Total Cost of Ownership Analysis of Ethernet FTTH vs. GPON Architectures

Network Strategy Partners, LLC

MANAGEMENT CONSULTANTS TO THE NETWORKING INDUSTRY

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Executive Summary

Fiber optic distribution systems are gaining favor for delivering Triple Play and Carrier Ethernet service offerings. Optical cabling and associated cable management systems such as distribution frames and splicing methods have been perfected and made scalable for large scale deployments. Controversy remains, however, on the best technology for lighting the fiber and delivering services. This paper examines the Total Cost of Ownership tradeoffs between Ethernet FTTH (E-FTTH) and GPON (Gigabit Passive Optical Network).

The TCO of three wire center types is analyzed—urban, suburban and rural. This is done to model the varying cable lengths and dispersion of equipment across representative topologies with their respective demographic variations. The analysis is comprehensive. It includes all elements of the Optical Distribution Network (ODN)—cables, structures, and outside plant apparatus, Optical Network Terminal (ONT), and Central Office equipment—Ethernet Switch, Optical Line Terminal (OLT), and Aggregation Router. All cost elements associated with each of these network elements also are accounted for including installation costs, equipment costs, and associated operations expense.

The analysis finds that protection of the investment in the ODN is a top priority. It accounts for a large majority of Total Cost of Ownership and has a 30+ year life. The analysis also shows that service flexibility and the ability to accommodate increasing bandwidth requirements are essential to achieving low TCO.

The E-FTTH architecture provides substantial protection of the ODN asset in the following ways:

- The E-FTTH architecture supports any Ethernet-based service with a bandwidth of 1 – 100 Mbps with no changes required to the ODN or EONT. Changes are minimized within each Ethernet Switch chassis because the chassis has a 40 Gbps capacity that is four times that of the OLT.

- In the case of an increase of CIR from 20 Mbps to 50 Mbps for 30% of all customers in the 4th year the following TCO results are found for the connectorized cabling method:
    - E-FTTH has 5% higher TCO than GPON for the urban wire center
    - E-FTTH has 4% lower TCO than GPON for the suburban wire center
    - E-FTTH has 11% lower TCO than GPON for the rural wire center

- E-FTTH has no effect on the ODN or Ethernet Switch ODN port configurations when CIR changes while GPON has the following impacts:
    - OpEx is incurred for rearranging splitters
    - CapEx is incurred for additional:
        - Splitters
        - Fiber in Feeder Cables
        - OLT ports

        - OLT chassis
        - Ports on Aggregation Routers
    - OpEx associated with the CapEx additions increases

- E-FTTH scales better than GPON. Since bandwidth demand has grown exponentially for decades, this scaling advantage will be critical over the 30+ year life of the ODN.

A second element of the analysis compares a connectorized cabling method with a fixed method where the ODN is built as a single project upon project initiation. TCO is calculated for the case where a constant CIR/ONT is maintained over the five-year study period. The findings include:

- GPON achieves lower TCO when using a connectorized cabling method and CIR/ONT is low. E-FTTH crosses over to be the low cost alternative when CIR/ONT exceeds 60 Mbps. This effect is due to the higher bandwidth capacity (and higher per chassis cost) of the Ethernet Switch used by E-FTTH.

- E-FTTH maintains a consistent TCO advantage over GPON when the fixed cabling method is used. It provides 1% to 7% lower cost at 20 Mbps CIR/ONT increasing to 17% to 42% at 80 Mbps CIR/ONT.

Taken as a whole the connectorized cabling method used with E-FTTH provides the lowest TCO when there are significant market risk, customer churn and rapid growth in bandwidth requirements. GPON is attractive when used with the connectorized cabling method, demand is not volatile and CIR/ONT is likely to remain below 50 Mbps for at least five-years.

The study also shows that the fixed cabling method is attractive when the wire center is quite stable and take-up rates are likely to be near 100%. The connectorized cabling method is attractive in those situations where both take-up rates and bandwidth levels are uncertain and volatile. These tradeoffs make the fixed method attractive for such projects as “Greenfield” construction in a high-income housing development and the connectorized approach suitable to an incumbent telecom vendor in its existing franchised territory.

Introduction

Fiber-optic distribution systems are gaining favor for delivering Triple Play services to residences and Carrier Ethernet services to enterprise establishments. The technical challenges of designing cable, optical distribution frames, and outside plant apparatus that is easy to install and manage have been met. In addition, construction methods for cable installation and splicing of optical fibers have been perfected to cost effectively support large scale deployments. Controversy remains, however, in choosing the best technology to light the fiber and deliver services. This paper examines the Total Cost of Ownership (TCO) tradeoffs between an Optical Distribution Network (ODN) that uses Ethernet FTTH (E-FTTH)[1] systems versus one using GPON[2].

The TCO analysis is performed for three wire center types—urban, suburban and rural. Analysis across differing wire center types is essential. The costs to construct the ODN[3] and reconfigure it as demand conditions change account for the majority of the cost of a fiber-optic distribution system. These costs in turn depend on the choice of the electro-optical system—E-FTTH or GPON. Consequently, all of the fiber-optic facilities, associated cable management equipment, electronics located in the Central Office and Optical Network Termination (ONT) must be accounted for in making the tradeoff analyses. It is equally important that all TCO categories be included. Operations Expense (OpEx) categories analyzed include:

- Engineering, Facilities, and Installation (EF&I)
- Capacity Management
- Network Upgrades & Patches
- Network Care
- Testing and Certification Operations
- Testing and Certification Capital
- Training
- Service Contracts
- Sparing Costs
- Floor Space Cost
- Power Cost
- Cooling Cost
- Network Management Equipment & Software
- Rearrangement Expense

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[1] Ethernet FTTH is classified as EP2P—Ethernet over Point-to-Point fiber by the FTTH Council. This paper analyses a design that employs 100BASE-BX 100 Mbps links transmitted over an individual single-mode fiber for up to at least 10 km as specified by IEEE 802.3ah.
[2] GPON—Gigabit Passive Optical Network is defined in ITU-T G.984. This paper analyzes an implementation with 2.5 Gbps bandwidth split over no more than 32 network terminations (ONT).
[3] The installation costs associated with cable structures, cable and outside plant apparatus are estimated to be as much as 68% of total capital expense.

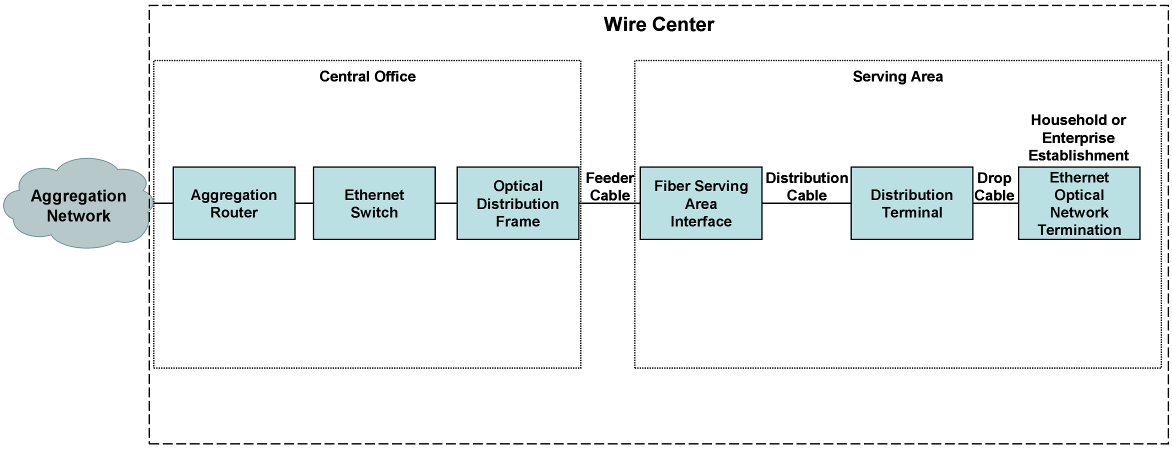
TCO is calculated by characterizing the number of residential households and enterprise establishments[4], the location of households and establishments, and the area served (Square Miles) of each wire center. Numbers of subscribers are calculated using projected take up rates for residential Triple Play and enterprise Carrier Ethernet services over a five-year study period. Traffic requirements are projected by applying a bandwidth per subscriber rate to the projected number of subscribers. Once these requirements are established a network design is then created for each architecture encompassing the ODN, ONT, and Central Office electronics. Once equipment quantities are known CapEx and OpEx are calculated using equipment prices and labor rates typically experienced by a large service provider[5].

