Towards Technologically and Competitively Neutral Fiber to the Home (FTTH) Infrastructure

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Abstract

This paper provides a framework for understanding competition and industry structure in the context of Fiber to the Home (FTTH). We present engineering cost models, which indicate that FTTH is a decreasing cost industry, thereby making facilities based competition an unlikely outcome. Non-facilities based competition (or service level competition) in FTTH can happen in data-link layer (or transport) services via unbundled dark fiber (i.e. unbundled network elements) and in higher layer (voice, video and data) services via logical layer unbundling (or open access). FTTH architectures differ in the extent to which they support unbundling and therefore the extent of non-facilities based competition in FTTH depends on the architecture of the shared network over which multiple service providers offer service. Among the four different FTTH architectures considered, the curbside single-wavelength Passive Optical Network architecture (PON) (that has isolated pole-mounted splitters) has the most economical fiber plant but permits unbundling only at the logical layer. Physical plant unbundling is made possible in PONs by establishing Optimal Fiber Aggregation Points (OFAPs) that aggregate multiple splitters (and hence multiple distribution fibers or homes). Unbundling is achieved at the cost of longer distribution loop lengths (vis-à-vis a curbside PON). OFAP architectures further lead to higher utilization of splitter and Optical Line Termination (OLT) ports in markets that have less than 100% penetration, lowers NPV Capital Costs and provides the service provider with a real option to (i) defer investment in OLT ports (ii) deploy multiple data-link layer technologies and (iii) effectively phase in new technologies - under both monopoly and competition.

Keywords: FTTH architectures, economics, competition, unbundling, open access, industry structure

1 Introduction

The (hitherto)[1] lack of initiative among Incumbent Local Exchange Carriers has forced Local Governments and Communities to take interest in Fiber to the Home (FTTH). Today, many such communities are making fundamental choices of technology and architecture, designing networks, planning deployment strategies and determining the range of services to offer. Municipalities and community associations are likely to have a greater interest (in economic welfare, and hence) in competition. Against this industry backdrop, in this paper, we consider the implications of engineering, architecture, economics and ownership for competition in the FTTH industry.

We first discuss what we mean by competition in the telecommunications industry (Section 2). We then consider the engineering-economics of four different FTTH network architectures (Section 3 and 4): (i) Home Run Fiber (ii) Active Star (iii) Passive Star (or Passive Optical Network - PONs) and (iv) Wavelength Division Multiplexed Passive Optical Networks (WDM - PONs). Further we define different models for competition in the FTTH industry. Results from the engineering cost models of these architectures in three different deployment scenarios: (i) Urban (ii) Suburban (iii) Rural are then used to comment on the implications that network architecture has for competition (Section 5). We show that the lowest cost FTTH architecture supports different models of FTTH competition (Section 5). We conclude with a discussion on issues in FTTH industry structure (Section 5).

2 Models for Competition in Telecommunications

Competition in the telecommunications services industry can be facilities based or non-facilities based; the Telecommunications Act of 1996 contemplates both forms of competition.

2.1 Facilities based Competition

Under this arrangement, each service provider serves the market using its own physical network (Figure 2.1). In the United States, the most common example of facilities based competition is the

[1] The FCC triennial review seems to have created a lot of interest in FTTH among the ILECs, but it remains to be seen if this interest will translate into initiatives in the near future.

mobile personal communications services market where each mobile telephony services provider builds, owns and maintains its network[2].

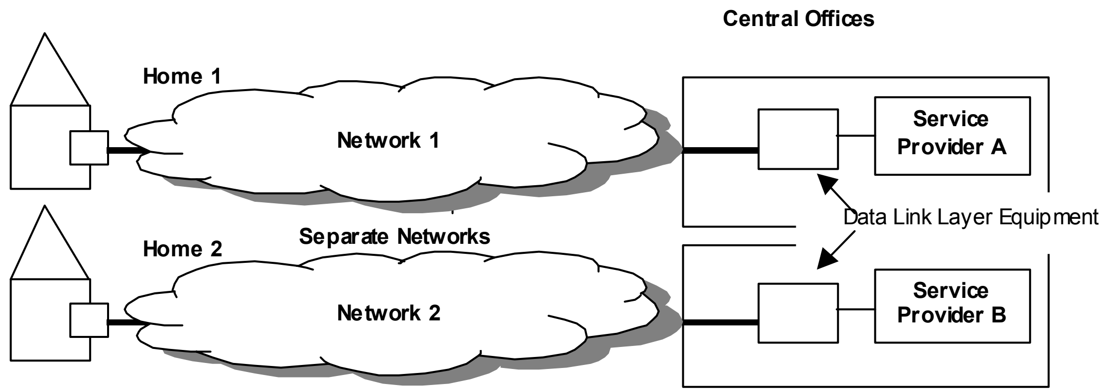

Figure 2.1 Facilities based competition

2.2 Non-Facilities based Competition or Service level Competition

In this context, each service provider shares the resources of a common network to provide service to its customers. We consider two models for this sharing:

2.2.1 'Unbundled Network Elements (UNE)' based Model for Competition: Each service provider co-locates its data-link layer equipment at the CO and offers voice, data, video and data-link layer services to its customers by renting 'unbundled network elements' (like a copper loop) from the network owner (Figure 2.2). The Local telephone service industry exhibits this model of competition with CLECs (Competitive Local Exchange Carriers) renting UNE-loops from the Incumbents to provide telephone or DSL service. For UNE[3] based competition to be possible, physical plant unbundling must be feasible.

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[2] However in order to reduce costs for 3G Wireless deployments, European mobile operators are moving to shared cell infrastructure

[3] Henceforth, by UNE we allude to UNE-loops

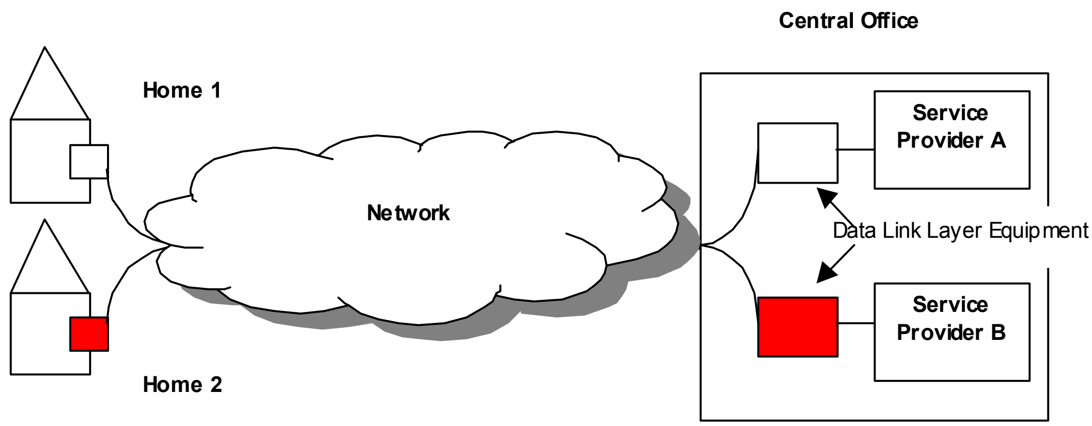

Figure 2.2 UNE based Competition

2.2.2 'Open Access' based Model for Competition: Each service provider has to share the common data-link layer (generally belonging to the network owner) in order to provide voice, video or data services (Figure 2.3). Multiple ISPs providing Internet services over a single cable TV network would be an example.

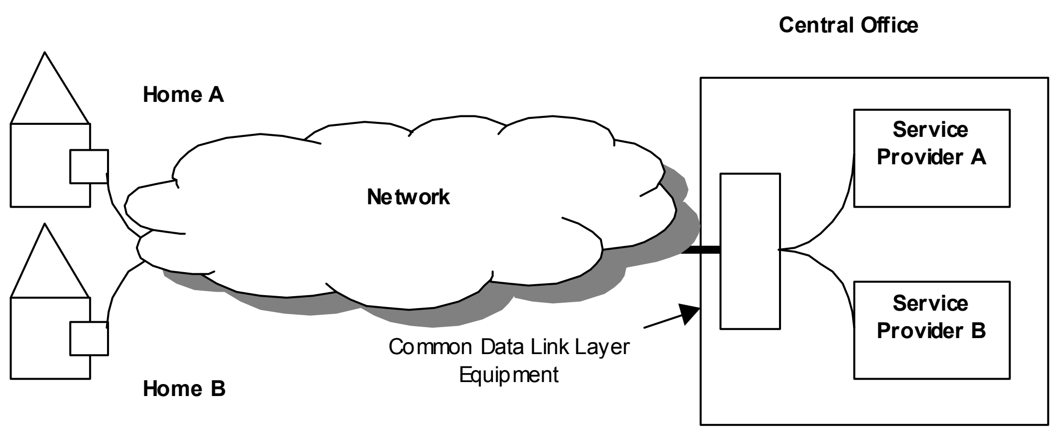

Figure 2.3 Open Access based Competition

3 Fiber to the Home Architectures

Fiber to the Home network architectures can be divided into two main categories [Reed92]: Home Run architecture (where a dedicated fiber connects each home to the CO[4]) and Star architectures (where many homes share one feeder[5] fiber through a remote node that performs switching, multiplexing or splitting - combining functions and is located between the homes served and the CO). Star architectures can be active or passive depending on whether the remote node is powered or not. Further, the passive star can be a single wavelength system (all homes served by a common wavelength[6]) or a Wavelength Division Multiplexed (WDM) system (where each home is served by a different wavelength). Below we examine: (i) Home Run Fiber (ii) Active Star (iii) Passive Star (more commonly known as the Passive Optical Network or PON); and (iv) WDM PON.

