

# **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. Consequently, though a PON supports 'open access' based competition in higher layer services like voice, data and switched digital video, it does not facilitate competition in data-link layer services or in the provision of analog broadcast video services. In complete contrast, the Home Run architecture has the highest initial (fiber related) capital cost, but permits unbundling of both the physical plant and at the logical layer. The Home Run architecture therefore supports a per subscriber choice of data-link layer services (via UNE based competition) as well as competition in higher layer voice, video and data services (via open access).

This work further identifies deployment strategies, which can facilitate physical plant unbundling at costs much lower than the Home Run architecture. Physical plant unbundling is made possible by establishing Optimal Fiber Aggregation Points (OFAPs) that aggregate multiple distribution fibers (or homes). Unbundling is achieved at the cost of longer distribution loop lengths (vis-à-vis a curbside PON). Ideally, both passive splitters and active electronics can be deployed at an OFAP. OFAP architectures further lead to higher utilization of splitter and Optical Line Termination (OLT) ports in markets that have less than 100% penetration thereby providing 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.

As a result of the FCC's recent Triennial Review decision, incumbents who invest in FTTH are not obligated to offer UNEs at regulated rates. In deploying fiber to the home, incumbents may consider it unnecessary, therefore, to adopt an architecture that enables physical plant unbundling or they may be tempted to

design the deployed fiber architecture in a way that eliminates the potential for future competition based on unbundled dark fiber elements even at negotiated rates. This paper argues why it may be desirable to have the option of deploying multiple data-link layer technologies and goes on to show that the minimum cost fiber network - taking into account the real options an OFAP provides - results in fiber layout, which is, in fact, hospitable to physical plant unbundling and Unbundled Network Element (UNE) competition. Such a fiber layout can, conceivably, support both point-to-multi-point (P2MP) PON architectures as well as point-to-point (P2P) active star and home run architectures.

While it is too soon to predict the effect of the Triennial Review on the pace of investment by incumbents in FTTH, the lack of such investment to date has led a number of municipalities and large subdivision developers to directly invest in FTTH systems. Municipalities and community associations are likely to have a greater interest in service level competition than incumbents, and therefore need to be aware of the significance of the choice of fiber layout strategies as discussed in this paper.

## **1 Introduction**

The (hitherto)<sup>1</sup> 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**

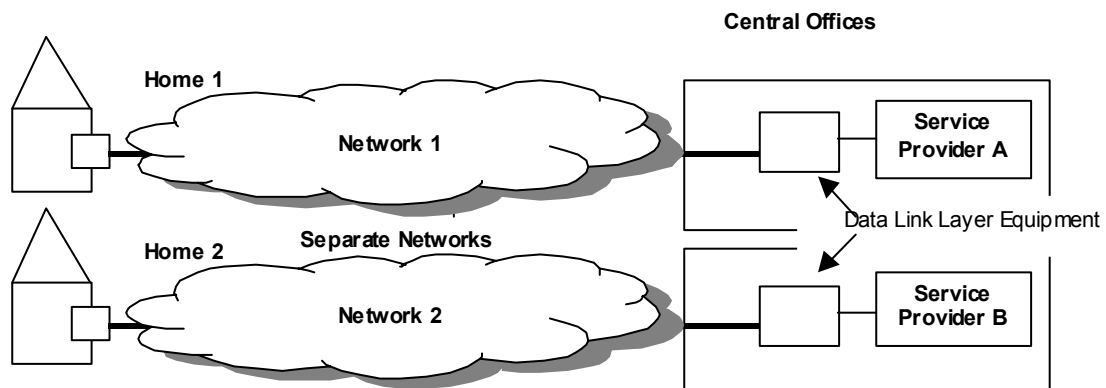
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<sup>1</sup> The FCC triennial review seems to have created a lot of interest in FTTH among the ILECs, but it remains to be seen if this interest will translate into initiatives in the near future.

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 mobile personal communications services market where each mobile telephony services provider builds, owns and maintains its network<sup>2</sup>.



**Figure 2.1 Facilities based competition**

## 2.2 Non-Facilities based Competition or Service level Competition

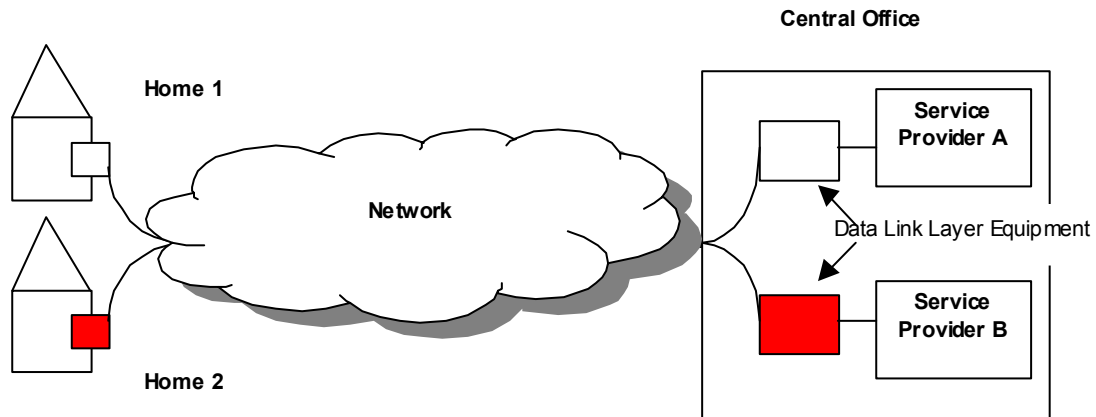
In this context, each service provider does not have a separate network but shares the resources of a common network to provide service to its customers. Depending on how resources are allocated to competitors by the network owner, non-facilities based competition can have the following models:

### 2.2.1 'Unbundled Network Elements (UNE)' based Model for Competition:

Each service provider can co-locate its data-link layer equipment at the CO and offer 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 service. For UNE<sup>3</sup> based competition to be possible, physical plant unbundling must be feasible.

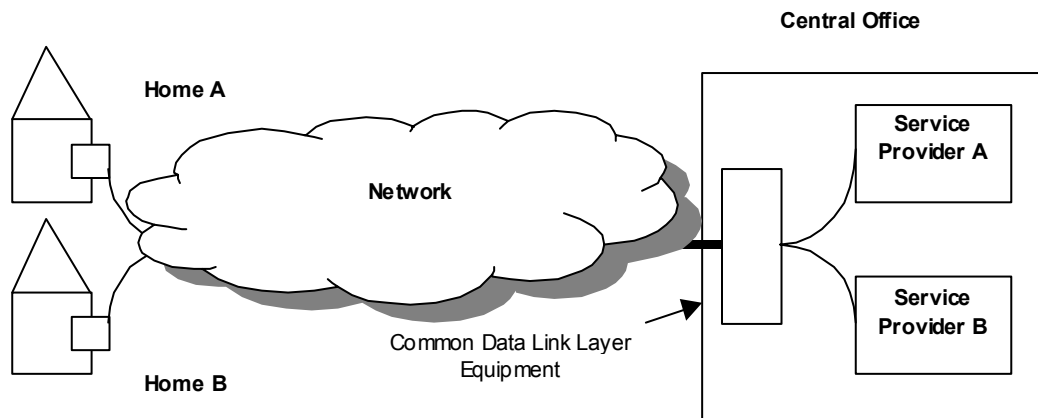
<sup>2</sup> However in order to reduce costs for 3G Wireless deployments, European mobile operators are moving to shared cell infrastructure

<sup>3</sup> 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 and data services (Figure 2.3). A typical example of this type of competition is the various ISPs that provide Internet services over a single Cable network.



**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<sup>4</sup>) and Star architectures (where many homes share one feeder<sup>5</sup> fiber through a remote node that performs switching, multiplexing or splitting - combining functions and is located between the homes served and the CO). The 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<sup>6</sup>) or a Wavelength Division Multiplexed (WDM) system (where each home is served by a different wavelength). This section examines the following FTTH architectures: (i) Home Run Fiber (ii) Active Star (iii) Passive Star (more commonly known as the Passive Optical Network or PON) (iv) Wavelength Division Multiplexed (WDM) PON.