The subsequent sections describe the E-FTTH, GPON and respective ODN architectures, the wire center characterizations and the TCO analysis results.

Ethernet FTTH Architecture

Figure 1 is a schematic of Optical Distribution Network with E-FTTH electronics.

Figure 1
Ethernet FTTH Architecture



The schematic shows all of the cable, outside plant facilities and electro-optical equipment used to connect a residence or enterprise establishment to the aggregation network. The Ethernet Optical Network Termination (EONT) is attached to the outside of a single unit household or in a telephone equipment closet or panel in the case of multiunit households or enterprise establishments. The EONT uses industry standard Ethernet technology to connect to the subscriber's internal network and the 100BASE-

[4] An enterprise establishment refers to a single physical place of business. For example, this could be a three person law office in a high-rise office building or a single business that occupies an entire building such as a gas station. For this analysis the size of the enterprise is not considered since the gas station may be part of a multi-national oil company and the law firm may be a single proprietor enterprise—they both place similar requirements on the ODN.

[5] This includes the very substantial equipment price discounts that large service providers are able to obtain through their buying power.

BX standard to connect to the ODN. A fiber-optic drop cable connects the EONT to the Distribution Terminal (DT). The Distribution Terminal provides a connection point for each Drop Cable fiber to be connected to a separate fiber in the Distribution Cable. Two types of Distribution Terminals are used. Single family Distribution Terminals accommodate up to four households and multi-unit Distribution Terminals accommodate up to either 24 households or 24 enterprise establishments. The Distribution Cable provides the connection between the Distribution Terminal and the Fiber Serving Area Interface. Separate Distribution Cables are used for each customer type—Single Unit Household, Multi Unit Household, Enterprise Establishment. The Fiber Serving Area Interface (FSAI) is a fiber distribution frame used to connect fibers in the distribution cable to fibers in the Feeder Cable. The area served by all of the Distribution Cables connected to a particular FSAI is called the Serving Area. The Feeder Cable connects the FSAI to the Optical Distribution Frame located in the Central Office. The Optical Distribution Frame provides connections between individual fibers in the Feeder Cable and a 100BASE-BX port on the Ethernet Switch[6].

The Ethernet Switch provides Ethernet Layer 2 switched services to each subscriber. This design addresses the needs of small to medium enterprise establishments and residences (Households). As such it uses 100BASE-BX ports that provide up to 100Mbps full duplex Ethernet connections on a single mode fiber to each EONT. (Though not modeled in this design, a Gigabit Ethernet line card employing 1000BASE-BX ports can be inserted into the Ethernet Switch to provide Gigabit Ethernet service on a single fiber to any subscriber.) Up to four 10 GE connections are provided between the Ethernet Switch and the Aggregation Router.

The use of the 100BASE-BX ports conserves fiber by supporting Ethernet transport in both directions on a single fiber. It provides high levels of service flexibility because Committed Information Rates (CIR) between 1 Mbps and 100 Mbps can be assigned to any subscriber using management software without truck rolls or manual changes in the Central Office. Also the rich set of QoS and service types defined by the Metro Ethernet Forum's Carrier Ethernet service specification (and OAM specifications) can be provisioned to any subscriber with no physical changes to the Ethernet Switch, ODN or EPON[7]. Also, the bandwidth capacity of the Ethernet Switch can be expanded up to 40 Gbps by adding additional 10 GE connections between the Ethernet Switch and the Aggregation Router[8].

The Aggregation Router provides the interface between the wire center ODN and the Aggregation Network. This study uses Layer 2 switching throughout, however, the Aggregation Network can be configured to be an MPLS network by replacing the Layer 2

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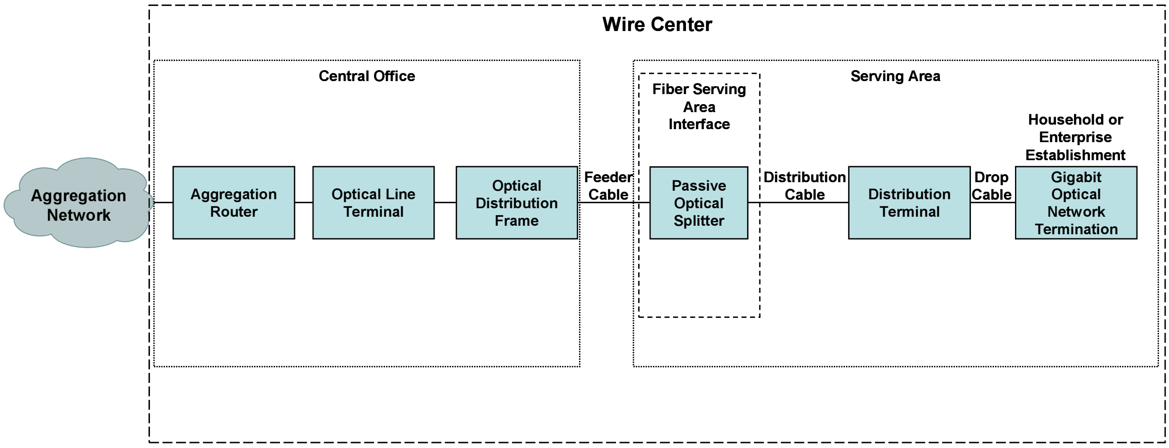
[6] The strategies for configuring the ODN to achieve both flexibility and to minimize CapEx and OpEx are discussed in a subsequent section of this paper.
[7] See MEF 6 – Ethernet Service Definitions – Phase I, Metro Ethernet Forum, June 2004 for the technical specification of Ethernet services.
[8] In this design each Ethernet Switch use two Supervisory Cards with at least one 10 GE port activated to provide redundant connectivity to the Aggregation Router. A third and fourth 10GE port can be activated to meet increasing bandwidth requirements by the addition of short reach XFP optics.

line cards that connect to other nodes in the Aggregation Network with MPLS capable line cards.

GPON Architecture

Figure 2 is a schematic of the Optical Distribution Network with GPON electronics.

Figure 2
GPON Architecture



Many elements of the GPON architecture are identical to the E-FTTH architecture. The differences are as follows:

- A Gigabit Optical Network Termination (GONT) is used instead of an EONT. The GONT conforms with ITU-T G.984.

- The FSAI includes a Passive Optical Splitter which in this design permits up to 32 GONTs to be connected to a single fiber in the Feeder Cable. The bandwidth capacity of each Feeder Cable fiber is limited by the port capacity of the Optical Line Terminal (OLT) located in the Central Office. This design uses an OLT port with a data rate of 2.5 Gbps. Therefore, the number of GONTs per splitter is the lesser of 32 or N = 2.5/CIR. Where CIR is the Committed Information Rate for a single subscriber.

- The same Feeder Cable is used as for the E-FTTH architecture however the fiber count is reduced by the Splitter Ratio (1/N).

- The Optical Line Terminal replaces the Ethernet Switch. Each Feeder Cable fiber is connected to an OLT port that conforms with ITU-T G.984.

