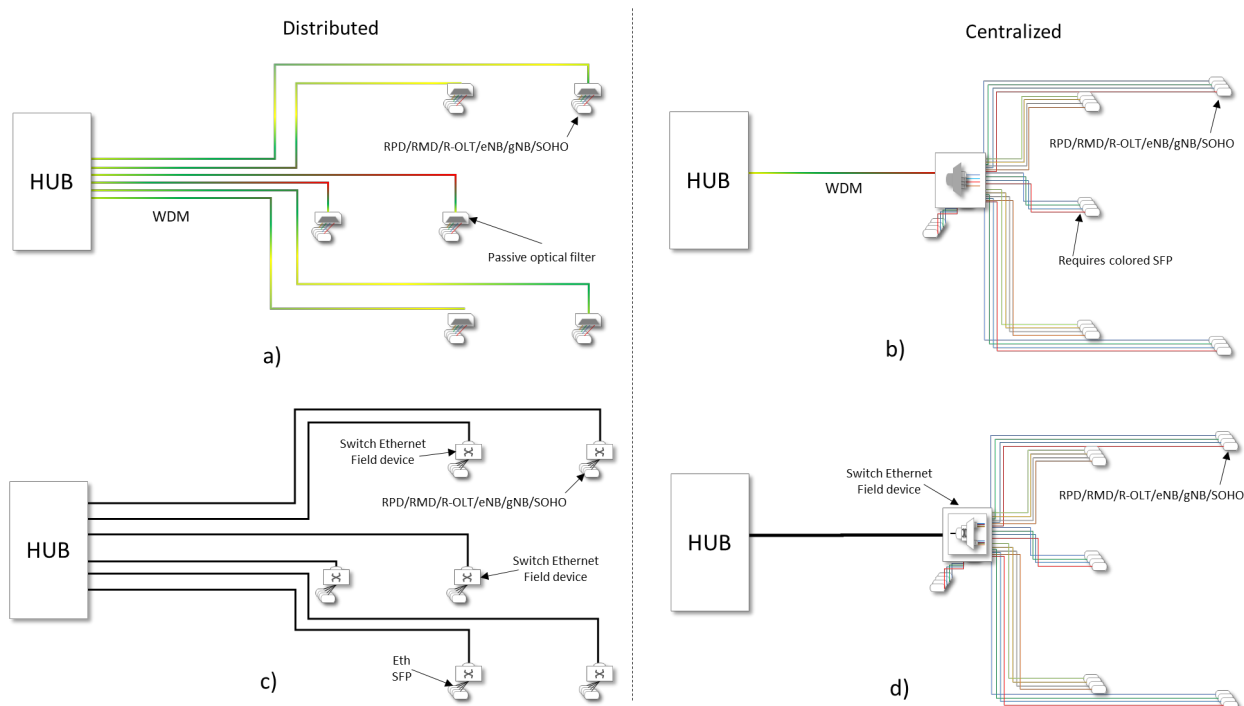


Figure 35 – Access Transport Technologies

The realistic criteria to build the access transport network is based which part of the former companies' networks that is more appropriate. The analysis is based on using the part of the network that is convenient for Telecom due to its strategic location and getting the fiber vacancy to support the technology and the future service requirements. The goal is to protect the existing investment, while reducing the TCO and time-to-deployment, reducing the time-to-market, and avoiding delay that external plant construction could generate.

In the scenarios that Telecom has analyzed, in general, the WDM solutions are more cost effective than Ethernet aggregation switches solutions. The Ethernet aggregation switches solution requires a bigger initial investment. This is the reason why the rest of the analysis was done comparing WDM with dark fiber from a switch in the hub directly to the services such as RPD, RMD, etc., without any multiplexing mechanism in the fiber (dark fiber). The use of WDM techniques is the result of different considerations:

- Not every technology is suitable to be carried in WDM systems, as is the case of xPON over all passive external plant, referred to as the optical distribution network (ODN).
- The tradeoff between reusing the existing FO with WDM techniques and install new fiber trunks will depend on the distance of the trunk and the amount of the services to be carried (DOCSIS, mobile backhaul/midhaul, business services, remote OLTs). WDM could accelerate the time-to-market because it requires less deploying time and less labor force than deploy new fiber trunks.
- As an alternative to new fiber cable installation, neither of them represents significant TCO compared with fixed access infrastructure (CPEs, ODN, etc.), but WDM accelerates time-to-market and does not require labor force for cable landing.
- WDM introduction can be cost effective when the plant evolution is distributed in time, i.e. an area with many HFC nodes that has to be evolved with FTTH overlay at one node per year.
- In the FTTH overlay and HFC scenarios, as the external plant requires active equipment in outside plant, the use of remote optical line termination (rOLT) for residential and some small office home office (SOHO) customers, and direct fiber for bigger customers, the use of WDM optimizes the reuse of existing fiber infrastructure without regard for the former company's origin.

4.5.7. Virtualization and Cloudification

Access services have dedicated infrastructure for CMTSs, OLTs, and broadband network gateways (BNGs). With the network virtualization, or network cloudification, there are some components of those equipment that will be virtualized. Several functions that are in a CMTS are also in the BNG. For instance, subscriber management, DHCP, IP/MPLS forwarding, routing protocol, and others. Of course, there are certain functions that are only characteristics of technology with CMTS, BNGs and OLTs, but those also could be virtualized and there are other functions that will keep as physical network functions.

Nowadays most of the developments in the industry are moving from a legacy concept of virtualization to the new one, that is “cloudification.” The “legacy” way to virtualize a network function has been changed with the new cloud native paradigm. This means rebuilding the system based in open-source software components and in microservice oriented architecture, where those microservices are containerized and orchestrated dynamically.

Microservice architecture means that the system is divided into small applications that could be developed and scale independently of each other, improving and accelerating the agility, maintenance and development of new capabilities. Containerization provides a light way to virtualize each microservice or process, it could be packaged in isolated way, which provides an easy way to be reproduced and deployed. Finally, the orchestration and automation manage and schedule the resource utilization, providing mechanism to simplify the deployments and scaling of containerized applications.

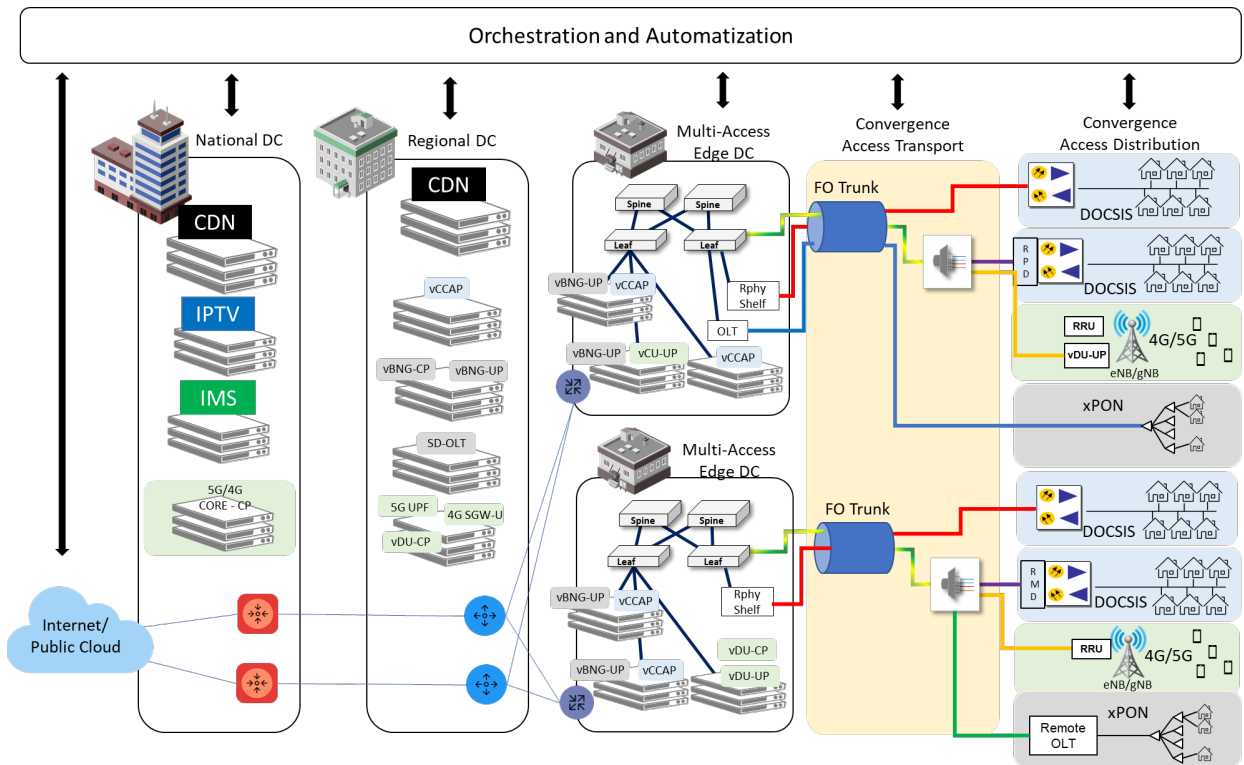


Figure 36 – Virtual or Cloud Access Services

Those virtual network functions or cloud native functions will share almost the similar physical and logical infrastructure. That is a big advantage if we think in FTTH overlay architecture where we could reuse the same infrastructure to deploy capacity for CMTS, BNG and OLTs. Furthermore, if we think in a DOCSIS to FTTH migration, we could discuss with the vendors to move licenses cost from a virtualized CMTS to a virtualized BNG, for example, to protect investments. Of course, we would not replace the CMTS and BNG that we have today with virtualized versions. However, when capacity expansion is needed, we will deploy the new virtualized CMTSs or BNGs instead of the traditional physical versions.

Virtualization would also enable us to move some of the functions to a more centralized location, such as a regional data center (DC), to have a better scale, and leave in the hub/CO, or the new edge DC, or far edge DC, just the functions required to guarantee latency or to keep capacity closer to the end user. Regarding the optimization of the location of different components, the CUPS architecture applies too. The BNG is a typical use case of CUPS where the control plane (CP) can be in a regional or national DC, and the user plane (UP) is distributed across edge DCs. This substantially improves the management of BNG infrastructure.

4.6. Vodafone

4.6.1. Background and Context

Vodafone started as a mobile operator in the UK in 1985 and subsequently expanded its mobile operations into other countries around the globe via a combination of owned networks and partner markets to reach over 300 million customers. Vodafone has mobile operations in 22 countries and partners with mobile networks in 42 more.

Vodafone has grown its fixed line business via a combination of acquisition, self-build and joint ventures. Examples of fixed network acquisitions include Arco in Germany, Tele2 in Italy and Spain, C&W in the UK and Hellas Online in Greece. Vodafone then became the largest local loop unbundler in Europe using its own ADSL and single-pair high-speed DSL (SHDSL) equipment on rented copper lines from incumbents. It also used sub-loop unbundling in Italy and Germany to deploy its own very high-speed DSL (VDSL) equipment in street cabinets.

Vodafone has been deploying FTTH for over a decade and, for example, has now fiber-passed over half the population in Portugal. It has also expanded FTTH via partnerships and joint ventures (JV) such as in Ireland where SIRO is a FTTH JV between Vodafone and ESB, the electricity utility.

In terms of cable, Vodafone acquired KDG in Germany, ONO in Spain and more recently the Liberty Global cable networks in Germany, Czech, Hungary and Romania. Vodafone also acquired ABcom in Albania. This has resulted in Vodafone becoming the largest broadband operator in Europe and one of the largest cable operators globally.

Vodafone provides fixed broadband in 17 countries. As of 30 June 2020, Vodafone Group had 27 million fixed broadband customers and 22 million TV customers, including the customers in Vodafone's joint ventures and associates. Vodafone's European fixed broadband technology presence is illustrated in Figure 37.

