The Future of Fixed Access:

A Techno-Economic Comparison of Wired and Wireless Options to Help MSO Decision Process

A Technical Paper prepared for SCTE•ISBE by

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Introduction

Recent major advances in centimeter/millimeter wave, massive Multiple In Multiple Out (MIMO) antennas, beam forming, hybrid radio technologies, and new systems such as 5th Generation (5G) wireless, Wireless Gigabit (WiGig) have accelerated Fixed Wireless Access (FWA) solutions to become an alternative to wired solutions such as Hybrid-Fiber Coax (HFC), fiber, and copper for providing ultra-broadband access to residences and small to medium-sized businesses. Innovative spectrum solutions that include unlicensed and shared regime, besides the licensed spectrum, further enhance the attractiveness of FWA. These advances have facilitated both gigabit per-second service for high-end subscribers in metropolitan areas as well as tens of megabits per-second peak service in lower housing density and rural areas at competitive costs. Prior to these advances, FWA was a viable solution only in providing lower data rate services in certain niche markets, such as rural and in developing countries.

However, FWA, even with the recent advances, will not be a solution of choice for all end-user requirements, nor in all usage scenarios. This paper provides a techno-economic analysis comparing different FWA and wired technologies including HFC, fiber, and copper under different deployment scenarios to establish the relative "Zones of Advantages" for each solution. It identifies the optimal technology of choice for a given deployment, considering factors such as throughput requirements, household densities, morphology, deployment conditions, take rates, capital and operational expenses (CapEx and OpEx).

Background

Fixed access continues to be a key business segment for Communications Service Providers (CSPs) and it is expected to remain relevant in the foreseeable future, given the predicted growth in demand for ultra-high bandwidth services like 12K and 16K or volumetric Television and Virtual Reality (VR) with full head and body movement. Such services may generate multi-gigabit per second (Gbps) throughput per user. On the other end of the spectrum, there is a substantial population in the country that live in low housing density areas where it is challenging to provide a few megabits per second (Mbps) connectivity economically, even though much higher demands exist.

Historically, higher-bandwidth fixed services in metropolitan and suburban areas with higher population densities have been provided through fixed access technologies like copper, HFC or FTTH. In rural areas with lower population densities, the primary vehicle for providing low-bandwidth fixed access service has been copper and wireless technologies (both terrestrial as well as satellite).

Recently, two fundamental developments are shifting the dynamics of the solutions. First, improvement in trenching technologies has driven the cost of fiber deployment much lower; this has positively impacted the techno-economics of all the fixed access technologies, thus enabling higher throughput at lower cost points. Secondly, major developments in wireless technologies like Long Term Evolution Advanced (LTE-Adv), 5G and WiGig have made it technically feasible to deliver multi-gigabit per second services over a fully wireless connection as illustrated in Figure 1.

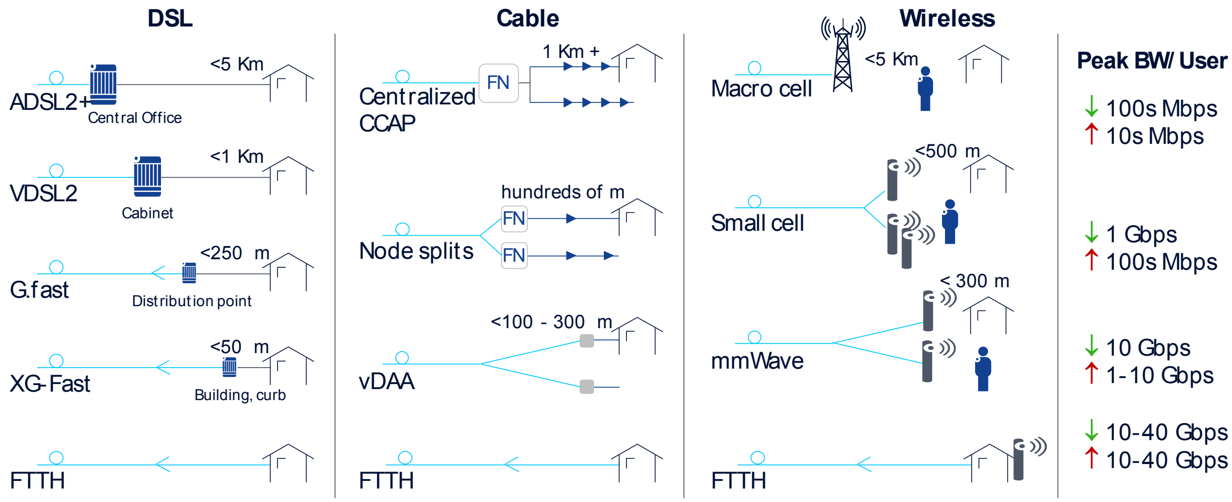

Figure 1 - Rate and range of fixed access echnologies

FWA is expected to grow significantly over the next few years, as predicted by The Carmel Group [1] and depicted in Figure 2.

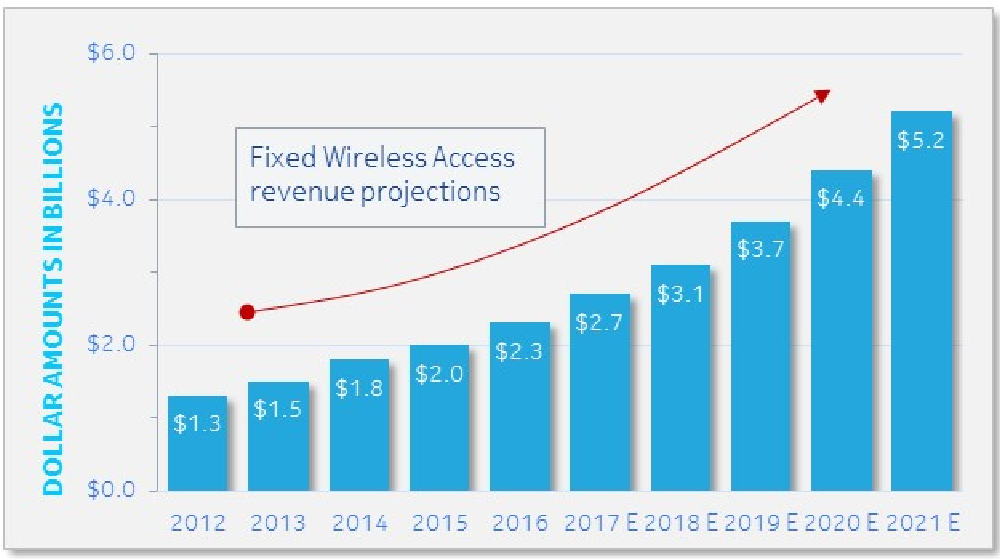

Figure 2 - Fixed Wireless Access business growth [The Carmel Group]

However, over-all cost and performance of different fixed access solutions vary tremendously and establishing which technology suits best under which circumstances, i.e., a zones of advantage (ZoA), is a challenge. To compare solutions in a meaningful way, we refer to solutions for two different target services – higher-bandwidth services for metropolitan and suburban housing densities, and lower bandwidth services for rural housing densities.

The rest of the paper is structured in the following way. The reference target service rates are established first, followed by a description of various technology options to deliver target services. We then present key performance modeling results for emerging wireless technologies. Finally, we present a cost modeling analysis and associated results for two deployment options in metropolitan and rural areas respectively. Since the challenge is greater in lower housing density areas, this paper provides more details for the rural deployment. We bring the analysis together in the final section to draw over-all conclusions.

Service Targets

Before delving into solution architecture details service targets need to be established. Two distinct service criteria are defined – peak throughput and sustained throughput. Peak throughput is the highest instantaneous bandwidth capacity demand per household. Sustained throughput is the average bandwidth capacity demand during the busy hour per household. In [2] such sustained throughput requirements have been calculated from a bottom-up perspective. The average sustained throughput per household is expected to be a few megabits per second, even though peak throughput may be several hundred megabits or even multiple gigabits per second.

Throughput is often (mistakenly) associated with technology advancements or advertised speeds. For example, one may associate a 1 Gbps service over a gigabit HFC network with the actual usage of the customer, which is far from reality. In a typical HFC network, even though a subscriber may be able to burst at 1 Gbps occasionally, the engineered capacity for sustained throughput of all users on the system may only be a few hundred Mbps.