Each feeder fiber is terminated at the Central Office (CO) on equipment know as an Optical Line Termination (OLT) unit. The CO OLT equipment can be designed to support various data-link layer interface types and densities: 100FX Fast Ethernet, SONET, ATM, and Gigabit Ethernet among others. On the service provider side the CO equipment has multi-service interfaces that connect to the Public Switched telephone Network, IP routers / ATM switches or to core video networks [KP02].

The Customer Premises Equipment (CPE), also known as the Optical Network Unit (ONU) has POTS (Plain Old Telephone Service) and 10/100 Base-T Ethernet interfaces and, optionally, an RF video interface. The upstream data and voice signal generally uses the 1300 nm window (1310 nm) while the downstream signal uses the 1500 nm window (1490 or 1510 nm) [KP02, Klim02]. Broadcast analog video can be delivered (in PONs or in Home Run architectures) over a separate wavelength as an analog modulated RF multiplex of channels using the 1550 nm wavelength.

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[4] The Central Office or CO is variously called the 'Meet Point' or 'Main Node' in contemporary FTTH literature. We however will use 'CO' in this paper

[5] The feeder loop is the portion of the local loop between the CO and the Remote Node. The distribution loop is from the remote node to the terminal, while the drop loop is from the terminal to the home

[6] It is customary to use two or three wavelengths even in the so-called 'single wavelength' systems. Later we have describe the use of each of these wavelengths.

3.1 Home Run Fiber

The Home Run architecture has a dedicated fiber that is deployed all the way from the CO to each subscriber premise. This architecture requires considerably more fiber and OLTs (one port per home) compared to the other, shared, infrastructures [Reed92].

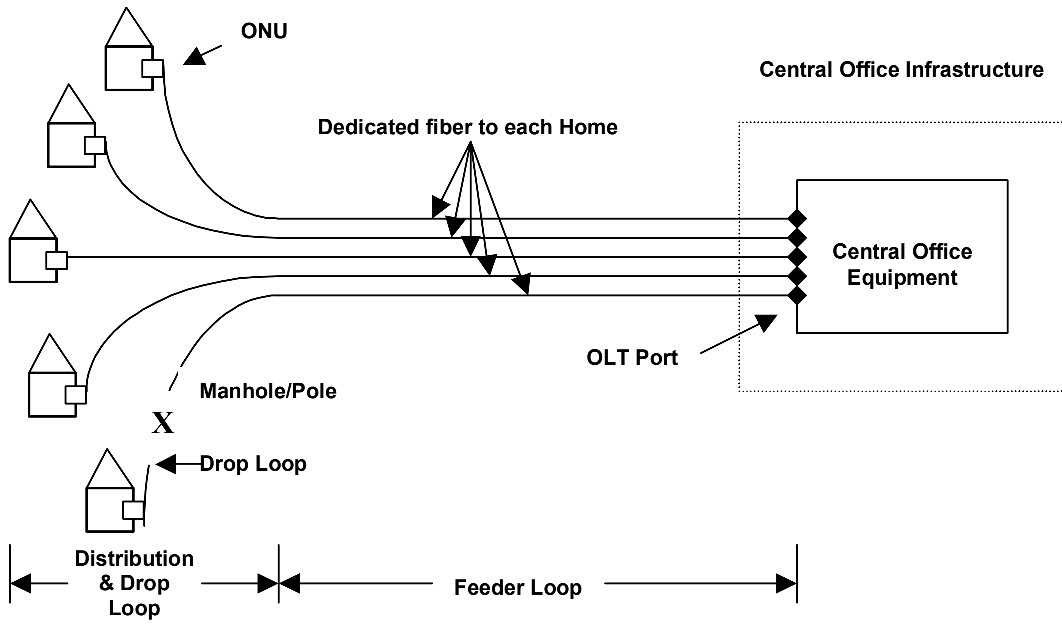

Figure 3.1 Home Run Fiber Architecture

3.2 Active Star

An Active Star architecture (also known as a Double Star) reduces the total fiber deployed and hence lowers costs through feeder fiber sharing. In the Active Star, a remote node is deployed between the CO and the subscriber's premises. Each OLT port and the feeder fiber between the CO and the remote node is shared by anywhere from four[7] to a thousand[8] homes (the split ratio) via dedicated distribution links from the remote node [Reed92].

The Remote Node in the Active Star network can be either a multiplexer or switch. The remote node switches signals in the electrical domain and hence OEO conversions are necessary at the remote node [Reed92]. Since the feeder bandwidth is shared among multiple end points, the

[7] In this case the remote switch is an environmentally hardened device and is mounted on a pole
[8] In this case a large cabinet containing the active electronics is deployed

maximum sustained capacity available to each home – both upstream and downstream – is typically less with an active star architecture than with Home Run fiber.

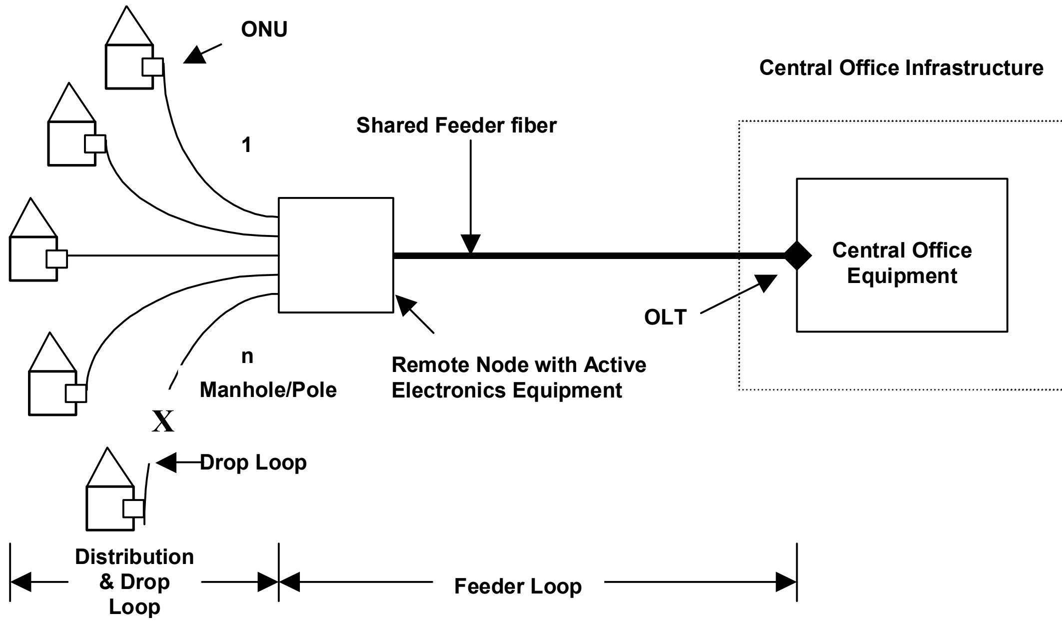

Figure 3.2 Active Star Architecture

3.3 Passive Star (Passive Optical Network – PON)

In the Passive Star network, the outside plant has no active electronics (and hence does not need power). At the remote node, a passive splitter replicates the downstream optical signal from the shared feeder fiber onto the (4-64) individual distribution fibers while a coupler combines optical signals from the individual homes onto the feeder fiber using a multi-access protocol. The OLT allocates time slots to the ONU to transmit upstream traffic [Reed92, KP02].

As in Home Run Fiber, in practice, most PON designs use two wavelengths: 1310 nm for upstream traffic and 1490/1510 nm[9] for downstream traffic [KP02, Klim02]. Generally the 1550 nm window (1530-1565 nm) is used to provide a WDM overlay for delivering broadcast analog video [KP02].

[9] ITU standard G.983 recommends the use of 1310 nm for upstream traffic and 1490 nm for downstream traffic [Klim02]. Some EPON vendors prefer to use 1510 nm downstream however.