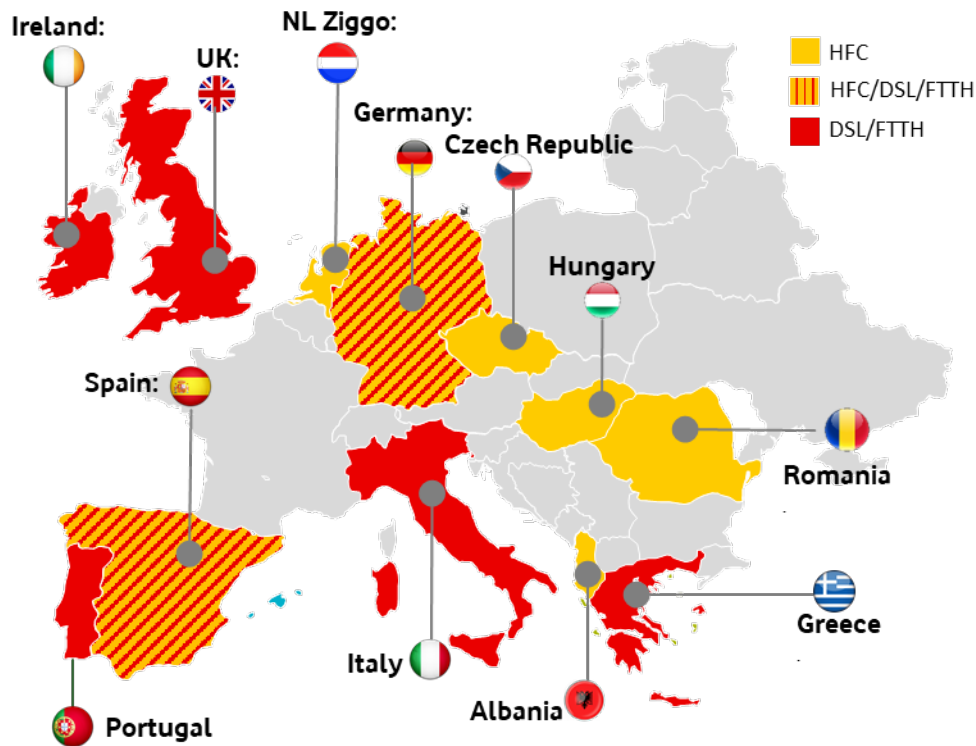


Figure 37 – Vodafone's European Presence

Outside of the European footprint above, Vodafone also has operations including fixed broadband in Turkey and a number of AMAP (Africa, Middle East, Asia-Pacific) countries too including South Africa and Ghana.

Vodafone is now a converged operator whose roots are in mobile. Hence in comparison to many US and Canadian cable operators, Vodafone has significant mobile spectrum and network assets. It therefore has a slightly different approach to convergence in that it is not an MVNO and it does not seek to use the CBRS spectrum. Also, whilst Vodafone has experience of deploying Wi-Fi hot spots in some markets, it is not highly dependent on having a vast number to offer “wireless untethered access” outside of the home.

Vodafone has 2G, 3G, 4G and 5G networks. Mobile network evolution will significantly grow 5G coverage, capacity and functionality over the next few years in addition to other mobile network capabilities such as narrowband IoT (NB-IoT). Mobile innovation will continue with developments such as Open-RAN and Crowd-Cell. There are also opportunities to couple such mobile capabilities with our fixed network assets for convergence at the network and service layers. The following sections give an overview of Vodafone's approach to convergence.

4.6.2. Motivation for Convergence

It has been over a decade since some service providers offered “triple-play” service bundles of fixed voice, broadband and video. Convergence refers to combining both fixed and mobile capabilities resulted in “quad-play” with the addition of mobile voice/data to the bundle. This has become increasingly common across Europe where some markets such as Spain are highly converged with multiple operators offering converged service bundles to customers.

There are three main commercial benefits that have motivated Vodafone's move to become a converged operator:

1. *Reduced Churn*

Customers buying a bundle of converged fixed plus mobile services tend to be “stickier” and less likely to churn. They are often incentivized by getting a discount on the bundle (compared to procuring each service individually), and/or more included benefits (e.g. extra data, additional mobile lines, higher speed).

2. *ARPU Improvement*

When a service provider becomes a converged services provider for the first time then they have the opportunity to cross sell fixed services to mobile customers and vice versa.

3. *Cost Reduction*

Convergence at the network level enables savings compared to operating disparate fixed and mobile networks. Hence, this is usually one of the first activities to drive synergy savings following M&A activity between fixed and mobile operators. The fixed and mobile services can then share common backhaul and core transport networks as well as data centers and server capacity, which is increasingly important as we move to software-defined virtualized networks. This is illustrated in Figure 38.

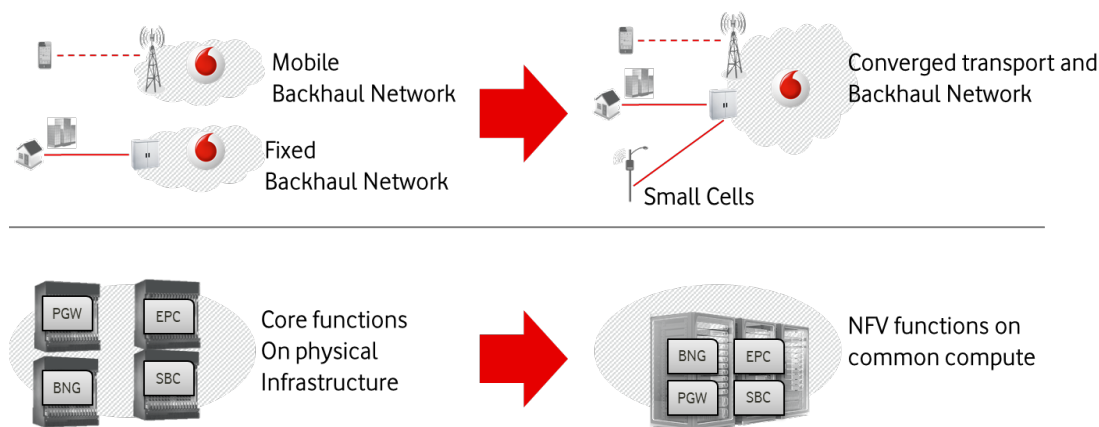


Figure 38 – Infrastructure Convergence

The simplest form of convergence is on the customer's bill – a single bill to span both fixed and mobile services. However, more sophisticated convergence approaches are feasible, convergence can take several forms from convergence at the service level through to convergence at the network infrastructure level. A simplified view of convergence in four different domains (or layers) is illustrated in Figure 39 for the Vodafone context.



Figure 39 – Vodafone Four Layers of Convergence

At the bottom layer we have network connectivity and infrastructure such as compute processing capacity in data centers. The next layer has the capabilities, systems and processes that turn the network and compute resources into a technology platform. This is where policy, analytics, operations processes and automation (SDN control and orchestration) reside. This layer interfaces to the Services and Application layer above it via standardized APIs (effectively a Network Exposure Layer) to create a “Network as a Platform” paradigm. Then any converged product and service development can focus on developing to the APIs (ideally TM Forum compliant) with worrying about details of the underlying network technologies and their associated idiosyncrasies.

Development of new products and services can then be more rapid and also more rapidly deployed across multiple markets (without repeating integration heavy lifting for each new geography). This benefits time to market for internal Vodafone product development teams but also facilitates engagement with third-party partners. Finally, the top layer is for Channels and Customer Service – effectively the touchpoints for the end user customers.

4.6.3. Convergence Use Case Examples and Network Scenarios

A converged network, as illustrated in Figure 40, allows a variety of converged services to be offered.

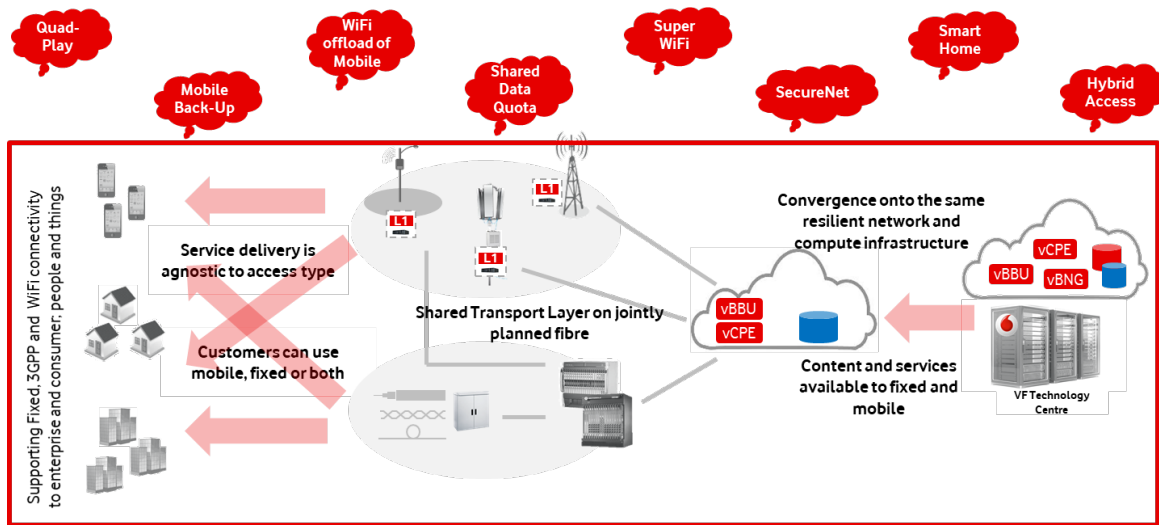


Figure 40 – Convergence Use Cases

The following sections discuss examples of converged services and network capabilities.

4.6.3.1. **Vodafone TV**

This enables a seamless, device agnostic TV experience in and out of the home which is personalized across all sources. It gives easy access to all content – integrating traditional/linear channels with on-demand, catch-up and the best OTT streaming services – with advanced search, including voice. The banding is shown in Figure 41.

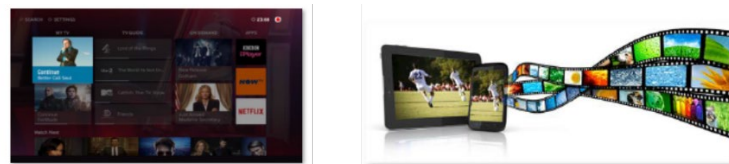


Figure 41 – Vodafone TV

A further converged Vodafone TV variant that had previously been deployed in one of Vodafone's local markets is illustrated in Figure 42.

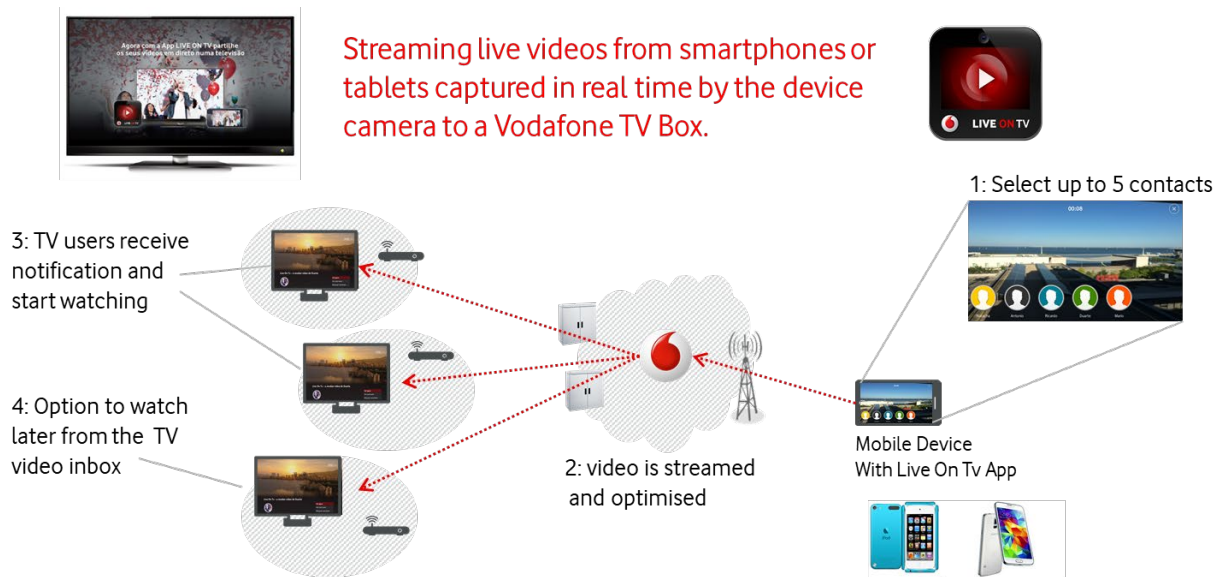


Figure 42 – Local Streaming

For example, if one of your children was playing a football game on a cold, wet Saturday morning, someone from the family could attend and use their smart phone camera to “video” the game which would be relayed to the TV where the rest of the family can watch it in warm, dry comfort. The process of making this happen is shown in Figure 42. There are now alternative ways to achieve similar capabilities since over-the-top (OTT) platforms (Facebook, YouTube, etc.) can offer live streaming capabilities and cast them to the TV too.