For our discussions, we consider true user requirements for peak and sustained throughputs as those parameters driving a solution's techno-economic feasibility. In addition, planning for fixed access networks should consider subscriber needs for the next five to ten years as technology investments typically have long payback periods.

1. High-bandwidth service targets

For high-bandwidth services, we consider delivery of VR applications with full eye, head and body movement. As Table 1 below shows, the throughput requirement can vary widely, depending upon various parameters.

Table 1 - VR Bandwidth Requirements

	Field of View	Eye and Head movement			Eye, head and body movement		
Parameters	Basic	Basic	Codec improv.	Higher refresh	Basic	Codec improv	Acuity, refresh imp.
Visual Acuity (Arc-minute)	1	1	1	1	1	1	0.7
FOV (HXV degrees)	30X30	120X150	120X150	120X150	180X360	180X360	180X360
Pixels	3.2M	64.8M	64.8M	64.8M	233.2M	233.3M	476,.1M
Frame rate (per sec)	60	60	60	120	60	60	120
Pixels/sec	194.4M	3.9G	3.9G	7.8G	14G	14G	57.1G
Coding (bits/pixel)	0.125	0.125	0.08	0.08	0.125	0.08	0.08
Throughput (Mbps)	24.3	486	311.04	622.08	1,749.60	1,119.74	4,570.38

We consider a peak user throughput requirement of 1 Gbps for our modeling purposes. In reality, a fraction of users will be active during the busy hour and such individual users will likely use the service for a fraction of the busy hour period.

For sustained throughput requirements, we will refer to [2] and consider user requirements at the 99th percentile as these high-bandwidths will most likely be targeted in metropolitan areas where competition will be fierce. The target sustained throughput requirements are 70 Mbps per user for designing a network five to ten years down the road.

2. Low-bandwidth service targets

For low-bandwidth service targets we assume that the peak throughput demand will be driven by a mix of limited VR applications and high-end TV resolutions as shown in Table 2.

Table 2 - TV Resolution and Throughput

Parameters	FHD(2K)	UHD(4K)	8K	12K
Display	**1920X1080**	**3840X2160**	**7640X4320**	**12288X6912**
Pixels	2.1M	8.2M	33.0M	84.9M
Refresh rate (per second)	30	60	120	120
Raw bit rate (per second)	62.2M	497.7M	3.98G	10.2G
Bits per pixel**	0.08	0.04	0.03	0.018
Throughput (Mbps)	**4.98**	**19.91**	**119.4**	**183.5**
YouTube 24/30fps (Mbps)	4.5			
Netflix 24fps (Mbps)	4.8*	~15.0 (24fps)		
Broadcast 1080p (Mbps)	6 to 8			

We assume a 100 Mbps peak throughput for the low bandwidth future service target, which is substantially higher than the few 10's of Mbps service available today in sparsely populated areas. For sustained throughput requirements we again refer to [2] but limited to the 75th percentile (rather than the 99th percentile for the high-bandwidth services since most likely these bandwidths will be targeted to rural areas where competition is less) and set a service target of 25 Mbps.

Technology options

Different technology options for delivering fixed access services are explored. Some options are evolutions of older technologies to increase performance, some options are in the bleeding edge of evolution.

1. Copper using G.fast/x digital subscriber line (xDSL)

G.fast [3, 4] technology enables delivery of gigabit speeds over copper loops for distances up to 100m using Orthogonal Frequency Division Multiplexing (OFDM) in a 212 megahertz (MHz) frequency spectrum. This requires deploying fiber deep to distribution point units (DPUs) to keep copper loop length under 100m.

Different versions of DSL, Asymmetric Digital Subscriber Line (ADSL), Very high bit rate (VDSL), etc., commonly known as xDSL can be used [5, 6] to deliver lower bandwidth services over shorter copper loops.

2. Hybrid Fiber-Coax (HFC) using data over cable interface specification (DOCSIS)

DOCSIS provides asymmetrical high-speed data services on HFC networks. Multiple versions exist, with DOCSIS 3.1 [7] deployments underway to provide Gbps downstream bandwidths and multi-hundred Mbps upstream bandwidths in conjunction with a migration to deeper fiber and smaller fiber nodes. The move to Distributed Access Architectures (DAA) will push fiber even deeper as nodes get closer to users and enable higher per subscriber sustained bandwidths. Full-Duplex (FDX) DOCSIS [8, 9] will bring multi-Gbps symmetrical service bandwidth in the future.

3. Fiber using Passive Optical Network (PON)

Most FTTH solutions are based on PON architectures where the point-to-multipoint (P2MP) outside fiber plant has no active elements and the capacity is typically shared across up to 64 or 128 subscribers via a tree and branch. Multiple PON technologies are available and can co-exist on the same PON. Time Division Multiplexing (TDM)-PON, which includes GPON [10], GE-PON, XG-PON [11], 10G EPON, uses a passive splitter to connect multiple users or optical network units (ONU) to one optical line termination (OLT) port. Wavelength Division Multiplexing (WDM)-PON uses a passive wavelength router that enables a logical one-to-one channel mapping between the ONU and the corresponding OLT port. Time-Wavelength Division Multiplexing TWDM)-PON(e.g., NG-PON2) uses a splitter but combines multiple (typically 4) TDM wavelength pairs on a given fiber. As a result, TWDM-PON achieves even higher throughputs (e.g., symmetric 40Gbps).

4. Fixed Wireless Access (FWA) based on 5G (mmWave and mid band)

5G technology is the latest evolution from a large family of mobile wide area systems, predecessors of which include 2nd generation (2G), 3rd generation (3G), and 4th generation (4G)/LTE [12]. 5G [13, 14] employs key technologies to enable very high service targets compared to any previous technology:

- Wider carriers: Up to 1 GHz of spectrum can combined in a channel to deliver higher bandwidth.
- Higher frequency operating bands: since most lower bands (below ~2.5 gigahertz (GHz)) have already been exploited, 5G is expected to be deployed around 3.5 GHz spectrum, often referred as “mid band”, for wide area coverage. Much larger spectrum is likely to be freed up in centimeter (cm) or millimeter (mm) wave bandwidths (e.g., 24, 26, 28, 39 GHz or even higher).
- Massive multiple input, multiple output (mMIMO): Antenna dimensions are inversely proportional to frequency. Thus, in the higher cm and mm wave frequencies, antenna elements become quite small. This size reduction can be exploited to enable mMIMO arrays that help overcome higher path and penetration losses. They also enable advanced beam forming and higher order MIMO techniques. These techniques help improve coverage and capacity.

5. FWA based on WiGig

WiGig is a technology standardized by IEEE as 802.11ad [15], and is often referred to as “Gigabit Wi-Fi”. WiGig’s first applications have been focused on in-home use as a wireless replacement for a high-definition multimedia interface (HDMI), delivering up to 8 Gbps. It also has traction for use as a “last mile” broadband access solution, with first product availability in 2018, referred to as wireless PON (WPON).

WPON relies on a line-of-sight operation between the customer premise equipment (CPE) and the access point (AP), due to its operation in the 60 GHz frequency spectrum where radio signals fade very quickly with increased distance between CPE and AP. This is especially true if they are not on direct Line of Sight (LoS). WiGig leverages mMIMO technology and through phased array antennas, narrow beams can be formed pointing towards the CPEs, thus improving the signal quality.

WiGig FWA (also known as WPON) products come equipped with a wireless relay capability feature, where APs can connect with each other via self-backhaul. Either dedicated WiGig channels are employed for the backhaul relay link or the channel(s) is/are shared across the drop links (to the connected CPEs) and the other AP/distribution nodes using time division multiplexing (TDM). This wireless relay function is a crucial element for reducing total cost of ownership (TCO) across all pole-based FWA solutions as it enables savings on civil works for fiber backhaul installation.

FWA performance modeling

Key FWA performance modeling aspects are described in this section. Modeling results vary tremendously, based on morphology, LoS, AP height, CPE location and target sustained and peak throughputs [17]. Since these variabilities are less associated with copper, HFC or FTTH and the performance of those technologies is much more predictable their modeling is skipped in the interest of brevity.