Regardless of architecture, each feeder fiber is terminated at the Central Office (CO) on an Optical Line Termination (OLT) unit. The CO 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 (which direct traffic to the core data network) and to core video networks [Pesa02].

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, in the case of PONs and Home Run architectures, the ONU can also have 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 (1510 nm) [Pesa02]. 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 and it generally uses the 1550 nm wavelength. All FTTH models discussed here use single mode fiber [Reed92].

#### 3.1 Home Run Fiber

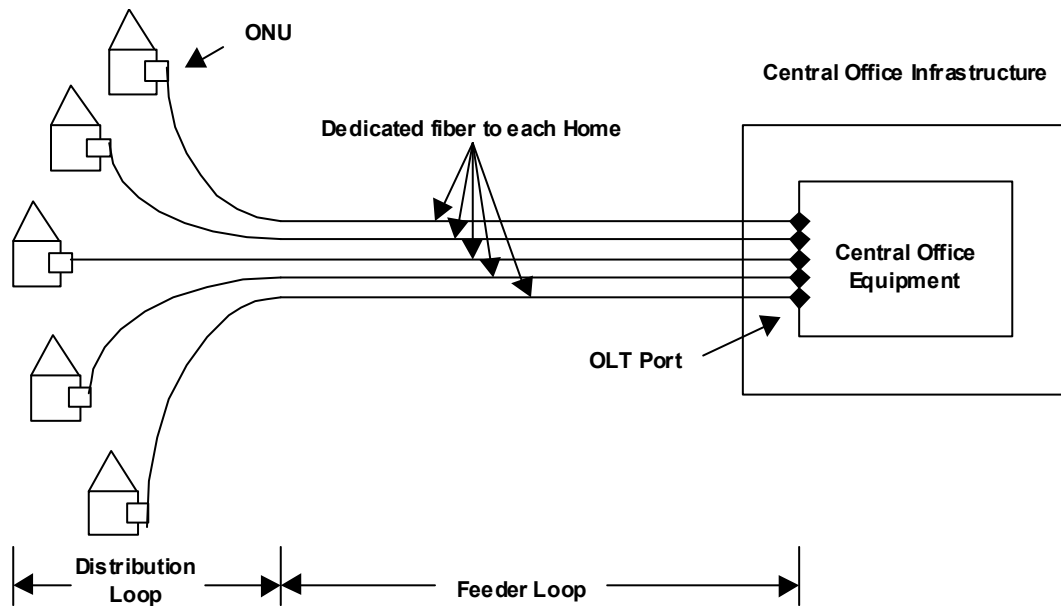
The Home Run architecture (also known as a Point-to-Point architecture or Single Star architecture) has a dedicated fiber that is deployed all the way from the CO to each subscriber premises. This architecture requires considerably more fiber and OLTs (one OLT port per home) compared to the other, shared, infrastructures [Reed92].

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<sup>4</sup> 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

<sup>5</sup> 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

<sup>6</sup> 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.



**Figure 3.1 Home Run Fiber Architecture**

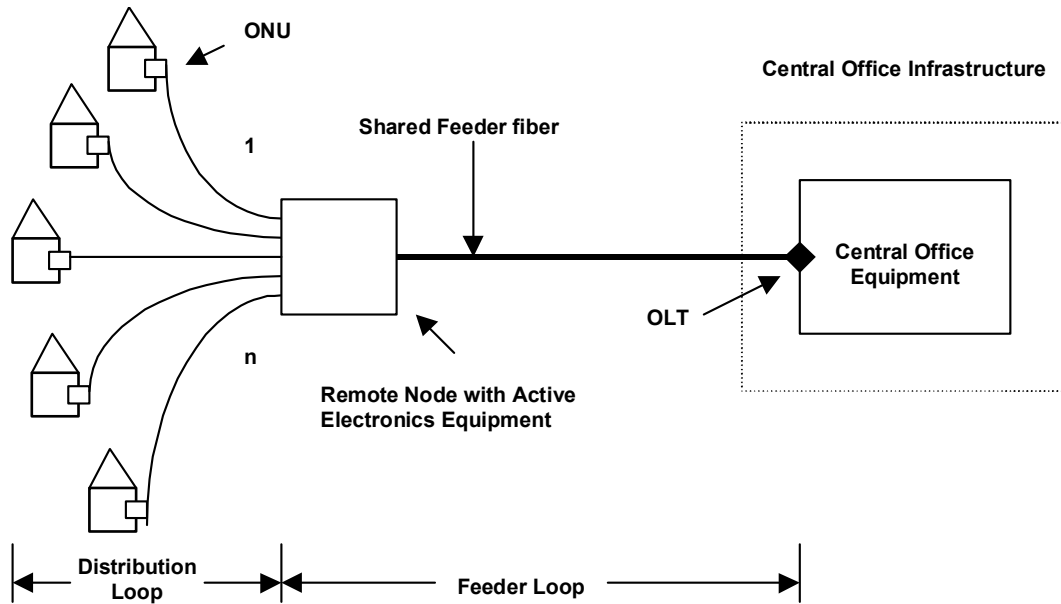
### 3.2 Active Star

A Star architecture (also known as a Double Star) is an attempt to reduce the total amount of fiber deployed and hence lower costs by introducing feeder fiber sharing. In a star architecture, 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 to a thousand homes (the split ratio) via dedicated distribution links from the remote node [Reed92].

When the remote node contains active devices such as a multiplexer (or switch), the architecture is referred to as an Active Star as the remote node needs to be powered. The Remote Node in the Active Star network has a multiplexer / demultiplexer. The remote node switches the signal in the electrical domain (to the intended recipient) and hence OEO conversions are necessary at the remote node [Reed92]. Since the feeder bandwidth is shared among multiple end points, the maximum sustained capacity available to each home – both upstream and downstream – is less with an active star architecture than with Home Run fiber. Typically each remote node in an active star architecture supports anywhere from sixteen<sup>7</sup> to a thousand<sup>8</sup> (or more) homes.

<sup>7</sup> In this case the remote switch is an environmentally hardened device and is mounted on a pole

<sup>8</sup> In this case a large cabinet containing the active electronics is deployed



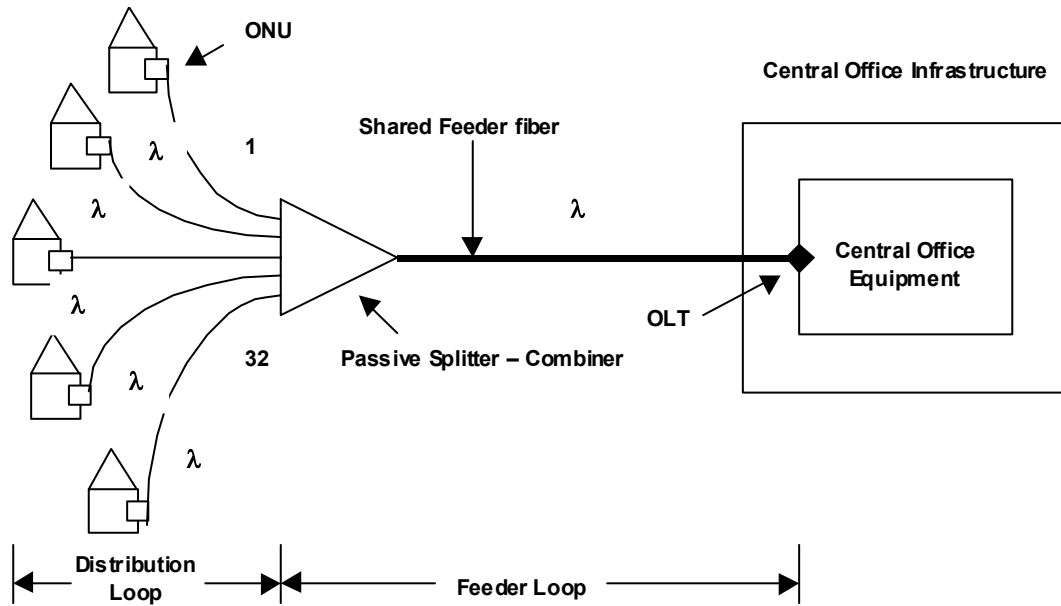
**Figure 3.2 Active Star Architecture**

### 3.3 Passive Star (Passive Optical Network – PON)

In the Passive Star network, the outside plant does not have any active electronics (and hence does not need any powering arrangements). At the remote node, a passive splitter replicates the downstream optical signal from the feeder fiber onto the (4-64) individual distribution fibers while a coupler combines optical signals from the individual homes onto the feeder fiber using. The OLT and the ONU have to support an additional ‘ranging’ media access and control protocol that allocates time slots to the ONU to transmit upstream traffic [Reed92, Pesa02].