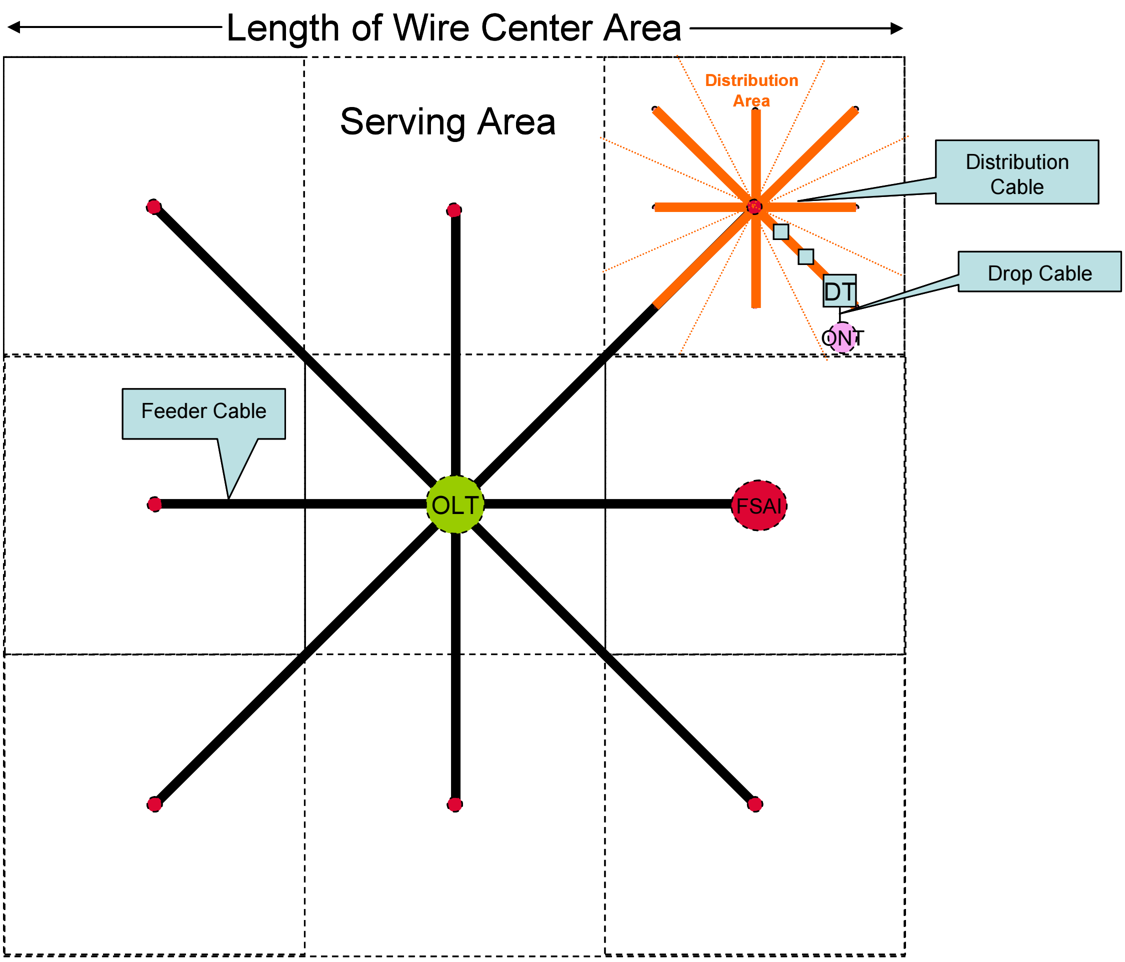
- The Optical Line Terminal has two 10 GE connections to the Aggregation Router. However, unlike the Ethernet Switch the dual supervisory cards provide switch over protection rather than simultaneous operation. This limits the OLT's bandwidth capacity to 10 Gbps.

ODN Design Principles

This section outlines the design principles used in designing the fiber optic cable network (ODN) so that network flexibility is maximized while minimizing CapEx and OpEx. Where differences exist in the E-FTTH architecture versus GPON architecture they are noted.

Figure 3 is a schematic layout of a wire center. Urban, suburban and rural wire centers are distinguished by the total area of the wire center and the number and mix of single and multi unit households and enterprise establishments. The wire center geometry is the same for all three wire center types.

Figure 3
ODN Schematic



The schematic shows that the wire center is subdivided into nine Serving Areas. This conforms to the Serving Area Concept for outside plant design of telephone company wire centers that has been used in the U.S. and elsewhere for at least forty years. The FSAI is located at the center of each Serving Area and acts as a point of concentration so that all of the fibers within the Serving Area can be connected to one or more Feeder Cables that follow the same route back to the Central Office—where the OLT is located in the schematic.

Economic Benefits of Serving Area Concept

Partitioning the wire center into Serving Areas so as to concentrate distribution cables to a few points and limit the number of routes that feeder cables take back to the Central Office reduces construction as well as maintenance costs in the following ways:

- The cost of support structures whether underground or aerial are minimized by reducing the number of routes taken to the Central Office. This is the largest single CapEx item in the ODN.

- Feeder Cable and associated installation costs are minimized because the number of routes to the Central Office is minimized. Costs also are reduced because common costs are spread across the largest number of fibers and mass splicing techniques can be used. Costs are further reduced because concentrating demand to a single point reduces the variability of cable capacity forecasts.

- The use of an Optical Distribution Frame at the FSAI facilitates testing and trouble shooting of service outages. This reduces OpEx and improves network availability.

- Location of a single tier Passive Optical Splitter at the FSAI as compared to the use of 2 tier Splitters improves Splitter and OLT port utilization. This is achieved by concentrating a large number of lit fibers at a single point.

Cabling Strategies for the ODN

Two methods of cabling of the ODN are analyzed. They are:

1. Connectorized – An Optical Distribution Frame is used at the FSAI and connections are made between the Distribution Cable and the Feeder Cable as subscribers are added within each Serving Area. The Feeder Cable is provisioned with enough optical fibers to meet three years of demand with an 80% utilization at exhaust rule. Under this method PON Splitters (and associated OLT ports at the Central Office.) are added over time as demand develops.

2. Fixed – Feeder Cable capacity and PON Splitters (if required) are provisioned to meet ultimate demand at project initiation.

The ODN is managed identically for both methods in the following ways:

- Distribution Cables together with Distribution Terminals are sized with fiber counts equal to the ultimate capacity. This minimizes construction costs and other fixed cost items that are much greater than the variable cost of additional fibers.

- Drop Cables and ONTs are added when customer orders are received. The Drop Cable and the ONT are a significant portion of cost per subscriber. This procedure ties these costs to compensating new revenue.

- OLT ports and Ethernet ports are provisioned only when required to light the fiber to subscribers. This is done over time as demand develops.

Wire Center Demand Model

The wire center demand model drives projections of CapEx and OpEx expenditures for each architecture over a five-year study period. The demand forecast is made in four steps.

1. The wire center area and total number of single and multiple unit households and enterprise establishments is established for each wire center type.

2. The number of single and multiple unit households and enterprise establishments in each of the nine Serving Areas and for each of the eight Distribution Areas (See Figure 3) is calculated. This calculation follows typical usage patterns where enterprises are located closest to the Central Office, followed by multiple unit households and then single unit households.

3. Using the results from the preceding steps Triple Play and Carrier Ethernet service penetration rates are projected for each year using current market research and prior Network Strategy Partners' business case studies[9].

4. Bandwidth requirements are calculated by applying a CIR/ONT factor to the results of Step 3.

[9] See *A Business Case Comparison of Carrier Ethernet Designs for Triple Play Networks*, Network Strategy Partners, March 2007 and *The Business Case for Carrier Ethernet over MSPP SONET Networks*, Network Strategy Partners, November 2006 for detailed demand projections. Papers are online at www.nspllc.com .