1. mmWave system on a utility pole

The first example is a utility pole mounted AP using 400 MHz of spectrum in the 28 GHz band delivering services to an externally home mounted antenna in vLoS (vegetation LoS) conditions. Figure 3 shows the cumulative distribution function (CDF) for varying inter-site distance (ISD) between the poles. With 228m ISD, 80% of users can be served with peak throughput of 1 Gbps or higher.

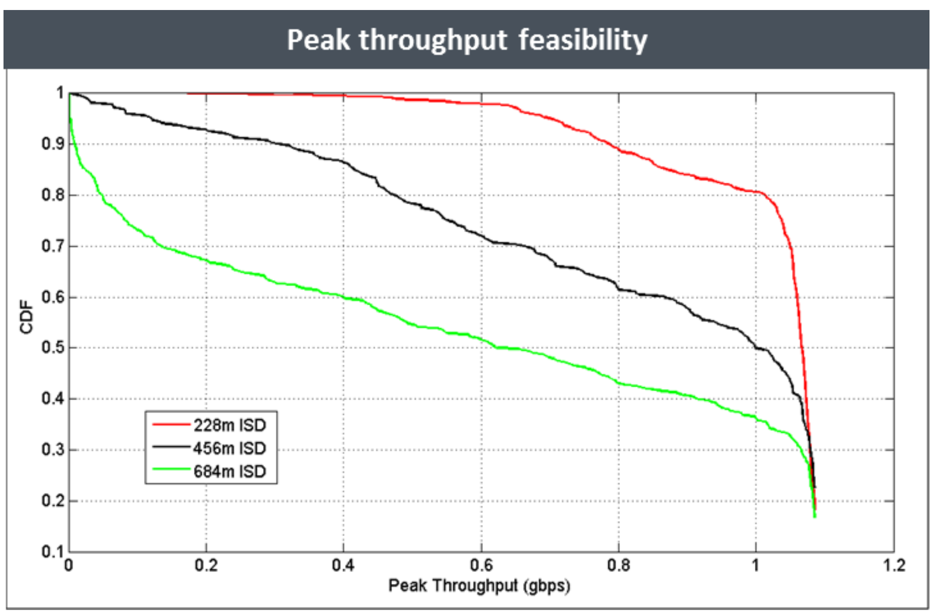

Figure 3 - Throughput vs. ISD with pole mounted small cells in 28 GHZ with 400 MHz BW

2. mmWave system on a macro tower

Figure 4 illustrates coverage for a 28 GHz system when the service is provided from a macro tower (25m height) in a suburban environment. Similar results are available for dense urban and urban morphologies as well but are left out of this paper for the sake of practicality. At 0.5 km ISD, 22 users can be simultaneously served with 100 Mbps service, i.e., sector throughput of 2.2 Gbps and a sector throughput of >4 Gbps is achievable with an ISD of 0.2 km or less. Under typical RF conditions, this would imply a peak throughput of 4Gbps or higher is achievable (under lightly loaded conditions) for 80% households within the coverage area with a 228m ISD.

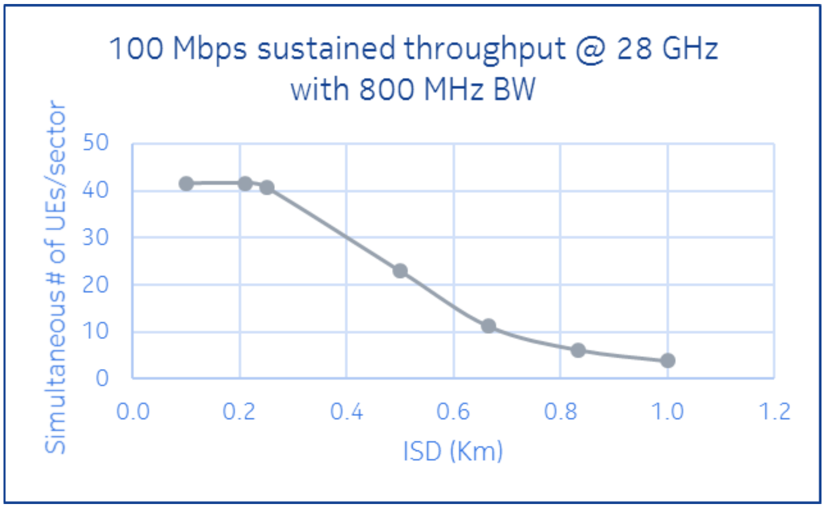

Figure 4 - Capacity vs. ISD for 28GHz macro deployment with 800 MHz spectrum

3. Mid band system on a macro tower

Figure 5 illustrates performance simulation results for a 4 GHz system in a rural environment. Since greater coverage is achievable at 4 GHz, the results are more applicable to lower household density areas. The amount of spectrum, peak and sustained bandwidth available is less than other models. At 10 km ISD, 15 users can be simultaneously served with 25 Mbps service, i.e., sector throughput of 375 Mbps and a sector throughput of >600 Mbps is achievable with an ISD of 6 km or less. Under typical RF conditions, this would imply a peak throughput of 600 Mbps or higher is achievable (under lightly loaded conditions) for 80% households within the coverage area with 10 km ISD.

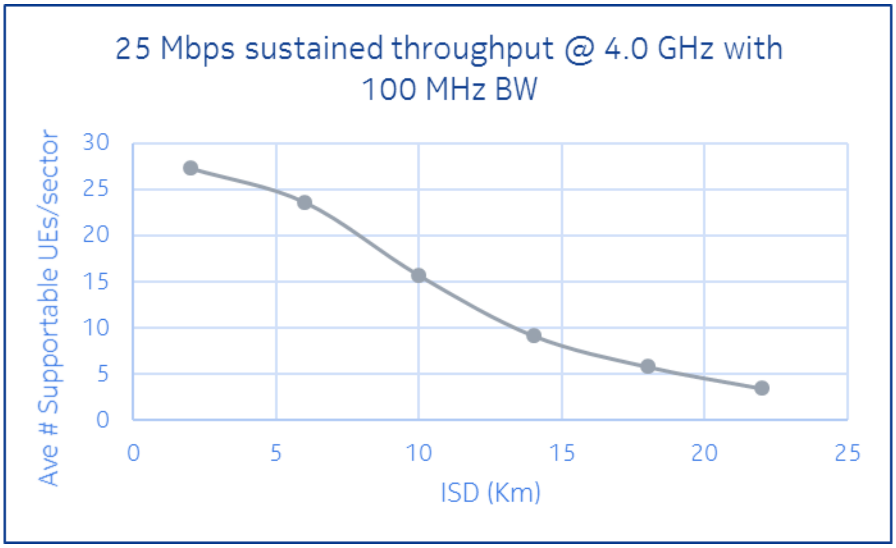

Figure 5 - Capacity vs. ISD with 4 GHz band and 100 MHz spectrum

4. WiGig on utility pole

Typical WiGig performance, using a 1x2.15 GHz channel, will provide 1 Gbps at a distance up to 100m from the AP, even under heavy rain conditions, if the AP and the CPE are within LoS. These results have been obtained from field measurements. Higher WiGig capacities will be enabled through carrier aggregation (e.g., 2 x 2.15 GHz channels) specified in the next version IEEE 802.11ay standard. Since WiGig is deployed in unlicensed spectrum, some unpredictable performance degradation may occur over time if multiple operators start using the same spectrum in the same area.

Cost modeling for different technologies

The cost of delivering service targets in metropolitan and rural morphologies is determined in this section. Since the service targets and housing densities are vastly different for the two morphologies, the analysis focuses on technologies that are relevant for the given morphology. The selection of architectures and technologies is based on deployment practices as well as Bell Labs Consulting's experience of modeling different technologies.

1. Metropolitan deployments

1.1. Overview

The TCO of 4 different solutions enabling Gigabit access speeds are compared for metropolitan areas.

A street model for the metropolitan TCO is used with the following assumptions: all deployments are built and owned by the operator (no rental fees except for pole rental cost for FWA and WiGig deployments), housing is equally spaced and distributed along both street sides. We also assume that at the street entrance a fiber and (if required) a power feed point-of-presence (PoP) is available. The TCO of each solution is compared to serve one gigabit access speed (peak throughput) to each household, excluding the cost to bring and install the (feeder) fiber (or powering feed) to near the street entrance.