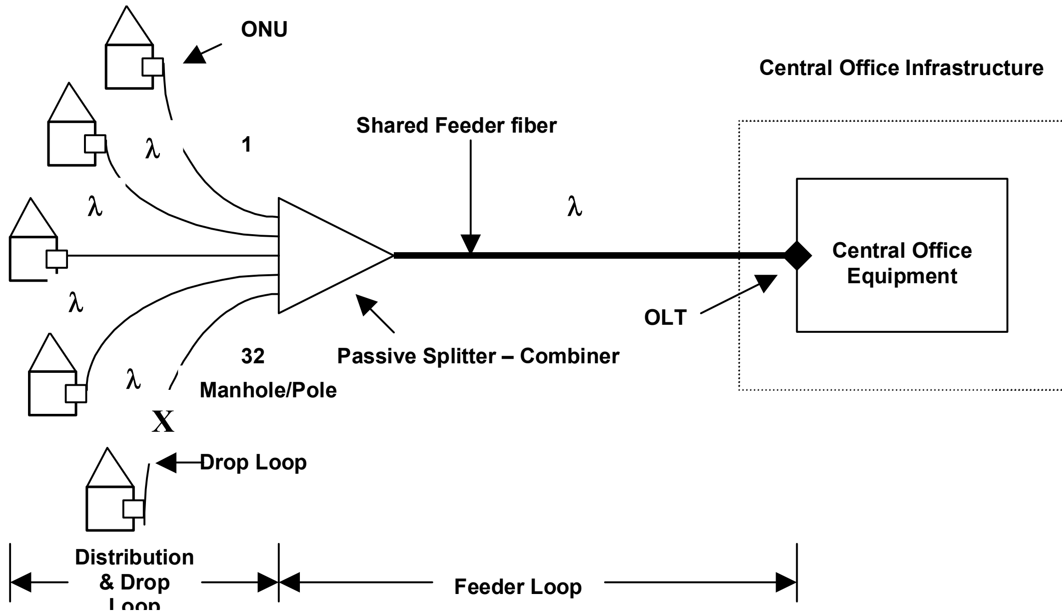

Figure 3.3 Passive Optical Network

3.3.1 Design Considerations for a PON. A key design consideration for PONs is the location of the splitter. Intuitively, the lowest cost PON architecture is one with isolated pole-mounted splitters placed to minimize the amount of distribution fiber. In this paper we denote such a PON layout as a "Curbside PON" (Figure 3.4).

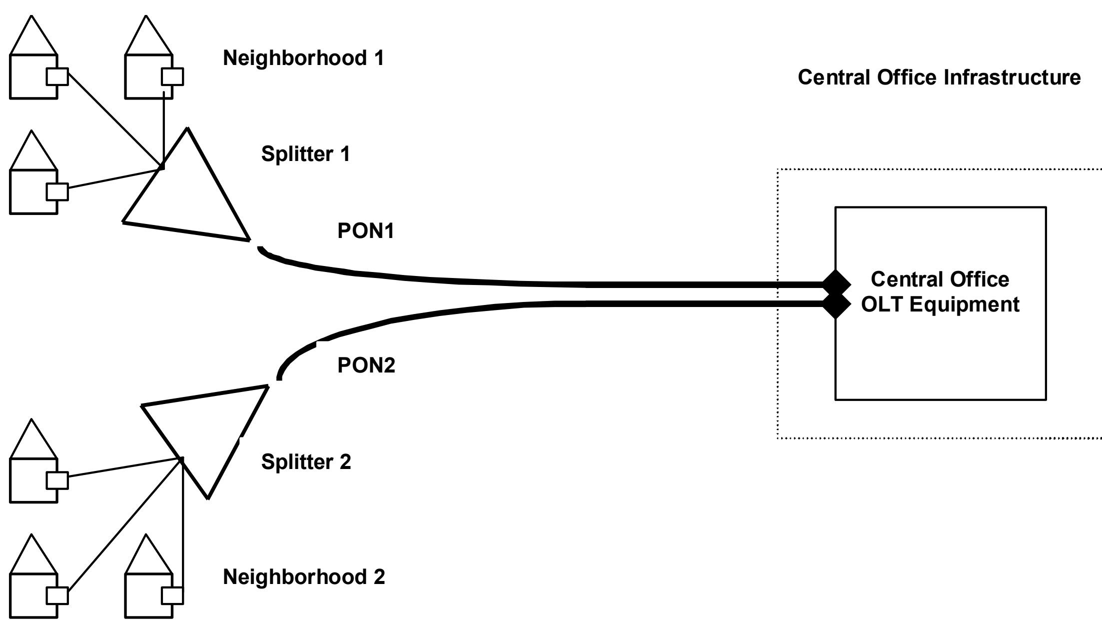

Figure 3.4 Curbside PON deployment

Notice that in a curbside PON, two OLT ports have to be deployed as soon as the first home in each 32 home 'neighborhood' takes service. Clearly, if we aggregated both splitters at one point (Figure 3.5), and connected distribution fibers to splitters only as needed, we would need to deploy the second OLT only after 32 out of the 64 (or 50%) of homes subscribed.

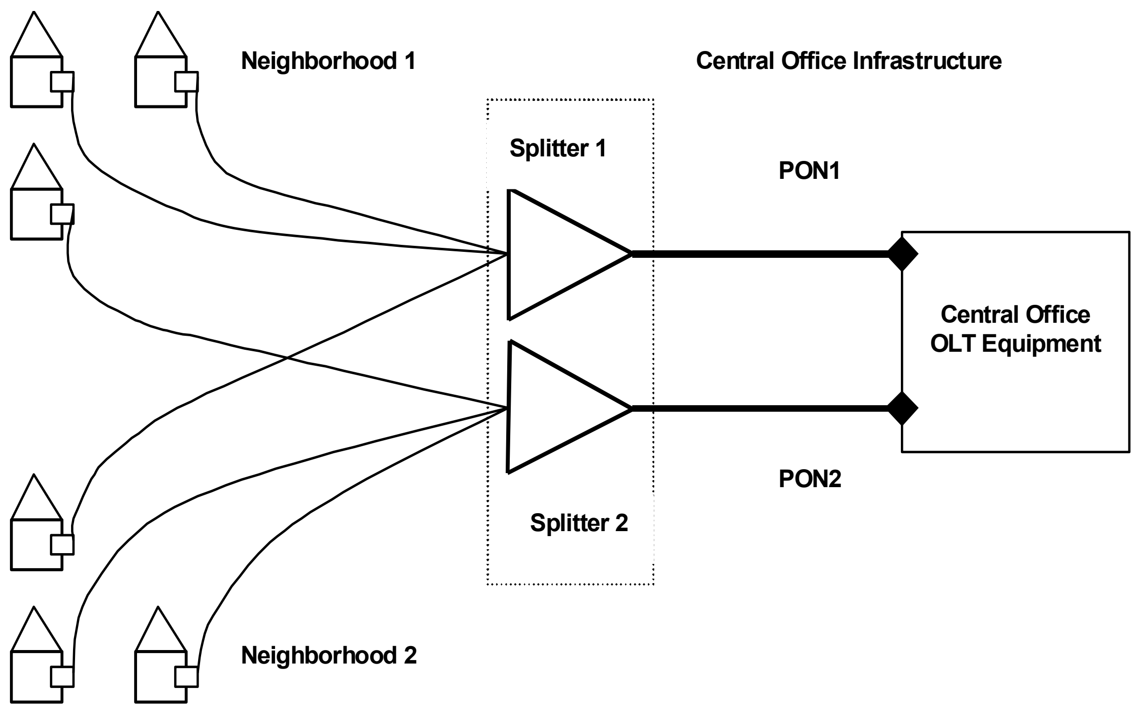

Figure 3.5 Fiber Aggregation Point (FAP)

The resultant savings from deferring OLT port deployment may be offset by the cost of longer distribution loops (and hence more deployed fiber).

OLT port deployment can also be deferred by distributed splitting. Typically in a 1:32 distributed split PON, there is a 1:8 (or a 1:4) splitter closer to the CO[10] which reproduces the downstream signal on each of 8 (or 4) distribution fibers. Each of these 8 (or 4) distribution fibers, in turn, terminate on a 1:4 (or a 1:8) splitter. Each of these splitters serves 4 homes (or 8 homes), got s yoysl dpliy og 8x4 or 32 homes. The 'upstream' splitters, if placed in the CO, basically permit homes on different 'downstream' splitters to share the same OLT port (even without any splitter

[10] In fact it can be located within the CO

aggregation). These tradeoffs (trading off more distribution fiber or distributed splitting or both in order to save on OLT ports) have been largely unexamined heretofore. We address in section 4.3 how many splitters should be aggregated at an 'Optimal' Fiber Aggregation Point (OFAP).

3.4 WDM Passive Optical Networks

Wavelength Division Multiplexing (WDM) is Coarse (CWDM) or Dense (DWDM) depending on the number of wavelengths multiplexed on to the same fiber. The OLT puts all the wavelengths onto the shared feeder fiber and the splitters replicate the wavelengths to each home. While CWDM PONs are currently being marketed, DWDM PONS require expensive frequency stable, temperature controlled lasers , and are, for the present, not economically feasible, and will not be considered further.[11]

4 Economics of Fiber to the Home

Understanding the cost structure of the industry is a prerequisite to understanding the viability of competition. This section examines the engineering-economics of the different FTTH architectures.

4.1 Cost Model Assumptions

It is assumed that the fiber infrastructure is an overbuild in a community already served by copper and co-axial cable. Once the fiber is deployed, video, telephone and data services can be expected gradually shift to the fiber network. Capital Cost per Home, as we shall show, is very sensitive to loop lengths (and hence to housing densities) and therefore we consider three deployment scenarios: (i) Urban (ii) Suburban and (iii) Rural.

Service providers will find it efficient to lay sufficient fiber during initial construction to support all subscribers in a community, even if only a fraction of them initially sign-up for service. The cost of trenching or making poles ready is prohibitively high to go back and retrofit fiber as more homes subscribe to the service. By contrast, the drop loop[12] and the Optical Networking Unit

[11] Personal communications with Vendor A reveal that the cost of a 8-wavelength system can be as high as $160,000.

[12] It is not abnormal to pre-provision the drop loop as well. In builds where the fiber drop into each home is buried (and especially in new builds) one would in fact expect the drop loop to be provisioned when the rest of the FTTH network is built.