4.6.3.2. Safety, Parental Control & Smart Home

A range of “Smart Home” services is illustrated in Figure 43 are connected to the fixed broadband access line (via Wi-Fi, Zigbee etc.), but the control point is the customer’s mobile handset. Such services can provide customers with control in and out of the home, across all devices, fixed and mobile. Capabilities can include mobile control and notifications. Security capabilities can include alarms, locks, smoke and leak sensors, IP cameras. Smart energy can also be facilitated via remote mobile control of thermostats.

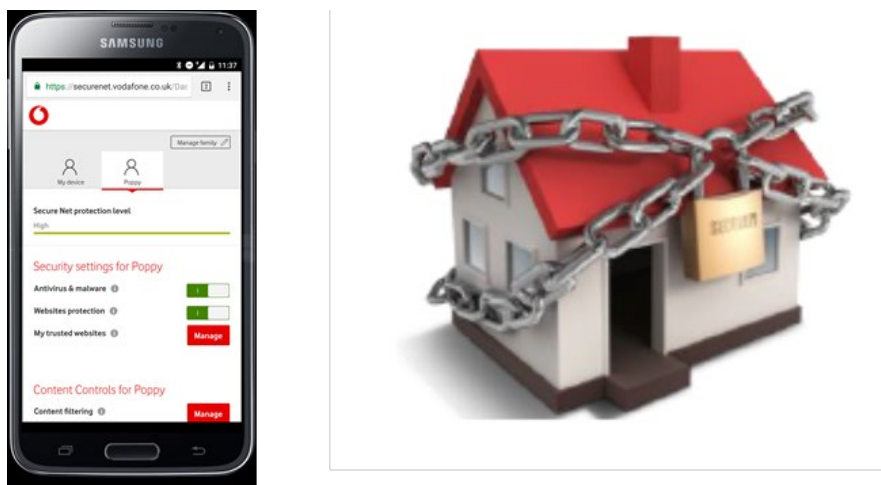


Figure 43 – Smart Home

4.6.3.3. Hybrid Access (Fixed-Mobile Bonding)

Hybrid access combines the throughput of a low-speed fixed broadband connection such as ADSL with mobile 4G/5G data using a hybrid router. This enables customers to burst to higher speeds beyond the capacity constraints of their fixed broadband connection. It can be used to provide an ‘always-on’ service i.e. a resilient service with mobile backup in case of fixed service failure.

Vodafone’s initial deployment of this capability, optimized for the small-medium enterprise market, integrated the bonding client into the consumer broadband CPE. This is shown in Figure 44. A variant is also feasible that uses a customer’s mobile handset to provide the mobile access connection to temporarily boost the customer’s fixed broadband access speed.

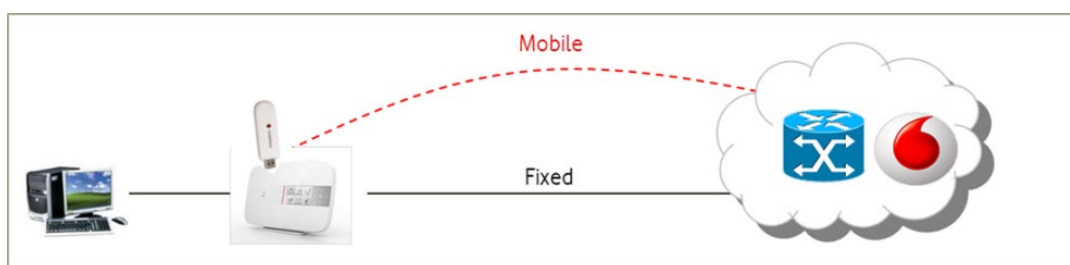


Figure 44 – Hybrid Access

Other variants of such technologies (including 3GPPs ATSSS) can also help to facilitate seamless roaming between mobile and Wi-Fi connectivity, preferably whilst maintaining the same IP address. This can ensure that the customer always has the best connectivity (based on both RF signal strength and network congestion). Such mobile/Wi-Fi roaming capabilities also have Enterprises use-cases e.g. in hotels, conference facilities etc.

4.6.3.4. Always-On Service

A precursor to the hybrid access approach illustrated above was to leverage the availability of both fixed and mobile access connectivity in a more manual way in order for the customer to be able to carry on accessing the Internet if their fixed broadband fails. This was deployed in a few countries including in Vodafone Greece.



Figure 45 – Always-on Service

4.6.3.5. Fixed Wireless Access (FWA)

FWA is a technology option as illustrated in Figure 46 is considered for low to medium speed broadband access for areas with no or poor fixed access. It can be used as a tactical deployment where wholesale fixed broadband costs are excessive. It is usually avoided for deployment in urban and sub-urban (Residential) areas with good next generation access (NGA) penetration. It is often a “last resort” technology because there can be high customer equipment costs (especially if outdoor hardware and professional installation is required).

There can also be significant capacity implications for the costly spectrum on the mobile network (e.g. somebody binge-watching a 4k video stream for a few hours. Hence such solutions are most commercially viable in areas underserved by high-speed fixed networks and with low customer penetration, or amongst specific customer segments (e.g. customers who move residences frequently etc.). The Vodafone “Gigacube” 4G/5G FWA product has been deployed in Germany, UK and Ireland.

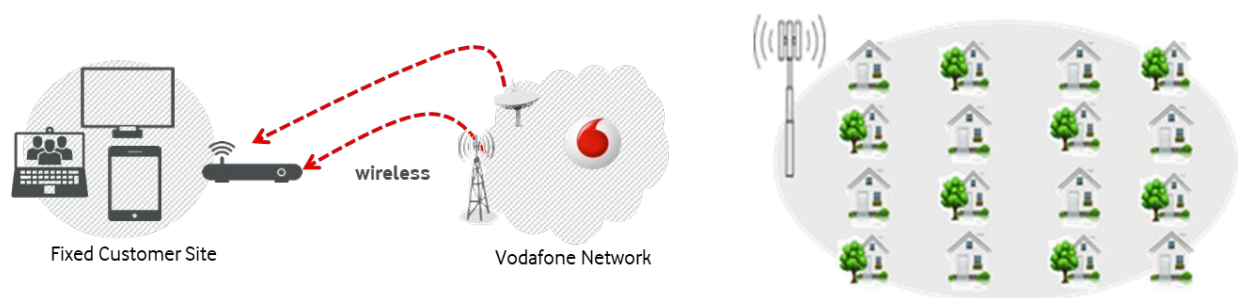


Figure 46 – Fixed Wireless Access

4.6.3.6. Converged Access & Aggregation Network

As NGA technologies have evolved, it becomes feasible to examine their potential to provide backhaul from mobile base-stations as an alternative to point-to-point fiber and leased lines. Vodafone had previously used GPON to connect a few base-stations in some countries. This approach then evolved to evaluate PON backhaul from 4G and 5G base-stations including the evolution from GPON to XGS-PON. XGS-PON products including the necessary Synch support (IEEE 1588v2 & SYNC-E) and have been

successfully proven. DWDM over PON is also a potential technology option which is under investigation. This is illustrated in Figure 47.

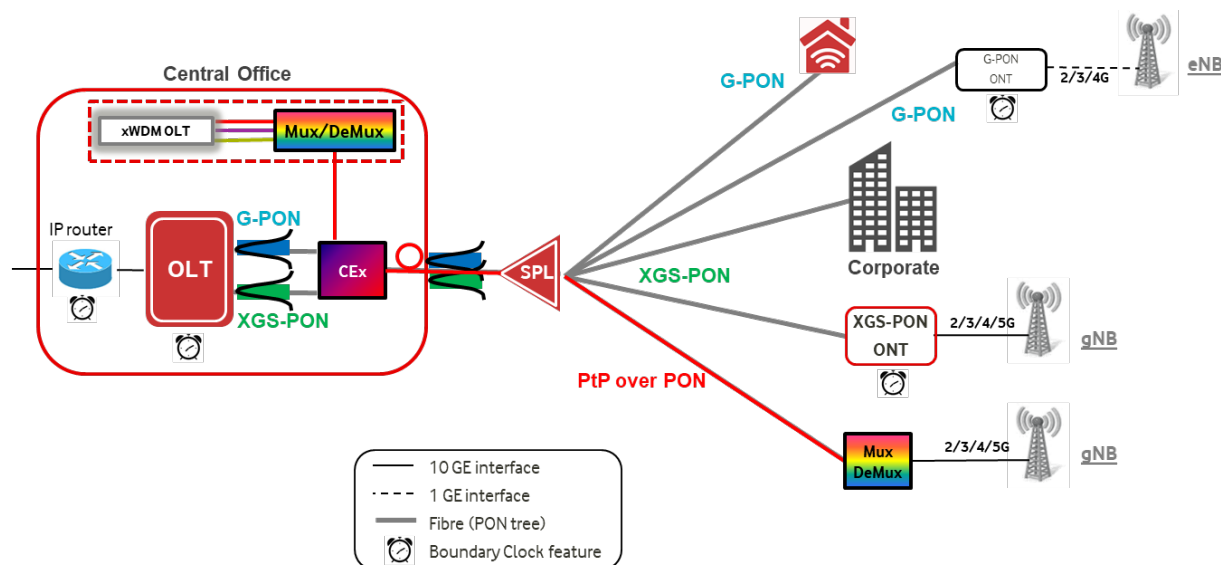


Figure 47 – Converged Access with DWDM PON

Thus far, mobile RAN developments such as SON (self-optimizing networks) and active antennas (also known as massive MIMO) have successfully increased the RAN capacity from macro-cell base-stations, which has deferred the need for large-scale deployment of small cells. Nevertheless, where required, Vodafone has deployed a number of external public small cells as well as indoor femto-cells for consumers and pico-cells for business customers to enhance indoor coverage.

Vodafone has previously trialed mobile backhaul over DOCSIS 3.0 in order to understand synchronization and bandwidth utilization requirements. The focus then shifted to examining mobile backhaul over DOCSIS 3.1. This is more challenging for macro-cells compared to using XGS-PON due to the lower bandwidth and potential implications for residential broadband users. However, there is a potential future role for using DOCSIS to provide backhaul from small cells, as and when their deployment may become necessary at any significant scale.

For mobile backhaul over DOCSIS, the phase and time requirements can be met due to the inclusion of the DOCSIS Time Protocol (DTP) in the DOCSIS 3.1 standard. QoS and mechanisms to manage the jitter are needed. Also, low latency (e.g. leveraging CableLabs Low Latency Xhaul – LLX) is needed to stay within a target latency of 5 ms (base station to backhaul aggregation). The various synchronization mechanisms are shown in Figure 48.

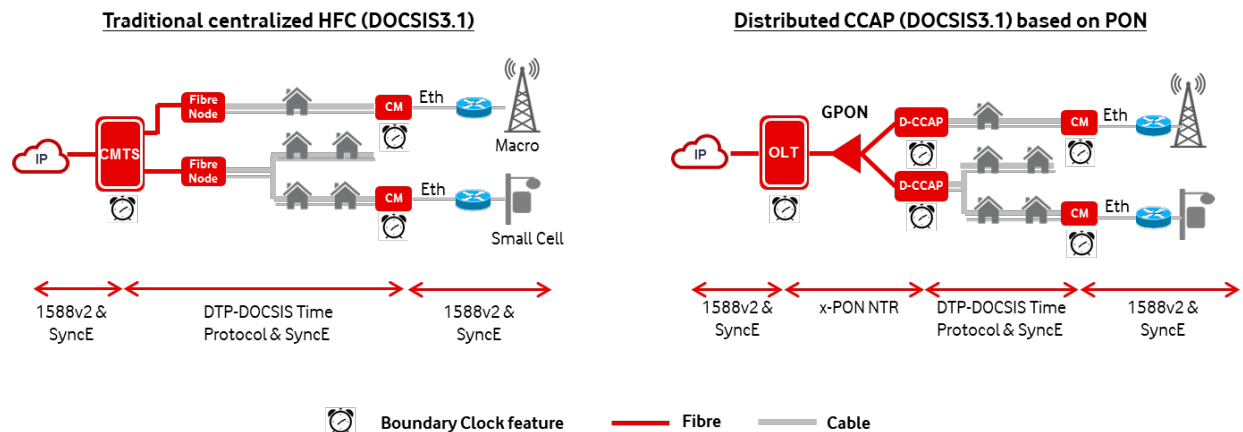


Figure 48 – Network Timing with DOCSIS and PON

Vodafone has been evolving its cable networks to a distributed architecture in some markets as we introduced DOCSIS 3.1. This requires fiber to be pushed deeper into the access network to connect to a remote PHY device (RPD) and remote MAC device (RMD) remote devices. This trend will continue as we evolve towards DOCSIS 4.0. Hence it creates the opportunity to have a single fiber access and aggregation network that can provide direct fiber connectivity (PON or point to point) to macro base-stations, enterprise customers, business parks and the cable network's remote nodes.