This provides for a comparative TCO analysis among Gigabit access solutions [18, 19] - all requiring a proximate fiber PoP - but where only the "last mile" is considered "in scope". Further, having a fiber PoP at the street entrance may represent a common scenario where only the main streets are initially provisioned with one or multiple fiber cables (e.g., buried underneath the sidewalk). These fiber strands enable FTTH services or selective FTT-Building (FTTB) service solution in the main street (first). The presence of fiber at the entrance of the (side) streets crossing the main street, is then also the "enabler" for gigabit access delivery in these side streets, which for our analysis will be based on any of the following gigabit access-capable technologies: G.fast, DAA/DOCSIS, FWA based on WiGig and FTTH.

Figure 6 illustrates the deployment practice for each of the four considered technologies:

1. For G.fast, DPU nodes are deployed in pitches (small holes) on the sidewalks leveraging the fiber umbilical to the fiber distribution point in the PoP located near the entrance of the street. The drop-side of the DPU leverages existing copper loops to connect to the customer locations.
2. For HFC/DOCSIS, remote Distributed Access Architecture (DAA) nodes are deployed and leverage existing coax drops and taps to connect customer locations.
3. For FTTH, distribution fiber and splitters are installed along both street sides to pass 100% of the customer locations. Drop fibers are used from splitters to connect subscriber premises.
4. For WiGig FWA, fiber is extended to one or multiple AP locations. The AP can be deployed on one (or both) side of the street to achieve LoS. Subscriber premises are connected via a wireless link extending from the AP to an outdoor CPE.

5G-based FWA has been purposely left out of this metropolitan area analysis. It is expected that the 5G infrastructure deployed will be shared between mobile and FWA applications and only a part of the infrastructure cost will have to be apportioned to FWA for realsitic cost comparisons. The degree of partitioning between fixed and mobile applications is still an open discussion in the industry and will vary greatly from operator to operator and market to market.

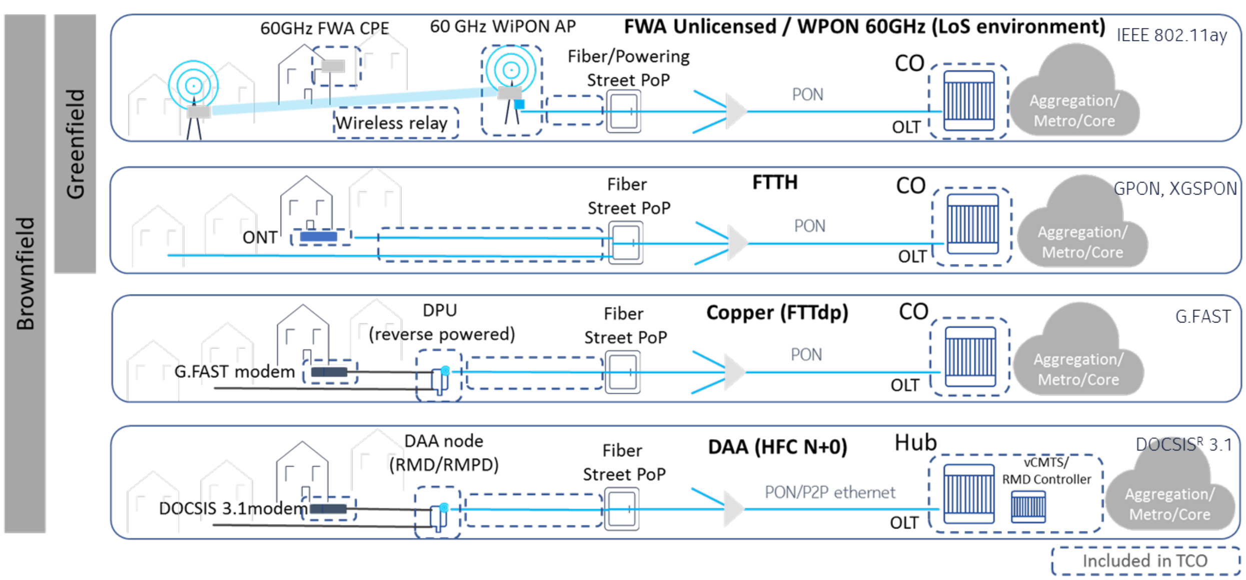

Figure 6 - Metropolitan areas deployment solution options

1.2. Modeling assumptions

The main assumptions are as follows:

1. 10-year TCO analysis covering capital expenditure (CapEx) and operating expenses (OpEx)
   - CapEx includes equipment and installation costs. All active equipment will be swapped and replaced by new generation equipment near year 10. Thus, equipment and installation costs are included twice -except for CPE installation.
   - OpEx covers annual recurring expenses such as outside plant maintenance, failing equipment repair/replacement (estimated at 2 or 4% failure rate depending on equipment type), equipment vendor support (i.e., licensing, maintenance contracts etc., set at 5% of the active equipment CapEx), powering expenses. For FWA (e.g., WiGig) a pole rental cost ($20/pole/year) is assumed. No depreciation is applied.
2. Household density (expressed as number of households per km^2) and service take rate are the two main TCO analysis parameters. If sensitivity analysis is shown for other parameters, a density of 3000 households/km2 (HH/km^2) and/or a take rate of 40% are assumed.
3. Baseline values for other key parameters are:
   - Distribution fiber underground installation cost of $40/m.
   - Street length can considerably impact the TCO. An 800m street length is assumed.
   - FTTH drop installation cost is fixed at $300, for both SDU (sub-urban) and multi dwelling unit (MDU) (dense urban) scenario[1].
   - CPE/optical network unit (ONU) installation cost (year 1) is $150 for both FWA WiGig and FTTH. For the FWA solution 50% of the CPE will be self-installed.
   - DPU/DAA and WiGig AP installation costs are respectively $400 and $1,000. It is assumed that WiGig utilizes wireless relay. For DPU node we assume 8 ports. The rather high cost for the AP installation includes the powering supply implementation cost. This can be realized for example by leveraging the AC main power available at a utility pole requiring technical support from the utility/pole provider. The baseline scenario assumes availability of a local power supply.

1.3. Analysis Results

1.3.1. Baseline

The TCO results for the baseline scenario are presented in Figure 7. The top table shows the “lowest cost” solution for each density/take rate combination, the bottom table the associated TCO ($) per connected household, and the middle table the relative TCO difference with the “second lowest cost” solution. The top table clearly shows the zones of advantage for WiGig FWA, DAA and FTTH. For example, WiGig is the lowest cost solution for HH density of 500 HH/km^2, with a TCO ranging from $2.2K to $6.7K per household connected (HHC). However, as the HH density increases, WiGig only remains the least cost solution for low take rate areas, while other solutions such as DAA and especially FTTH become most economical for higher take rate and higher density areas.

[1] Vertical riser fiber implementation may impact costs.

lowest TCO solution		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	WPON	WPON	WPON	WPON	WPON
	20%	WPON	WPON	WPON	DAA	DAA
	30%	WPON	WPON	DAA	DAA	DAA
	40%	WPON	DAA	DAA	FTTH	FTTH
	50%	WPON	DAA	FTTH	FTTH	FTTH

Relative TCO difference		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	67%	50%	42%	30%	23%
	20%	50%	30%	7%	4%	16%
	30%	44%	6%	16%	21%	26%
	40%	32%	7%	22%	17%	14%
	50%	21%	18%	16%	12%	5%

10 year TCO/HHC ($)		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	6,763	3,755	2,827	2,452	2,218
	20%	3,979	2,368	2,029	1,762	1,524
	30%	2,930	2,033	1,551	1,283	1,124
	40%	2,483	1,702	1,244	1,337	1,231
	50%	2,215	1,427	1,351	1,207	1,122

Figure 7 - Metropolitan zones of advantage for gigabit access

1.3.2. Sensitivities

Figure 8 shows a TCO breakdown for each solution for the considered take rate and household density. For illustrative purposes, we have chosen a housing density of 3,000 households/km2, which borders suburban and urban housing densities; similar charts can be presented for all the housing densities shown in Figure 7.