(ONU) can be provisioned as users sign-up for service. OLT and remote node electronics can also be deployed based on penetration.

We have chosen three COs in Pennsylvania to represent urban, suburban, and rural scenarios,[13] using data from the HAI Model 5.0A. The HAI Model provides data on the CO area, number of clusters[14], the radial distance, aspect ratio and location of each cluster with respect to the CO, total number of homes and housing density for each cluster. Using this data, the costs of deploying feeder and distribution fiber for each scenario can be calculated.

Deployment	Homes per sq. mile	Homes served per CO	Number of Clusters
Urban	5,175	16,135	23
Suburban	514	10,183	14
Rural	116	5,871	10

Table 4.1 Deployment Scenarios

4.1.1 Capital Costs for Homes Passed. These are capital costs incurred irrespective of whether homes sign-up for service or not and include: (i) Construction Costs - cost of making poles ready (for an aerial build) or the cost of trenching for a buried fiber deployment and the cost of fiber deployment (ii) Fiber related capital costs - cost of feeder and distribution fiber, sheath, splicing and enclosures (iii) CO related capital costs - cost of CO real estate, powering, construction and CO fiber termination (iv) RT related capital costs - cost of splitter-combiner cabinets for PONs and cost of remote terminal real estate, powering arrangements and cabinet for Active Star networks.

(i) Construction Costs. Fiber deployment can either be underground or aerial. Underground deployment, traditionally[15] requires trenching. The cost of trenching varies depending on the deployment scenario (generally higher for urban compared to rural) and the underlying rock formations [HAIM]. Deploying aerial fiber on utility poles may involve freeing up space on each pole so that the optical fiber cable can be strung on the pole. Often electrical and telephone cables (and transformers) need to be moved around on each pole and sometimes a heavily loaded pole

[13] The CLLI codes for the urban, suburban and rural CO are PITBPASQ, HMSTPAHO, TNVLPATA respectively.
[14] In a cluster all homes are at a distance less than 18,000 feet from the center of a cluster
[15] There are newer underground deployment methods that do not require trenching. Our model assumes that trenching is a pre-requisite for buried deployments.

may have to be replaced with a longer pole in order to make space for the fiber at a cost of up to $1,000 for each pole that is replaced[16][17]. Our baseline model assumes 100% aerial construction.

Cost of Pole Replacement	$1,000
Percentage of Poles replaced	20% in Urban; 10% in Suburban; 1% in Rural
Cost of Pulling Fiber on Poles	$1.50 per foot

Table 4.2 Costs of Aerial Deployment[21]

Urban	$25 per foot
Suburban	$10 per foot
Rural	$3 per foot

Table 4.3 Costs of Trenching[21]

(ii) Fiber related capital costs. This includes the cost of feeder and distribution fiber, sheath, splicing and splice enclosures. The number of fiber strands that constitute a Feeder fiber bundle varies with the architecture and the deployment context[18]. For all the architectures we have assumed overprovisioning by 25% in both the feeder loop and distribution loop.

Single Mode Fiber (including the cost of sheath)	4 cents per strand-meter
Small Splice Enclosure	$150
Large Splice Enclosures	$800
Mechanical Splice[19]	$25
Fusion Splice	$5
Connector	$20

Table 4.4 Fiber related capital costs

[16] Personal Communications, Mr. Hal Etsell, Mountaintop Technologies, Johnstown, PA
[17] Personal Communications, XYZ Constructions, Pittsburgh, PA reveal that in certain cases the cost of pole replacement can actually be more like $5000
[18] We assume that each cluster is served by a seprate feeder bundle.

[19] A mechanical splice is used when fiber strands need to be spliced to (say) a splitter port. When two fiber bundles need to be connected, a fusion splice is used. A fusion splice tends to be typically much less expensive. (Personal Communications, Corning Cable Systems).

(iii) Cost of CO real estate, construction, fiber termination and powering. Typical costs at the CO include costs of CO real estate, construction and powering. Cost of managing the innumerable strands of fiber coming into a CO are often overlooked but merit attention, as these costs tend to be particularly high in the case of fiber rich architectures like the Home Run architecture. Table 4.5 – 4.7 show the key costs of CO infrastructure.

Cost of 7 ft patch panel rack	$ 400
Cost of jumper cable with connector	$20
Total Cost of terminating 728 fibers	**$22,600**

Table 4.5 Fiber management costs[20]

Deployment	Area (ft^2)	Real Estate Costs ($\$/ft^2$)	Construction Costs ($\$/ft^2$)
Urban	4,000	10	100
Suburban	4,000	10	100
Rural	2,000	7.5	85

Table 4.6 CO Real Estate and construction costs [HAIM]

Cost of Generator	$30,000
Cost of HVAC powering	$100,000

Table 4.7 Capital Cost of CO power[21]

(iv) Remote Terminal Costs. Remote terminal housing costs are modest for PONs. PON splitter cabinets do not require any heating or cooling and typically hang off poles. Since remote terminal cabinets for active star networks house active electronics, they require power (and may require heating and cooling) and need to be placed on a concrete pad. The cost of remote terminal real estate varies considerably depending on location (city, state).

Splitter Cabinets	$400 (Small Cabinets – 80 homes)
	$600 (Medium Cabinets – 200 homes)

[20] Personal Communications, Corning Incorporated

[21] Personal Communications, Grant County PUD, Washington State.

	$800 (Large Cabinets – up to 1000 homes)
Cabinets for Active Electronics	$6,000 (Small Cabinets – 60 homes) $10,000 (Medium Cabinets – 120 homes) $20,000 (Large Cabinets – 240 homes) $30,000 (X Large Cabinets – 480 homes) $50,000 (XX Large Cabinets – 960 homes)
Concrete Pad	$700
RT real estate	$4,000 (Urban); $3,000 (Suburban); $2,000 (Rural)
Capital cost of Powering	$1,500 per RT location

Table 4.8 RT costs

4.1.2 Capital Costs for Homes Served. Once the fiber is deployed, service provisioning requires deploying networking equipment at the CO (and remote node) and connecting the subscriber to the network by laying the drop loop. The splitters can be pre-positioned or incrementally deployed as more homes sign-up for service. The central office equipment is organized on racks with each rack accommodating a fixed number of shelves (usually different for each vendor). Shelves have slots where line cards are plugged in. We assume Ethernet as the data-link layer technology.

In the case of Home Run Fiber, the CO equipment consists of an Ethernet switch that supports 100 Mbps Fast Ethernet line cards. Each line card has a fixed number of ports (depending on the vendor) and one port is required to support each home[22]. Different equipment manufacturers make ONUs which have different interfaces and operate at different speeds. An ONU[23] is assumed to include, on the customer side, one 100baseT interface and two POTS (RJ11) ports. For the PON, each (Optical Line Termination) OLT port has a Gigabit Ethernet interface and supports 32 subscribers. The Active Star architecture CO equipment has Gigabit Ethernet ports, each shared between 32 homes[24]. The Remote Node in the Active Star architecture has a 100

[22] A typical example is the Cisco Catalyst 4000 series of switches with 100 FX Fast Ethernet ports

[23] We have come up with cost estimates of networking equipment after detailed discussions with senior technical and management staff at Vendor A, Vendor B, Vendor C, Vendor D, Vendor E and Vendor F. For reasons of non-disclosure we cannot provide pricing information for products of any specific company.

[24] In in a real world active star deployment a Gigabit Ethernet port at the CO would probably support more than 32 homes; however so that we compare 'apples with apples' it is assumed that a GigE port is added at the CO for every 32 subscribers.

Mbps optical ethernet port per subscriber and Gig-E uplink. We have assumed SONET to be the technology for inter-CO transport. Video is assumed to be switched for delivery over the Ethernet link. Costs for a video headend or telephony softswitch are not included within the model.

The following table gives the estimated cost of FTTH networking equipment.

Equipment Description	Cost
Rack	$2,000
Shelf (5 shelves per rack)	$1,000
Point to Point Ethernet Line card (20 cards per shelf; 24 ports per card; 1 home per port)	$6,500
EPON Line card (20 cards per shelf; 4 ports per card; 32 homes per port)	$16,000
Control Card (1 card per shelf)	$3,500
OC48 Interoffice SONET transport card	$8,000
IP video card (10,000 streams per card)	$6,500
P2P 100 Mbps Fast Ethernet ONU	$350
EPON 1 Gbps ONU[25]	$500

Table 4.9 FTTH networking equipment summary[28]

4.2 Cost Model Results

Figure 4.3 shows the Capital Cost per Home Passed for the three architectures for each of the three density scenarios. The Capital Cost per Home Served depends quite heavily on the penetration achieved.

[25] The PON ONU is more expensive compared to the ONU of point-to-point architectures (such as Home Run Fiber and Active Star) is because it uses 1 Gbps optics. Additionally, it has a chip that implements the PON protocol.