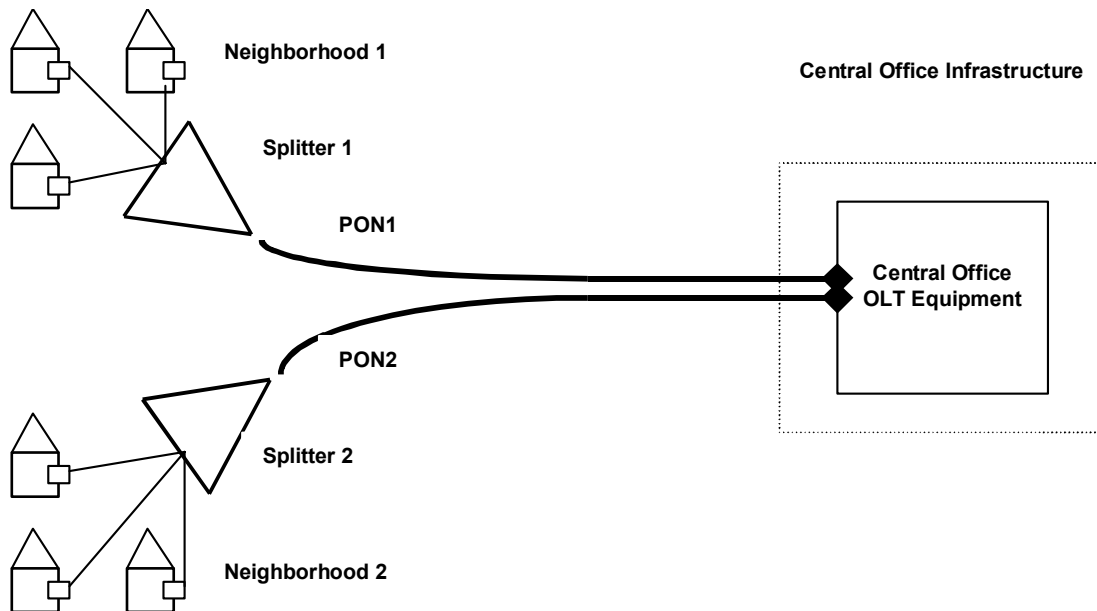
As in Home Run Fiber, in practice, most PON designs use two wavelengths: 1310 nm for upstream traffic and 1510 nm<sup>9</sup> for downstream traffic [Pesa02, Klim02] as this provides better isolation between the laser transmitters and receivers and eliminates the need for expensive beam-splitting devices [Pesa02]. Generally the 1550 nm window (1530-1565 nm) is left unused to provide a WDM overlay in the future. Many vendors now use the 1550 nm wavelength for delivering broadcast analog video [Pesa02]. As with the active star the feeder capacity is shared between multiple end points.

<sup>9</sup> The specifications produced by the Full Services Access Networks (FSAN) initiative and adopted by the ITU as standard G.983 recommends the use of 1310 nm for upstream traffic and 1490 nm for downstream traffic [Klim02]. Though ATM PON vendors like Alcatel use the 1310 nm and 1490 nm wavelengths, some EPON vendors like Vendor B prefer to use the 1310 nm and 1510 nm wavelengths for upstream and downstream traffic respectively.



**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 such that the amount of distribution fiber<sup>10</sup> is minimized. In this paper we allude to such a PON layout as the Curbside PON (Figure 3.4).

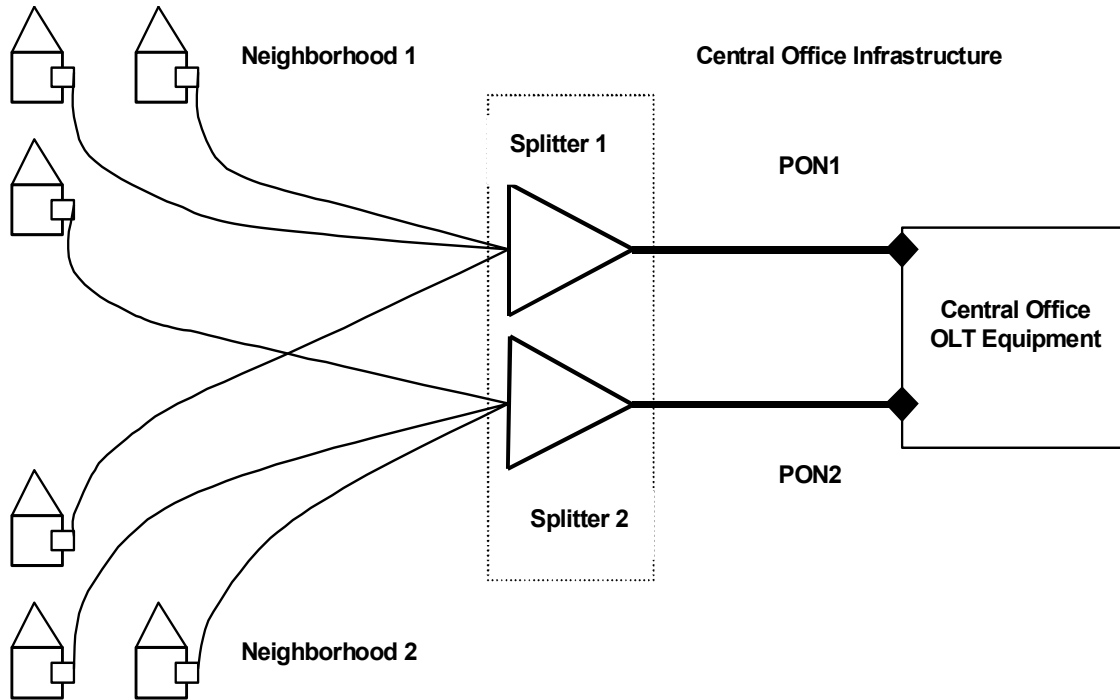


**Figure 3.4 Curbside PON deployment**

<sup>10</sup> Fiber from the splitter to each home



Notice that in a curbside PON, two OLT port have to be deployed only if 1 home in each 32 home ‘neighborhood’ takes service. Clearly, if we aggregated both splitters at one point (Figure 3.5), we would need to deploy the second OLT only after 32 out of the 64 (or 50%) homes took service.



**Figure 3.5 Fiber Aggregation Point (FAP)**

While aggregating multiple homes (or splitters) at a particular location lead to longer distribution loops (and hence more fiber related costs), they result in savings from having to pre-position fewer OLT ports.

Another strategy that could potentially reduce the number of OLT ports that need to be pre-positioned is distributed splitting. Typically in a 1:32 distributed split PON, there is a 1:8 (or a 1:4) splitter closer to the CO<sup>11</sup> 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), there by resulting in the feeder fiber and the OLT port being shared by 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 aggregation). These tradeoffs (trading off more distribution fiber or distributed splitting or both in order to save on OLT ports) are largely unknown. Given a certain expected take rate with time, one would like to know how many splitters should be aggregated at an ‘Optimal’ Fiber Aggregation Point (OFAP) and gather more insights into distributed splitting.

<sup>11</sup> In fact it can be located within the CO

### 3.4 WDM Passive Optical Networks

PONs can have multiple wavelengths as well. Though it will be sometime before there are affordable WDM PONs (if ever), some vendors are introducing products that can introduce more wavelengths on to a PON<sup>12</sup>.

