WHITE PAPER

Access Loop Model for the Economic Analysis and Optimal Design of PON FTTx Architectures

Based on Ciena's 10G XGS-PON Solution

1. Introduction

This white paper presents an access (subscriber) loop model for the techno-economic analysis and optimal (minimum cost) design of Passive Optical Network (PON) FTTx (fiber-to-the-home, building, curb) and Fixed Wireless Access (FWA) network architectures based on Ciena's 10G XGS-PON solution. Over time, PON has established itself as the access technology of choice among telecom network operators for the mass delivery of broadband services to their customers.

The major attraction of the PON architecture is that it has an all-passive Outside Plant (OSP)/Optical Distribution Network (ODN). This greatly simplifies network operation and maintenance by eliminating active electronics, which are typically fault-generating points, from the OSP. In PON-based networks, active electronics is confined to the central office/local exchange Optical Line Terminal (OLT) and the customer premises.

However, despite the great promise of the PON architecture as a vehicle for the massive introduction of fiber in the access loop network to achieve all-optical networks in support of broadband services, cost remains a major barrier to achieving this goal. The access loop is the costliest part of the telecommunications network, constituting approximately 40 percent of end-to-end network cost. Further, a breakdown of the access loop cost shows that OSP constitutes approximately 70 percent of the cost, arising from high labor and construction costs, while the electronics cost is around 30 percent. Consequently, the OSP cost—not the electronics cost—is the main barrier preventing network operators from large-scale deployment of fiber in the access loop.

This is especially true within highly suburban demographics in North America, where access loop distances—from the Central Office (CO) to the subscriber premises—are typically very long, easily averaging around seven miles. Within urban and dense urban demographics in Europe and Asia, access loop distances are typically less than three miles. This explains why network operators in Europe and Asia have had more success in deploying fiber in the access loop compared to their North American counterparts.

Ciena proposes an access network solution that helps network operators address the major OSP cost challenge they face in trying to deploy fiber in the access loop. Minimizing these costs is critical to enabling network operators to achieve cost-effective mass rollout of PON FTTx access architectures to support broadband services, especially in suburban America, where the cost of deployment of fiber access networks is highest.

The access network model presented in this work achieves this critical goal of helping network operators minimize their OSP costs. Therefore, the objectives of this white paper are threefold:

- To employ an ***Access (Subscriber) Loop Model for the Techno-economic Analysis and Optimal Design of Fiber/Radio Network Architectures*** to help network operators minimize their OSP costs by determining the optimal OSP physical implementation that minimizes the PON FTTx access architecture network cost
- To enable Ciena Sales and Marketing to position Ciena's 10G XGS PON solution versus major competitors as a solution that addresses the major pain-point—the OSP/ODN cost—for network operators, as opposed to addressing only the electronics cost of the OLT and Optical Network Termination (ONT)
- To enable Ciena's 10G XGS PON solution to deliver the lowest cost per bit versus major competitors

2. Strategy for the optimal design of PON FTTx access architectures

In a PON access architecture, the optical splitting of a signal multiplexed on a feeder fiber at the OLT can be implemented in a number of ways, including centralized (or local convergence) or cascade optical splitting, and at different network nodes, including the cabinets and/or the Distribution Points (DPs) or pedestal nodes. Consequently, how (centralized or cascade) and where (cabinet or DP nodes) in the network the PON optical splitting is implemented can result in logically equivalent PON architectures, but with very different physical implementations.

The physical implementation of the PON architecture impacts distribution, and drop loops cable distances and capacities, causing wide variation in OSP network costs. This is a result of the dependence of OSP cost on a combination of factors, including building density, material and labor costs, and service penetration rates, among others. Since these network parameters and material/installation costs vary from one network to the other, it is difficult to consistently design PON access architectures optimally based on established practices for outside plant design, as is typical with network operators. To minimize end-to-end network cost, PON access architectures must be designed on a case-by-case basis, taking into account how these factors and variables are changing in a specific network. The model in this document minimizes network costs by including these variables as inputs to determine the optimal PON FTTx access network architecture's physical design.

3. Model application: Use cases

The following two use cases demonstrate the power of this model to help network operators minimize their PON access FTTx architecture costs:

- **Use case 1:** The first use case analyzes a number of logically equivalent PON architectures with a 1:32 optical splitting and their physical implementations based on Ciena's 10G XGS PON solution. In this use case, the network is designed using *t-Line DP nodes for a network containing 1,024 buildings with building-densities ranging from 500/sq. km (suburban demographic) to 10,000/sq. km (ultra-dense urban demographics). A 100 percent service penetration rate is assumed.
- **Use case 2:** The second use case considers a competitive environment with multiple operators, or one in which the network operator makes a strategic decision to target only SMB/E buildings and can reasonably expect to achieve a penetration rate of only about 20 to 25 percent.

This section also examines the question of how the network design needs to change (if at all) from use case 1 to achieve a minimum cost network design under use case 2. Finally, this section employs the model presented to demonstrate how to solve this problem.