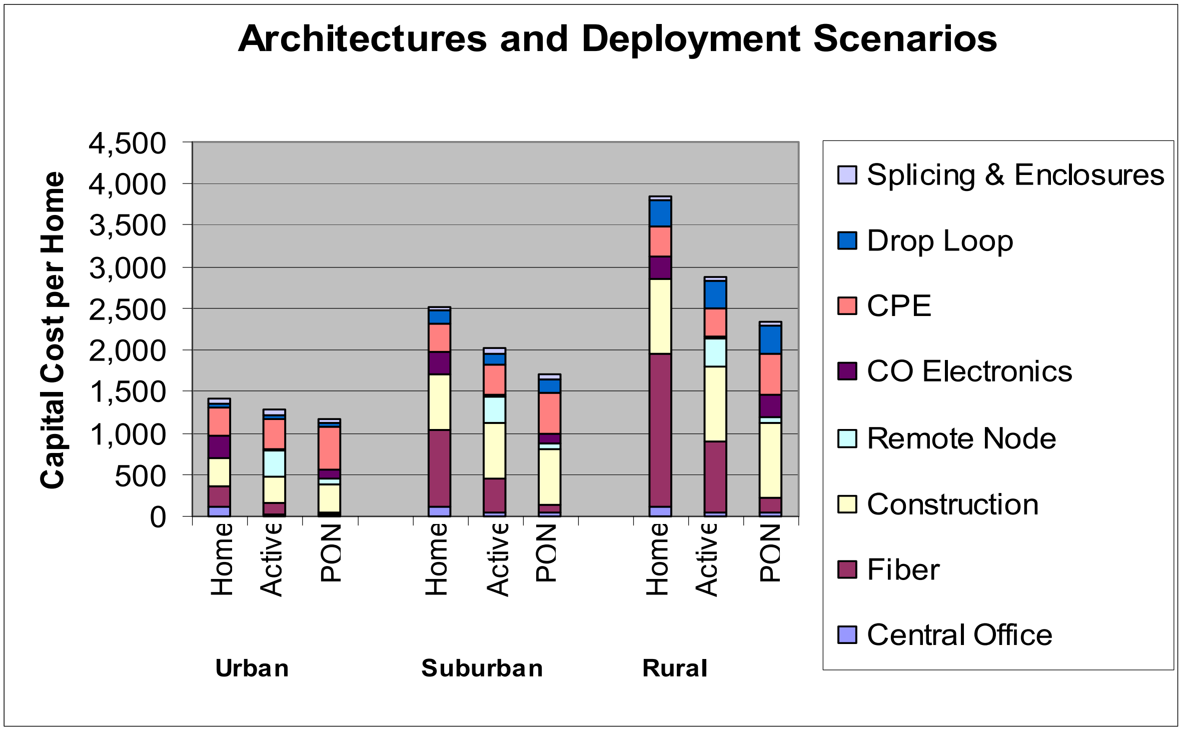

Figure 4.1 Breakdown of Capital Cost per Home for FTTH architectures

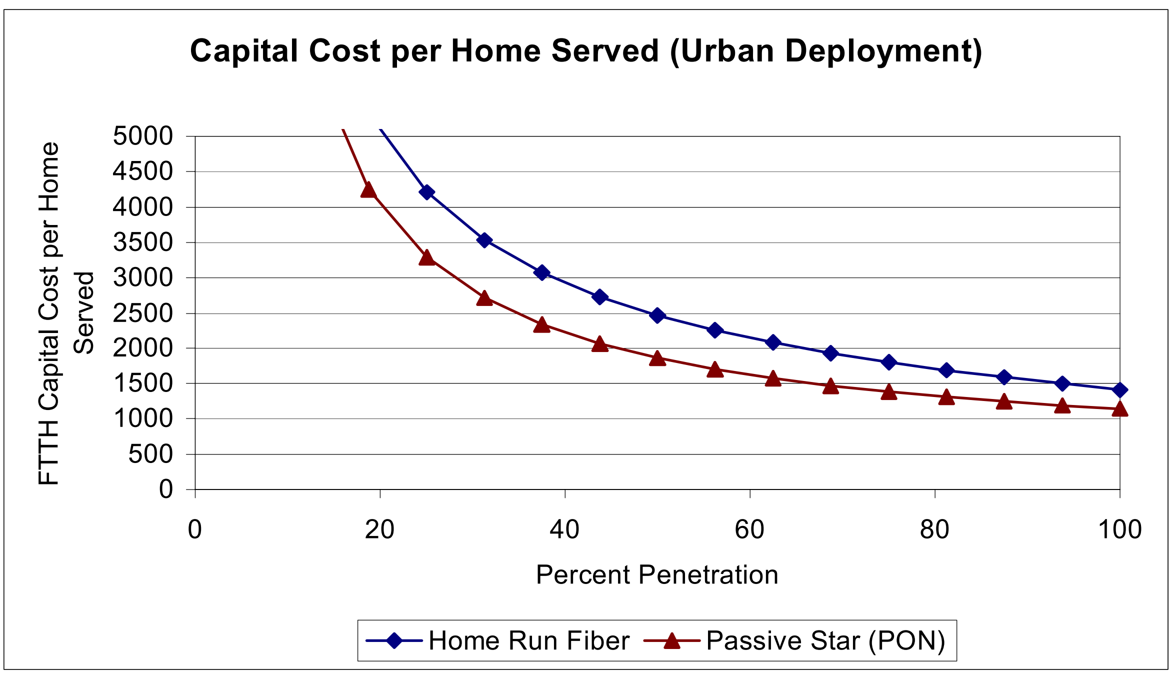

Figure 4.2 Capital Cost per Home Served for an Urban deployments[26]

[26] The curve for the WDM PON lies outside the scale chosen for all the plots

The necessity of deploying all the fiber up front, with its attendant construction costs makes FTTH a decreasing cost infrastructure with penetration. The curbside PON appears to be the most economical FTTH architecture. For very low levels of penetration the Home Run architecture is significantly more expensive as more fiber needs to be pre-positioned in the Home Run case, while for high levels of penetration the cost difference drops to about $ 200 (at 100% penetration) per home in an urban deployment.

The Cost per Home Passed (and Served) is sensitive to loop lengths especially for the Home Run architecture which has much higher costs than PON in rural areas (especially for low penetration levels).

4.3 OFAP as a Real Option: PON Network design under uncertainty

For curbside PONs, all OLT ports have to be pre-positioned irrespective of how many homes take service; PON architectures in which splitters are aggregated at FAPs require fewer OLT ports (Table 4.10) for penetration levels less than 100%. In an urban deployment a fiber aggregation point PON that aggregates four splitters (128 homes) needs 75% fewer OLT ports compared to a curbside PON at 20% penetration. Even at a higher penetration (60%) it requires 25% fewer OLT ports than a curbside PON[27].

The PON splitter that fills up the last in a particular Fiber Aggregation Point (that has multiple splitters) serves less than 32 homes. Two such splitters (belonging to two different FAPs) that serve less than 16 homes can be served by the same OLT port through a 1:2 splitter placed in the CO. Thus, distributed splitting further reduces the number of OLT ports deployed at low penetration levels. The savings in the Central office however come at a cost: longer distribution loop lengths. As more splitters are aggregated at a FAP the distribution loops are lengthened resulting in higher fiber costs per home (Figure 4.4). Aggregating 960 homes (30 splitters) adds $134 in terms of fiber related capital cost per home for an urban deployment.

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[27] For any value of penetration, we assume that the probability P(n), 0 < n < (FAP Size), that n homes sign up for service is binomially distributed with parameter p = % penetration. The probability that an OLT port is required for any neighborhood is 1 – P(0) in a curbside PON. The approach can be extended for FAP PONs and distributed split PONs.

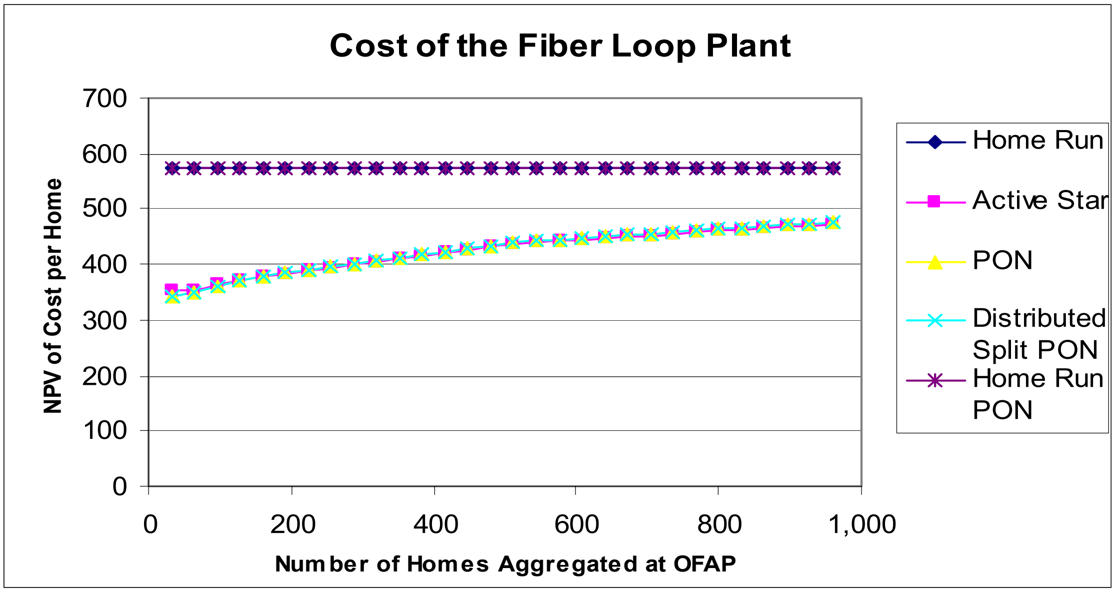

Figure 4.4 Increase in Fiber related Capital Costs per home as distribution loops are lengthened (Urban deployment)

4.3.1 Option to defer investment in OLT ports. We now investigate the tradeoffs between Central Office cost savings and increased distribution fiber costs in order to gain insights into FAP design. Since FAP (and distributed split) architectures sharply reduce the number of OLT ports that need to be pre-positioned (vis-à-vis the curbside PON), investment in OLT ports can be deferred till more users sign up. The slower the take-rate, the longer the investment in OLT ports can be deferred. Using Net Present Value analysis, Figures 4.5 – 4.6 show that even for an optimistic take-rate[28] in the urban context, the lowest cost architecture – taking into account the additional fiber related costs and OLT port savings – has an OFAP (Optimal Fiber Aggregation Point) size of about 200 homes. In rural areas this is reduced to 96-128 homes. Note that if one further resorts to distributed splitting (in addition to aggregation), the NPV capital costs are even lower; however there will be additional operational expense to rearrange splitters at the Central Office and the OFAP as penetration changes.