Wavelength Division Multiplexing (WDM) is Coarse (CWDM) or Dense (DWDM) depending on the number of wavelengths multiplexed on to the same fiber. Vendors are of the opinion that a CWDM PON can support 3 – 5 wavelengths, while supporting more than 5 wavelengths requires a DWDM overlay<sup>13</sup>. For DWDM, the ONUs (and the OLTs) require expensive frequency stable, temperature controlled lasers<sup>6</sup>. The OLT puts all the wavelengths onto the shared feeder fiber and the splitters replicate the wavelengths to each home<sup>14</sup>.

## 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 focuses on 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 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.

It is important to emphasize that while serving a community (of 20,000 say), the service provider will find it efficient to lay sufficient fiber in the feeder<sup>15</sup> and the distribution loop to be able to support all 20,000 subscribers even if only a fraction of them initially sign-up for service. This is because the cost of trenching or making poles ready to deploy fiber is prohibitively high for one to go back and retrofit fiber as more homes subscribe to the service. However, it is assumed that the drop loop<sup>16</sup> and the Optical Networking Unit (ONU) are provisioned as users sign-up for service. Also additional line termination equipment is added at the CO, and possibly, at the Remote Node as more users subscribe to the service.

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<sup>12</sup> At the time of writing this, Vendor A has a product that can add upto 8 wavelengths to a PON

<sup>13</sup> Personal Communications with Vendor A and Vendor B

<sup>14</sup> Personal communications with Vendor A reveal that the cost of a 8-wavelength system can be as high as \$160,000. It appears that WDM PONs will be economically unviable in the near term at least. Therefore, our engineering cost model does not include WDM PONs.

<sup>15</sup> As a reminder, 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

<sup>16</sup> 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.

We have used CO data from HAI Model 5.0 A for our engineering economic model. We have chosen three COs in Pennsylvania to represent the urban, suburban, and rural scenarios<sup>17</sup>. Among other things, the HAI Model provides data on the CO area, number of clusters<sup>18</sup>, the radial distance, aspect ratio<sup>19</sup> and location of each cluster with respect to the CO, total number of homes and housing density for each cluster.

The following table provides an overview about each of the deployment scenarios:

<b>Deployment</b>	<b>Homes per sq. mile</b>	<b>Homes served per CO</b>	<b>Number of Clusters</b>
Urban	5175	16,135	23
Suburban	514	10,183	14
Rural	116	5,871	10

**Table 4.1 Deployment Scenarios**

It is assumed that each cluster is served by a dedicated feeder bundle from the CO. Also, each cluster is assumed to be laid out on a rectangular grid. The length of the feeder is calculated based on the data on radial distance and location. Lot sizes are estimated from data on cluster area, housing density and aspect ratio.

**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<sup>20</sup> 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 is a cheaper alternative. However, one needs to get access to utility owned poles and get the poles ready for such a deployment. This involves 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

<sup>17</sup> The CLLI codes for the urban, suburban and rural CO are PITBPASQ, HMSTPAHO, TNVLPATA respectively.

<sup>18</sup> In a cluster all homes are at a distance less than 18,000 feet from the center of a cluster

<sup>19</sup> Aspect ratio of the cluster is the ratio of breadth to length of the cluster

<sup>20</sup> There are newer underground deployment methods that do not require trenching. Our model assumes that trenching is a pre-requisite for buried deployments.

around on each pole and sometimes a heavily loaded pole may have to be replaced with a longer pole in order to make space for the fiber<sup>21</sup>. This activity costs anywhere between almost nothing (for a pole that is retained) to \$1,000<sup>22</sup> for each pole that is replaced.

Cost of Pole Replacement	\$1000
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<sup>21</sup>**

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

**Table 4.3 Costs of Trenching<sup>21</sup>**

**(ii) Fiber related capital costs.** This includes the cost of feeder and distribution fiber, sheath, splicing and splice enclosures. Fiber splicing is necessary in order to join two bundles of fiber<sup>23</sup> (fusion splicing) or when each fiber strand has to be connected to a splitter port (mechanical splicing). All splices are housed in splice enclosures. When a fiber is connected to a line card (or ONU), it typically requires fiber connectors<sup>24</sup>.

The number of fiber strands that constitute a Feeder fiber bundle varies with the architecture and the deployment context<sup>25</sup>. 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 <sup>26</sup>	\$25
Fusion Splice	\$5
Connector	\$20

**Table 4.4 Fiber related capital costs<sup>23</sup>**

<sup>21</sup> Personal Communications, Mr. Hal Etsell, Mountaintop Technologies, Johnstown, PA

<sup>22</sup> Personal Communications, XYZ Constructions, Pittsburgh, PA

<sup>23</sup> Splicing is required when one needs to 'splice down' a larger feeder bundle (say, of 96 strands into two smaller bundles of 48 strands). Also, splicing is required every 2 miles (Personal Communications, Corning Cable Systems).

<sup>24</sup> Personal Communications, Corning Cable Systems

<sup>25</sup> We assume that each cluster is served by a separate feeder bundle.

<sup>26</sup> 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 costs of CO infrastructure.

Cost of 7 ft patch panel rack	\$ 400
Cost of jumper cable with connector	\$20 - \$30
<b>Total Cost of terminating 728 fibers</b>	<b>\$22,600</b>

**Table 4.5 Fiber management costs<sup>23</sup>**

<b>Deployment</b>	<b>Area (ft<sup>2</sup>)</b>	<b>Real Estate Costs (\$/ft<sup>2</sup>)</b>	<b>Construction Costs (\$/ft<sup>2</sup>)</b>
Urban	4000	10	100
Suburban	4000	10	100
Rural	2000	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<sup>27</sup>**

**(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 heating, cooling and powering 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) \$800 (Large Cabinets – upto 1000 homes)
Cabinets for Active Electronics	\$6000 (Small Cabinets – 60 homes) \$10000 (Medium Cabinets – 120 homes) \$20000 (Large Cabinets – 240 homes) \$30000 (X Large Cabinets – 480 homes) \$50000 (XX Large Cabinets – 960 homes)
Concrete Pad	\$700
RT real estate	\$4000 (Urban); \$3000 (Suburban); \$2000 (Rural)
Capital cost of Powering	\$1500 per RT location

<sup>27</sup> Personal Communications, Grant County PUD, Washington State.

**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. This engineering model assumes Ethernet as the data-link layer technology. 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. 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<sup>28</sup>. Different equipment manufacturers make ONUs which have different interfaces and operate at different speeds. In our cost model we use the estimated cost of an ONU<sup>29</sup> that supports (on the customer side) a 10/100 Mbps twisted copper interface (10/100 base T) and 2 POTS lines for all the architectures. 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<sup>30</sup>. The Remote Node in the Active Star architecture has 100 Mbps optical ethernet ports that are housed in the cabinets. We have assumed SONET to be the technology for inter-CO transport. Also, the CO equipment switches video and hence switched digital video (and not analog video) is assumed to be delivered.