4. The access (subscriber) loop network

Figure 1 shows the access (or subscriber) loop network. It consists of a concatenation of nodes and links as follows:

i. The OLT node at the Central Office/Local Exchange (CO/LEX)

ii. The feeder loop

iii. The cabinet (sometimes called the Remote Distribution Unit [RDU]) node

iv. The distribution loop

v. The Distribution Points (DPs) or Pedestal nodes

vi. The drop loop

vii. The ONT customer premises node

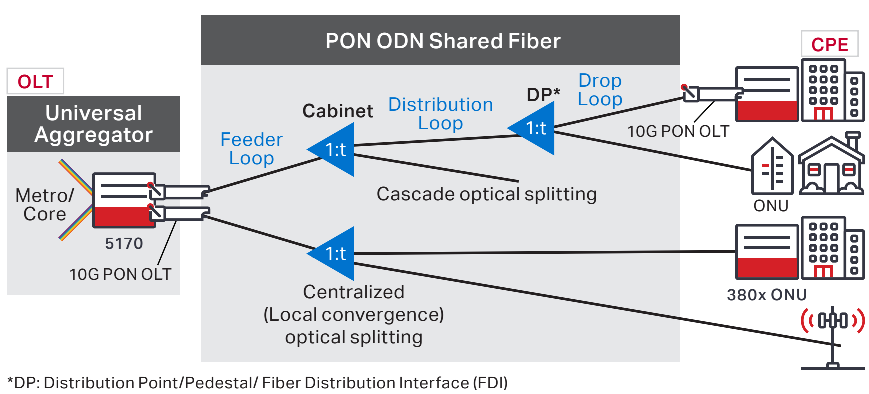


Figure 1. The access (subscriber) loop network based on Ciena's 10G XGS PON solution
**t = 4, 8, 16 and 32*

The cost of the PON access architecture OSP constitutes approximately 70 percent of the network cost, compared to around 30 percent for electronics. This disparity is driven by several factors, including:

- Network demographics: housing-density (or road-km covered by network)
- Service penetration rates
- OSP material/installation labor costs for aerial, UG, conduit/ducts, direct burial, etc.
- How/where the optical splitting is implemented, resulting in logically equivalent PON architectures with different physical implementations that can cause wide cost variations

5. Analysis of PON FTTx architectures: Logically equivalent networks and their physical implementations

This section provides an analysis of a number of logically equivalent PON access FTTH architectures and their physical implementations wherein a feeder fiber undergoes a total of 1:32 optical splitting.

5.1 PON architecture #1: 1:32 centralized (local convergence) split at cabinet

Analysis of the logical network

Figure 2a shows the logical network architecture wherein a single feeder fiber from the OLT is split into 32 distribution

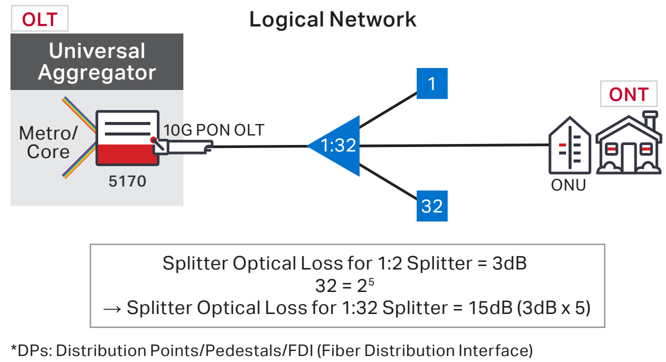


Figure 2a. PON architecture #1: Logical 1:32 centralized (local convergence) split at cabinet node

fibers by a 1:32 optical splitter/coupler. Optical splitting loss is calculated as follows:

- Splitter optical loss for 1:2 splitter = 3dB
- Since 32 = 2^5
- Therefore, optical splitting loss of a feeder fiber with 1:32 split = 15dB (3dB x 5)

Analysis of the physical network implementation

Figure 2b shows the physical network implementation of the architecture wherein a single feeder fiber from the CO/LEX OLT is split into 32-fiber distribution cable by a 1:32 optical splitter located at the cabinet node, as shown. The 32-fiber distribution cable connects 8 x 4-Line DPs in a daisy chain, with four fiber strands being dropped at each of eight DP nodes. Each DP node connects four customers to the network over drop fibers, as shown.

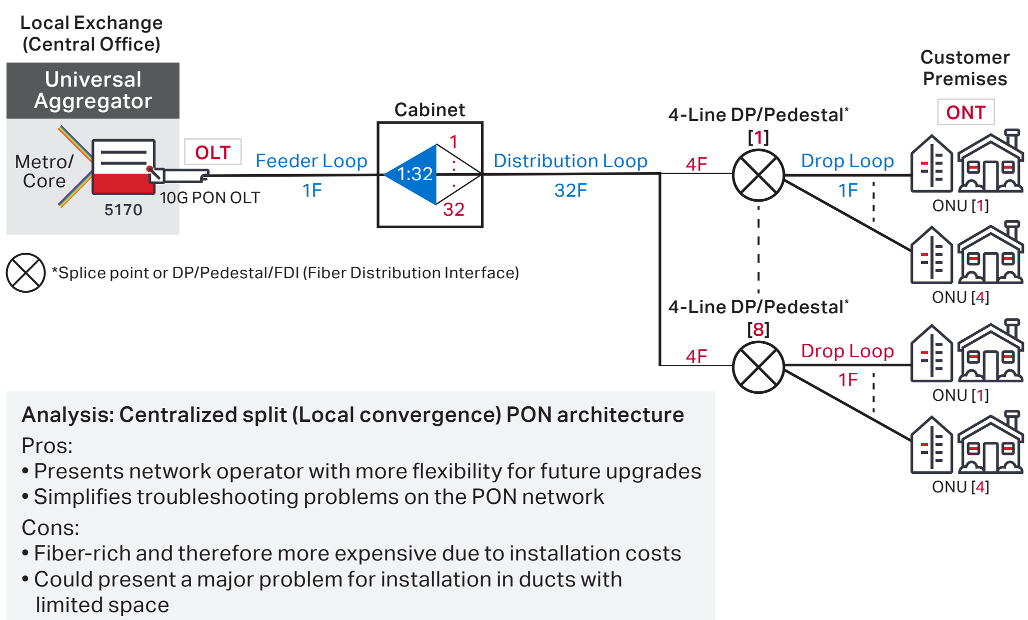


Figure 2b. PON architecture #1: 1:32 Centralized (local convergence) split: cabinet split: 1:32; DPs: no split (with 4-line capacity DP nodes)