[28] The optimistic take rate scenario assumes that we have 30% of homes taking service by year 5 and 70% of the homes taking service by year 10.

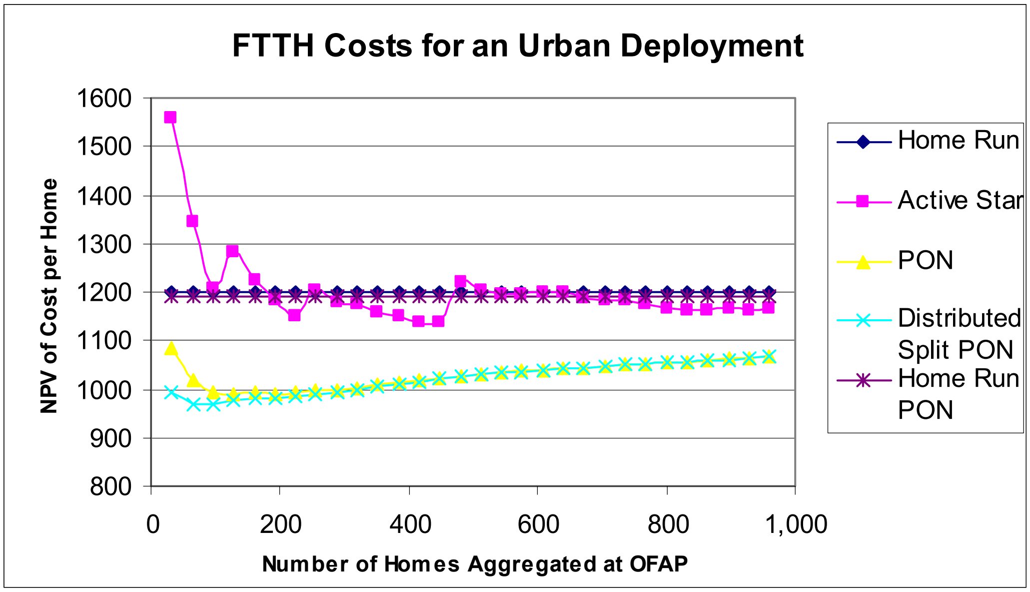

Figure 4.5 NPV of Total Cost per Home for Urban deployment for an optimistic take-rate

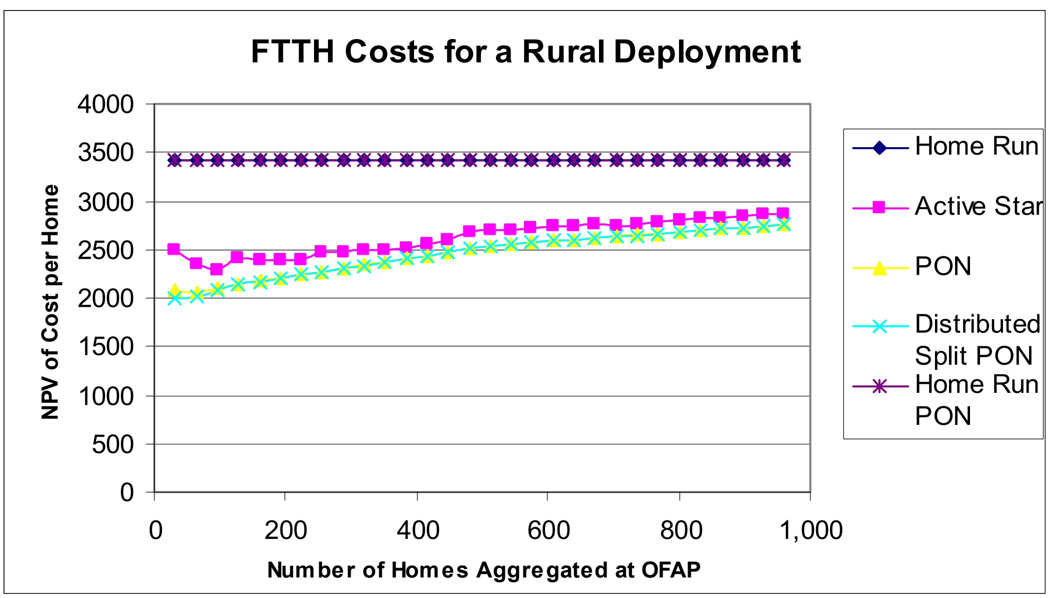

Figure 4.6 NPV of Total Cost per Home for Rural deployment for an optimistic take-rate

4.3.2 Option to phase in new technologies (and deploy multiple link-layer technologies).

With technology continuously evolving, one can expect to see next generations PONs with higher OLT port speeds in the future. In a curbside PON deployment, even if one home (among the 32 homes served by each standalone splitter) needs to be served by the next generation PON, the OLT port and all the 32 ONUs must be replaced. On the other hand, in an OFAP deployment, while most splitters (and corresponding OLT ports) can continue to support the older technology, a few OLT ports can be upgraded to newer technology. Therefore a service provider that deploys a BPON[29] today can gradually phase in a GPON[30] when that becomes available. Extending this idea further, a service provider could simultaneously deploy different link layers, or group heavy-use subscribers onto a splitter with a lower split ratio. Not only can they deploy an ATM PON and an Ethernet PON simultaneously, but also they can also simultaneously deploy PONs that have different OLT port speeds and split ratios[31].

4.5 Sensitivity Analysis

The discussion on FTTH economics is incomplete without a short discussion on sensitivity.

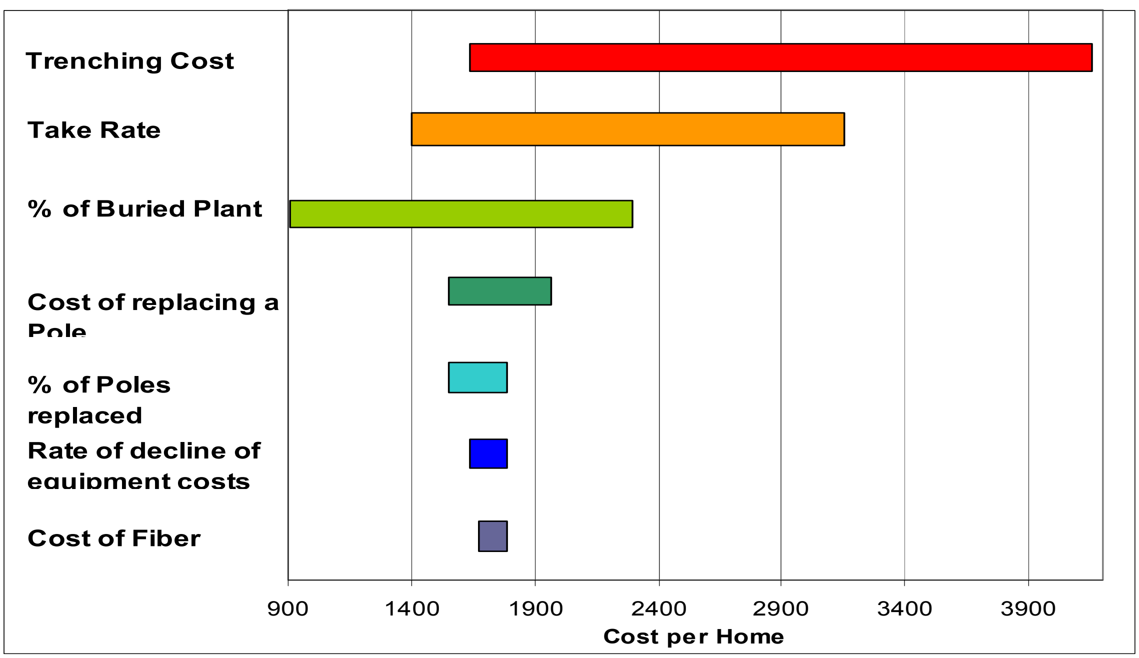

Figure 4.7 Sensitivity Analysis for a PON FTTH Urban deployment

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[29] A BPON has a downstream bandwidth of 622 Mbps and a 1550 nm wavelength overlay
[30] A GPON has a downstream bandwidth of 1.2 Gbps or 2.4 Gbps

Trenching costs are very uncertain in any FTTH build. The cost of trenching depends, among other things, on the underlying bedrock. Also, in urban areas, restoring the sidewalk and front lawns are additional expenses. Therefore it is not very uncommon to see the costs of buried deployment varying between $25 and $100 per feet. From figure 4.7, we see that the outside plant cost per home is most sensitive to trenching costs (this is assuming that a 50% buried build). For a PON architecture, a variation in trenching costs can make the cost per home vary by as much as $2504. Varying the take rate (at the end of year 10) from 30% to 90% results in a variation of $1776 per home. Since, aerial construction costs are cheaper, plants that are 100% aerial are cheaper than plants that are completely buried by as much as $1403 a home. For aerial builds, the cost of making poles ready and replacing poles (that have no space left on them) can vary between $400 per pole to $5000 per pole and results in a cost variation of $208 per home. Variation in the cost of decline of optical and electronics networking equipment and the variation in the cost of fiber, have only a modest impact.