As more bandwidth is required on such a “unified fiber access/aggregation” network, coherent optical technology has the potential to play a key role, especially for the backhaul from remote aggregation locations. This converged fiber access/aggregation network approach is illustrated in Figure 49.

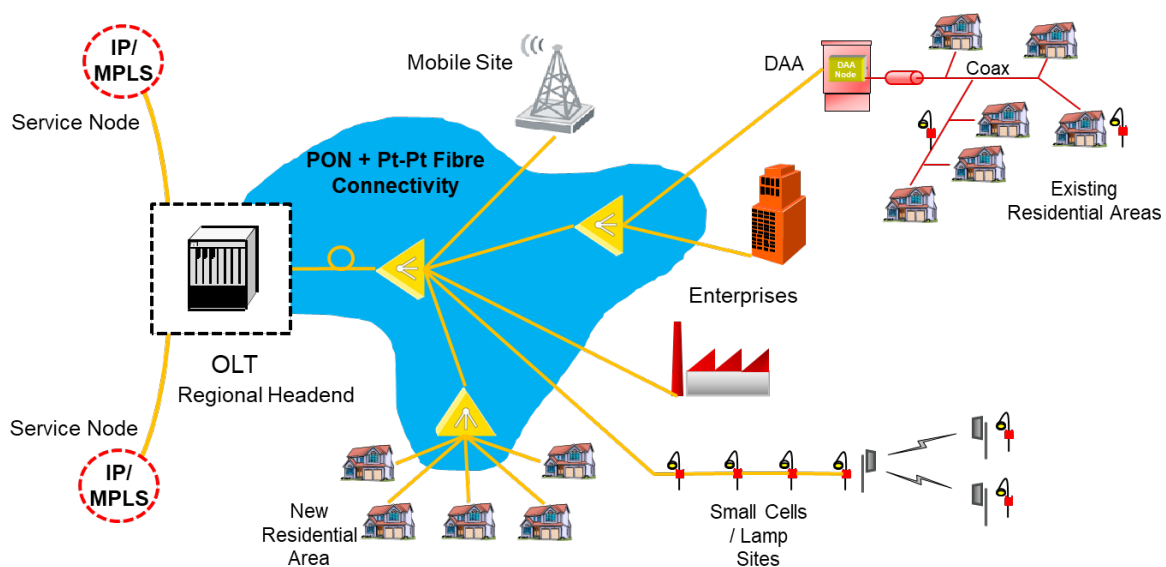


Figure 49 – Unified Fiber Access/Aggregation Network

A further enhancement to this access network is to introduce session steering or slicing from the access node in order to steer sessions to a user plane (software or hardware) that is appropriate in terms of location (latency) and scalability/cost to the particular session's traffic. For example, low margin consumer traffic from OTT streaming could be steered to a scalable, cheap (and dumb) user plane whereas enterprise traffic

may be steered to a user plane where service chaining is to occur for value-added services like security (firewall, malware scrubbing etc.). In the convergence context, LTE mobile backhaul traffic could be steered to the Gi LAN.

4.6.3.7. **Broadband Access to Converged 5G Core**

There are a number of incentives for ensuring that the next generation 5G core network can support wireline access instead of treating it as “untrusted”, as was the case in previous 3GPP mobile core network standards. These are summarized in Figure 50.

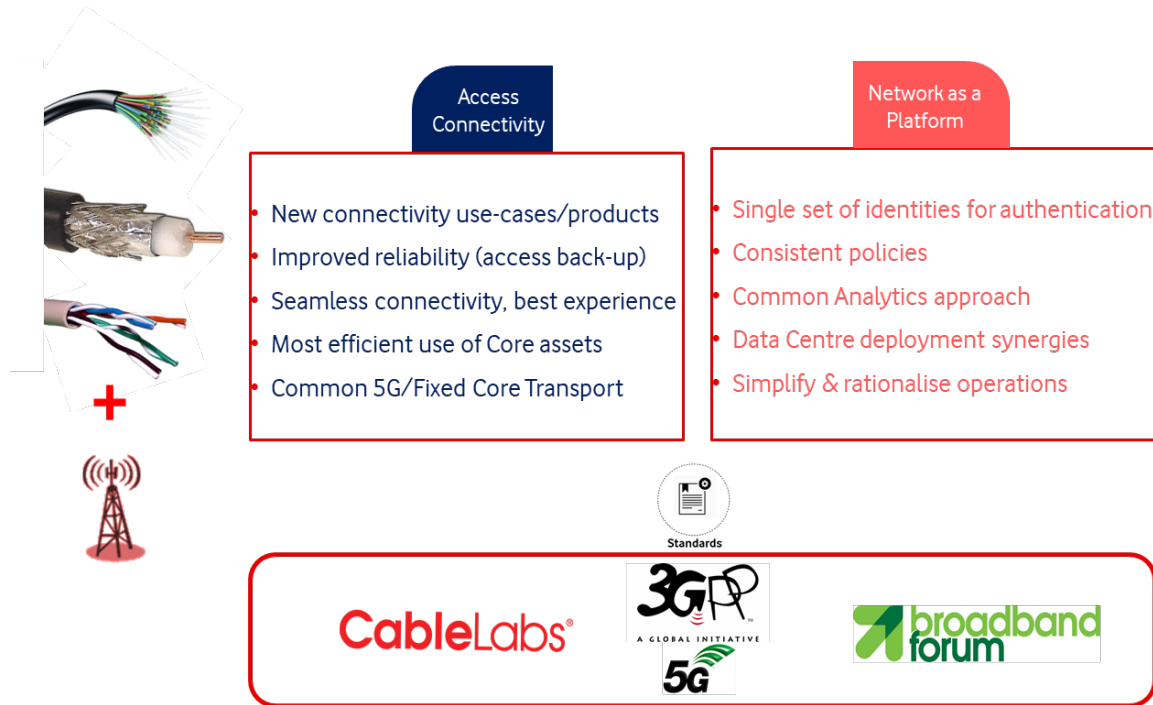


Figure 50 – Wireline Support in 5G

The technical approach has been to develop an Access Gateway Function (AGF) that effectively translates from the wireline protocols to those used by 3GPP. 3GPP has been working with both CableLabs and the Broadband Forum on standards in this area. The network context of the AGF is shown in Figure 51.

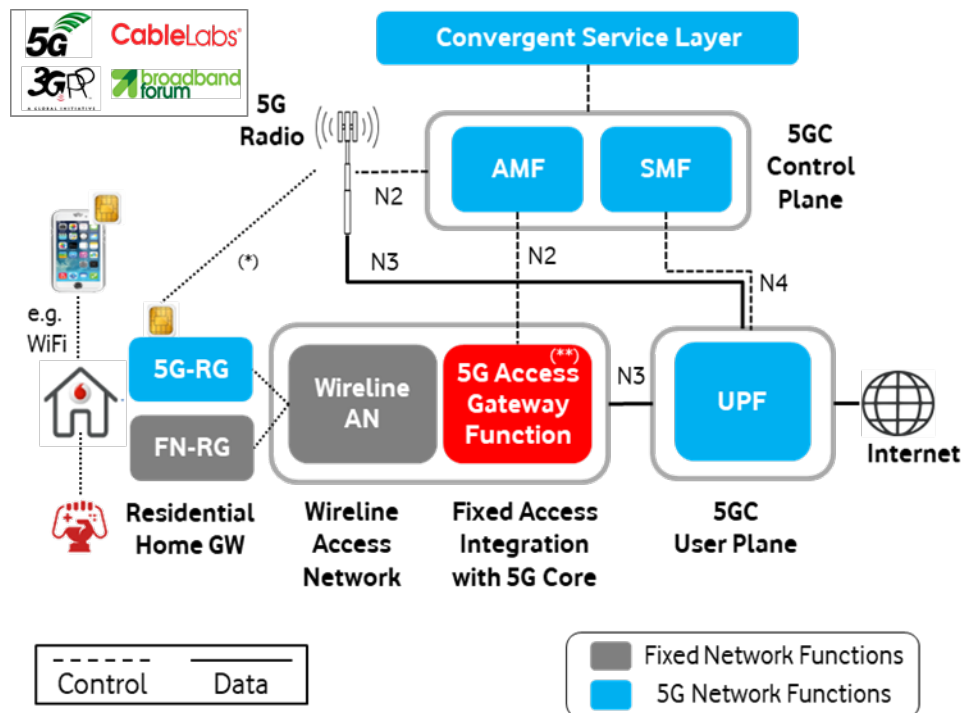


Figure 51 – Wireline Connection to 5GC with AGF

Residential gateways (RGs) will also evolve to encompass functionality that enables enhanced capabilities. These new RGs are denoted “5G-RG” in the standards documents. The new “5G-RG” functionality in CPE will enable more dynamic session connectivity. A 5G device (UE) behind the 5G-RG can be treated as “trusted”. QoS requirements can then be signaled on a per application basis and multiple IP sessions can be added dynamically for a class of device. The 5G-RG is illustrated above. The “FN-RG” is the legacy fixed network RG that can be used to access the converged 5G core but will have less flexible/dynamic capabilities than the 5G-RG.

4.6.3.8. Improving In-Home Mobile Voice Coverage

Vodafone has extensive experience of using femto-cells plugged into the customer’s broadband router to improve in-home mobile voice coverage. A product known as “Sure Signal” which was a 3G femto-cell was used in significant numbers in Vodafone UK. During Covid-19 lockdown in 2020 it proved useful for some of Vodafone’s own staff where, for example, their home office was in the basement or modern building materials (especially glazing) meant their home was effectively a Faraday cage.

An alternative to femtocells for improving mobile voice coverage is to enable VoWiFi on the mobile network (assuming internal Wi-Fi coverage in the house or basement is better than the mobile coverage). This is supported and easy to set up on modern smart phones. This is shown in Figure 52.



Figure 52 – Voice over Wi-Fi

4.6.3.9. Converged Measurement & Analytics

As both fixed and mobile access speeds have increased, latency (and other aspects of “broadband quality”) have become more important. 5G in particular was the first technology to use ultra-low latency in its marketing. Cable technology has also evolved to include Low Latency Xhaul (LLX) and Low Latency DOCSIS (LLD). In addition, CableLabs has worked on Low Latency Wi-Fi.

Vodafone’s recommended latency measurement method at the IP layer has been TWAMP (Two-Way Active Measurement Protocol). However, as we seek to further optimize customer experience and application performance we needed a more hi-fidelity technique for latency and performance measurement.

After extensive scouting and testing we selected the new Quality Attenuation technique, sometimes referred to as ΔQ (pronounced Delta Q). ΔQ emphasizes the gap between real performance and perfection (i.e. zero loss and delay) and has been standardized in BBF TR-452.1 with some early vendor capabilities available. The Quality Attenuation measurement and analysis approach can disaggregate a round trip time (RTT) into three constituent components as shown in Figure 53 in each direction (downstream and upstream), for a total of six components.

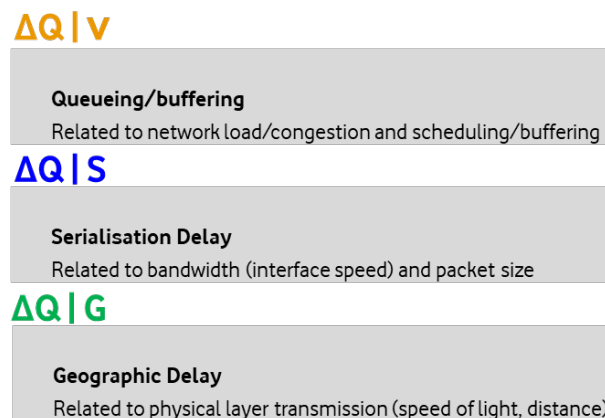


Figure 53 – Quality Attenuation technique

Vodafone has trialed the Quality Attenuation technique in four countries over a range of fixed and mobile access technologies including DOCSIS, 4G, GPON and VDSL. Different fixed and mobile access technologies behave differently at the physical layer and these manifests themselves as different packet latency and loss characteristics at the IP layer, which in turn determines the application outcome and customer experience.