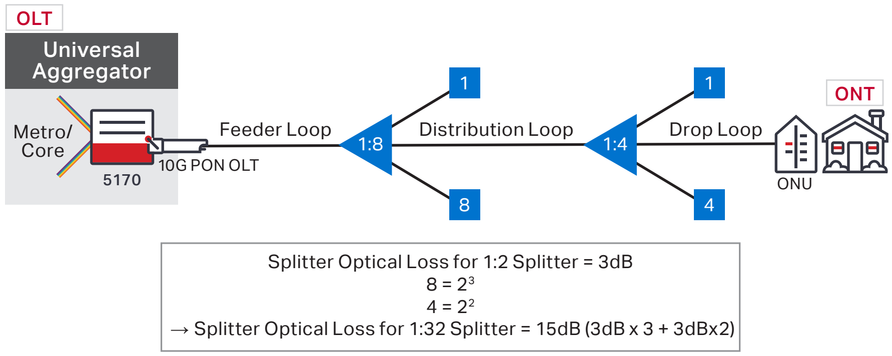


Figure 3a. PON architecture #2: Logical 1:32 cascade optical split: with 1:8 and 1:4 splits in cascade

5.2 PON architecture #2: 1:32 cascade split: cabinet: 1:8; DPs: 1:4

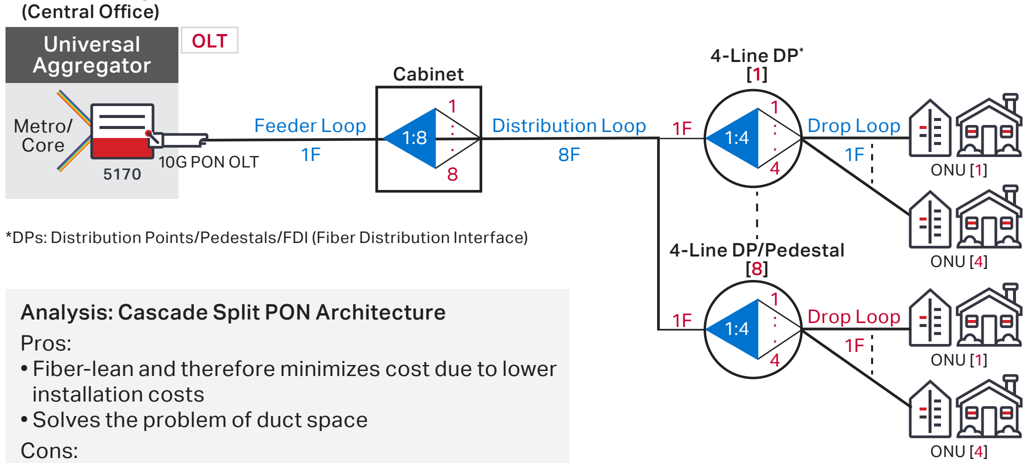
Analysis of the logical network

Figure 3a shows the logical network architecture where a signal carried by a single feeder fiber from the OLT is first split into eight distribution fibers by a 1:8 optical splitter at the cabinet node. Each of eight distribution fibers is further split into four drop fibers by 1:4 couplers at the DP nodes for a total of 1:32 split of a feeder fiber. Therefore, the total optical splitting loss is calculated as follows:

- Splitter optical loss for 1:2 splitter = 3dB
- Note that $8 = 2^3$ and $4 = 2^2$
- Therefore, optical splitting loss of a feeder fiber with 1:32 total split = 15dB (3dB x 3 + 3dBx2)

Analysis of the physical network implementation

Figure 3b shows the physical network implementation of the architecture wherein a single feeder fiber from the OLT is first split into an eight-fiber distribution cable by a 1:8 optical splitter at the cabinet node. The eight-fiber distribution cable connects eight 4-line DPs in a daisy chain with each of the eight fiber strands, further split by 1:4 couplers at the DP nodes onto four drop fibers at each of eight DP nodes. Each DP node connects four customers to the network over drop fibers, as shown.



*DPs: Distribution Points/Pedestals/FDI (Fiber Distribution Interface)

Analysis: Cascade Split PON Architecture

Pros:
- Fiber-lean and therefore minimizes cost due to lower installation costs
- Solves the problem of duct space

Cons:
- Presents network operator with less flexibility for future upgrades
- Could make troubleshooting problems on the PON network more difficult

Where/how the optical splitting is implemented impacts Distribution Loop cable lengths/capacities and required numbers of DP/Pedestal/FDI nodes

Figure 3b. PON architecture #2: Equivalent physical implementation of 1:32 cascade split: cabinet split: 1:8; DP node split: 1:4 with 4-line DPs in daisy chain

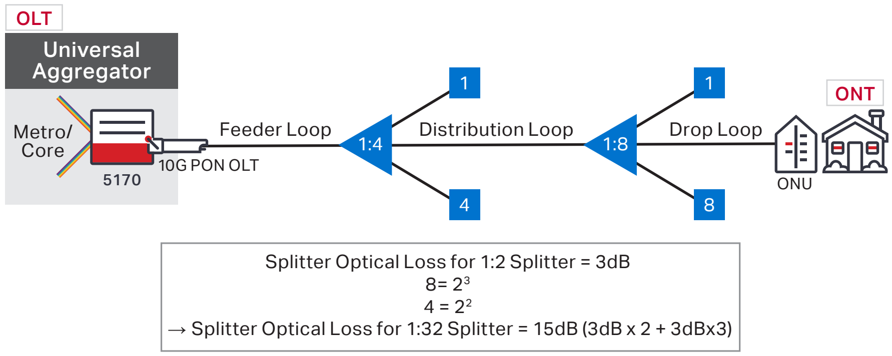


Figure 4a. PON architecture #3: Logical 1:32 cascade optical split: with 1:4 and 1:8 splits in cascade