Table 1 shows the demographics of each wire center.

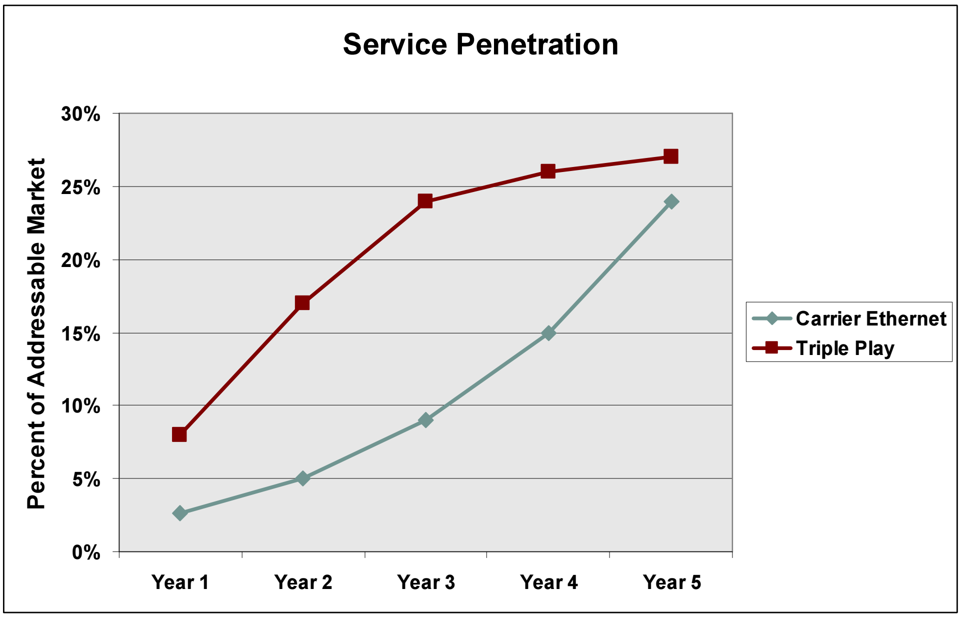
Table 1
Wire Center Demographics

Wire Center	Area Served (Sq. Mi.)	Single Unit Households	Multiunit Households	Enterprise Establishments
Urban	35	13,350	11,650	1,750
Suburban	53	5,944	2,056	280
Rural	124	2,283	717	60

The urban wire center encompasses a smaller area and has many more households and enterprise establishments than the other wire centers. It also has proportionally more multiunit households and enterprise establishments. The rural wire center covers the largest area despite serving the smallest number of potential customers. The longest fiber distance covered in this wire center is 7.8 miles (12.6 km). This is well within the range of both the GPON and E-FTTH architectures.

Figure 4 shows the service penetration rates that are applied to the available market as defined by Table 1.

Figure 4
Service Penetration Rates



The service penetration rates are applied to the wire center level demographic data and then projected for each of the nine Serving Areas. Figure 5 shows the resulting projection of ONT requirements by each customer type for the suburban wire center in year 5.

Figure 5
ONTs by Serving Area for Suburban Wire Center Year 5

SA 1 **SU HH 302**	**SA 2** **SU HH 302**	**SA 3** **SU HH 302**
SA 4 **MU HH 436**	**SA 5** **SU HH 114** **MU HH 272** **EST 75**	**SA 6** **SU HH 265** **MU HH 55**
SA 7 **SU HH 302**	**SA 8** **SU HH 302**	**SA 9** **SU HH 302**

Legend: SA = Serving Area; SU HH = Single Unit Household;
MU HH = Multiunit Household; EST = Enterprise Establishment

This distribution of customers across the nine Serving Areas provides a vehicle for modeling the lengths and sizes of Feeder and Distribution cables as well as the fill rates for PON Splitters, OLT ports and Distribution Terminals. Also, note that the Central Office is located at the center of Serving Area 5. Therefore, establishments and multiunit households are clustered closest to the Central Office (Town Center).

Bandwidth per Subscriber

Demand generated by households and small and medium enterprise establishments is analyzed in this study. As such it is assumed that each subscriber's entire communications needs are met by a single ONT. Therefore, the CIR per ONT reflects the total bandwidth requirement of each household and establishment. Table 2 shows typical bandwidth requirements for the Triple Play service elements.

Table 2
Bandwidth Requirements of Triple Play Service Elements

Service Element	Mean Data Rate (Mbps)	Peak Data Rate (Mbps)
Standard Definition Television	2	2
High Definition Television	9	9
VoIP	.032	.032
High Speed Internet Service	.25	4

The table displays both the mean and peak data rates for each service. Mean data rates are used to estimate bandwidth requirements where traffic is aggregated—for example within the Ethernet Switch at the Central Office and within the Aggregation Network. Peak data rates must be used when capacity is allocated for a small number of resources. Bandwidth capacity estimates for a single household requires that peak data rates be used because the consumer is very likely to have several television sets turned on, while using the telephone and the Internet. For example, a household with three High Definition Televisions (HDTV), two computers and one telephone line should be allocated 22.032 Mbps of bandwidth at the ONT—18 Mbps for HDTV, 4 Mbps for the two computers (bandwidth sharing is feasible here), and .032 Mbps for telephone service. However, when planning capacity at the Central Office level average usage levels, average number of services per user and the probability that services will be active simultaneously can be used to estimate aggregate bandwidth usage levels.

Today many Carrier Ethernet service offerings are simple point-to-point Ethernet Private Line offerings. Within small and medium establishments the primary application is for Internet access. However, much of the growth in Carrier Ethernet services will be for Ethernet Virtual Private Line services where the custom port is partitioned among several virtual circuits with individual QoS policies and E-LAN services that may also be partitioned into several Class of Service (CoS) categories. Applications for these services will include separate services for Internet access, voice and video service, and intranet applications.

Wire Center Cost Model

All of the ODN and optical-electronic elements of the ODN and CO equipment are included in the cost model. The ODN elements are:

- Drop Cable for Multiunit Households and Establishments
- Drop Cable for Single Unit Households
- Distribution Terminal for Single Unit Households
- Distribution Terminal for Multiunit Households and Establishments
- Distribution Cable for Establishments
- Distribution Cable for Multiunit Households
- Distribution Cable for Single Unit Households
- Fiber Serving Area Interface
- Fiber optic splices
- Passive Optical Splitter
- Feeder Cable
- Optical Distribution Frame

The electro-optical elements of the E-FTTH architecture are:

- EONT
- Ethernet Switch
- Aggregation Router

The electro-optical elements of the GPON architecture are:

- GONT
- Optical Line Terminal (OLT)
- Aggregation Router

Total Cost of Ownership Results

Four scenarios are examined to explore the TCO tradeoffs between E-FTTH and GPON. They are as follows:

Connectorized Cabling Method

1. Bandwidth per ONT (CIR) is constant across the five-year study

2. Bandwidth per ONT is 20 Mbps for years 1 – 3 and then 30% of all ONTs increase bandwidth to 50 Mbps in the fourth and fifth years