50 Mbps on 4G is not the same as 50 Mbps on DOCSIS or FTTH. It is increasingly important to understand such issues as in the converged network we increasingly seek to use FWA, hybrid access to boost speed or to back-up fixed access with a failover to mobile access. Common tools for measurement and analytics across the mobile and fixed access elements of the converged network will become increasingly important as we seek to deliver our customer's applications in a seamless manner, irrespective of access technology.

4.6.3.10. CPE Management

Vodafone has millions of Customer Premises Equipment (CPE) devices managed using the TR-069 protocol. Globally, there are now over a billion devices worldwide managed by hundreds of service providers using this protocol which is included as an option in CableLabs' eRouter standard. 3GPP and the Small Cell Forum have also developed data models to be used with TR-069 for the management of small cells.

TR-369 is the successor to TR-069 and is a new standard known as the User Services Platform (USP). It has a number of improvements but the most notable is the ability to have multiple controllers. This facilitates new commercial models with external 3rd party partners for example the ability to outsourcing Wi-Fi optimization to an external partner with smart algorithms, AI and machine learning based in their own Cloud. They would only be able to access the Wi-Fi parameters in the Residential Gateway. An overview of user services platform (USP) as defined by TR-369 showing the multiple controller capability is illustrated in Figure 54.

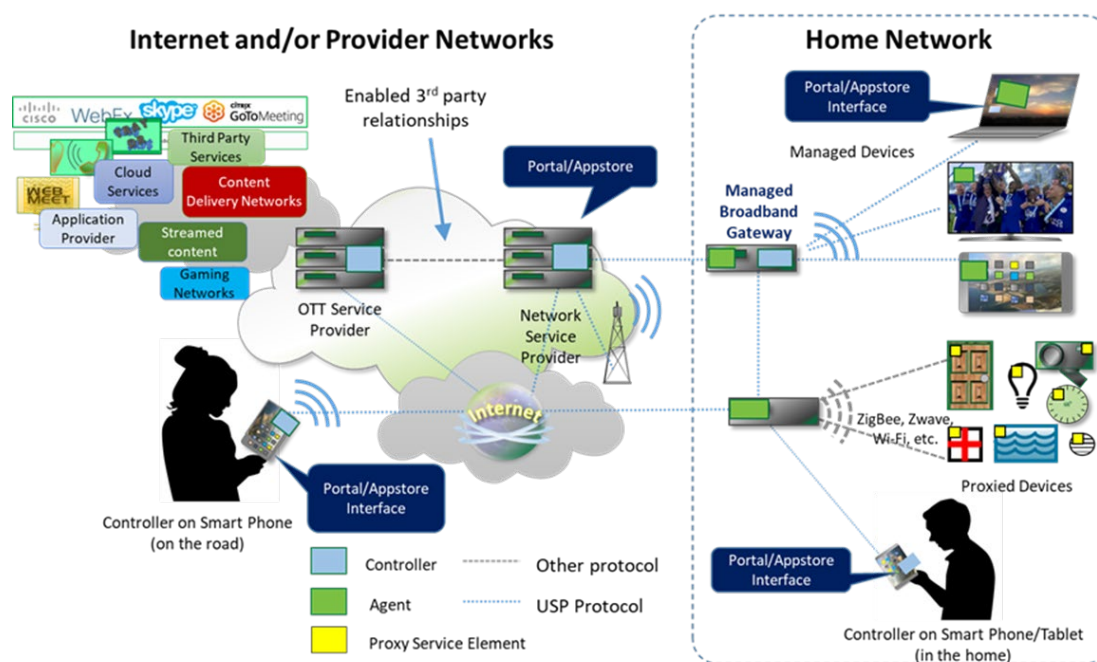


Figure 54 – USP TR-369 in Deployment

In the convergence context, this could, for example, enable the fixed broadband experts to manage the residential gateway but the mobile experts to manage any connected small cells.

For an integrated CM and Residential Gateway (router), TR-369 can be used in conjunction with existing DOCSIS provisioning systems and processes as illustrated Figure 55.

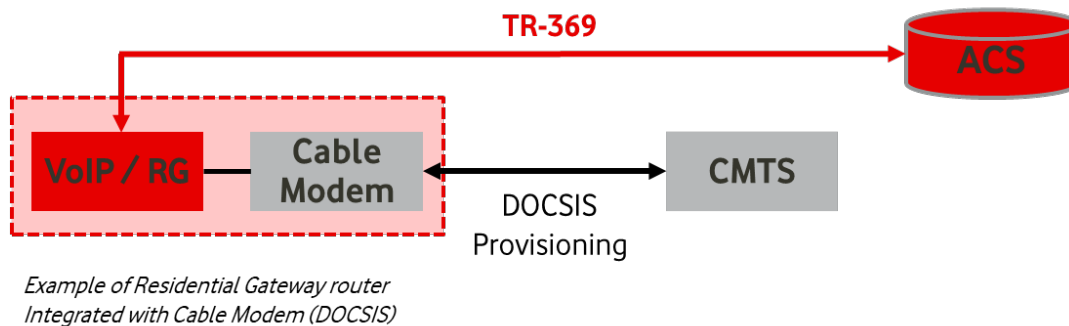


Figure 55 – DOCSIS GW with TR-369

4.6.4. Summary

This section has presented how a range of technologies can be used to facilitate convergence at the network and service layers for a converged operator. It is important to note the key role that standards play in this evolution. In the past, standards have been siloed in either the fixed domain or the wireless domain. In an increasingly converged business, it is vital that CableLabs, 3GPP, Wi-Fi Alliance and Broadband Forum and other such organizations collaborate and cooperate in order to deliver effective solutions for network operators and service providers.

This is especially true for capabilities above the physical layer such as architecture frameworks, management protocols, data models, performance measurement techniques, telemetry and analytics. Alignment on such areas will be key in the new software-centric world of virtualized, distributed and disaggregated networks with a growing focus on automation leveraging SDN, AI and ML.

5. Convergence – Technologies

In the previous section, we covered business objectives and technology viewpoints of the cable-mobile operators. In this section, we recap some of the common technologies that have been highlighted to enable convergence between cable and mobile deployments.

5.1. DOCSIS Technology

Every wireless network is dependent on a wireline network. Traditional wireline network that supports the wireless deployment is fiber. But that is about to change. DOCSIS technology is one of the key enablers for mobile deployments because of its near-ubiquitous availability in urban and suburban areas. Residential femto, strand-mounted small cells, as well as SMB inside-out will provide inside and outside coverage economically compared to fiber.

Since the cable industry first specified the DOCSIS standard in 1997, the technology has evolved through five generations of progressive improvements over several key performance criteria, including capacity and latency. Table 7 shows the capabilities of the most recent DOCSIS standards. The currently deployed DOCSIS 3.1 is capable of supporting multi-gigabit per second downstream speeds. As MSOs move to reclaim spectrum previously used for traditional video services, upstream spectrum can be significantly increased by moving from the low split of 42 MHz to the high split of 204 MHz. Multi-gigabit per second of speeds on the upstream can be reached this way in the near term. In the longer horizon, DOCSIS 4.0, currently being specified, is expected to provide greater upstream speeds.

Table 7 – DOCSIS Capabilities

Requirements	D3.1 today (2020)	D3.1 max (future)	D4.0 (2023-2024)
	Shared spectrum with video	Full spectrum through video reclamation	Extending to 1.8 GHz, possibly 3 GHz
Downstream spectrum	54 - 1002 MHz	258 - 1218 MHz	602 - 1794 MHz
Upstream spectrum	5 - 42 MHz	5 - 204 MHz	5 - 492 MHz
DS Capacity	8.5 Gbps	8.6 Gbps	10.8 Gbps
US Capacity	0.1 Gbps	1.4 Gbps	3.7 Gbps
Latency	Best Effort : 5 - 50 ms.	With LLX / CTI : 1 - 2 ms (can be further reduced)	
Synchronization	Frequency sync only No time sync	Frequency + time sync through DTP	

5.2. Low Latency Xhaul (LLX)

DOCSIS technology supports a variety of scheduling mechanisms to meet the latency needs. The most commonly used best effort scheduler can deliver a typical latency of around 10 to 15 milliseconds (ms), but is dependent on the channel loading condition (see Table 7). DOCSIS also natively supports real-time polling (RTPS) and proactive grant service (PGS). These schedulers intend to reduce the request-grant delay that is typical in any point-to-multipoint scheduled systems. But they have some drawbacks, such as not able to achieve low enough latency needed for mobile xhaul, or incurring too much bandwidth overhead.

To address these drawbacks and to better support mobile xhaul over the DOCSIS network, Cisco and CableLabs co-invented a mechanism that pipelines the scheduler operations of the mobile and the DOCSIS systems. The pipelining mechanism forms the basis of the Low Latency Xhaul (LLX) technology, which has been standardized by CableLabs [6].

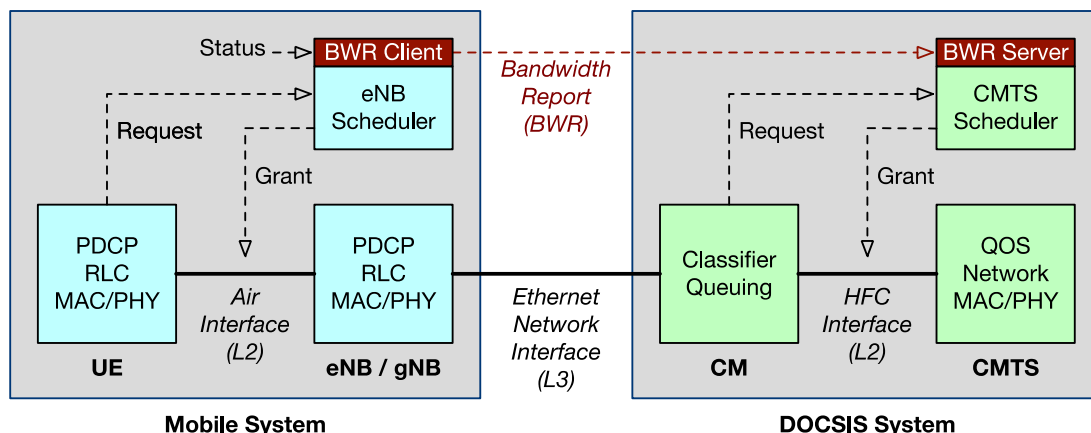


Figure 56 – Scheduler Pipelining with Bandwidth Report (BWR)

In a nutshell, LLX uses the decisions made by the mobile scheduler to inform the CMTS scheduler what is about to happen. By doing so, LLX creates a low latency transport for mobile traffic.

As shown in Figure 56, mobile and DOCSIS systems are both point-to-multipoint scheduled systems. This means both systems have an inherent latency due to request-grant delay in the upstream. In LLX, that latency is incurred once in the mobile system. The results of the request-grant process, in the form of a BWR message, are then passed to the DOCSIS system so the CMTS can grant the CM directly without waiting for a native layer 2 DOCSIS request.

Let's look at an example.

1. The UE has an application that wants to send 1000 bytes. It sends a request to the eNB scheduler.
2. The eNB scheduler responds and says that the UE may send the 1000 bytes 8 ms from a reference time.
 - a. The eNB scheduler, now that it knows what is about to transpire on its air interface, makes a determination of what will happen across the network interface that it shares with the DOCSIS system. In our example, the eNB adds 1 ms of engineering margin to cover any buffering and internal path delays.
3. The eNB sends a BWR message to the CMTS system that says that 1000 bytes will be arriving on the shared network port 9 ms from the reference time.
 - a. The CMTS scheduler, now that it knows when the bytes will arrive in the CM, determines when it wants to send a grant to that CM. In this example, it adds 1 ms of engineering margin to cover any buffering or scheduling jitter.
4. The CMTS sends a DOCSIS MAP to the CM at the correct time telling the CM to transmit the 1000 bytes 10 ms from the reference time.

The net result is that the latency of the DOCSIS system is effectively reduced by hiding it under the mobile system. In theory, LLX should be able to achieve near-zero latency on the DOCSIS upstream. In practice, one to two milliseconds of engineering margin is added.