5.3 PON architecture #3: 1:32 cascade split: Cabinet: 1:4; DP nodes: 1:8

Analysis of the logical network

Figure 4a shows the logical network architecture wherein a signal multiplexed onto a single feeder fiber from the OLT is first split into four distribution fibers by a 1:4 optical coupler at the cabinet node. Each of the four distribution fibers is further split into eight drop fibers by 1:8 couplers at the DP nodes for a total of 1:32 split of a feeder fiber. Therefore, the total optical splitting loss is calculated as follows:

- Splitter optical loss for 1:2 splitter = 3dB
- Since $4 = 2^2$ and $8 = 2^3$
- Therefore, optical splitting loss of a feeder fiber with 1:32 total split = 15dB (3dB x 2 + 3dBx3)

Analysis of the physical network implementation

Figure 4b shows the physical network implementation of the architecture wherein a signal carried by a single feeder fiber from the OLT is first split into a four-fiber distribution cable by a 1:4 optical coupler at the cabinet node. The four-fiber distribution cable connects 8 x 4-Line DP nodes in a daisy chain with each of the four fiber strands further split by 1:8 couplers at the DP nodes onto eight drop fibers at each of four DP nodes. Each DP node connects eight customers to the network over drop fibers as shown.

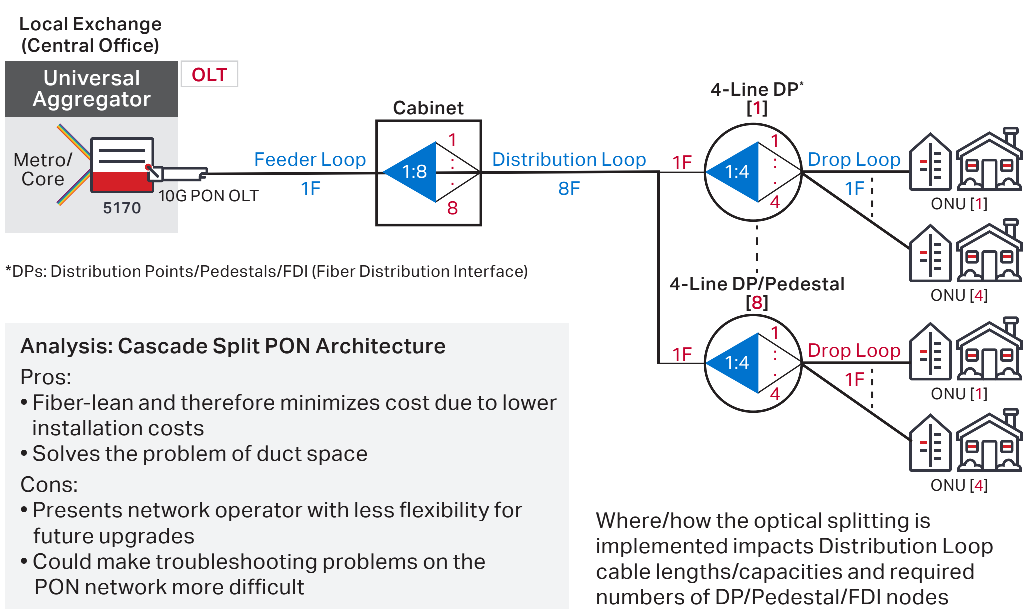


Figure 4b. PON architecture #3: Equivalent physical implementation of 1:32; Cascade split: Cabinet split: 1:4; DP nodes split 1:8; (with 8-line DPs in daisy chain)

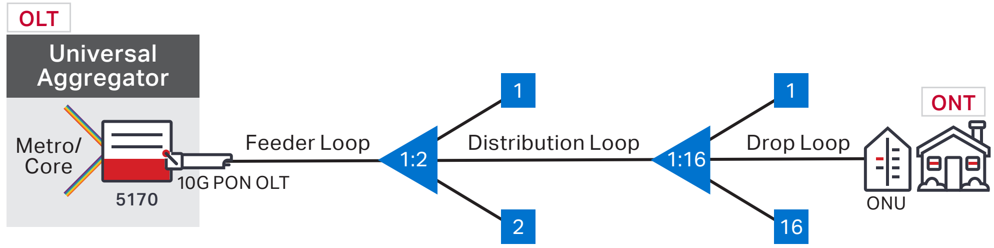


Figure 5a. PON architecture #4: Logical 1:32 cascade optical split; with 1:2 and 1:16 splits in cascade

5.4 PON Architecture #4: 1:32 Cascade split: Cabinet: 1:2; DP nodes: 1:16

Analysis of the logical network

Figure 5a shows the logical network architecture wherein a signal carried by a single feeder fiber from the OLT is first split into two distribution fibers by a 1:2 optical coupler at the cabinet node. Each of the two distribution fibers is further split into 16 drop fibers by 1:16 couplers at the DP nodes for a total of 1:32 split of a feeder fiber. Therefore, the total optical splitting loss is calculated as follows:

- Splitter optical loss for 1:2 splitter = 3dB
- Note that $2 = 2^1$ and $16 = 2^4$
- Therefore, optical splitting loss of a feeder fiber with 1:32 total split = 15dB (3dB x 1 + 4dBx3)

Analysis of the physical network implementation

Figure 5b shows the physical network implementation of the architecture wherein a single feeder fiber from the OLT is first split into a two-fiber distribution cable by a 1:2 optical coupler at the cabinet node. The two-fiber distribution cable connects 2 x 16-Line DP nodes in a daisy chain with each of the two fiber strands further split by 1:16 couplers at the DP nodes onto 16 drop fibers at each of the two DP nodes. Each DP node connects 16 customers to the network over drop fibers as shown.