Copper/coax solutions have a balanced contribution of network equipment cost, civil works/fiber install cost, CPE cost and OpEx to the 10-year TCO. However, the FTTH and FWA WiGig solutions show a different cost break down: FTTH civil works (e.g., fiber install, including the fiber drop) accounts for 75% of TCO (with very low OpEx and equipment cost contributions). FWA is the reverse, fiber install only contributes 15% to the TCO, with very high equipment cost contribution - driven by the CPE cost included twice due to equipment replacement cycle in year 10 and relative high OpEx.

The lower total fiber install cost for the WiGig FWA solution is because the APs (5 required for the modelled scenario) can, to a certain extent, rely on the wireless relay/backhaul capability. This backhaul link has limited capacity/reach and for high load (high take rate and/or higher sustained bit rate per connected HH) as well as high-density scenarios, fiber must be pulled deeper into the street, as the wireless backhaul link can no longer carry the traffic load of all connected HHs in the street as in a low load scenario.

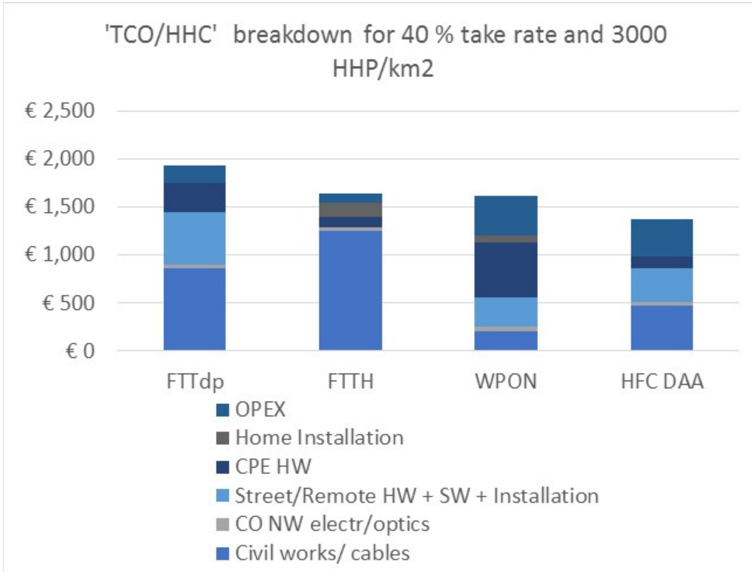

Figure 8 - TCO breakdown for each solution

Full advantage of the wireless relay capability for FWA is only possible when no power cable must be installed for the APs, the assumption for the baseline scenario.

Figure 9 shows the ZoA view for two other scenarios. The differences with the baseline scenario are:

- Scenario 1 (left): FWA WiGig where dedicated powering cable must be installed ($40/m install cost). We maintain the high AP installation cost accounting for a remote DC supply implementation requiring DC up convertor in the CO and a down convertor per AP.
- Scenario 2 (right): same as scenario 1, but no trenching is needed for fiber/power cable install (use existing ducts or aerial cabling) resulting in a much lower install cost for fiber/power cable of $8/meter, applied to all solutions.

For scenario 1, we have basically the same ZoA result for FWA WiGig, DAA and FTTH as considered earlier. For Scenario 2 (duct or aerial cabling deployment), FTTH becomes the preferred solution across all density and take rate combinations, with a TCO of less than $800/HHC for take rates beyond 20% and densities of 4000 HHP/km2 or more.

lowest TCO solution		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	WPON	WPON	WPON	WPON	DAA
	20%	WPON	WPON	DAA	DAA	DAA
	30%	WPON	DAA	DAA	DAA	DAA
	40%	WPON	DAA	DAA	FTTH	FTTH
	50%	DAA	DAA	FTTH	FTTH	FTTH

lowest TCO solution		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	FTTH	FTTH	FTTH	FTTH	FTTH
	20%	FTTH	FTTH	FTTH	FTTH	FTTH
	30%	FTTH	FTTH	FTTH	FTTH	FTTH
	40%	FTTH	FTTH	FTTH	FTTH	FTTH
	50%	FTTH	FTTH	FTTH	FTTH	FTTH

Relative TCO difference		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	15%	10%	5%	1%	2%
	20%	11%	1%	8%	13%	16%
	30%	6%	8%	16%	21%	26%
	40%	2%	13%	22%	20%	14%
	50%	2%	18%	16%	12%	5%

Relative TCO difference		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	248%	185%	157%	137%	115%
	20%	190%	128%	81%	57%	42%
	30%	162%	79%	43%	25%	14%
	40%	133%	51%	21%	59%	47%
	50%	105%	33%	43%	40%	29%

10 year TCO/HHC ($)		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	9,848	5,132	3,797	3,168	2,724
	20%	5,408	3,048	2,164	1,762	1,524
	30%	3,981	2,162	1,551	1,283	1,124
	40%	3,206	1,702	1,244	1,337	1,231
	50%	2,688	1,427	1,351	1,207	1,122

10 year TCO/HHC ($)		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	1,755	1,187	1,022	949	906
	20%	1,221	937	854	818	796
	30%	1,043	853	798	774	760
	40%	954	811	770	752	741
	50%	900	786	753	739	730

Figure 9 - Zones of Advantage, with trenching (left) and without trenching (right)

Finally, it must be noted that FTTdp/G.FAST did not show up as lowest cost solution in previous ZoA views. However, when considering urban areas where no good Line of Sight conditions occur (too much foliage, ruling out WPON as potential solution), FTTdp has also its sweet spot for a CSP (i.e., we leave out the DAA solution as well for the ZoA result), but it does require in general a take rate of at least 40% to beat FTTH for underground fiber deployment scenario. DPU nodes with higher port count (e.g. 16 or 32, with DPU installed in the MDU buildings' basements) allowing to share the DPU node cost across more connected HHs, can also lower FTTdp TCO for high density/high take rate area. In the ZoA view of Figure 9, no HW equipment replacement cycle was considered in the 10 year period.

lowest TCO solution		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	FTTH	FTTH	FTTH	FTTH	FTTH
	20%	FTTH	FTTH	FTTH	FTTH	FTTH
	30%	FTTH	FTTdp	FTTH	FTTH	FTTH
	40%	FTTH	FTTdp	FTTdp	FTTdp	FTTdp
	50%	FTTdp	FTTdp	FTTdp	FTTdp	FTTdp

Relative TCO difference		HH density (/km2)				
		500	2000	4000	6000	8000
Take rate	10%	20%	15%	28%	35%	42%
	20%	12%	5%	13%	17%	20%
	30%	7%	1%	5%	6%	8%
	40%	3%	7%	3%	2%	2%
	50%	0%	12%	10%	10%	10%

Figure 10 - Zones of Advantage

[key assumptions: $40/m fiber/power cable installation cost (underground deployment), no equipment replacement cycle, no LoS (WPON not considered), Telco view (DAA not considered)

2. Rural deployments

2.1. Overview

In rural areas characterized by low population density, rolling out gigabit access services will, in general, be cost prohibitive [20, 21]. Competition is often lacking and there is no incentive for a service provider to be best-in-class. However, providing high service speeds can result in higher average revenue per user (ARPU) for the service provider as it enables triple play packages. Regulation and digital agendas may impose a certain requirement, for example, a 50 Mbps peak service rate in exchange for government funding. In this rural deployment analysis, we consider 100 Mbps as downstream peak rate and 25 Mbps as maximum sustained speed per connected household.

To compare the cost of different solutions enabling up to 100 Mbps service speeds in rural area, we built a model where the present mode of operation (PMO) constitutes a low-speed service deployment over a completely passive copper outside plant. The service provider offers 10 Mbps internet access service based on legacy ADSL2 technology from one or multiple CO locations via a twisted copper pair to each subscriber's premise. This service provider now wants to provide higher (peak) service rates up to 100 Mbps. The solutions enabling these higher Future Mode of Operation (FMO) speeds included in the model are listed below and shown in Figure 10. Items in boxes with solid outline are active equipment included in the model; boxes with dotted outline imply that new passive equipment (i.e., fiber) costs are also included. Since copper exists in the deployments, no additional cost is modeled.