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

<b>Equipment Description</b>	<b>Cost</b>
Rack	\$2000
Shelf (5 shelves per rack)	\$1000
Point to Point Ethernet Line card (20 cards per shelf; 24 ports per card; 1 home per port)	\$6500
EPON Line card (20 cards per shelf; 4 ports per card; 32 homes per port)	\$16000
Control Card (1 card per shelf)	\$3500
OC48 Interoffice SONET transport card	\$8000
IP video card (10,000 streams per card)	\$6500
P2P 100 Mbps Fast Ethernet ONU	\$350
EPON 1 Gbps ONU <sup>31</sup>	\$500

**Table 4.9 FTTH networking equipment summary<sup>28</sup>**

<sup>28</sup> A typical example is the Cisco Catalyst 4000 series of switches with 100 FX Fast Ethernet ports

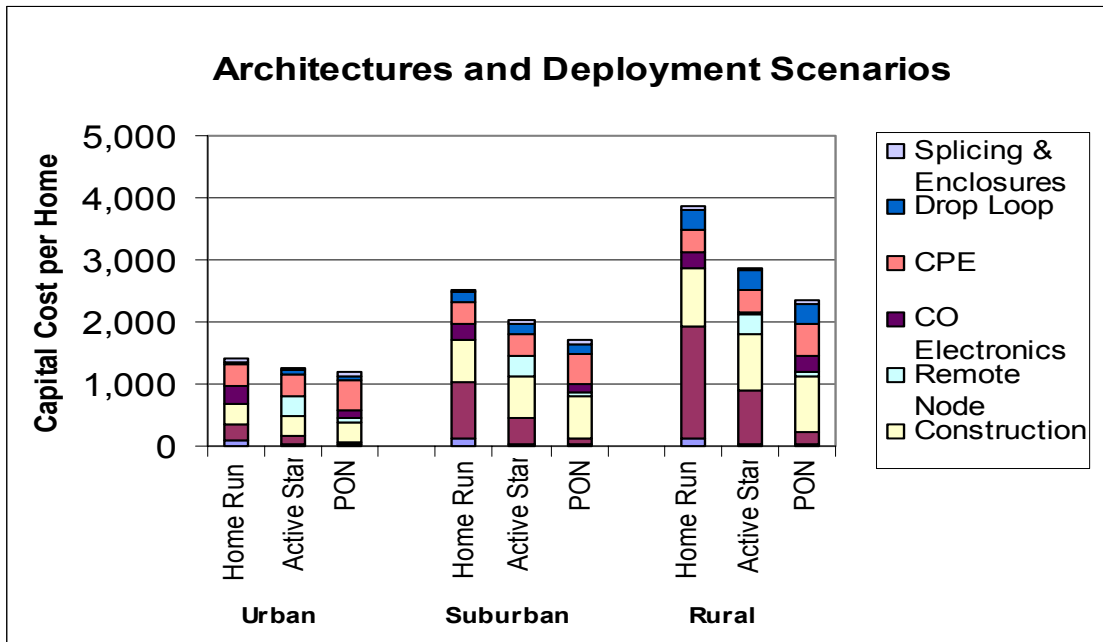
<sup>29</sup> We have come up with cost estimates of networking equipment after detailed discussions with senior technical and management staff at Vendor A, Vendor B, Vendor C, Vendor D, Vendor E and Vendor F. For reasons of non-disclosure we cannot provide pricing information for products of any specific company.

<sup>30</sup> 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.

<sup>31</sup> 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.

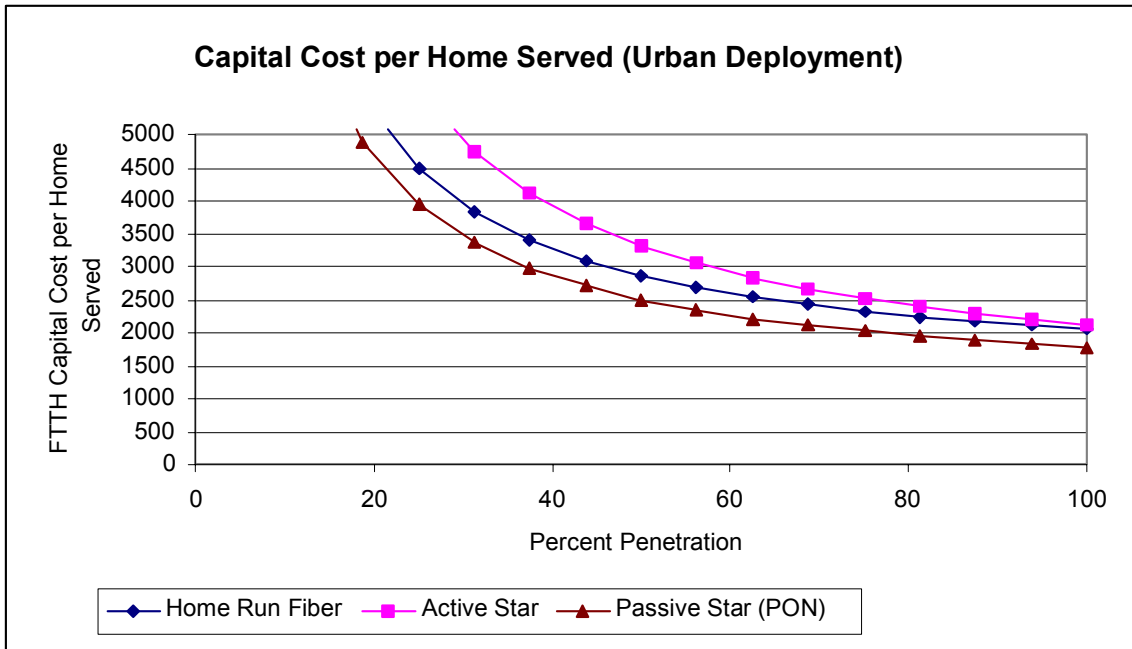
## 4.2 Cost Model Results

The Capital Cost per Home Passed for the Home Run Architecture, Active Star and the PON architecture for each of the deployment scenarios for a community being served out of one CO is shown in the following figure:



**Figure 4.1 Breakdown of Capital Cost per Home for FTTH architectures**

The Capital Cost per Home Served depends quite heavily on the penetration achieved. The following figure shows the Capital Cost per Home Served for the three FTTH architectures for different penetration levels: Home Run Fiber, Active Star Architecture and a Curbside PON for two deployment scenarios: Urban and Rural.



**Figure 4.2 Capital Cost per Home Served for an Urban deployments<sup>32</sup>**

Clearly, FTTH is a decreasing cost infrastructure. This is mainly due to two reasons: (i) making poles ready (or trenching) is a huge fixed cost, and (ii) in serving a community all the fiber in the feeder and distribution loops has to be pre-positioned regardless of the number of homes that eventually subscribe.

Also, for our modeling scenarios, 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 \$ 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. Therefore in the context of Rural deployments, we see that the Cost per Home Passed (and Served) is much higher for a Home Run architecture (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)<sup>33</sup> for penetration levels less 100%.

<sup>32</sup> The curve for the WDM PON lies outside the scale chosen for all the plots

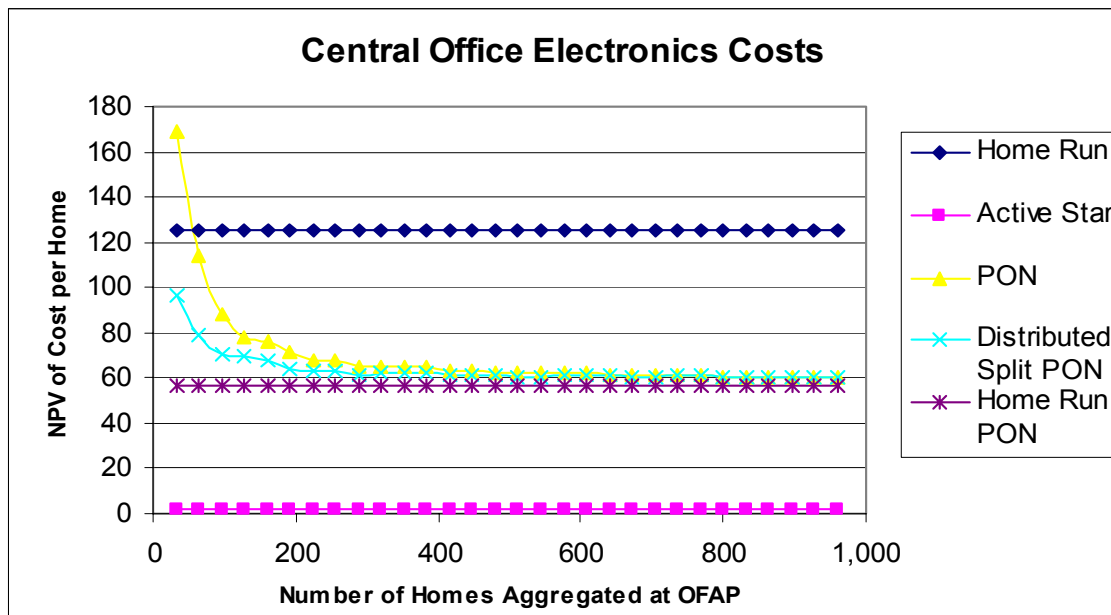
<sup>33</sup> The estimation of the number of OLT ports for a FAP PON requires elementary probability theory. We present our approach to this estimation exercise in Appendix 1.