5.5 PON architecture #5: 1:32 centralized (local convergence) split: Cabinet: No split; DP nodes: 1:32

Analysis of the logical network

Figure 6a shows the logical network architecture wherein a single feeder fiber from the OLT is split into 32 drop fibers by a 1:32 optical coupler at the DP node. Optical splitting loss is calculated as follows:

- Splitter optical loss for 1:2 splitter = 3dB
- $32 = 2^5$
- Therefore, optical splitting loss of a feeder fiber with 1:32 split = 15dB (3dB x 5)

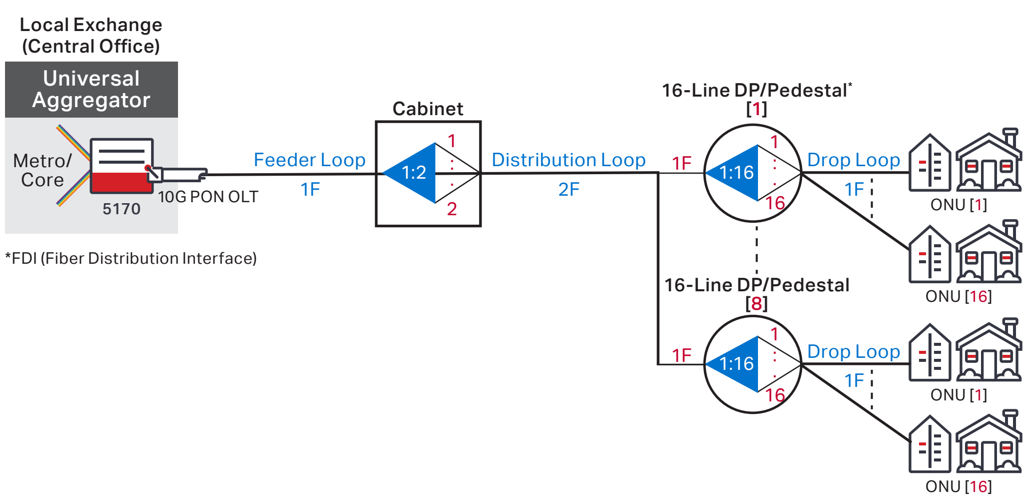


Figure 5b. PON architecture #4: Equivalent physical implementation of 1:32: Cascade split: Cabinet split: 1:2; PD nodes split: 1:16 (with 16-line DP/pedestals in daisy chain)

Analysis of the physical network implementation

Figure 6b shows the physical network implementation of the architecture wherein a single feeder fiber from the OLT is split onto 32 drop cables by a 1:32 optical coupler at the DP node as shown. Note that in this architecture, the cabinet node is just a splice point.

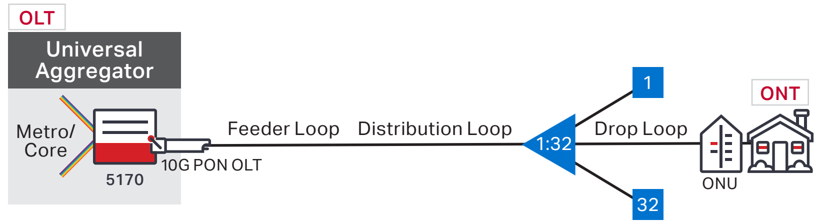


Figure 6a. PON architecture #5: Logical 1:32 centralized (local convergence) optical split

6. Access loop model for the techno-economic analysis and optimal design of PON FTTx /FWA networks

The model assumes that the cabinet/Remote Distribution Unit (RDU) is served from a Local Exchange (LEX) or central office over a feeder cable as shown in Figure 7.

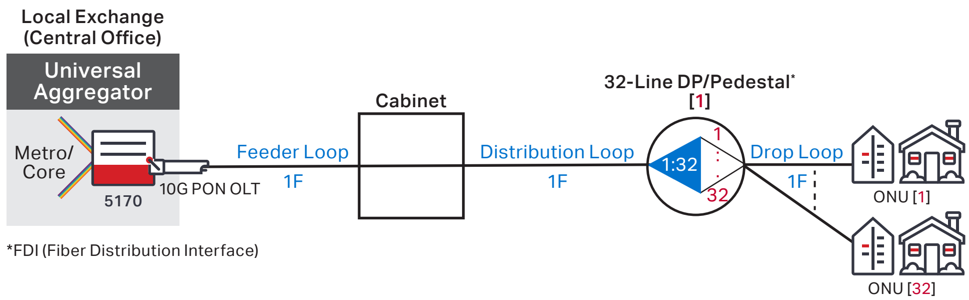


Figure 6b. PON architecture #5: Logical 1:32 centralized (local convergence) optical split: with cabinet: No split; PD node split: 1:32 (with 32-line DP nodes)