Numerous test results have been previously published using a physical testbed and reported that BWR achieves one to two milliseconds of DOCSIS upstream latency in a variety of channel loading conditions up to 70% on the DOCSIS network. Details of how LLX works and lab trial results can be found in [11][12][13][14][15].

5.3. Synchronization and Timing

Depending on the type of mobile deployment, frequency only, or frequency and phase, synchronization is required for the small cell. Timing and synchronization requirements for FDD, TDD, LTE, and 5G are shown in Table 4.

Table 5 in Section 4.1.4.4 lists common options to consider when it comes to support timing and synchronization. Network-supported timing using Precision Time Protocol (PTP) is needed for indoor deployments and to lower the cost of the small cells.

The DOCSIS network is asymmetrical. If the PTP protocol is sent over-the-top of the DOCSIS network, it may incur variable buffer delay which can cause packet delay variation (PDV) and large time transfer errors. For LTE FDD, PTP over-the-top may be a workable solution with some mitigation work, such as assigning PTP packets with higher priority DiffServ code point (DSCP). But the mitigation may not be enough for LTE and 5G TDD.

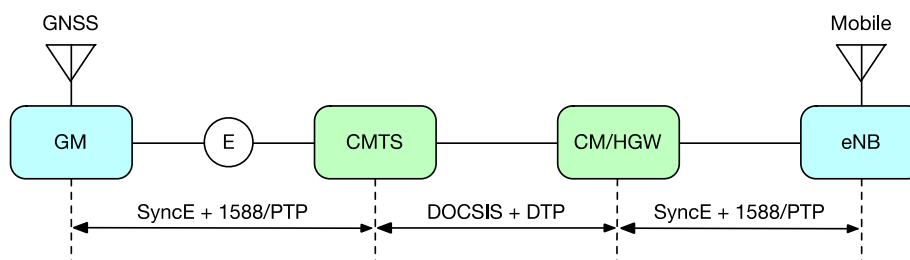


Figure 57 – 1588 Timing over DOCSIS Network with DTP

To meet the TDD requirement, a better way to carry PTP over the DOCSIS network is through the DOCSIS Time Protocol (DTP), as shown in Figure 57. In a nutshell, timing from the global navigation satellite system (GNSS) is received by a primary reference time clock (PRTC) that generates the PTP messages. The PTP messages are sent through one or more Ethernet switches that support PTP. The PTP timing domain is terminated by the CMTS.

The DOCSIS system is already a synchronous network with its own timestamp. The CMTS's job is to align the DOCSIS timestamp with the PTP timestamp. The DTP algorithm is run between the CMTS and the CM to compute the one-way downstream delay. Upon receiving the DOCSIS timestamp as part of the normal DOCSIS operations. The CM adds the one-way delay to the DOCSIS timestamp. The CM passes on the recomputed timestamp and appears as a PTP master to the small cell downstream.

Details of the DTP algorithm and preliminary test results can be found in [16][17][18]. DTP is now part of the synchronization specification standardized by CableLabs [19].

5.4. DOCSIS DAA for Mobile People

This section briefly discusses the splits for the 5G radio access network (RAN) and then compares them to the choices made by DOCSIS when it split its access network with the distributed access architecture (DAA). The contrast of the two architectures are shown in Figure 58.

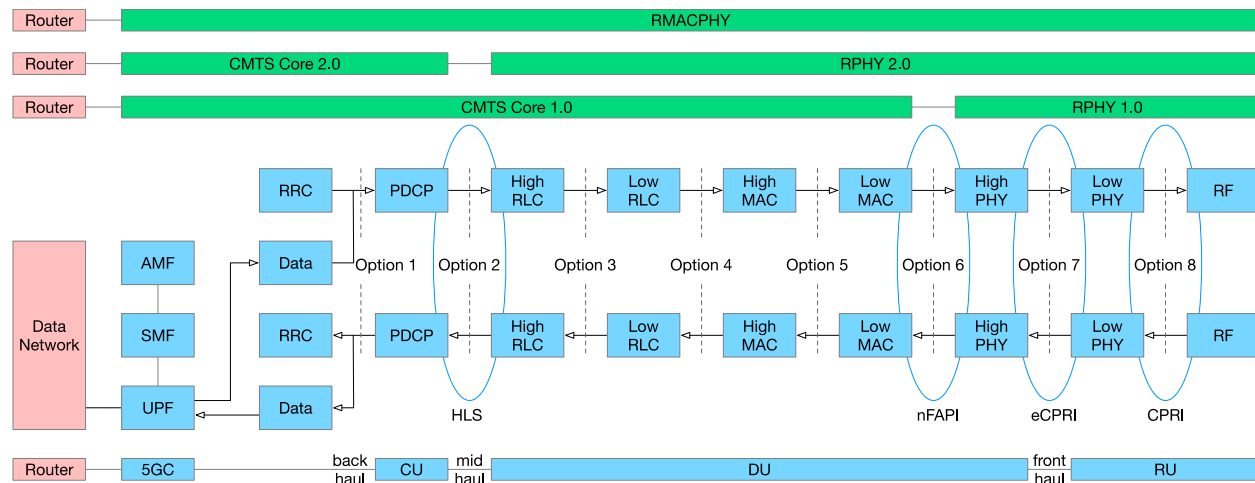


Figure 58 – Mobile RAN Splits with DOCSIS DAA

The 3GPP task force defined eight splits in the RAN architecture and then picked higher layer split (HLS), while the O-RAN Alliance further specified the interoperability required to enable lower layer split (LLS). The original common public radio interface (CPRI) was a raw digital to analog conversion style of interface. It has a very large bit rate and is considered semi-proprietary. The enhanced CPRI (eCPRI) lowered the bandwidth to make it fit better on 10 Gbps fiber links and was adopted as the LLS / option 7 split between the radio unit (RU) and the distributed unit (DU). This interface is also referred to as the fronthaul interface.

The DU contains layer 2 framing and the uplink scheduler. The DU is intended to be located near the RU location. Typically, the RU is outdoors and the DU is indoors. A DU product may service multiple RU products. The network side of the DU is a packet interface with a data throughput slightly above the payload rate due to only having payload encapsulation and signaling. The split between the DU and the centralized unit (CU) is done with option 2 and is referred to as the HLS.

The first architecture for DAA was Remote PHY (RPHY) [20][21]. Remote PHY is well defined as an open standard [22]. It is a shipping product with multiple manufacturers and operators deploying RPHY with several million attached devices. The goal of RPHY is to centralize software and distribute the radio frequency (RF) hardware. Because the DOCSIS protocol has encryption built into it, it was convenient to put the DOCSIS layer 2 framer centrally to ensure the backhaul link was encrypted. This would be the equivalent of 3GPP's option 6. In fact, before option 2 and option 7 were chosen for the mobile RAN, there was a proposal from Cisco for an option 6 network functional application platform interface (nFAP) in the Small Cell Forum (SCF) [23].

After Remote PHY was defined, and broader architecture was defined called the flexible MAC architecture (FMA). The first phase of FMA is the remote MAC and PHY (RMACPHY) which is really a full layer 2 cable modem transport system (CMTS) that includes the entire CMTS Core, or the equivalent of a full EPC,

located in the remote fiber node. In the mobile world, FMA resembles incorporating the 5G Core into an integrated gNB, both located the remote node. At the time of writing, FMA is a pre-standard draft.

There is a next generation of Remote PHY, informally called RPHY 2.0 [24], that is proposed but not yet standardized. A RPHY 2.0 Device (RPD 2.0) provides DU-like capabilities that include the DOCSIS upstream scheduler [25] and the DOCSIS framer. The first version of RPHY was designed about a remote RF device and a centralized physical set of DOCSIS and video cores that were located within a 100 mile (160 km) radius of the RPD. By contrast, the second version of RPHY will be designed to put latency sensitive signaling such as the upstream scheduler into the remote node. Doing so allows distances in excess of 100 miles to cloud-based cores that are located at the service provider (SP) edge or in true cloud such as Amazon or Azure.

5.5. DOCSIS for Mobile Xhaul

Similar to the DOCSIS protocol, LTE and 5G have their own protocol stack. LTE eNB or 5G gNB are full-stack integrated units. In 5G, the RAN can be further functionally decomposed into a central unit (CU), a distributed unit (DU), and a radio unit (RU). Mobile standards organization 3GPP specified the option 2 split, which splits the PDCP and above layers into the CU while the layers below remain in the DU and RU. The ORAN Alliance defined option 7-x split, in which the RU consists of the RF and a portion of the PHY, while the layers above remain in the DU and the CU. A backhaul, midhaul, or fronthaul network, collectively known as xhaul, interconnects the different functional components together.

Functionally, the DOCSIS network can interconnect the small cells as shown in Figure 59. However, the requirement on capacity and latency vary between backhaul, midhaul, and fronthaul. Backhaul and midhaul are both based on an IP encapsulation of the original mobile transport. Thus, the bandwidth requirement on the transport network roughly matches the mobile traffic rate.

The latency requirement for backhaul is based on the application. Additional service-level agreement (SLA) can be specified by the mobile operator. Midhaul latency is less deterministic. Some standards have defined it to be less than 10 ms [26], while some vendors require one to three milliseconds of CU-DU latency. LLX can be implemented to ensure these requirements can be met, as well as providing better latency performance, particularly for latency-sensitive flows.

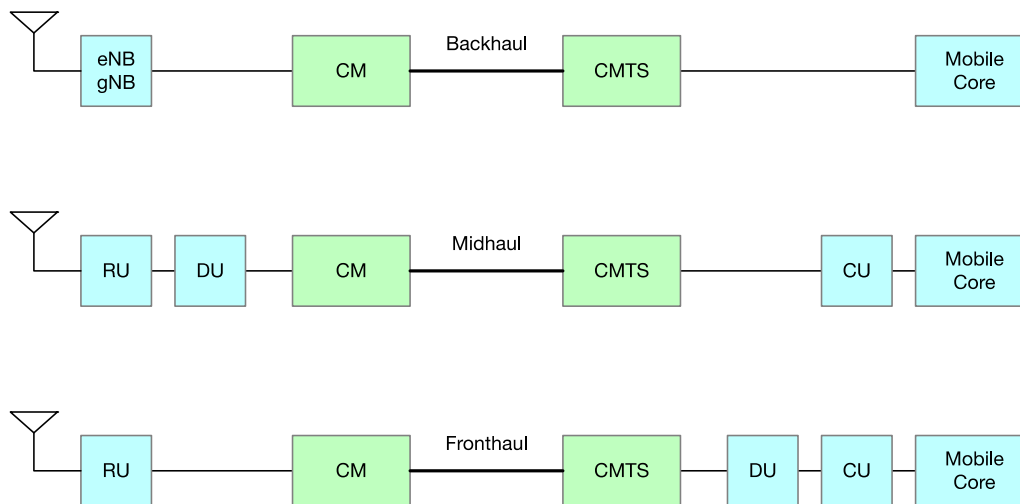


Figure 59 – Mobile Xhaul over DOCSIS Architecture

Fronthaul is much more difficult to support over the DOCSIS network. Studies have shown that the eCPRI-based fronthaul transport needs significantly more bandwidth, overhead, and one-way latency in the neighborhood of 250 microseconds between the RU and DU [20]. Even with LLX, it will be difficult to reduce the DOCSIS latency to this level. Because of the stringent requirements, fronthaul is better carried over fiber.

5.6. Common Quality of Service (QoS) Framework

The DOCSIS network is a finite pipe with multiple endpoints sharing resources. Rather than dedicating resources to meet the peak capacity all the time, the DOCSIS network is designed to meet the bandwidth demand most of the time. Traffic is separated into multiple flows. During times of congestion, latency-sensitive flows such as signaling or 5G ultra-reliable low-latency communication (URLLC) traffic are sorted into separate queues and are generally served before latency-tolerant flows. This is the goal of quality of service.

The mobile system is also a point-to-multipoint system where resources are shared among users. It has its own set of QoS rules and queue configurations that may be different from the DOCSIS network.