Fixed Cabling Method

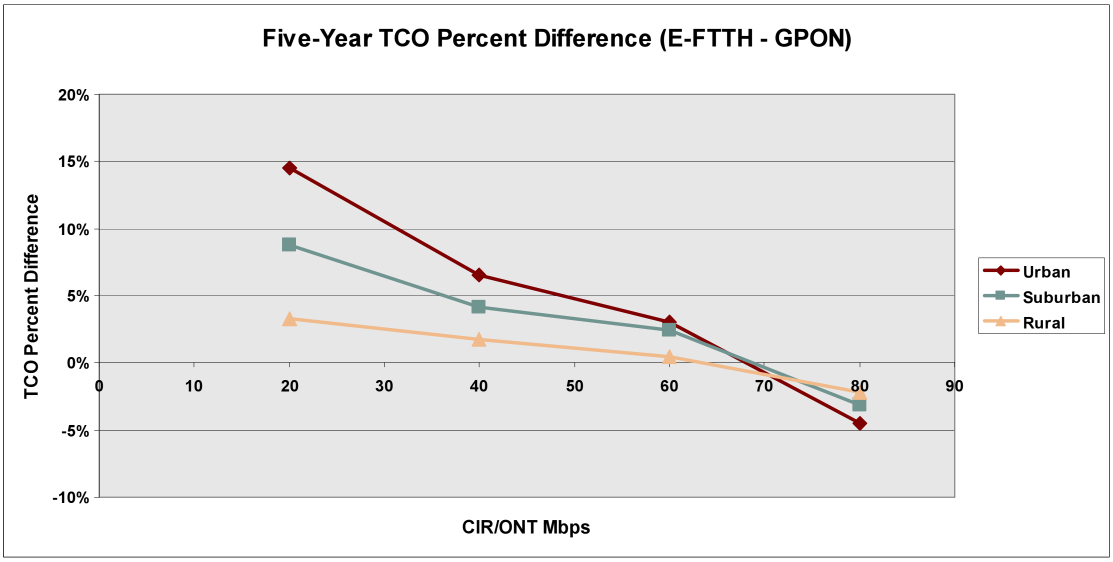
3. Bandwidth per ONT (CIR) is constant across the five-year study

4. Bandwidth per ONT is 20 Mbps for years 1 – 3 and then 30% of all ONTs increase bandwidth to 50 Mbps in the fourth and fifth years

TCO for Scenario 1 – Connectorized with Constant Bandwidth

Figure 6 shows the five-year TCO percent difference of E-FTTH compared to GPON at varying levels of bandwidth (CIR/ONT).

Figure 6
TCO Comparison Connectorized with Constant Bandwidth



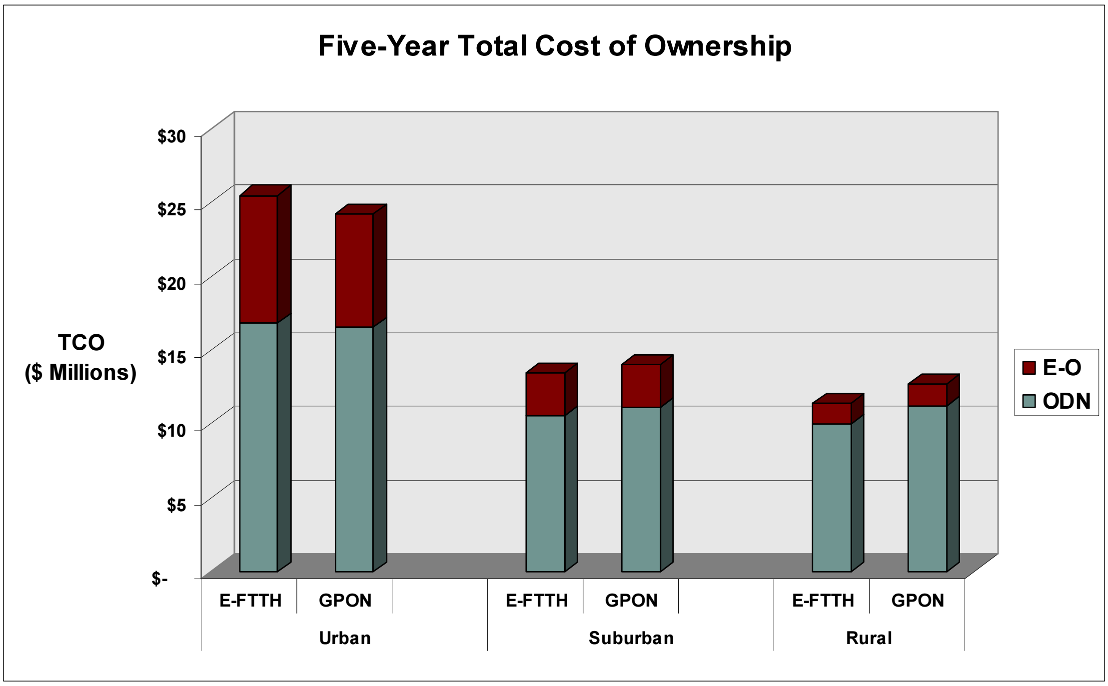
GPON enjoys a TCO advantage over E-FTTH when bandwidth is low while E-FTTH has lower TCO when bandwidth is high. This is due to GPON's ability to accommodate more ONTs per OLT chassis through its use of PON splitters. However, the OLT chassis has 1/4th the overall bandwidth capacity of E-FTTH's Ethernet Switch chassis. Therefore, as bandwidth increases a point is reached where GPON requires more chassis than E-FTTH. At this point the TCO tradeoff favors E-FTTH.

TCO for Scenario 2 – Connectorized with Changing Bandwidth

In the second scenario all subscribers use 20 Mbps CIR/ONT in the first three years but in the fourth and fifth year 30% of all new and existing subscribers shift to 50 Mbps CIR/ONT. This is the most likely scenario in that bandwidth requirements have been rising dramatically for decades and are expected to do so in the future.

Figure 7 compares the five-year TCO of E-FTTH with GPON for the connectorized method and changing bandwidth.

Figure 7
TCO Comparison Connectorized with Changing Bandwidth[10]



The figure shows that TCO is dominated by ODN costs and that the total cost is very similar for both solutions—E-FTTH is 5% higher than GPON in the urban wire center, 4% lower in the suburban wire center and 11% lower in the rural wire center. The next several sections drill down into the sources of the cost differences of the two architectures.

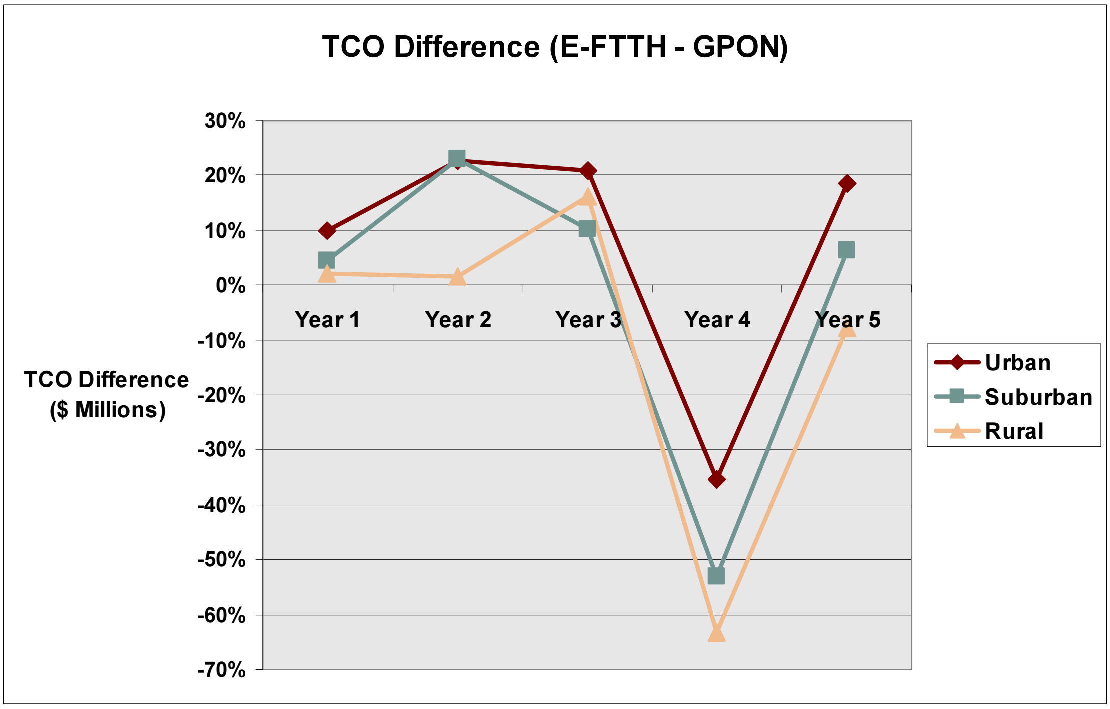
Figure 7 also shows why the cost differences shown in Figure 6 are greatest for the urban area and least for the rural area. The urban wire center uses less fiber per subscriber than the rural wire center, therefore, the cost of the electro-optical equipment is more important to overall TCO in the urban area as compared to the rural area.