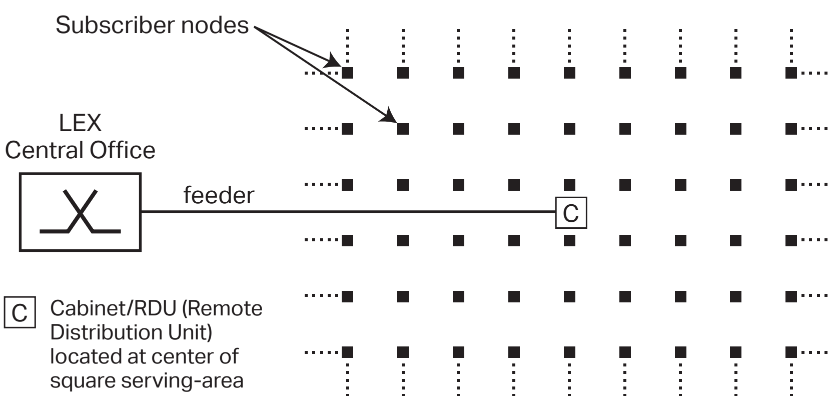
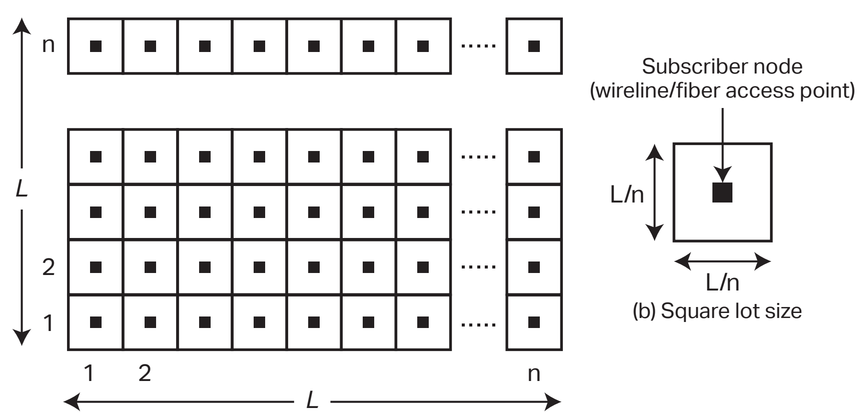


Figure 7. Model assumes a square serving area of side L containing n^2 housing lots uniformly distributed and served over a feeder from the local exchange

- Generally, in a real network, the serving area is typically an irregular geographical layout in which housing lots are non-uniformly distributed.
- However, for the purpose of developing a network model, we assumed that the cabinet serving area is a square of side **L** in which $\mathbf{n^2}$ housing lots are uniformly distributed as shown in Figure 8.
- This assumption reasonably simplifies network modeling and yet leads to reliable results.



(a) Square cabinet/RDU serving-area (the RDU node is assumed located at the center of the serving-area)

(b) Square lot size

Figure 8. Square cabinet/RDU serving area model with a uniform subscriber distribution

6.1 Formulation of model for the computation of distribution and drop loop cable lengths

From Figure 8, it is easy to show that the housing lots are squares of size **L/n** x **L/n**. Therefore, the area occupied by a housing lot is $\mathbf{(L/n)^2}$, from which the density of housing lots = $\mathbf{(n/L)^2}$. Next, the figure shows that the model algorithms to generate the distribution and drop loop distances as parametric functions of the size of the housing lot, L/n.

6.2 Model algorithms

Next, the model algorithm generates the distribution and drop loop cable distances iteratively, enabling its easy implementation in a computer program. The total drop loop cable lengths ***b*** is generated from the algorithm:

$$b(j,k) = 2\frac{L}{n}\sum_{k=0}^{q_t-1}\sum_{j=0}^{p_t-1}(1+2j)+(1+2k) \qquad \text{eqn. 1}$$

Where L is the length of the side of the square cabinet/RDU network serving-area and n^2 is the number of housing lots in the cabinet serving area where ***j***, ***k***, are integers.

Where pt, qt are integers whose values depend on the termination capacity of the DP, as follows:

(i) $P_4 = 1$ and $q_4 = 1$ For 4-line capacity DP serving-areas

(ii) $P_8 = 2$ and $q_8 = 1$ For 8-line capacity DP serving-areas

(iii) $P_{16} = 4$ and $q_{16} = 1$ For 16-line capacity DP serving-areas

(iv) $P_{32} = 8$ and $q_{32} = 1$ For 32-line capacity DP serving-areas

Similarly, the total distribution loop cable lengths ***d*** is generated from the algorithm:

$$d(j,k) = 4\frac{L}{n}\sum_{k=0}^{q_d(t)-1}\sum_{j=0}^{j_d(t)-1}([2g(1+j)-1]p_t + (1+2k)q_t \qquad \text{eqn. 2}$$

Where **g**, j_d**(t)**; k_d**(t)** are integers

$j_d(t) = n/4gP_t$ and $k_d(t) = n/4q_t$

- **1≤g ≤n/4P_t; g** is a critical model parameter used to configure the distribution loop network as required:
  - **g**=1 => that the DP nodes are deployed on a point-to-point topology from the cabinet node
  - **g**>1 => that the DP nodes are daisy-chained from the cabinet node where g is the number of DP nodes sharing a common distribution cable
- The model can also implement ring configurations for path protection

The loop distances are obtained as parameters functions of the square housing lot size **L/n**. Therefore, to estimate loop distances, the model just requires as input geographic/demographic and network parameters that enable it to estimate **L/n**.

This model requires as input any one of the following readily available demographic and network parameters:

- Building density
- Road-miles / km covered by the network

Model inputs

- Building density
- Route miles/km covered by the network
- PON system, OSP material, and installation cost

Model algorithms

Distribution and drop loop distances are parametric functions of the square housing lot size L/n.

$$b(j,k) = 2\frac{L}{n}\sum_{k=0}^{q_t-1}\sum_{j=0}^{p_t-1}(1+2j)+(1+2k)$$

$$d(j,k) = 4\frac{L}{n}\sum_{k=0}^{q_d(t)-1}\sum_{j=0}^{j_d(t)-1}([2g(1+j)-1]p_t + (1+2k)q_t$$