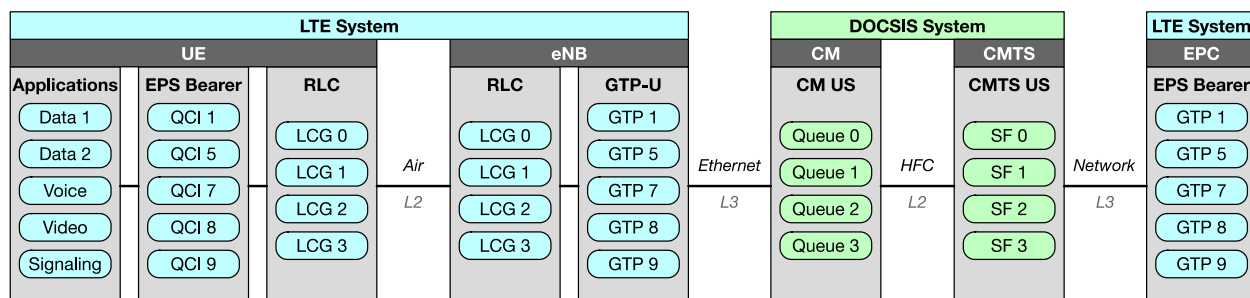


Figure 60 – Common Quality of Service Framework for MBH over DOCSIS

To ensure consistent treatment of traffic when they move across the mobile and DOCSIS networks, a common QoS framework as shown in Figure 60 between the mobile system and the transport system needs to be supported. There are many variations of how this could be done, but fundamentally, it should:

1. Use the same number of queues in the transport system as there is in the mobile system
2. Use the same classifier mechanism in the transport system as there is in the mobile system
3. Use the same policy/queue-weighting mechanism in the transport system as there is in the mobile system

Details of the common QoS framework can be found in [6][9][27].

5.7. A 5GC View of Convergence

The advent of 5G promises several key enhancements to previous mobile technology generations including faster speeds, lower latency, and increased service velocity which enables new use cases such as enhanced mobile broadband, massive IoT and mission critical enterprise applications. Along with new enhancements in the RAN, the 5G core (5GC) has been rearchitected to support these new use cases.

The 5GC architecture includes service-based design concepts, on-demand network slicing and service orchestration, and cloud native design principles such as web-based control plane protocols, microservices and container orchestration. One of the most innovative architectural concepts is wireless and wireline convergence (WWC); allowing different access networks such as Wi-Fi, cable, and fixed broadband networks to interwork with the 5GC as shown in Figure 61. Achieving 5G convergence enables new use cases and consistent subscriber quality of experience (QoE) while reducing cost of ownership.

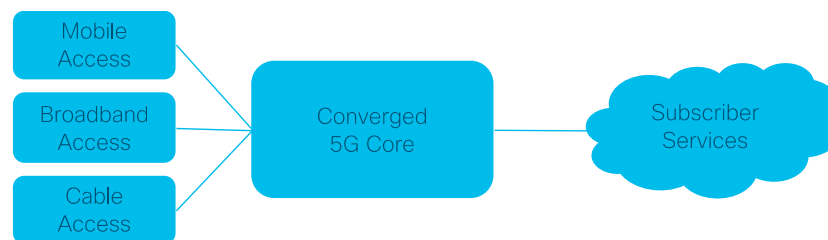


Figure 61 – 5G Convergence

5G convergence enables multi-access operators to harmonize subscriber services across access networks. As subscribers move between their home broadband and mobile networks, a converged core enables an improved quality and consistency of user experience. This includes use cases such as call continuity so that voice and video calls are seamlessly handed off between connections. Policy based services, such as bandwidth speed and latency tiers, as well as parental controls, security and content filtering can also be consistently enforced.

Convergence also enables connection redundancy which has become increasingly important for enterprises and consumers as users are working and schooling from home during the pandemic. For example, a 5G fixed wireless access service can be coupled with a fixed broadband service to enable service resiliency in an active/active or active/standby design.

Arguably as important as QoE, convergence allows operators to reduce their capital and operating expenditures. Historically, each access network has been deployed and operated as a silo in the SP network

with different infrastructure, networking and applications. Network convergence allows SPs to collapse these silos into a common, converged network where the edge and core infrastructure, applications and orchestration systems are common across access networks. Convergence also results in OpEx reductions as existing siloed networks collapse into a common converged core.

In addition to the network, convergence allows the consolidation across all aspects of the SP operations extending into OSS/BSS systems (not covered in this paper). There are three common approaches to converging subscriber QoE across access technologies. The platform, policy, and system level convergence approaches represent different steps towards the path to convergence. Each of these steps, along with their benefits, are shown in Figure 62 and are described in the following paragraphs.

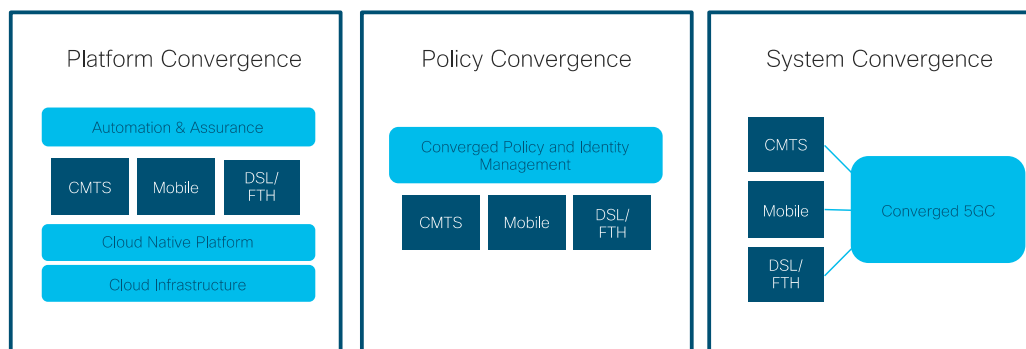


Figure 62 – Platform, Policy, and System Convergence

Platform convergence utilizes a common platform to achieve operational and software development efficiencies. The converged platform includes both physical and virtual infrastructure, as well as cloud native application technologies to deploy and operate the different access systems. It provides common compute and virtualization technologies, such as microservices, containerization, Kubernetes, and cloud assurance and automation systems, to provide a consistent operations experience for SP operation teams. Platform level convergence does not require each access function to be converged by a common system and protocol architecture, but means common tooling is used for deploying, automating, orchestrating and assuring each access function.

Policy level convergence enables common policy and identity control plane systems but does not try to converge the network user plane components. This approach enables policy coordination across access networks where each access network is responsible for enforcing policies provided by the common policy layer. Therefore, although there are separate transport and user planes for each access network, the subscriber experience is maintained by the converged policy layer across networks, e.g., a parental control service can be enforced on both a broadband and mobile network. Many SPs are already on the path to subscriber and policy level convergence as a first step towards transport and user plane convergence across accesses.

System level convergence of the end to end architecture is not a new concept and has been a topic of previous technology generations – but as an afterthought. Convergence was included as part of the 5G standalone design from its inception and allows existing access networks to be integrated with a common converged core based on an interworking approach. This allows existing access technologies to be integrated into the converged core as opposed to requiring each access to be reimplemented. WWC is being designed in standards as a cooperation across 3GPP, BBF, CableLabs and other standards bodies. WWC is the long-term strategy for most multi-access providers, but it comes with significant cost and complexity for brownfield networks. Many MSOs are deploying greenfield 5G networks and are looking to provide

convergence with their Wi-Fi and DOCSIS networks over time. Figure 5 in the earlier section provides a detailed view of the converged access architecture proposed for combining mobile and cable access.

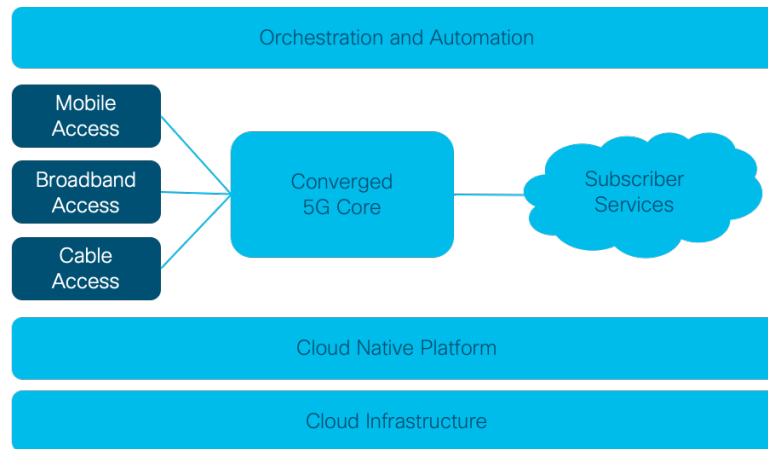


Figure 63 – Common Cloud Native Platform

To successfully navigate the migration to a converged core, operators must determine which convergence type can be justified based on their business. Additionally, operators must structure their product and operations teams to align with their chosen level of convergence. Ultimately, we expect the industry to pursue a common cloud native platform architecture as shown in Figure 63 to simplify and automate operations, common policy and subscriber components to unify the subscriber QoE, and a fully converged core to harmonize the services and applications into a common network architecture.

5.8. Managing the RAN with YANG

One of the key principles of the vRAN architecture is to establish open, standard interfaces, facilitating a transition from today's single vendor, monolithic RAN solutions, to a competitive, multi-vendor environment where functionality can be sourced from a variety of vendors that address the unique needs of MSO deployments around the world. While control and user-plane protocols are naturally required to be interoperable, an often-overlooked aspect is the integration "tax" required to deliver a fully orchestrated multi-vendor system.

Crucially, there are no procedures in 3GPP to ensure that all the parameters necessary for 5G can be configured using the 3GPP management specifications. This gap is being filled by the Open RAN (O-RAN) alliance that has already defined the use of native YANG models for configuring its distributed Radio Unit, the so-called O-RAN RU (O-RU). Not only does the use of native YANG models ensure the easiest route to full multi-vendor interoperability, but it also eases the integration of the management for the lower layer split deployment into existing systems. This has been demonstrated by multiple multi-vendor deployments of the O-RAN fronthaul interface.

YANG (RFC 7950) is a modelling language that was initially adopted by the xRAN Forum in March 2018, to model the configuration and operational state of its 5G Radio Unit, together with defining remote procedure calls (RPCs) for supporting tasks like software management, and notifications for indicating xRAN defined alarms. In 3GPP Release 16, YANG has been adopted as a new protocol-specific solution-set that leverage a protocol-neutral Network Resource Model (NRM). Now incorporated into the O-RAN Alliance, the O-RU specifications use YANG to define syntax, relationships and constraints between the data, enabling operators of O-RAN's open fronthaul to validate configuration data against the model before committing the configuration of the O-RAN Radio Units.

Recognizing that O-RAN Radio Unit suppliers need to be able to support vendor differentiation, the YANG models are extensible, allowing them to be augmented to support enhanced vendor-specific functionality, while simultaneously ensuring baseline multi-vendor interoperability of the standardized functionality defined by O-RAN.

The use of augmented IETF standard YANG models, together with O-RAN specific models, lays the foundation for cross-domain orchestration of the RAN with other domains that have already adopted NETCONF/YANG. Importantly, the definition of the transport interfaces in O-RAN leverages the IETF standard defined YANG models which should then facilitate the use of common tooling to be used across transport and RAN domains.

These same YANG models also provide the foundation for model-driven telemetry. Instead of ill-documented command line interface (CLI) or poor scalability of simple network management protocol (SNMP), model-driven telemetry enables data to be streamed from network devices continuously using a push model and provides near real-time access to operational statistics. Applications can subscribe to specific data items they need, by using standard-based YANG data models over NETCONF-YANG.

6. Convergence – A Vision of What is to Come

6.1. Integrated and Converged HFC, DOCSIS and Mobile Network

To converge or not; the answers may be in the business case. The operators have the choices of levels of convergences that they are comfortable with, starting with spending little CapEx and loosely coupling the two systems, to spending more capex and tightly coupling the two systems.

Up to this point in the paper, we have looked at a broad framework for convergence, the visions of convergence from multiple operators, and specific technologies of convergence. In this section, we will pull the basics of transport and infrastructure convergence into one vision.