[10] E-O refers to the electro-optical equipment—ONT, OLT, Ethernet Switch and Aggregation Router.

The Cost of Changing CIR per ONT

Figure 8 shows the annual percent difference in TCO where a positive amount means that E-FTTH costs more than GPON.

Figure 8
Annual Percent TCO Difference



The chart shows that GPON holds a cost advantage in the first three study years but then drops to a large cost disadvantage in the fourth year. GPON's cost advantage is due to the PON Splitter leverage that is achieved at low bandwidth usage levels. The large cost disadvantage in the fourth year is due to the switch of 30% of all customers to 50 Mbps usage up from 20 Mbps.

The E-FTTH design incurs no OpEx or CapEx penalties when the network experiences a demand increase to 50 Mbps by 30% of its customers. (The next section will show that E-FTTH TCO is quite insensitive to bandwidth usage increases over a wide range.) The GPON architecture, in contrast, tends to lock in the network at its original bandwidth design. This is so for two reasons.

1. The maximum number of ONTs deployed per PON Splitter decreases as CIR per ONT increases. A limit is reached where less than 32 ONTs can be deployed on each Splitter. This also reduces the number of ONTs supported per OLT port. In comparison each E-FTTH port can support 100 Mbps per ONT—there is one port for each ONT.

2. The maximum bandwidth capacity of the OLT chassis is limited to 10 Gbps. This limits the number of OLT ports that are operating at a full 2.5 Gbps to 4 per chassis. This is well below the 32 physical ports that can be supported by the OLT chassis. The E-FTTH chassis has a 40 Gbps capacity.

The TCO impact of an increase in CIR per ONT on the GPON design includes:

- Additional OLT chassis must be deployed and OLT line cards must be transferred to new chassis so as to limit the bandwidth capacity of each OLT chassis. In addition, high bandwidth ONTs connected to Splitters filled to the 32 ONT design capacity must be removed and re-spliced to new Splitters with lower total splitter ratios. This has the following TCO effects:
    - An OpEx rearrangement expense charge is incurred for re-splicing each existing ONT that is moved to a new Splitter.
    - A CapEx charge is incurred for adding new Splitters to the ODN.
    - A CapEx charge may be incurred if an additional Feeder Cable is needed to support the new Splitters.
    - A CapEx charge is incurred for splicing each new fiber at the Optical Distribution Frame in the Central Office.
    - A CapEx charge is incurred for adding additional OLT ports.
    - A CapEx charge is incurred for adding additional OLT chassis and transferring OLT ports to the new chassis.
    - Aggregation Router CapEx increases because more 10 GE ports are needed to support the additional OLT chasses
    - Many OpEx charges are increased due to the additional cable, and OLT and Aggregation Router chasses under management.

- Each additional PON Splitter installed in Year 4 must be limited to a lower split ratio so as to avoid the large rearrangement costs. This has the following TCO effects:
    - CapEx increases because more Splitters are required.
    - Higher Feeder Cable CapEx and OpEx are incurred
    - OLT CapEx and associated OpEx increase because more OLT ports are required.
    - Aggregation Router costs increase proportionately with the addition of OLT chasses.

Operations Expense Comparison

Figure 9 through Figure 11 shows Operations Expense for E-FTTH and GPON.