5 Competition, FTTH Architecture and Industry structure

We now examine competition in the FTTH industry and examine the viability of each model of competition (section 2) in the context of the FTTH architectures (section 3) in light of FTTH economics (section 4).

5.1 Facilities based competition

Considering capital costs only, FTTH is a decreasing cost infrastructure (Figure 4.2). Without consideration of operating costs one cannot say definitively that FTTH is a natural monopoly, but it is clear that large economies of scale and large fixed costs are likely to create significant barriers for a second entrant.

From our cost models, the Capital Cost per Home per home passed is about $600 and the sunk cost to serve an urban community of 16,000 is $9.6 million. Average revenue per subscriber per month can be assumed to be about $130 (assuming that each home subscribes for Voice, Video and Internet services) and further assuming that direct costs are about 50% of revenues, the gross

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[31] For example a PON that has a downstream bandwidth of 155 Mbps and 4 splits can co-exist with a PON that has a downstream bandwidth of 622 Mbps and 32 splits.

monthly margin is about $65 per subscriber[32]. In order to cover plant costs and the cost of electronics for all subscribers that are being served with its net revenues (in 5 years[33] with an IRR of 20%), one needs a penetration rate of about 35-40%. Notably, our simple calculation shows that if a 35-40% penetration is required for profitability, then in the long run at most two firms can profitably serve the same market.

In suburban, small town and rural areas, where the supply side economics are even less attractive it is difficult to image that there will be more than one FTTH firm in the long run. In general, therefore, facilities-based competition in FTTH seems very unlikely.

5.2 Competition at the Optical Layer

Natural monopoly at the physical layer does not preclude competition at higher layers. There are two models for how a single physical facility could support multiple competitors at the optical layer.

(i) 'Wavelength per Service Provider' Model: Multiple providers can simultaneously rent different wavelengths on a physical fiber owned by a different party. Each service provider could offer data, voice or broadcast video services with a data-link layer technology of the provider's choice on its wavelength. While the WDM PON and the Home Run architecture support this model of competition, single wavelength systems like the PON and Active Star do not facilitate this model of competition. Implementing competition at the Optical Layer for a WDM PON would require each feeder fiber to terminate on a port in an Arrayed Waveguide Grating (AWG) that routes each wavelength to the appropriate service provider OLT. Under this arrangement, at the most two or three[34] providers can be supported using CWDM, which would not require frequency-stable temperature-controlled lasers both for the OLT and ONUs. Implementing this on a Home Run system is unnecessary as each dedicated fiber can be connected directly to the OLT of the desired service provider.

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[32] This monthly margin goes towards paying back the infrastructure as well as meeting operations costs though here we assumed that the entire amount goes into paying back the infrastructure
[33] It is reasonable to assume that private players expect payback time horizons of 5 years or less and IRRs of 20% and
[34] Indications are that not more than 2-3 competitors can be supported using CWDM. PON equipment is economical because it does not use very sophisticated lasers. This requires sufficient isolation between wavelengths and may limit the number of wavelengths to 3-4 on each PON. If each competitor uses 2 wavelengths – one for upstream traffic and one for downstream traffic – it will be difficult to have more than 2 competitors.

(ii) 'Wavelength per Subscriber' Model: Each subscriber can be served on a different wavelength. Given the number of wavelengths required (equal to the split ratio), this amounts to Dense WDM, implying the use of expensive frequency stable temperature controlled lasers in both the OLT and the ONU. Needless to say, the Active Star architecture does not support this model of competition either. To implement this model of competition on a WDM PON a Wavelength Router is needed in place of the AWG to route each wavelength to the desired service provider. Each home uses a different wavelength requiring the ONUs to support different wavelengths, creating an inventory management problem in the absence of variable wavelength lasers. Note that in this context, a WDM PON closely resembles the Home Run architecture in that each user's traffic is isolated on a unique wavelength. The DWDM overlay in effect creates a 'virtual' dedicated point-to-point facility over the shared PON architecture. However for the Home Run architecture, each subscriber's fiber can be directly connected to the OLT of the desired service provider, and the use of multiple wavelengths is unnecessary.

DWDM overlays are economically infeasible today in the access space, and hence close the discussion on WDM PONs and wavelength based competition at this point.

5.3 Data link layer (UNE based) Competition.

If the FTTH physical plant is amenable to unbundling, competitors can rent the fiber as a UNE (unbundled network element) and choose the link layer technology to be used over the physical medium. Providers could use ATM, SONET, Ethernet or Analog modulated RF carriers as their data link layer technology. Since all users served by the same splitter – combiner on a curbside PON (and by the same Remote Node in an Active Star architecture) have to be served by the same data-link layer technology, a curbside PON-physical plant cannot be unbundled, and therefore this model of competition is not possible in curbside PONs and Active Star architectures. In the case of the Home Run architecture this is easy to implement by directly connecting each subscriber's fiber to the OLT of the desired data-link layer service provider.

An OFAP architecture, besides having a lower NPV cost than a curbside PON, also enables data-link layer competition. Aggregation of many splitters at an OFAP does not require all homes served by the same splitter to be in the same neighborhood. Splitters at the OFAP can be assigned to different service providers served by different OLTs at the CO, using data-link technology of the competitor's choosing. The number of competitors is limited by the number of splitters at the

OFAP—generally 6-8. Aggregating too few splitters not only raises costs but also reduces the potential for data-link layer competition.

Clearly, if there are multiple link-layer service providers, some of the savings from deferring investment in OLT ports will be lost; in fact if there are as many service providers as the number of splitters aggregated, all OLT ports will need to be pre-positioned. This cost of competition depends on the extent to which investment in OLT ports could otherwise be deferred. If the take rate is high, the impact on costs will be modest.

5.4 Network (and higher) layer based (Open Access) Competition.

Different Internet Service Providers (ISPs), telephone service providers and switched digital video providers can use traditional ‘open access’ to provide data, voice and switched digital video services. There are two possible models:

(i) The service provider can wholesale transport from the data link layer provider and resell service bundles to the subscriber. Each subscriber in this context has only one dedicated ISP. This is typical of current DSL and cable open access arrangements [DONN00].

(ii) The Data link layer provider can sell unbundled transport direct to the subscriber. The subscriber can make separate agreements with one or more service providers and can select an ISP on demand using switching / routing technology provided by the data-link provider. [DONN00] This is similar to today's dialup ISP access model.

The existence of thousands of ISPs today indicates that the barriers to entry for service providers are considerably less than at the facilities, or data link layers. Data-link layer service providers, can, through vertical integration, leverage economies of scale in facilities or the data-link layer to uneconomically limit competition at the services layer.

5.5 Why UNE based Competition is preferable to ‘Open Access’ based Competition?

‘Open Access’ based on competitive provisioning of Voice, Data and Video services over a shared transport network is made possible by ‘unbundling’ the network at the ‘logical layer’ and the ‘re-sale’ of data-link layer services. In the absence of dark fiber unbundling, service providers and subscribers are obliged to rely on the data-link technology choice of the facilities/data-link monopoly even if they would have preferred an alternate data link technology, such as ATM versus Gigabit Ethernet. In effect the natural monopoly of the physical layer is extended to the data link layer.

The absence of competition at the data link layer may limit the pace of data link layer innovation. More importantly, voice, video and data service possibilities may be limited by the capabilities of the chosen data link layer. For example, if the network owner selected a PON that does not support a video overlay at 1550 nm, service providers are precluded from offering analog broadcast video services.

Finally, Open Access competition depends on the data link operator to provision and police the quality of service provided to each network layer competitor. With data link competition, QoS of each service provider is essentially independent and under the competitor's control.

Link layer competition is not just about ATM vs Ethernet. The link layer also defines the port speed (downstream and upstream capacity), the number of splits (in a PON) and therefore, in effect, bandwidth per home. So one can imagine that with UNE based competition, different competitors can provision the same flavor of data link technology (whether APON, EPON, BPON or GPON) with different upstream and downstream capacities and split ratios. It is conceivable that competitors may even choose to deploy an Active Star while a competitor deploys a PON (for example using hardened electronics at the OFAP cabinet).

In the event that the loop architecture facilitates data-link layer competition between multiple players, each data-link layer service provider could either choose to integrate vertically with higher layer service providers (like ISPs or video service providers) or choose to provide 'open access'. Vertical integration would permit only as many higher layer service providers as there are data-link layer service providers. Whether this is a 'sufficient' number of ISPs or video service providers depends on precisely how many data-link service providers can be supported and on second mile costs, operations and marketing costs all of which we have yet to consider. If the number of link layer competitors is small, it may be desirable to have 'open access' as well to ensure maximum competition at the services layer.