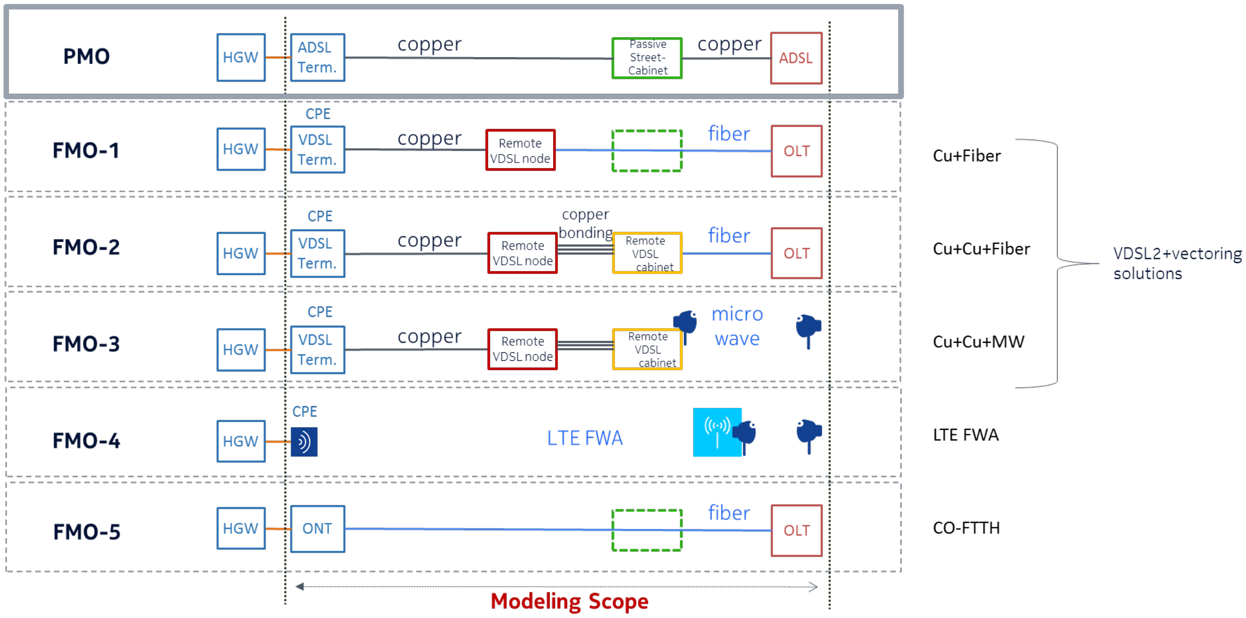

Figure 10: Rural scenario deployment solutions considered

2.1.1. VDSL2 with fiber backhaul (Cu+Fiber)

Higher spectrum (compared to ADSL2) and crosstalk interference mitigation enabled by vectoring technology, enable speeds of 100 Mbps and beyond to be achieved with VDSL2 solutions for loop lengths under 400m. Optimally, active equipment is placed near existing street cabinets containing the copper loop distribution frames. This requires bringing fiber to those locations for backhauling traffic to the CO. The new remotely positioned equipment must also be power-fed which could be based on remote DC powering (from the CO) or local AC powering.

2.1.2. VDSL2 with copper + fiber backhaul (Cu+Cu+Fiber)

To reduce the amount of fiber installation labor, existing copper loops can be leveraged for backhauling the traffic from VDSL2 nodes at remote locations, to a VDSL2 node positioned near a street cabinet location closer to the CO. To provide sufficient backhaul capacity, 8 pairs of copper loop are bonded and VDSL2 with vectoring is applied on the bonded pairs. Depending on the exact physical topology of the copper outside plant and the capabilities and sizes (e.g., port counts) of the VDSL2 (remote node) equipment, a star connectivity or a daisy chained copper bonding backhaul connectivity overlay for connecting the different remote nodes with one another can be used.

2.1.3. VDSL2 with copper + microwave backhaul (Cu+Cu+MW)

Another variant considered for the VDSL2 solution based on copper bonding backhaul where the fiber BH between the node that is aggregating all copper-backhauled traffic and the CO is replaced by a microwave (MW) link. This may be a suitable solution when fiber deployment is very costly (e.g. requiring high cost trenching). A MW link may typically enable up to 1.5 Gbps capacity across several kms of distance.

2.1.4. Fixed Wireless Access (FWA)

Both 4G and 5G FWA solutions were considered, where the CPE antenna is placed outdoor:

- LTE (1.8 Ghz, 2 x 20 MHz spectrum, 4x2 MIMO with 16dBi gain CPE antenna, available today
- 5G (3.5/4 GHz band, 100 MHz spectrum, 8x4x2 MU-MIMO, with 10dBi gain CPE antenna placed at rooftop (6m height). This solution is expected to become available in 2019.

The macro base stations are equipped with a 3-sector radio and associated baseband processing, with an initial ISD that depends on the household density of the area. If capacity is not sufficient, then new sites are added (site densification). The cost of adding these new sites is high since it entails new tower installations, along with radio and baseband processing equipment/installation, but also backhaul must be accommodated, which is assumed to be a microwave link. As this investment co-purposes both mobile and FWA services, a cost sharing split of 20%-80% and equivalent capacity sharing split where the larger portion is allocated to FWA are assumed. It is expected that 5G usage for mobile applications will take some time to reach significant penetration in rural areas.

2.1.5. Fiber to the home from the central office (CO-FTTH)

FTTH, based on GPON technology, with the OLT located in a central location is assumed. FTTH may make sense as in some areas where government funding is available. Such funding for rural deployment can make the FTTH business case more attractive.

2.2. Modeling assumptions

For the rural model, CapEx investments required for each solution are compared. This model is not based on a street simulation as applied for the urban/metropolitan environment, but rather on statistical derivations considering that the rural area is vast and any dependency on street patterns or specific clustering of houses may be questionable.

The main assumptions include:

- Street cabinet density(PMO), initial (PMO) and minimum (FMO) FWA base station inter-site distance (ISD) and average FTTH drop cost are all dependent on the household density of the considered area.
- Copper loop length distribution is Rayleigh distribution model based
- Non-VDSL2 solutions require a truck roll when subscribers opt in for the enhanced service: a customer premise visit for installing the FWA CPE, and a double truck roll for FTTH: 1) one for drop implementation, and 2) one for ONU installation and service activation.
- Equipment and implementation costs are based on United States (US) market broadband deployment benchmarks, with a cost estimate for the 5G FWA solution (since it is not yet commercially available).

Table 3 - Rural deployment assumptions that vary with HH density

HH density (/km2)	10	50	100	500
Street cabinet density (/km2)	0.5	1	2	2
Initial ISD (km)	10	5	4	2
Minimum ISD (km)	2	1	1	1

HH density (/km2)	10	50	100	500
FTTH drop cost ($)	800	400	250	150

The CapEx of the different solutions is compared on the following key parameters and associated values: household density (10, 50, 100 and 500 HH/km2), service take rate (30, 40, 50 and 60%), service peak bit rate (10, 25, 50 and 100 Mbps), sustained bit rate per connected household (3, 6, 12 and 25 Mbps, capped by the service peak bit rate), and fiber installation cost per meter for the distribution/feeder sections (20, 30, 40 or 50 $/m). Unless mentioned otherwise, the copper backhauled VDSL2 solution is deployed in a daisy chain mode.

Note that the fiber may be installed in existing ducts, on poles or it may require civil works for underground deployment. The fiber installation cost/m can reflect any or a mix of these installations.

The baseline values for the key deployment parameters were chosen to be 50 HH/km2, 50% service take rate, 50 Mbps peak service bit rate, 6 Mbps sustained bit rate per HHC and a fiber install cost at $30/m.

2.3. Analysis results

Results of the rural modeling exercise are based on the main parameters as discussed above. Note that in Figure 11 through Figure 14, the FWA solution is based on LTE 1.8 GHz (40 MHz spectrum).