Architecture	No. of Splitters Aggregated	Penetration				
		20%	40%	60%	80%	100%
Curbside PON	1	199	199	199	199	199
FAP PON	2	101	101	199	199	199
FAP PON	4	52	98	154	188	199
FAP PON	8	32	88	132	171	199
FAP PON	16	32	86	126	164	199
FAP PON	32	30	85	122	162	199

**Table 4.10 Number of OLT ports required for different penetration levels (Urban deployment)**

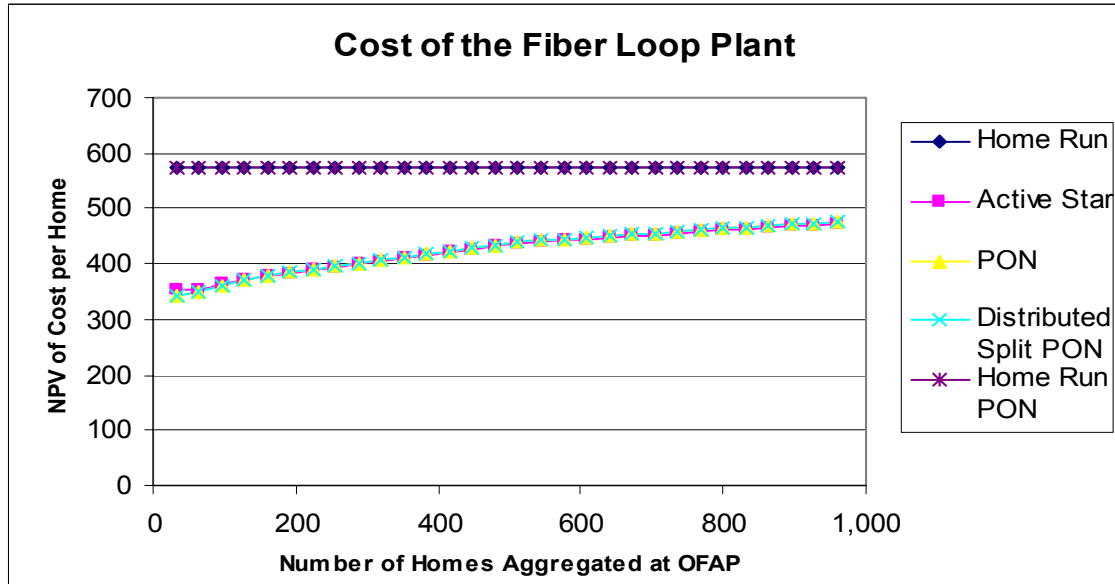
The PON splitter that fills up the last in a particular Fiber Aggregation Point (that has multiple splitters) serves less than 32 homes. Two such splitters (belonging to two different FAPs) that serve less than 16 homes (but more than 8) can be served by the same OLT port through a 1:2 splitter placed in the CO. Similarly four splitters that serve less than 8 homes (but more than 4 homes) can be served by the same OLT port through a 1:4 CO splitter. Clearly, distributed splitting further reduces the number of OLT ports deployed (Figure 4.3).



**Figure 4.3 Central Office Capital Cost per Home (Urban deployment)<sup>34</sup>**

<sup>34</sup> A 'Home Run PON' is an architecture that has a dedicated point-to-point fiber from the CO to each home. However, each OLT port is shared between 32 homes by a splitter located at the CO. While the architecture is fiber rich, among all PON architectures, this requires the minimum number of OLT ports to be prepositioned.

The savings in the Central office however come at a cost: longer distribution loop lengths. As we aggregate more splitters (while fewer OLT ports need to be pre-positioned), 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.



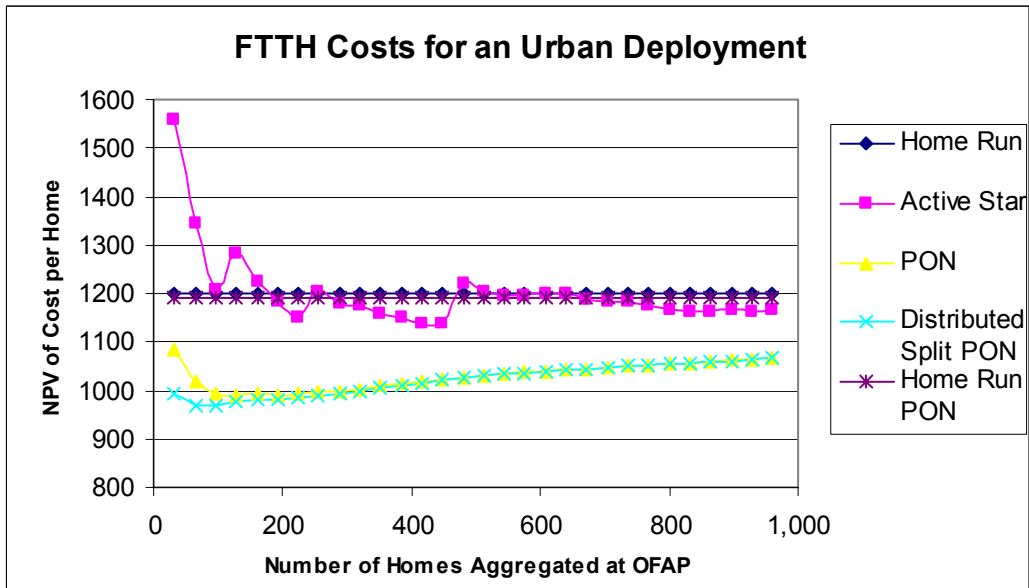
**Figure 4.4 Increase in Fiber related Capital Costs per home as distribution loops are lengthened (Urban deployment)**

**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 in FAP design. Obviously, the up take of voice, video and data services will occur gradually over time. Since FAP (and distributed split) architectures vastly 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. Figures 4.5 – 4.6 show that even for an optimistic take-rate<sup>35</sup> it is optimal<sup>36</sup> to aggregate about 192-224 homes (6-8 splitters) in an urban deployment and 96-128 homes in a rural deployment. 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. Note that if one further resorts to distributed splitting (in addition to aggregation), the costs are even lower provided the splitter ports can be ‘moved’ costlessly<sup>37</sup> between the Central Office and the OFAP.

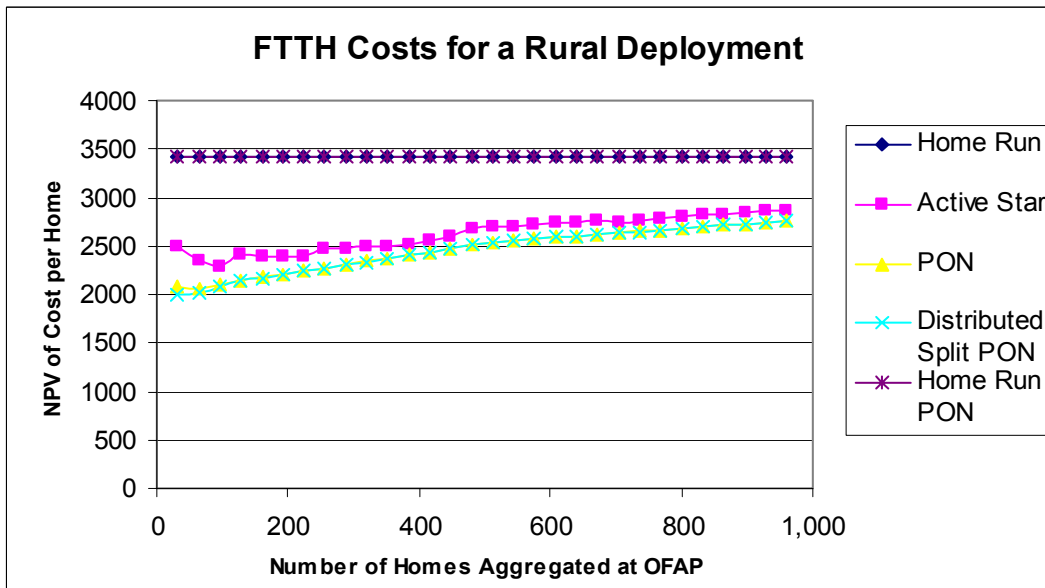
<sup>35</sup> The optimistic take rate scenario assumes that we have 30% of homes taking service by year 5 and 70% of the homes taking service by year 10.