Figure 64 represents a vision of the points of convergence that might ultimately take place:

- transport network convergence – common CIN and coax carry mobile, DOCSIS, and PON traffic
- common cloud platform – run apps on common edge
- converged cloud native functions (CNF) – common policies, common user plane functions

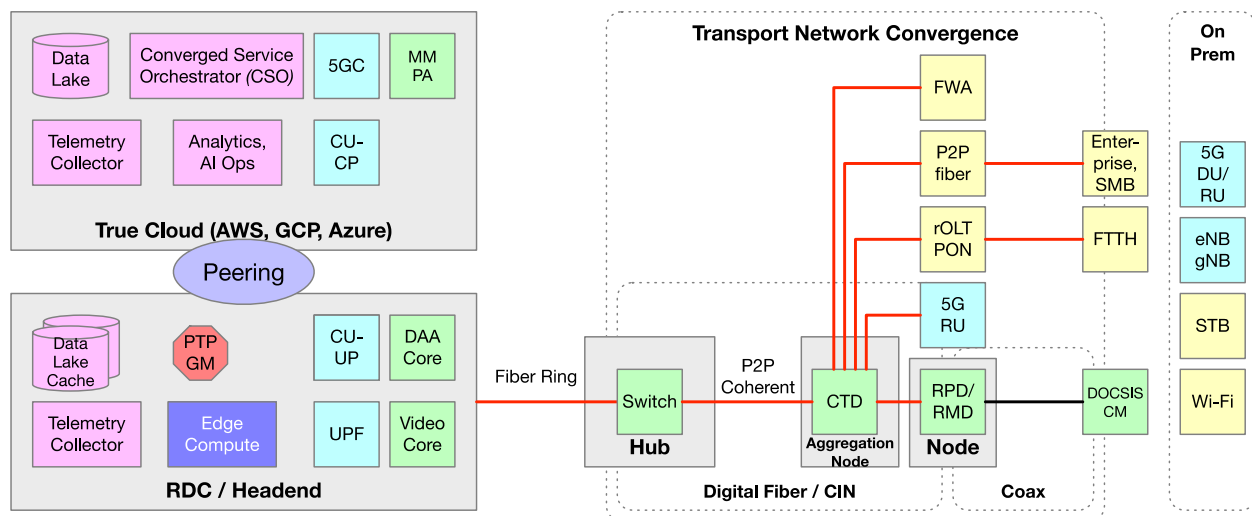


Figure 64 – DOCSIS-Mobile Network Convergence

6.2. Converged Transport of Mobile Xhaul over DOCSIS

Mobile xhaul over DOCSIS is a form of transport network convergence that does not require significant CapEx spending by allowing the MSOs to reuse their HFC plant to carry mobile traffic. All MSOs deploy integrated CMTSs (I-CMTS) today. The DOCSIS network today can be used to carry mobile traffic. Some of the technologies described in a section above such as LLX and DTP can enable enhanced and optimized mobile xhaul deployments.

6.3. Converged Transport with Common CIN

The next level of convergence takes place as MSOs modernize their DOCSIS network to meet the capacity demands on the HFC network.

One of the classic tools in the MSO toolbox to increase plant capacity is node segmentation. When an operator decides to segment a node, there is an opportunity to transform the cable-specific analog optics technology into digital. This is one of the benefits that the remote PHY (R-PHY) architecture brings. By disaggregating the PHY and RF-generating components of the DOCSIS stack to the node location, operators can replace their old analog lasers with new digital lasers, and in the process, increase capacity and open up the optical network. This upgrade also means that a generic Ethernet switch can be deployed in the aggregation node, connecting not just the remote PHY device (RPD) or remote MACPHY device (RMD), but also small cells and PON networks.

The analog to digital optics transformation of the HFC plant requires the buildout of the converged interconnect network (CIN), which includes the layer 2 switches that enable the same fiber network to be used by DOCSIS, mobile, and PON. This is another important aspect of transport network convergence.

6.4. Common Cloud Platform

As mobile and cable vendors adopt cloud native technologies, many software processes that run on dedicated hardware platforms today can be run as cloud native applications on generic servers. This can include upper layers of DOCSIS, 5G core, and some of the RAN functions. These processes from the DOCSIS network and the mobile network can run on the same server complex.

With control and user plane separation (CUPS) architecture, user plane processing that requires lower latency can be split from the more latency-tolerant control plane functions. These data plane functions, including CU-user plane (CU-UP), 5G's user plane function (UPF), and DOCSIS data plane (DP), can be run as software process at the edge, whereas CU-CP, much of the 5GC, and DOCSIS CP can be relocated to the cloud for large scalability.

To operate and monitor a network, telemetry data need to be collected and processed as part of the service assurance framework. A converged data lake and telemetry collector can be used for both DOCSIS and mobile networks.

Traditionally, MSOs own and operate a variety of real estate besides the fiber and coax runs. Of these resources, headends or regional data centers (RDC) can most likely be scaled to run data center applications. It is here that DOCSIS and mobile software processes can be located.

6.5. Virtual and Cloud Native Functions

When software was first moved to server complexes, which was primarily with mobile architectures, it was done using virtualized network function (VNF). In virtualization, existing code can be ported from a physical platform, such as a physical EPC, into a virtual machine (VM) on a server. The advantage of this approach was preservation of code and time to market. The goal was cost reduction and a use of generic servers. Unfortunately, the costs savings did not materialize, and the code was still old code with maintenance, complexity, and scalability challenges.

The new way of writing code involves cloud native functions (CNF). In cloud technologies, old code needs to be rearchitected and rewritten, often using newer languages such as the Go language. The code is often written to be stateless so that processes can quickly restart when the crash without the loss of a session.

The code is partitioned into microservices which are then placed into Docker containers. Kubernetes (K8S) is used to do workload placement of these containers into a server-based system. The result is a system that is highly elastic and highly resilient. This represents new functionality which has tremendous market value and makes the move to servers based on an increase in value, rather than just cost reduction.

7. Conclusion

Convergence is equally important now as providing a clear path to the end of the tunnel. On the road to that end deployment state, tools controlling the operating costs are evolving today, including the movement to cloud-native architecture. In addition to virtualization, the following are the common technologies to enable mobile deployment identified by most MSOs:

- optimizations to enable mobile xhaul over DOCSIS such as DTP, LLX, and orchestration
- the upcoming HFC buildout from analog optics to a digital fiber network
- the CIN, whether be it simpler DWDM multiplexer or Ethernet switch for better scalability
- 5G NSA core for MSOs operating existing LTE networks, while transitioning to 5G NR
- DSS for migration from LTE RAN to 5G NR in existing LTE spectrum
- DSDS to support better MVNO economics with better data offloading
- CUPS to enable virtualization while still providing lower user-plane latency
- tools for service convergence: common policy, common subscriber management
- model-driven telemetry and AI operations for network automation

Today's cable operators are tomorrow's mobile operators.

Subscribers, operators, and networks are converging. Ignoring that reality is no longer an option. There is now a whole new world of mobile operators, just in time for 5G.

Every great wireless network needs a great wireline network.

Of all the variations amongst the operators, there are some commonalities. Most certainly, the end state for network deployment will not be a single physical fiber-based network to rule them all, but a combination of physical networks that involve fiber, coax, and wireless, to support DAA, FTTH, FWA, mobile deployments.

Everything reduces to an IP network with different edge connectivity with common services, management and provisioning.

Remember the telephone network. It connected voice end points called telephones. The telephone network does not significantly exist anymore. The same will be true for cable and mobile networks. They were separate networks because they were owned and run separately, and they may have had unique backbone and edge requirements. But that is or has already changed.

Today, the mobile network has really become an IP over Ethernet network that connect radio gateways to specific user plane points and run by control and management applications running on generic servers. The mobile network is becoming a software-based design with an IP transport terminated in radios for end-point connectivity.

The same transformation is happening to the cable network. Once a closed HFC plant, with DAA there will be IP over Ethernet to the neighborhood with the RPD acting as a radio attachment point that drives the last mile of coax. Even DOCSIS is just a form of Ethernet over coax and acts like a fiber extension in DAA. That is why either fiber or coax can be used for mobile xhaul. Mobile xhaul over DOCSIS provides MSOs the economic advantage for deploying wireless networks. It is an obvious convergence opportunity.

Careful decisions have to be made on where convergence adds value and simplicity, or where it adds cost and complexity. Which decisions make money and which ones lose money. It is often elegance versus execution. But that is just the challenge of getting innovation right.

So, in the most simplistic of terms, both cable and mobile are really composed of different radios on a common IP network trying to do the same thing, and that is to deliver a common set of services to a subscriber no matter how they are connected. The job of convergence is to make this reality come true with both a common service model and an efficient and economical network and application infrastructure.

Let's go make it happen.

Abbreviations

2T2R	2 transmitters 2 receivers
3GPP	third generation partnership project
5GC	5G core
ADSL	asynchronous DSL
AFC	automated frequency control
AMAP	Africa, Middle East, Asia-Pacific
ANCTD	aggregation node with coherent termination device
AOI	area of interest
AP	access point
AR	augmented reality
ARPU	average revenue per user
ATSSS	access traffic steering, switching, and splitting
BNG	broadband network gateway
BSS	business support systems
BWR	bandwidth report
C-RAN	centralized radio access network
CCAP	converged cable access platform
CBRS	citizen broadband radio service
CBSD	CBRS device
CIN	converged interconnect network
CLI	command line interface
CM	cable modem
CMTS	cable modem termination system
CNF	cloud native function
CO	central office
CP	control plane
CPE	customer premise equipment
CPRI	common public radio interface
CSP	communication service provider
CTD	coherent termination device
CU	central unit
CUPS	control and user plane separation
DAA	distributed access architecture
DC	data center
DFS	dynamic frequency selection
DL	downlink
DOCSIS	data over cable system interface specification
DP	data plane
DS	downstream
DSCP	differentiated services code point
DSDS	dual SIM dual standby
DSL	digital subscriber line
DSS	dynamic spectrum sharing
DTP	DOCSIS Time Protocol
DU	distributed unit
DWDM	dense wave division multiplexing

eCPRI	enhanced CPRI
eMBB	enhanced mobile broadband
eNB	eNodeB
EPC	evolved packet core
eSIM	embedded SIM
FCC	Federal Communications Commission
FMA	flexible MAC architecture
FMC	fixed mobile convergence
FO	fiber optical, fiber optics
FTTC	fiber to the cabinet
FTTH	fiber to the home
FWA	fixed wireless access
gNB	gNodeB
GNSS	global navigation satellite system
GPS	global positioning system
HeBGW	home eNodeB gateway
HeMS	home eNodeB management
HeNB	home eNB
HFC	hybrid fiber-coaxial
HHP	households passed
HLS	higher layer split
HMNO	hybrid mobile network operator
ISED	department of Innovation, Science and Economic Development
IoT	Internet of things
IPBB	IP backbone
iWinS	intelligent wireless network steering
LAN	local area network
LLS	lower layer split
LLX	low latency xhaul
LTE	long term evolution
MDU	multi-dwelling units
MIMO	multiple in multiple out
MNO	mobile network operator
ms	millisecond
MSO	multiple system operator
MVNO	mobile virtual network operator
NB-IoT	narrowband IoT
nFAPI	network functional application platform interface
NFV	network function virtualization
NGA	next generation access
NPRM	notice of proposed rulemaking
NR	new radio
NRM	network resource model
NSA	non-standalone
NTP	network time protocol
ODN	optical distribution network
OEM	original equipment manufacturers
OLT	optical line termination
ONT	optical network termination
opex	operating expense

O-RAN	Open RAN
O-RU	O-RAN RU
OS	operating system
OTT	over the top
PON	passive optical network
PDV	packet delay variation
PGS	proactive grant service
PLMN	public land mobile network
PRTC	primary reference time clock
PTP	precision time protocol
QoE	quality of experience
QoS	quality of service
RAN	radio access network
RDC	regional data center
RF	radio frequency
RG	residential gateway
RGW	residential gateway
RMACPHY	remote MAC and PHY
RMD	RMACPHY device
rOLT	remote optical line termination
RPD	remote PHY device
RPHY	remote PHY
RTPS	real-time polling service
RTT	round trip time
RU	radio unit
SA	standalone
SCF	Small Cell Forum
SDN	software defined network
SeGW	security gateway
SFP	small form-factor pluggable
SG	service group
SHDSL	single-pair high-speed DSL
SLA	service level agreement
SMB	small and medium business
SNMP	simple network management protocol
SOHO	small office home office
SON	self-optimizing network
SP	service provider
TCO	total cost of ownership
TDD	time division duplexing
U-NII	unlicensed national information infrastructure
UE	user equipment
UL	uplink
UP	user plane
UPF	user plane function
US	upstream
USP	user services platform
URLLC	ultra-reliable and low-latency communications
vCCAP	virtualized CCAP
VDSL	very high-speed DSL

vEPC	virtualized EPC
VM	virtual machine
VNF	virtual network function
VoWiFi	voice over Wi-Fi
VR	virtual reality
vRAN	virtualized RAN
WDM	wavelength division multiplexing
WWC	wireless and wireline convergence

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