Model outputs

- Optimal cabinet and DP nodes splitter ratios to minimize PON end-to-end network cost
- Detailed nodes and links cost
- Bill of Materials (BOM)
  - Access loop cable lengths (feeder, distribution, and drop) and their capacities
  - Required number of splices, pigtails, connectors, terminals, and other materials
  - OSP construction/installation cost estimates for aerial, direct burial, duct/conduit

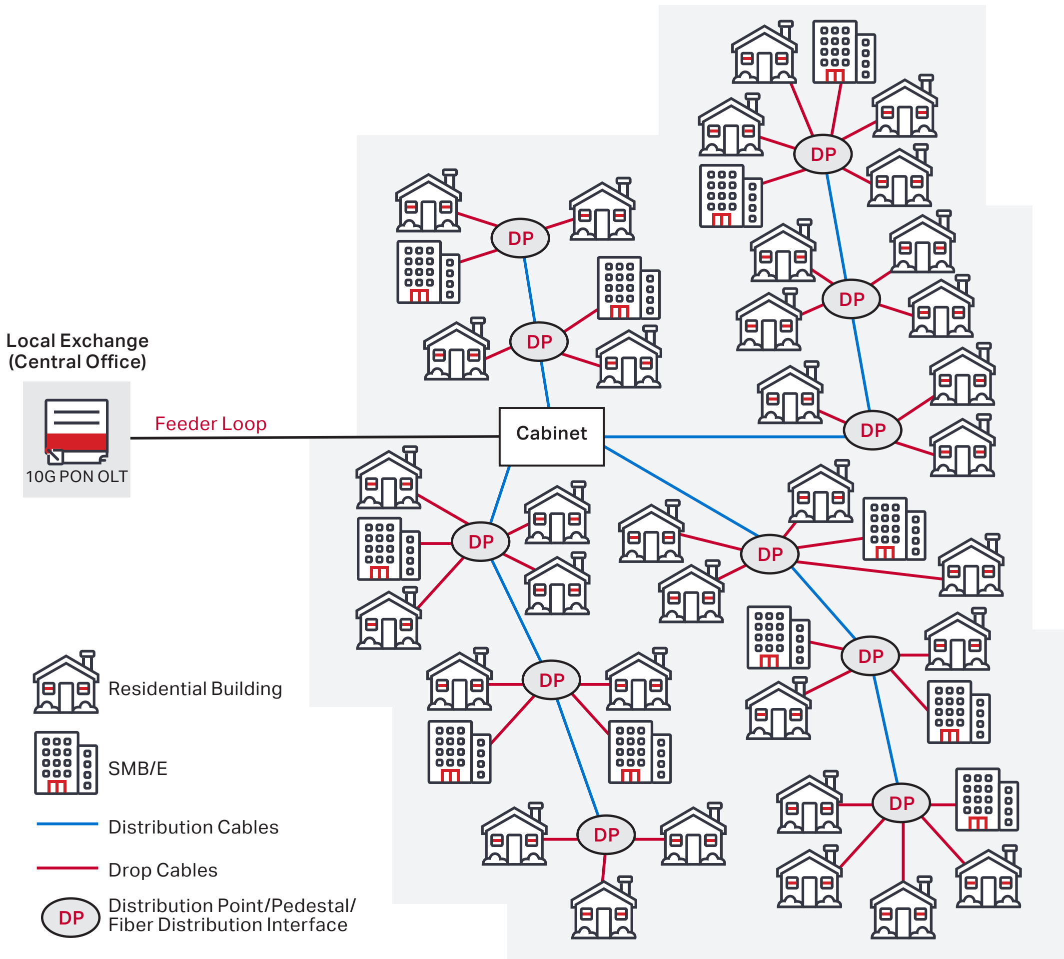


Figure 9a. Model application use case 1: Minimize cost of Ciena's10G XGS-PON solution for residential and SMB/Es at a 100 percent penetration rate

7. Access loop model application: Use cases

7.1 Use case 1

Figure 9 shows a network cabinet serving-area with 1,024 buildings served from a central office OLT over a feeder. The aim is to design a minimum-cost PON FTTH network architecture for the delivery of an average bitrate per subscriber of 311 Mb/s Symmetrical Bitrate Service based on Ciena's 10G XGS PON solution with a total optical split of 1:32 of a signal multiplexed on a feeder fiber. It is necessary to:

- Estimate end-to-end network costs (OSP/ODN + electronics) for the ~1,024 buildings, and the per-subscriber cost for building densities: 500/sq.km; 1,000/sq.km; 3,000/sq.km; 5,000/sq.km; and 10,000/sq.km
- Determine PON access architecture(s)—optimal optical coupler splitter ratios at the cabinet and DP nodes—that minimize(s) end-to-end network cost
- Assume 100 percent service penetration rate

7.2 Use case 2

In use case 1, what if the network operations in the area are not monopolies, but operate in a competitive environment with two or three operators?

- Under this scenario, network operators can reasonably be expected to achieve no more than about a 20 to 25 percent penetration rate.
- Or, if the network operator makes a strategic decision to target only SMB/E buildings in the network, comprising only about 20 to 25 percent of buildings in the network, see Figure 9b.
- How does the network design in use case 1, with 100 percent penetration rate, need to change, if at all, for the operator to achieve a minimum cost network design under this new scenario of lower service penetration rate?

The following section shows how to employ this model to minimize the cost of a PON FTTH network based on Ciena's 10G XGS-PON solution by analyzing a number of logically equivalent PON access network architectures, but whose OSP/ODN physical designs/implementation result in wide differences in network costs as housing density and/or service penetration rates vary.