<sup>36</sup> Aggregating 192-224 homes leads to the lowest cost fiber layout

<sup>37</sup> In distributed splitting, we deploy splitters are deployed in the CO and the OFAP. Splitters have split ratios of 1:2, 1:4, 1:8 and 1:32. So that the number of OLT ports deployed according to figure 4.5, feeder fibers need to be constantly switched from one splitter to another. Also, splitters need to be constantly moved from the CO to the OFAP. All this imposes costs, which are very difficult to estimate, but considered to be significant.



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



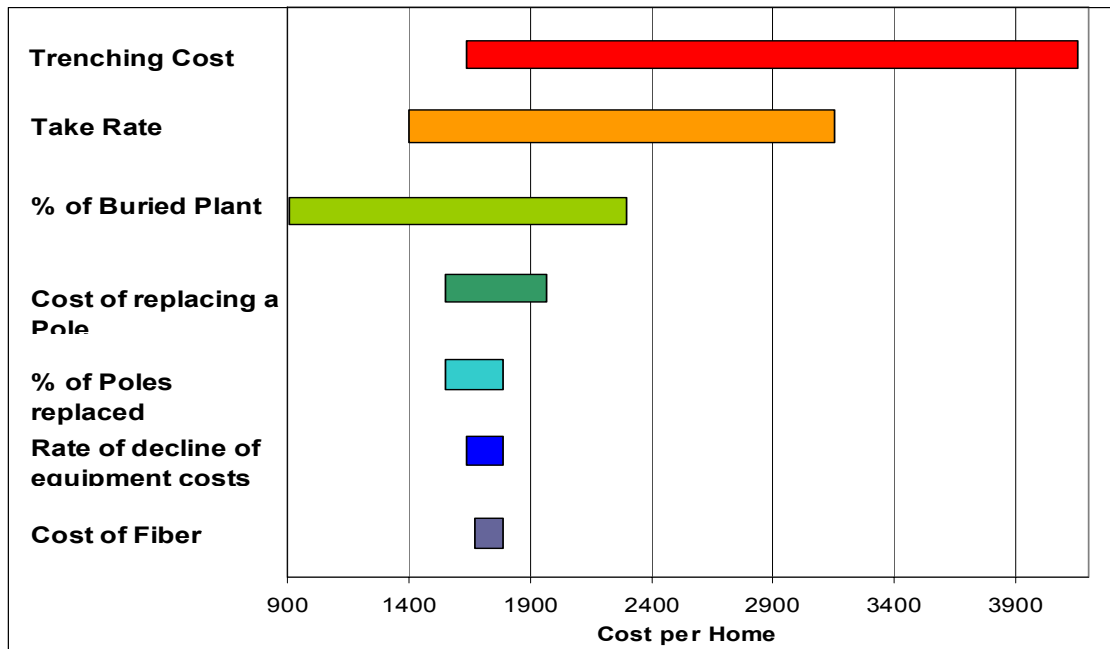
**Figure 4.6 NPV of Total Cost per Home for Rural deployment for an optimistic take-rate**

**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 near 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 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 to serve (presumably) fewer high bandwidth customers<sup>38</sup>. Therefore a service provider that deploys a BPON<sup>39</sup> today can gradually phase in a GPON<sup>40</sup> when that becomes available. Extending this idea further, a service provider can now simultaneously deploy different link layers. 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<sup>41</sup>. Finally, service providers can not only choose to simultaneously deploy incompatible PON products supplied by different vendors but can also deploy a point-to-point architecture by (i) placing hardened electronics in the splitter cabinet or on the pole (active star architecture) or (ii) patching a feeder fiber to a distribution fiber to provide point-to-point service out of the central office (home run architecture).

#### 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 deployment**

<sup>38</sup> For example, in an OFAP that has 6 splitters (or serves 192 homes), 5 splitters can continue to serve customers with older technology, while one splitter (and the corresponding OLT port) can serve customers with newer technology. A second OLT port needs to be upgraded to the newer technology only when more than 32 customers (out of 192) request the newer technology. Without an OFAP, all customers will have to migrate to the newer technology at the same time.

<sup>39</sup> A BPON has a downstream bandwidth of 622 Mbps and a 1550 nm wavelength overlay

<sup>40</sup> A GPON has a downstream bandwidth of 1.2 Gbps or 2.4 Gbps

<sup>41</sup> 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. In fact, one can also deploy a PON and an Active Star network simultaneously by deploying hardened electronics in the splitter cabinet.

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 to \$100 per feet. From figure 4.7, we see that the cost per home in an FTTH deployment is probably the most sensitive to trenching costs. For a PON architecture, a variation in trenching costs can make the cost per home vary by as much as \$250<sup>42</sup>. 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 Model for Competition in FTTH and issues in Industry Structure**

We now define 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).

### **5.1 Models for Competition in FTTH**

Competition in FTTH can be:

**5.1.1 Physical Infrastructure based competition.** It goes without saying that facilities based competition is technically viable in FTTH as it is in all telecommunications industries.

**5.1.2 Data link layer based (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.

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<sup>42</sup> Therefore, wherever possible, it is desirable to do a fully aerial deployment

**5.1.3 Unbundling at the Optical Layer:** There are two models for Optical Layer based competition:

**(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 service provider OLT. Under this arrangement, at the most two or three<sup>43</sup> 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. As a consequence of the fact that single wavelength PONs and Active Star networks do not support Wavelength based competition, competition in broadcast analog (or digital) video is not possible in either of these architectures.

**(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 PON and Active Star architectures do 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. 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.

DWDM overlays are economically infeasible today in the access space as it costs as much as \$10,000 to add a wavelength to an existing PON<sup>44</sup>. We do not consider Optical layer based competition economically feasible in FTTH, as WDM PONs will not be economically viable in the near future and hence close the discussion on WDM PONs and wavelength based competition at this point.

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<sup>43</sup> 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.

<sup>44</sup> Personal Communications, Vendor A

**5.1.4 Network (and higher) layer based (Open Access based Model of 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 ISP can wholesale transport from the data link layer provider and resell 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 ISPs and can select an ISP on demand using switching / routing technology provided by the data-link provider. This is similar to today's dialup ISP access model. It requires technology such as Redback's Subscriber Management System, and / or possibly PPoE to handle layer 2 switching [DONN00].

This model of competition is supported by all the FTTH architectures. The following table summarizes to what extent each of the architectures facilitate competition in FTTH.

<b>Competition</b>	<b>Home Run</b>	<b>Active Star</b>	<b>Curbside PON</b>	<b>WDM PON</b>
<b>Optical Layer</b>	Easy	Hard	Hard	Easy
<b>Data Link Layer</b>	Easy	Hard	Hard	Easy
<b>Higher Layers (Voice, Switched Video, Data)</b>	Easy	Easy	Easy	Easy
<b>Broadcast Video</b>	Easy	Hard	Hard	Easy

**Table 5.1 Architectures and Competition**

## **5.2 Why is UNE based Competition preferable to ‘Open Access’ based Competition?**

‘Open Access’ based 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. The primary disadvantage of this is the fact that all services have to run over the common data link layer selected by the network owner, even though there may be some customers who prefer an asynchronous transfer mode (ATM) data link layer and others who prefer Gigabit Ethernet technology at the data link layer.