2.3.1. Impact of household density

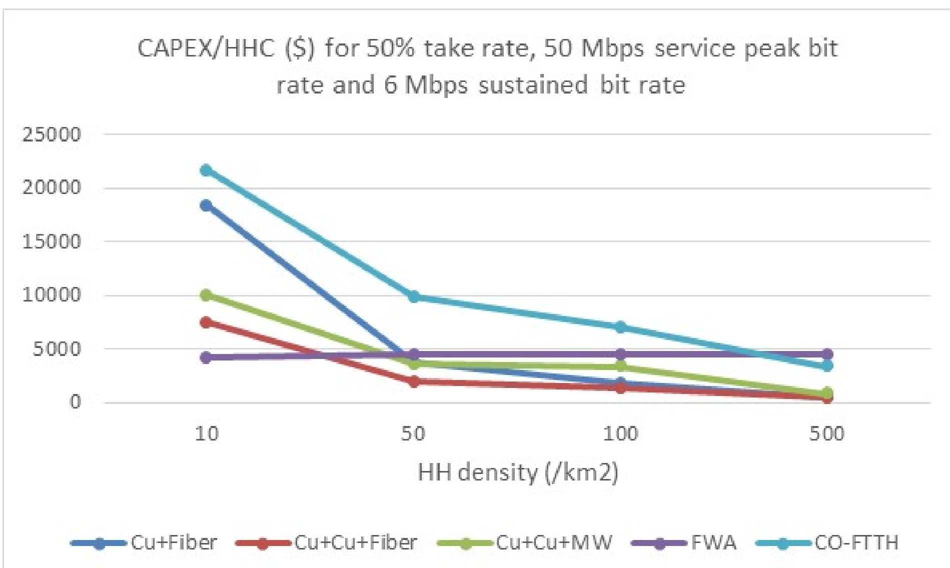

Figure 11 - Rural deployment CapEx per HHC as function of HH density

All wireline solutions have lower cost for higher density. For baseline values the VDSL solution with copper + fiber backhauling (Cu+Cu+Fiber) is always lowest cost for mid-to high HH densities (> 50 HH/km^{2}). For mid densities, the other VDSL solutions follow closely. For very low density (10 HH/km2), VDSL2 nodes have very low filling and combined with the longer fiber distances from the CO to the remote nodes, street cabinet density decreases with lower HH density, resulting in very high cost per connected subscriber. In such low-density areas, FWA becomes the lowest cost solution. For the very higher (500 HHs/km2) density, FTTH becomes lower cost than LTE FWA. This is because of the very high FWA base station site densification that is required to meet the given service requirements in a high household density area. The charts reveal that cost points per connected HH for 50 HH/km2, range between $2000 and $4500 when relying on the existing copper outside plant for the 50 Mbps peak bit rate service offering.

2.3.2. *Impact of service peak bit rate*

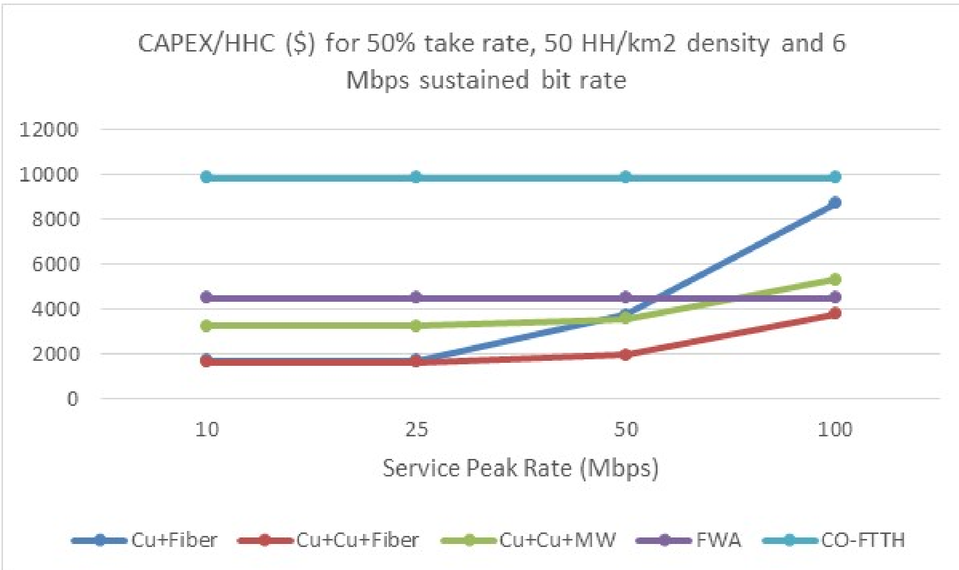

Figure 12 - Rural deployment CapEx per HHC as function of peak rate

Whereas the CO-FTTH and FWA LTE solutions' TCO have no dependency on the service peak bit rate (note that this peak bit rate is not necessarily guaranteed), the VDSL2 solutions' TCO show a high dependency on the service peak rate, starting from 25 Mbps. For 100 Mbps peak rate, the cost/HHC quadruples for fiber backhauled VDSL2, and doubles for the VDSL2 solutions relying on the copper bonding, which is explained by the requirement for higher VDSL2 node density. Note that for 100 Mbps peak service bit rate, the FWA LTE solution TCO almost approaches the VDSL2 solution with copper and fiber BH for the considered 50 HH/km^2 density.

Figure 13 shows the solutions' CapEx break down of active network equipment versus passive OSP investments.

LTE-based FWA is clearly not a sustainable solution for given service scenario and assumptions, where equipment cost (radio, baseband processing and MW Backhaul) and civil works costs for the new sites equally contribute to the CapEx as driven by cell densification.

It clearly shows that for FTTH, the fact that no active equipment is needed in the OSP cannot be taken advantage of because of the high civil works cost contribution. For Cu+Cu+MW, no civil works are required, but with CapEx based 100% on equipment/installation cost, a significant OpEx contributor can be expected.

The difference in CapEx between daisy chain and star (ST) topology for the VDSL2 copper BH solution is also shown. Star topology is higher cost than daisy chain - mainly driven by the higher equipment cost - but still its total cost is lower than the alternatives. For the given key parameter values, 7 active nodes must be deployed - 6 are copper backhauled to the node positioned near an existing street cabinet- to ensure the high peak rate offer (100 Mbps), but each node on average services only 6 subscribers. This means for a remote node with 48 ports, 34 ports are still left unused in star topology.

Figure 13 - Rural deployment CapEx breakdown per HHC

2.3.3. *Impact of fiber install cost*

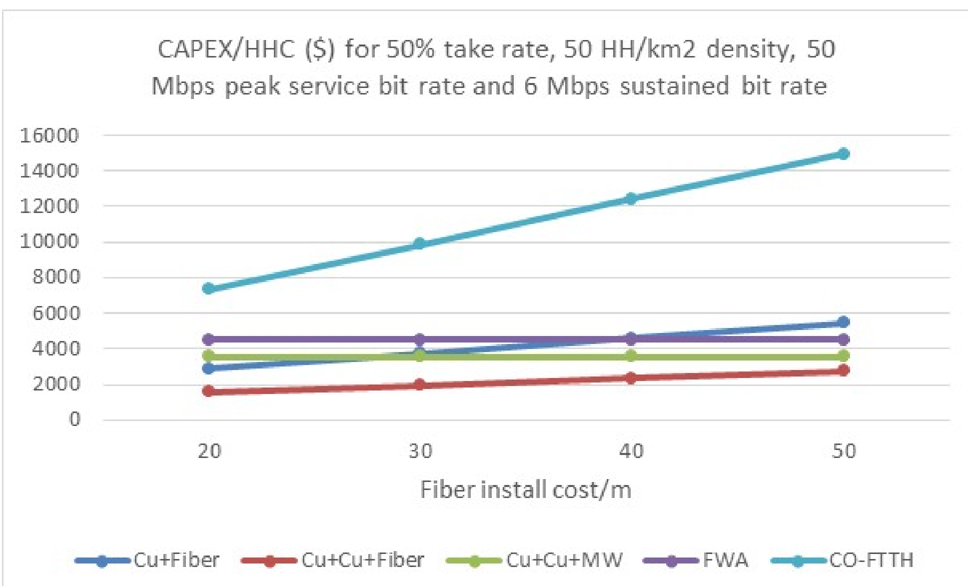

Figure 14 - Rural deployment impact of fiber install cost

Figure 14 shows the impact of fiber install cost. FTTH has the strongest dependency on the fiber install cost, followed by VDSL2 with fiber backhaul and the VDSL2 solution that depends both on copper and fiber backhauling.