5.6 Necessary Conditions for Competition in FTTH

Though a loop architecture that facilitates competition is a prerequisite to competition in FTTH, it is not a sufficient condition. The feasibility of competition in the 'last fiber mile' also depends on: (i) Second Mile Costs (ii) Ownership and Industry Structure (iii) Community (or Market) Characteristics

5.6.1 Second Mile Costs and Market Characteristics: The costs that we have accounted for in our economic model are only the loop infrastructure costs and data-link layer networking costs. However, when services are provisioned over this infrastructure, there are expected to be significant costs related to transporting voice, video and data services to the CO from regional nodes. These costs are known as 'Second Mile' Costs (the FTTH network being the 'First Mile'). Second Mile costs vary tremendously depending on the location of the community being served. Evidently second mile costs are expected to be lower for urban communities and can be sufficiently high for certain rural communities or small towns that competition may not be feasible regardless of the choice of architecture. An examination of Second Mile costs is an important next step for this research.

Community characteristics such as housing density have implications for cost as local loop lengths are directly related to housing density. The community size determines the number of homes that a particular CO can serve. Since our cost models indicate scale economies in FTTH deployment, smaller communities would have higher per 'Home Passed (or Served)' costs. Consequently a smaller community would be likely to support a fewer number of service providers. The income distribution of a community and thus the market demand for services also has implications for viability of competition in a particular market.

5.6.2 Ownership, Industry Structure and Competition. Since FTTH is a decreasing cost infrastructure, the most likely outcome is that there will be only one fiber per home. This fiber can be regarded as a bottleneck infrastructure. Therefore, entry into the services market by a large number of providers is likely to require access to unbundled elements supplied by the owner of the fiber infrastructure and/or open access. Experience from the local telephony industry[35] indicates that a vertically integrated entity that owns the infrastructure and provides services is

[35] Charles H. Helein, "A Call to Arms to Local Competitors", http://www.clec-planet.com/forums/heleinjune14.html

unlikely to emerge as an efficient, cost-based supplier of network elements to retail[36] competitors. Indeed, experience suggests that perhaps no amount of regulation – with the exception of total structural separation – can provide a level playing field to non-facilities based competitors.

Beard, Ford and Spiwak further argue in [BFS01] that a vertically integrated entity with a large retail market share will have even more incentives to discriminate against rivals in the wholesale market[37]. When a vertically integrated firm that has a large retail market share rents out network elements to a retail market competitor, it is very likely that it loses a customer in the process (to the competitor) and the retail margin accruing from the customer. The opportunity cost facing this firm, is therefore the average cost of production of the loop and the expected value of the retail margin that may be lost[38]. Therefore, the incentives to supply the "wholesale market" at cost-based prices, thus facilitating competition in the "retail" market, are inversely related to the market share of the firm in the retail market.

5.7 Industry Structure, Fiber Ownership and Competition.

Accordingly, given the existence of these discriminatory incentives and the economics of the Fiber to the Home industry, the most viable long-term competitive market structure involves the presence of a wholesale supplier (that is not vertically integrated) and its efficient functioning as a regulated common carrier.

The presence of a 'neutral' firm that builds and owns the fiber infrastructure and offers non-discriminatory access to all service providers will significantly lower entry barriers to firms intending to provide video, voice and data services. Since this 'neutral' firm will not provide retail services, it would have no incentives to raise a non-facilities based service provider's key input of production by non-price behavior. Consequently, the exclusively wholesale and neutral nature of such a firm would permit a market – that could have otherwise sustained only one (or at the most two) facilities-based competitors – to sustain multiple service providers.

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[36] In this context a 'retail' competitor is a non-facilities based competitor providing telecommunications and information service to each home

[37] In this context the 'wholesale' market is where the infrastructure owner rents out network elements so that non-facilities based competitors can provide telecommunications and information services in the retail market

We now explore who might build and own FTTH infrastructure and the implications of different ownership scenarios for competition.

5.7.1 Private Enterprise: Private players own most of the current FTTH deployments in the United States. Many ILECs, CLECs and Cable MSOs are in the process of making fundamental choices about technology and planning deployments. Private players are expected to build the lowest cost networks and networks that facilitate as little competition as possible. It comes as no surprise that all the private FTTH deployments in the United States today are curbside PONs. Though one can imagine private players (like electricity or gas companies) playing the role of a neutral infrastructure owner, ILECs, CLECs, Cable MSOs and other overbuilders who own the fiber infrastructure are expected to be vertically integrated providing services as well. This does not augur well for services competition above the facilities layer.

5.7.2 Subscriber (or Community): There have been a few suggestions in contemporary literature [Arna01], that just as subscribers own their home networks, they should own the fiber from the home to the CO. There are in fact new housing builds where builders are contemplating building a fiber to each home where the fiber is owned by the Homeowner's Association. This greenfield deployment can lead to a much lower cost trenching can be accomplished before roads are paved. Though one can imagine subscriber ownership in greenfield contexts, it looks very unlikely in current developed residential neighborhoods. One can expect practical problems of getting all homes to participate. Even if subscribers were to build and own their fiber, there has to be special arrangements for maintenance of the fiber.

5.7.3 Local Government: The local government on the other hand looks reasonably well positioned to build FTTH infrastructure [Arna01]. Local governments of many cities have evinced strong interest in building FTTH infrastructure in order to attract hi-tech investment, and many FTTH deployments to date are municipally owned, either directly or through a municipally owned electric utility. Government ownership of FTTH infrastructure can provide the neutral platform over which the private players can provide services. In many communities the public sector is a large consumer of bandwidth, therefore it seems reasonable for the local Government

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[38] Opportunity Cost = AC + (MS)*(γ); where AC = Average Cost of production; MS = Market Share and γ = Retail Margin. The opportunity cost goes up with retail market share. Intuitively this means that the higher the retail market share of the firm, the higher the probability a UNE sale represents a lost retail customer. Conversely, in the presence of infrastructure

to build this infrastructure. The involvement of the local government can lead to an early and widespread deployment (contrary to the 'cherry picking' that the private players are expected to engage in). Local governments also have easy access to rights of ways and depending on how the project is financed can also have access to low cost capital. By limiting its activities to building, owning and maintaining the fiber, and with the private players owning the end-electronics the local government does not have to keep pace with electronics technology that is changing rapidly. Therefore a public-private strategic partnership seems like one possibility that can lead to a competitive industry structure.

5.7.4 Investor owned regulated common carrier: A final ownership possibility is that of an investor owned common carrier that is rate of return regulated. One particularly interesting case is if private players (who intend to provide service) form a consortium that builds out and owns the fiber. The involvement of private players (who intend to provide services) in the shareholding of the firm that owns the infrastructure ensures that the firm has little incentive to vertically integrate and provide services in competition with its owners. If this consortium is regulated, this alternative can also potentially lead to a viable long-term competitive market structure.

5.7.5 Migration to desired industry structure

Most telecommunications markets in the United States presently have the following fixed infrastructures: the Public Switched Telephone Network (PSTN) and the Cable infrastructure owned by the ILECs and Cable MSOs respectively. The assumption of oligopoly rents (or for some services, monopoly rents) accruing to the network owner have increased the valuation of these network assets considerably as merger and acquisition activity in this industry has duly reflected time and again. An arrangement that lowers the barriers to entry and promotes competition will have a dramatic impact on these valuations. Therefore it should come as no surprise that incumbents are likely to oppose any industry structure which reduces barriers to entry by service providers and to lobby aggressively to frustrate any migration towards such a structure. Indeed, the ILECs have successfully persuaded the FCC that they should be free of any obligation to provide UNEs over newly constructed FTTH networks (FCC03), and the FCC has a

competition (e.g. from cable) a UNE sale can increase scale economies in infrastructure, thus raising the profitability of the firm's infrastructure whether leased to retail competitors or used for the firm's own retail operations.

pending Notice of Proposed Rule Making which would relieve them from providing open access as well (FCC02) .

6 Conclusion

Today, apart from telcos, municipalities, communities and power utilities are at the forefront of FTTH deployment; mostly with the intention of creating a competitively neutral platform that other service providers can use to deliver voice, video and data services. In a market full of vendors that offer different ‘flavors’ of FTTH technology, most FTTH infrastructure builders (like municipalities and communities) face hard decisions when it comes to selecting a platform (architecture and link layer) and a vendor; the decision being especially hard since they have little or no interest (and expertise) in voice, video and data services provisioning. Our work addresses precisely that predicament: we submit that infrastructure builders should build FTTH infrastructure that is technologically and competitively neutral; where voice, video and data service providers can choose and deploy the technology of their choice to support the services they plan to offer. This paper shows that the natural monopoly is in the FTTH infrastructure only; therefore while facilities based competition is unlikely, it is feasible to have service level competition. It further shows that OFAP PON architectures not only have the lowest costs, but also are technologically and competitively neutral in that they support both UNE based competition and open access. OFAPs not only allow higher layer service providers to deploy different types of PONs with different link layers and port speeds simultaneously, but also provide an economical real option for the deployment of point to point (active star and home run) facilities as well.

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