The lack of competitive provisioning of data link layer services may not only limit the evolution of data link layer technology, but 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 cannot offer analog broadcast video services.

Further, the natural monopoly is in the physical infrastructure; lack of UNE based competition extends the monopoly to the link-layer (or transport). UNE based competition leads to competitive provisioning of data link layer services and creates a competitive market for transport services. Finally, it does not seem as easy to police the quality of service provided to each of the competitors who have ‘open access’ as it is to monitor quality of service provided to those who have rented UNEs.

We would further like to point out that link layer competition is not just about ATM and Ethernet. A 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 different flavors of PONs (APON, EPON, BPON and GPON) with different upstream and downstream capacities and split ratios. It is conceivable that competitors may even provision P2P ethernet (100 Mbps or 1 Gbps to the home) from the splitter cabinet using hardened electronics.

### **5.3 Economic viability of Competition in FTTH**

**5.3.1 Facilities based Competition.** Though clearly FTTH is a decreasing cost infrastructure, in the absence of a model for operations costs, it is difficult to say whether it is a natural monopoly industry or not. However looking at the capital cost curves it seems likely that it will be economically most efficient for one service provider to serve a particular community. Huge 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 monthly margin is about \$65 per subscriber<sup>45</sup>. 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<sup>46</sup> 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 less attractive one can imagine that there will be only one firm even in the long run. Therefore, though it is difficult to say from our cost curves whether FTTH is a natural monopoly industry, facilities based competition looks very unlikely (at least in the foreseeable future) in this industry.

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<sup>45</sup> 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

<sup>46</sup> It is reasonable to assume that private players expect payback time horizons of 5 years or less and IRRs of 20% and more



**5.3.2 OFAPs and Data Link Layer Competition.** A curbside single wavelength PON has the most economical fiber lay out but supports only logical layer unbundling. The inability of a curbside PON to support UNE based competition arises from the fact that all 32 homes on one splitter (and in one neighborhood) have to be served by the same OLT port and hence, by the data-link layer service provider and technology.

The advantage of an OFAP architecture over a curbside PON is that though all homes on the same splitter have to be served by the same data-link layer, the aggregation of many splitters does not require all homes served by the same splitter to be in the same neighborhood. Our engineering cost model results shows that aggregating 6-8 splitters in one location (in the outside plant) results not only in the least cost architecture, but also in an architecture that is competitively neutral (i.e. supports 6-8 data-link layer service providers and multiple voice, video and data service providers). Aggregating too few splitters not only raises costs but may also preclude some subscribers from accessing some providers.

### **5.3.3 The Cost of Data-Link layer Competition**

Clearly, if there were multiple link-layer service providers, the savings from deferring the investment in OLT ports will be partially 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. Efficiency gain from competition comes at a cost: the cost of pre-positioning all OLT ports instead of a few that need to be provisioned under monopoly. The cost of competition depends on the extent to which investment in OLT ports can be deferred. If the take rate is high, the cost of competition is expected to be modest. In the event of low take rate, fewer competitors can be expected to realize the scale economies of fully utilized OLT ports and hence competition itself is likely to be a casualty.

### **5.3.4 Competition at Higher Layers**

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 appropriate to mandate data-link layer providers to provide 'open access' to ISPs and other higher layer service providers.

## **5.4 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

**5.4.1 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 significantly 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.

**5.4.2 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<sup>47</sup>. Experience from the local telephony industry<sup>48</sup> indicates that a vertically integrated entity that owns the infrastructure and provides services is unlikely to emerge as an efficient, cost-based supplier of network elements to retail<sup>49</sup> competitors. 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

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<sup>47</sup>Fiber infrastructure denotes the Optical Fiber cable, remote nodes and the CO

<sup>48</sup> Charles H. Helein, "A Call to Arms to Local Competitors", <http://www.clec-planet.com/forums/heleinjune14.html>

<sup>49</sup> In this context a 'retail' competitor is a non-facilities based competitor providing telecommunications and information service to each home

against rivals in the wholesale market<sup>50</sup>. 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<sup>51</sup>. 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.

**5.4.3 Desired Industry Structure to enable 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) physical network(s) – to sustain multiple service providers.

## 5.5 Ownership Alternatives

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

**5.5.1 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 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 evidently will not augur well for competition.

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<sup>50</sup> 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

<sup>51</sup> Opportunity Cost =  $AC + (MS) \cdot (\gamma)$ ; where AC = Average Cost of production; MS = Market Share and  $\gamma$  = 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 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.

**5.5.2 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. This can lead to a much lower deployment cost as it saves on trenching costs. 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 have to be special arrangements for maintenance of the fiber.

**5.5.3 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. Government ownership of FTTH infrastructure can provide the neutral platform over which the private players can provide services. Many communities the public sector is a large consumer of bandwidth, therefore it seems reasonable for the local Government 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 resort to). 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 fast. Therefore a public-private strategic partnership seems like one possibility that can lead to a competitive industry structure.

**5.5.4 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 provides services. If this consortium is regulated, this alternative can also potentially lead to a viable long-term competitive market structure.

## **5.6 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 our model industry structure and politically try to frustrate any migration.

## 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 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 it is also conceivable that OFAPs will allow higher layer service providers to deploy point to point Ethernet, T-1 circuits, ATM virtual circuits and SONET circuits as well.

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## Appendix: Estimation of OLT ports for single and distributed split PONs with OFAPs

For a deployment of  $N$  homes, in a curbside PON, the number of OLT ports that need to be pre-positioned<sup>52</sup> =  $\lceil N/32 \rceil \dots$  (1)

Assume that each OFAP aggregates  $n$  ( $n > 32$ ) homes. Therefore, the number of splitters aggregated at the OFAP =  $n/32$  and the number of OFAPs =  $\lceil N/n \rceil$

Assume that in the  $i$  th year, the fraction of homes that take service is  $h_i$ , therefore the probability that a home takes service is  $h_i$

### A.1 For Single split PONs

The number of homes that take service in each OFAP =  $nh_i$

Number of OLT ports required per OFAP =  $\lceil nh_i/32 \rceil$

Total number of OLT ports that are required to serve the fraction

$$h_i = \lceil N/n \rceil * \lceil nh_i/32 \rceil \dots (2)$$

### A.2 For Distributed split PONs

The probability that exactly  $r$  homes take service in an OFAP of  $n$  homes is given by

$${}^n C_r h_i^r (1 - h_i)^{(n-r)} \dots (3)$$

In a particular OFAP, all but the PON that fills up the last will have 32 homes. Therefore (from (2)), in a distributed-split architecture, there will be  $\lceil N/n - 1 \rceil * \lceil n * h_i / 32 \rceil$  PONs (and hence OLT ports) that will be completely filled. From (3), we can find the probability that (i) there are less than 8 homes on the PON that fills the last, (ii) there are 9-16 homes on the PON that fills the last and (iii) there are 17-32 homes on a PON that fills the last. Let the probabilities be  $p_8$ ,  $p_{16}$  and  $p_{32}$  respectively. Since there are  $\lceil N/n \rceil$  number of OFAPs, there will be  $\lceil p_8 * \lceil N/n \rceil \rceil$  PONs that have less than 8 homes,  $\lceil p_{16} * \lceil N/n \rceil \rceil$  PONs that have between 9 - 16 homes and  $\lceil p_{32} * \lceil N/n \rceil \rceil$  PONs that have between 16 - 32 homes. Now, four PONs that have less than 8 homes can be served by one OLT port through a 1:4 splitter placed in the CO; similarly two PONs that have between 9 and 16 homes can be served by one OLT port through a 1:2 splitter placed in the CO.

Therefore, the total number of expected OLT ports required for a distributed split PON =

$$\lceil N/n - 1 \rceil * \lceil n * h_i / 32 \rceil + 1/4 \lceil p_8 * \lceil N/n \rceil \rceil + 1/2 \lceil p_{16} * \lceil N/n \rceil \rceil + \lceil p_{32} * \lceil N/n \rceil \rceil \dots (4)$$

<sup>52</sup> The function  $\lceil x \rceil$  gives the smallest whole number greater than or equal to  $x$