Figure 9
Operations Expense Urban Wire Center

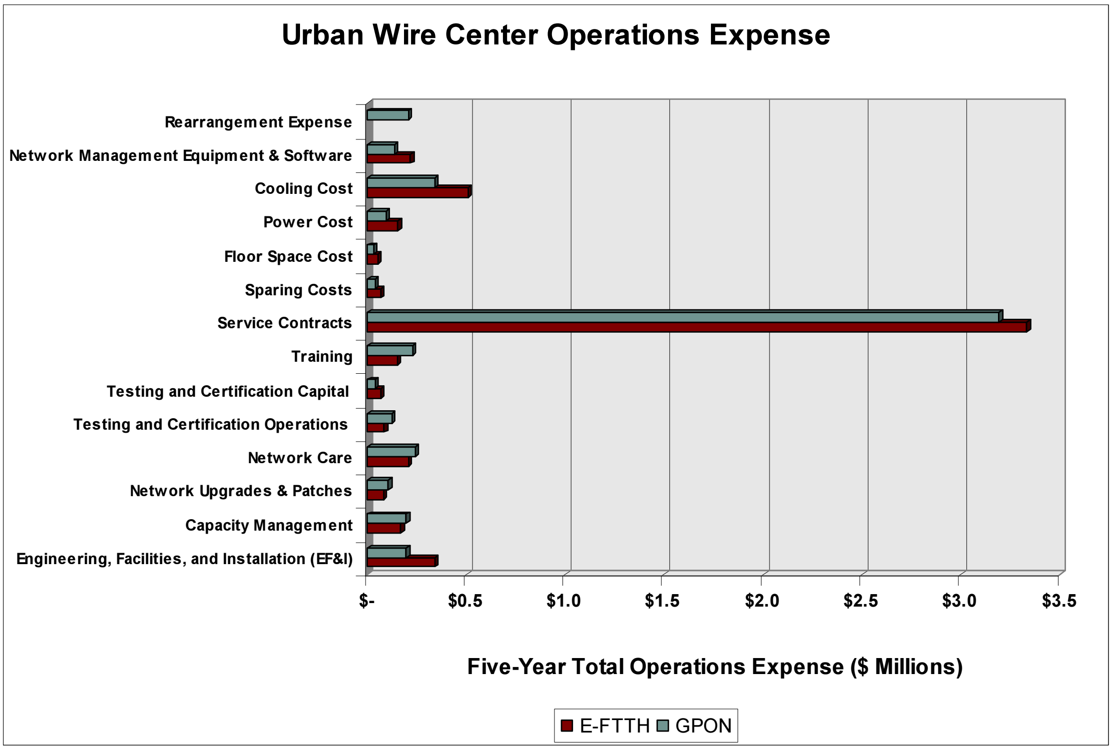


Figure 10
Operations Expense Suburban Wire Center

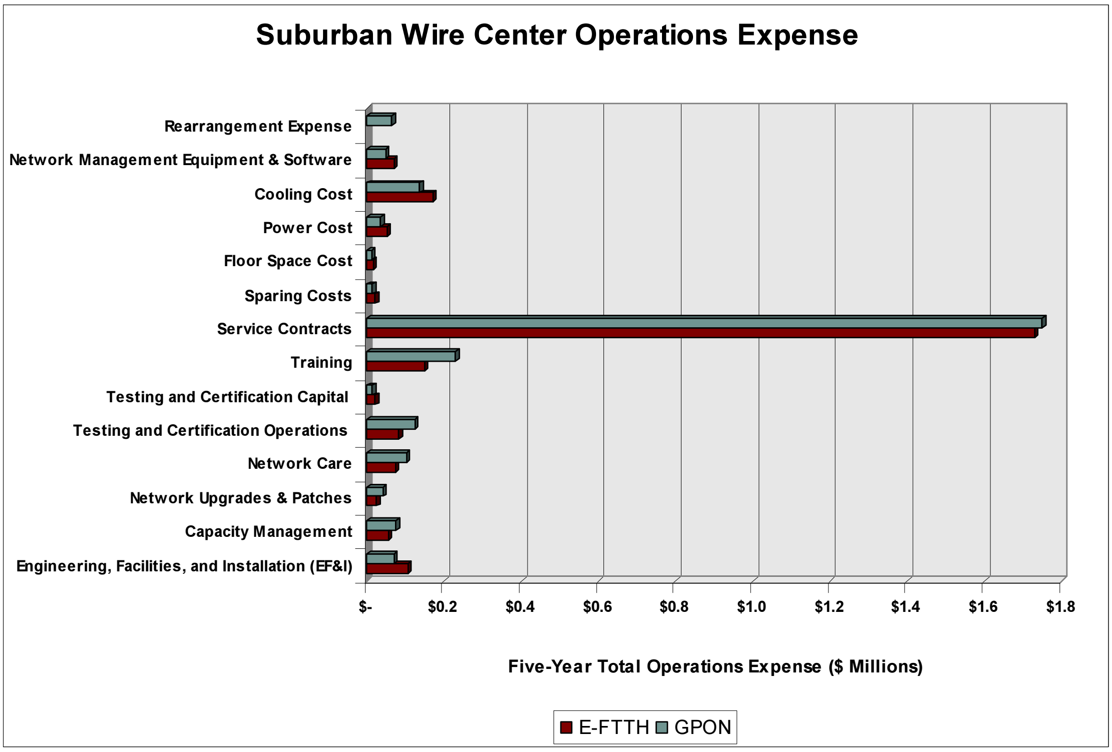
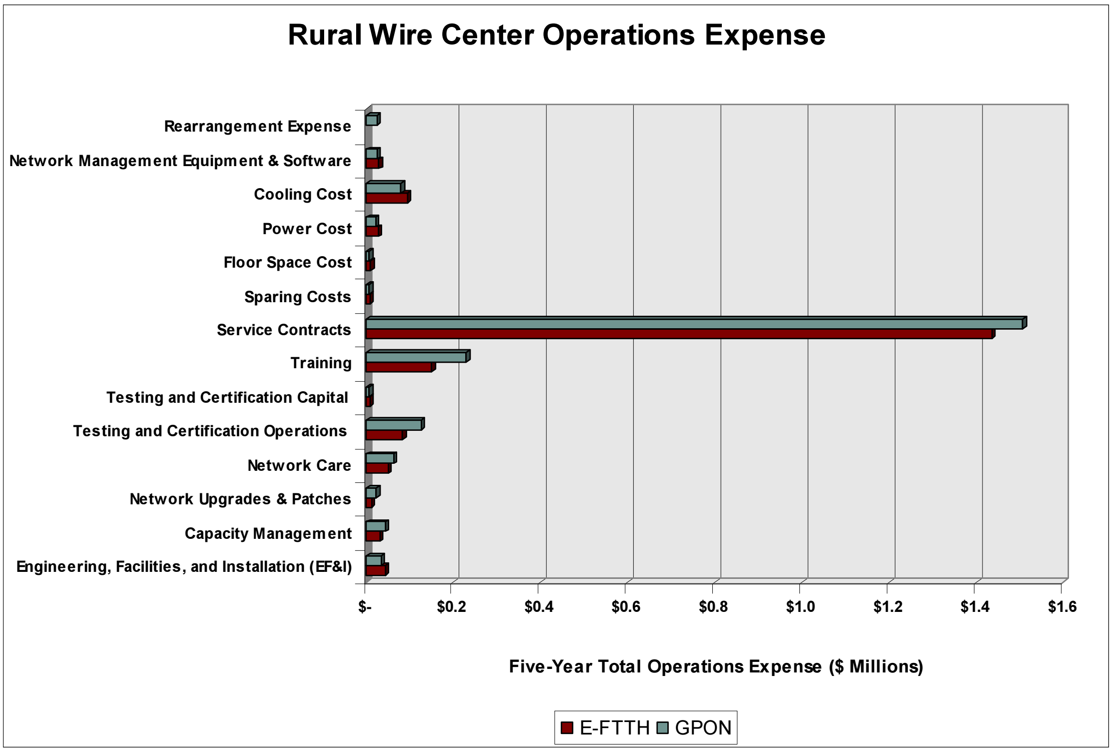


Figure 11
Operations Expense Rural Wire Center

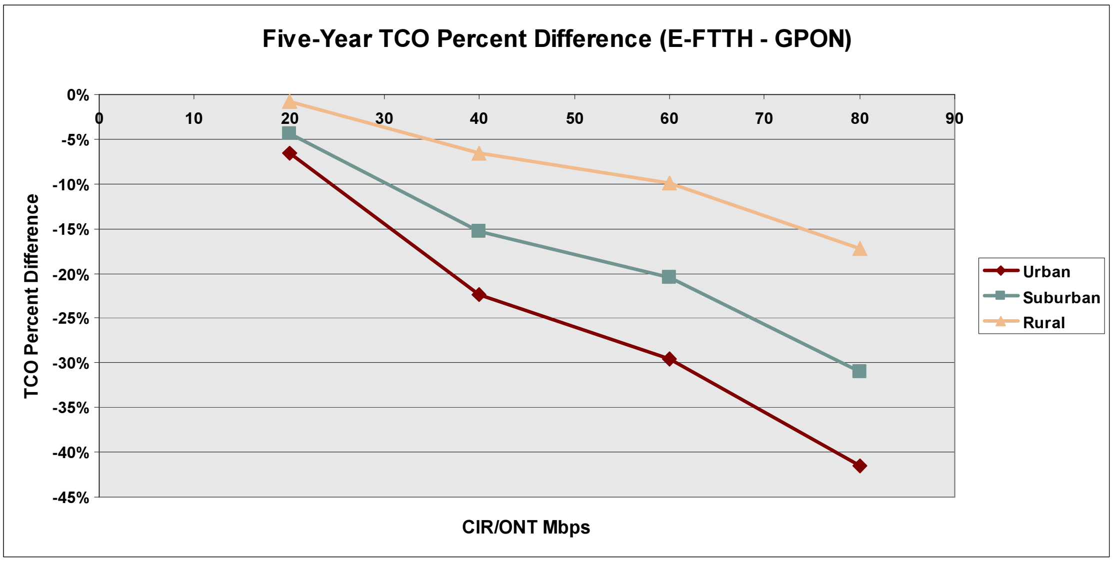


The three figures show that service contracts account for the majority of the operations expense. Service contracts include maintenance activities associated with maintaining the ODN and ONTs as well as the Central Office equipment. The other expense categories with the exception of rearrangement expense are associated with the Central Office equipment. Since that equipment is a small part of the FTTH infrastructure those expenses are of minor importance. Therefore, any investment in Central Office equipment that reduces the cost of ODN and ONT operations has great leverage on TCO. This is an important advantage of E-FTTH versus GPON in that E-FTTH rarely requires a truck roll or any manual operations in the ODN.

TCO for Scenario 3 – Fixed with Constant Bandwidth

Figure 12 shows the TCO differences over five-years for E-FTTH compared with GPON for the fixed capacity expansion method and varying CIR/ONT levels.