2.3.4. 4G FWA versus 5G FWA

As shown in previous section, the LTE-based FWA in most cases has relative high cost, and we now compare the wireline solutions with the 5G FWA solution. Similar to the metropolitan section, the matrices shown in Figure 15 present the Zone-of-Advantage (ZoA) for different HH densities and different sustained bit rates as follows: (top to bottom) 1) the lowest cost solution; 2) its cost/HHC; 3) the CapEx difference with the 2nd lowest cost solution; and 4) the 2nd lowest cost solution. On the left side of the ZoA matrix the FWA solution is based on LTE (1.8 GHz, 20 MHz FDD), on the right the FWA is based on 5G NR technology (3.7-4.2 GHz spectrum and 100 MHz TDD available).

Lowest CAPEX solution		HH density (/km2)			
		10	50	100	500
sust bit rate/HHC (Mbps)	3	FWA	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Cu+Fiber
	6	FWA	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Cu+Fiber
	12	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Cu+Fiber
	25	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Fiber

Lowest CAPEX solution		HH density (/km2)			
		10	50	100	500
sust bit rate/HHC (Mbps)	3	FWA	FWA	FWA	Cu+Cu+Fiber
	6	FWA	FWA	FWA	Cu+Cu+Fiber
	12	FWA	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Cu+Fiber
	25	FWA	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Fiber

CAPEX/HHC ($)		HH density (/km2)			
		10	50	100	500
sust bit rate/HHC	3	2307	1957	1308	434
	6	4167	1961	1310	458
	12	7494	1971	1315	500
	25	7540	1986	1381	538

CAPEX/HHC ($)		HH density (/km2)			
		10	50	100	500
sust bit rate/HHC	3	954	810	849	434
	6	1444	1235	1235	458
	12	2319	1971	1315	500
	25	4148	1986	1381	538

Relative CAPEX diff. Lowest- 2nd lowest		HH density (/km2)			
		10	50	100	500
sust bit rate/HHC (Mbps)	3	224%	21%	36%	21%
	6	79%	81%	36%	15%
	12	33%	80%	36%	6%
	25	32%	78%	30%	524%

Relative CAPEX diff. Lowest- 2nd lowest		HH density (/km2)			
		10	50	100	500
sust bit rate/HHC (Mbps)	3	682%	142%	54%	21%
	6	418%	59%	6%	15%
	12	223%	3%	36%	6%
	25	82%	78%	30%	524%

2nd lowest CAPEX solution		HH density (/km2)			
		10	50	100	500
sust bit rate/HHC (Mbps)	3	Cu+Cu+Fiber	FWA	Cu+Fiber	Cu+Fiber
	6	Cu+Cu+Fiber	Cu+Cu+MW	Cu+Fiber	Cu+Fiber
	12	Cu+Cu+MW	Cu+Cu+MW	Cu+Fiber	Cu+Fiber
	25	Cu+Cu+MW	Cu+Cu+MW	Cu+Fiber	CO-FTTH

2nd lowest CAPEX solution		HH density (/km2)			
		10	50	100	500
sust bit rate/HHC (Mbps)	3	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Fiber
	6	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Cu+Fiber	Cu+Fiber
	12	Cu+Cu+Fiber	FWA	Cu+Fiber	Cu+Fiber
	25	Cu+Cu+Fiber	Cu+Cu+MW	Cu+Fiber	CO-FTTH

Figure 15 - Rural access ZoA with FWA LTE (left) and FWA 5G (right)

LTE-based FWA is the lowest cost solution in the (left) ZoA only for very low density and very low sustained rate /HHC at a cost level above $2300/HHC (for 50% take rate). However, in the 5G era, FWA has lowest TCO for HH densities up to 100HH/km2 and sustained bit rate levels up to 25 Mbps, at cost points between $1,000 and $1,500/HHC. The difference in CapEx for the 5G FWA solution relative to the 2nd lowest cost solution (VDSL2 with copper bonding) is a minimum 60% for densities up to 50 HH/km2.

For higher densities and/or higher sustained rates, the copper + fiber BH based VDSL2 (Cu+Cu+fiber) solutions remain the lowest cost for the modeled 50 Mbps (or higher) peak bit rate service.

For the considered baseline values for the main parameters- 5G FWA solutions can indeed become a cost-effective alternative for (rural) broadband access deployments enabling, e.g., high definition (HD) video service packaging, once these solutions become available for mass deployment.

Conclusions

MSOs should review these conclusions from both an opportunity as well as a threat perspective. As the demand for high-bandwidth services increases, advancements in HFC architecture continue to give them a performance advantage over copper. If competition comes in the form of fiber, a deep fiber deployment supporting HFC keeps MSOs ready for fiber drop deployment quickly, whenever needed.

Competition is also expected in the form of FWA, primarily from wireless operators who will attempt to increase ARPU with quad-play. These deployments will likely be in licensed spectrum [17,18], and the wireless operators will be able to leverage the same infrastructure for both mobile and fixed services. But FWA, especially in unlicensed band, e.g., WPON, also provides opportunities for MSOs to expand into new territories without large investment in drop costs.

As we saw in this paper, the technologies and their ZoA are very different between the high-bandwidth and low-bandwidth services. For high-bandwidth services, FTTH comes in as advantageous whenever aerial deployments are feasible. While this is generally practical in suburban neighborhoods, local regulations may prohibit aerial deployment in urban and dense urban environments. FWA with 5G in centimeter-wave as well as WPON with millimeter-wave could become viable options, especially in good LoS conditions. Copper and HFC could also be advantageous under certain housing densities and take rates.

For low-bandwidth service, different VDSL options are often advantageous. In rural areas with low housing densities where HFC is not an incumbent technology, wireless options with LTE-Adv as well as 5G in mid-band can be viable options [20, 21] depending upon service targets and housing densities.

In the next few years, multi-Gbps technologies are expected to become more common, starting likely with enterprise access. Advancements in both wired and wireless technologies will render these deployments cost-competitive. At the same time, demand for high bandwidth services will continue to grow and the ZoA observed in the paper will continue to evolve. As cost points mature and technological advancements continue, the analyses will have to be revisited.

Abbreviations

2G	2nd generation wireless
3G	3rd generation wireless
4G	4th generation wireless
5G	5th generation wireless
AP	access point
ARPU	average revenue per user
BH	backhaul
CapEx	capital expenditure
CCAP	converged cable access platform
cm	centimeter
CDF	cumulative distribution function
CO	central office
CPE	customer premise equipment
CSP	communications service provider

DAA	distributed access architecture
DC	direct current
DOCSIS	data over cable interface specification
DPU	distribution point units
DSL	digital subscriber line
eMBB	enhanced massive broadband
FTTB	fiber to the building
FTTdp	fiber to the distribution point
FTTH	fiber to the home
FTT-SMB	fiber to the small/medium business
FMO	future mode of operation
FOV (HXV)	Field of vision (horizontal x vertical)
FWA	fixed wireless access
Gbps	gigabit per second
GHz	gigahertz
GPON	gigabit passive optical network
HDMI	high-definition multimedia interface
HFC	hybrid fiber-coax
HH	household
HHC	household connected
HHP	household passed
ISD	inter-site distance
LoS	line of sight
LTE-Adv	Long Term Evolution Advanced
MDU	multi dwelling unit
MHz	megahertz
mm	milimeter
mMTC	massive machine type communications
mMIMO	massive multiple input, multiple output
MSO	multiple system operator
MW	microwave
OFDM	orthogonal frequency division multiplexing
OLT	optical line termination
ONU	optical network unit
OpEx	operating expenses
OSP	outside plant
P2MP	point-to-multipoint
PMO	present mode of operation
PoP	point-of-presence
RF	radio frequency
RMD	remote MAC/PHY device
RPD	remote PHY device
RxD	remote x device
SDU	single dwelling unit
SG	service group
TCO	total cost of ownership
TDM	time division multiplexing
TWDM	time-wavelength division multiplexing

URLLC	ultra-reliable ultra-low latency
US	United States
VR	virtual reality
WiGiG	wireless gigabit
WPON	wireless PON
ZoA	zones of advantage

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