Figure 12
TCO Differences for Fixed Method



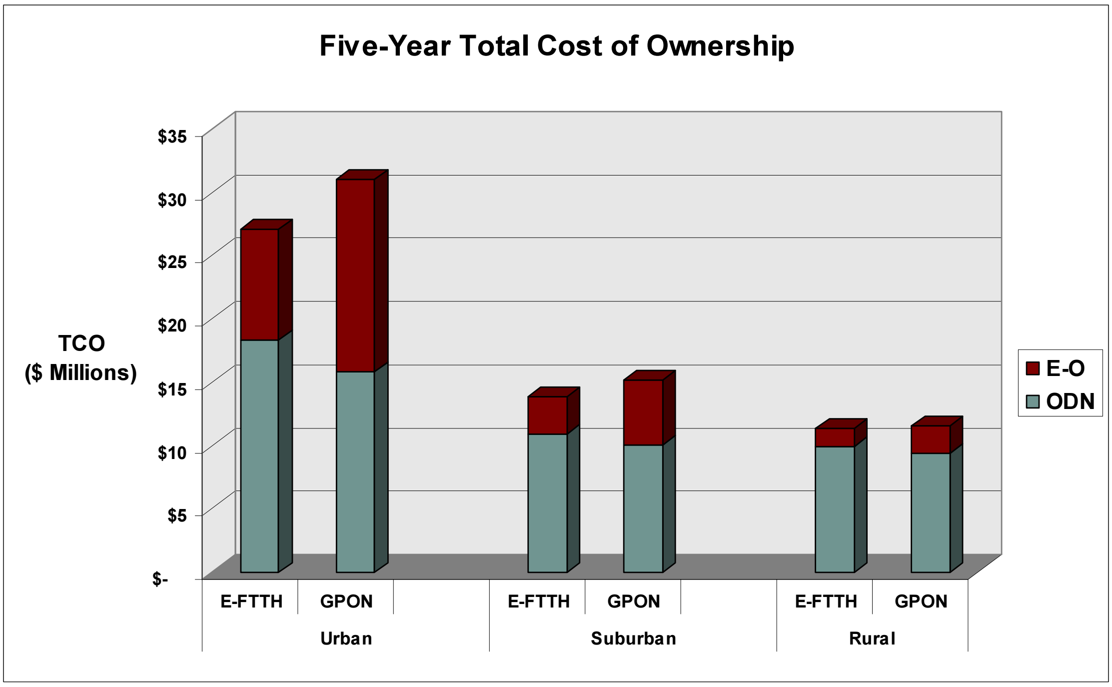
At 20 Mbps CIR/ONT E-FTTH holds a small TCO advantage over GPON. This TCO advantage increases significantly as CIR/ONT increases. This is due to the fixed method's deployment of all ODN network elements at project initiation. Under this approach permanent connections are made between the distribution cable, splitter and fiber cable upon project initiation. Consequently, an OLT port must be assigned to the fiber connected to each Splitter when any one of the possible 32 customers signs up for service. This results in poor utilization of the FTTH infrastructure in the early years of the project. In addition, GPON chassis have lower total bandwidth capacity than the Ethernet Switch chassis. Therefore, as CIR/ONT increases the TCO difference of E-FTTH compared to GPON increasing favors E-FTTH. (E-FTTH scales better than GPON.)

TCO for Scenario 4 – Fixed with Changing Bandwidth

In the fourth scenario the fixed cabling strategy is employed and all subscribers use 20 Mbps CIR/ONT in the first three years but in the fourth and fifth year 30% of all new and existing subscribers shift to 50 Mbps CIR/ONT. This is just like scenario 2 except that the fixed rather than connectorized cabling strategy is employed.

Figure 13 compares the five-year TCO of E-FTTH with GPON for the fixed cabling strategy and changing bandwidth.

Figure 13
TCO Comparison Fixed with Changing Bandwidth



The figure shows that while ODN costs are slightly lower for GPON than E-FTTH the Electro-Optical costs are substantially higher for GPON. TCO, consequently, favors E-FTTH for each wire center type—E-FTTH is 13% lower than GPON in the urban wire center, 9% lower in the suburban wire center and 2% lower in the rural wire center. The GPON's higher E-O costs are due to, as in Scenario 3, deploying all PON Splitters and the associated OLT ports at project initiation. In contrast, though all cabling also is deployed for E-FTTH the Ethernet ports are not installed until required until service turn-up for each individual subscriber.

The changing bandwidth assumption used in this scenario also adds cost to the GPON but not to the E-FTTH architecture. In the E-FTTH bandwidth per Ethernet Switch chassis need not be deployed until required and there is the opportunity to double the Ethernet Switch's bandwidth capacity by adding additional processing power. In the GPON case there is no flexibility in chassis bandwidth capacity. Consequently, a change in designed in CIR/ONT requires that some OLT ports be removed from the existing chassis and installed in new chassis to meet subscriber bandwidth expectations.

Conclusion

This analysis shows that protecting the investment in the ODN should be a top priority. It is a civil works project much like other projects such as roads, sewers or the electrical distribution system. It has high initial capital costs and a useful life of at least thirty years. The analysis also shows that service flexibility and the ability to accommodate increasing bandwidth requirements are essential to achieving low TCO.

The E-FTTH architecture provides substantial protection of the ODN asset in the following ways:

- The E-FTTH architecture supports any Ethernet-based service with a bandwidth of 1 – 100 Mbps with no changes required to the ODN or EONT. Changes are minimized within each Ethernet Switch chassis because the chassis has a 40 Gbps capacity that is four times that of the OLT.

- In the case of an increase of CIR from 20 Mbps to 50 Mbps for 30% of all customers in the 4th year the following TCO results are found for the connectorized cabling method:
  - E-FTTH has 5% higher TCO than GPON for the urban wire center
  - E-FTTH has 4% lower TCO than GPON for the suburban wire center
  - E-FTTH has 11% lower TCO than GPON for the rural wire center

- E-FTTH has no effect on the ODN or Ethernet Switch ODN port configurations when CIR changes while GPON has the following impacts:
  - OpEx is incurred for rearranging splitters
  - CapEx is incurred for additional:
    - Splitters
    - Fiber in Feeder Cables
    - OLT ports
    - OLT chassis
    - Ports on Aggregation Routers
  - OpEx associated with the CapEx additions increases

- E-FTTH scales better than GPON. Since bandwidth demand has grown exponentially for decades, this scaling advantage will be critical over the 30+ year life of the ODN.

A second element of the analysis compares a connectorized cabling method with a fixed method where the ODN is built as a single project upon project initiation. TCO is calculated for the case where a constant CIR/ONT is maintained over the five-year study period. The findings include:

- GPON achieves lower TCO when using a connectorized cabling method and CIR/ONT is low. E-FTTH crosses over to be the lower cost alternative when CIR/ONT exceeds 60 Mbps. This effect is due to the higher bandwidth capacity (and higher per chassis cost) of the Ethernet Switch used by E-FTTH.

- E-FTTH maintains a consistent TCO advantage over GPON when the fixed cabling method is used. It provides 1% to 7% lower cost at 20 Mbps CIR/ONT increasing to 17% to 42% at 80 Mbps CIR/ONT.

- E-FTTH also maintains a consistent advantage over GPON when an increase of CIR from 20 Mbps to 50 Mbps for 30% of all customers in the 4th year occurs. Specifically,
    - E-FTTH has 13% lower TCO than GPON for the urban wire center
    - E-FTTH has 9% lower TCO than GPON for the suburban wire center
    - E-FTTH has 2% lower TCO than GPON for the rural wire center

Taken as a whole the connectorized cabling method when used with E-FTTH provides the lowest TCO when there are significant market risk, customer churn and rapid growth in bandwidth requirements. GPON is attractive when used with the connectorized cabling method, demand is not volatile and CIR/ONT is likely to remain below 50 Mbps for at least five-years.

The study also shows that the fixed cabling method is attractive when the wire center is quite stable and take-up rates are likely to be near 100%. The connectorized cabling method is attractive in those situations where both take-up rates and bandwidth levels are uncertain and likely to be volatile. These tradeoffs make the fixed method attractive for such projects as "Greenfield" construction in a high-income housing development and the connectorized approach suitable to an incumbent telecom vendor in its existing franchised territory.