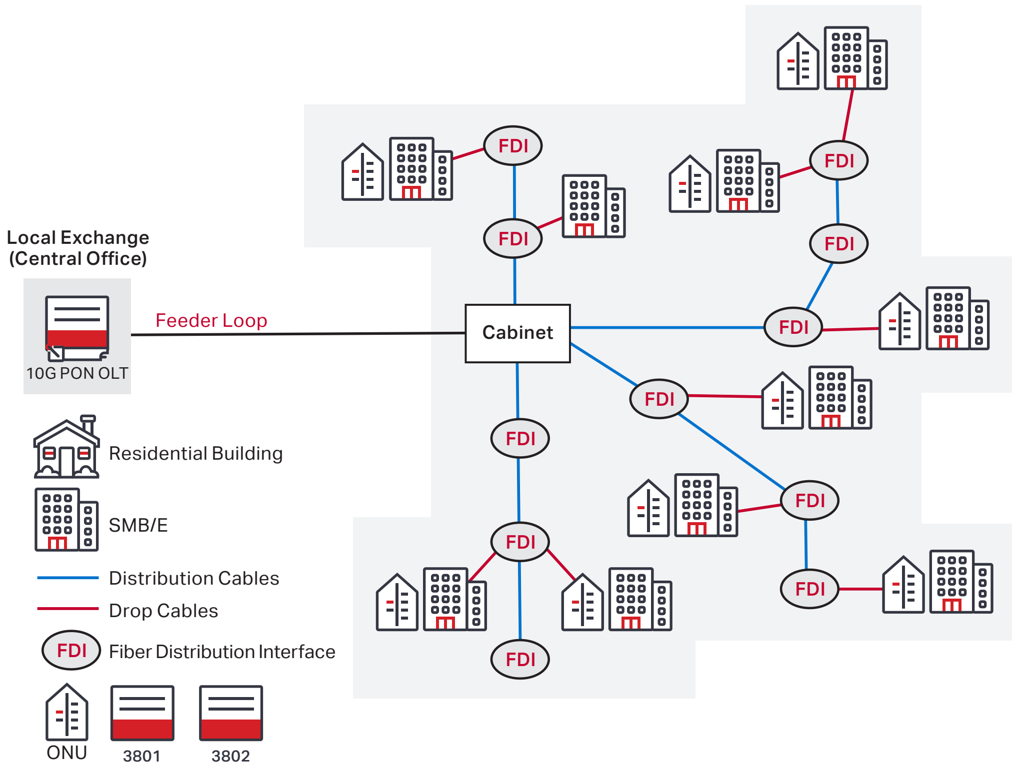
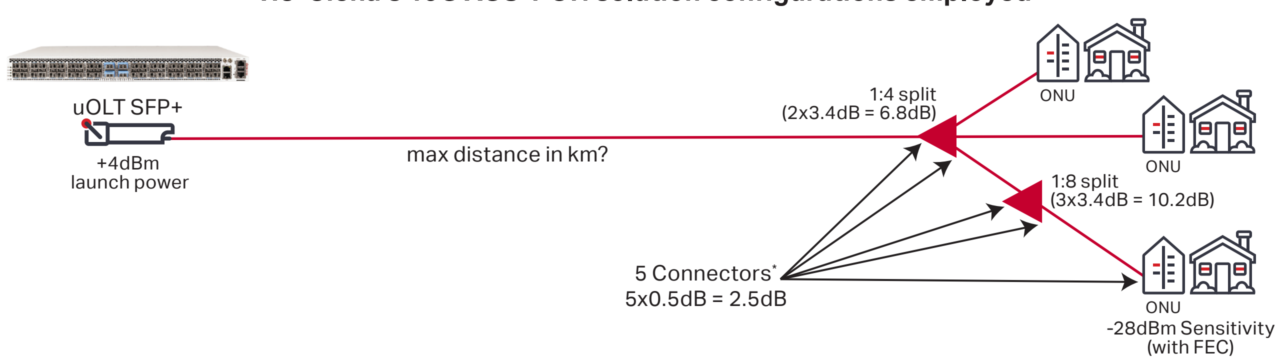


Figure 9b. Model application use case 2: Minimize costs of Ciena's 10G XGS-PON solution for SMB/Es only (~25 percent of buildings

7.3 Ciena's 10G XGS-PON solution configurations employed



1:128	1:64	1:32
Attenuation before fiber cable loss = **-22.3dB** (4dB – 23.8dB – 2.5dB = -22.3dB)	Attenuation before fiber cable loss = **-18.9dB** (4dB – 20.4dB – 2.5dB = -18.9dB)	Attenuation before fiber cable loss = **-15.5dB** (4dB – 17dB – 2.5dB = -15.5dB)
Max distance (L) within sensitivity range = **10 km** *Max allowable fiber cable attenuation = -28dB – (-22.3dBm) = -5.7dB* *L * 0.44dB ≤ 5.7dB* *L ≤ 13 km*	Max distance (L) within sensitivity range = **20 km** *Max allowable fiber cable attenuation = -28dB – (-18.9dB) = -9.1dB* *L * 0.44dB ≤ 9.1dB* *L ≤ 21 km*	Max distance (L) within sensitivity range = **27 km** *Max allowable fiber cable attenuation = -28dB – (-15.5dB) = -12.5dB* *L * 0.44dB ≤ 12.5dB* *L ≤ 28 km*

Numbers based on ITU spec. Vary based on optics vendor: some exceed spec and provide better reach. EOL margins can vary.
Distances factor in some margin. CoEx WDM not factored in.
*Only 4 connectors if using uONU plug

Figure 10. Ciena's 10G XGS-PON solution: 1xn split ranges (n = 32, 64 or 128)

Use-case1: Cost of PON FTTH Architecture/Subscriber (based on Ciena's 10G XGS-PON solution with 1:32 total splitting of a feeder fiber)

Variation of network cost with demographics and DP nodes termination capacity: Service penetration rate: 100%

(Costs normalized to the cost of 8-line capacity DP nodes)

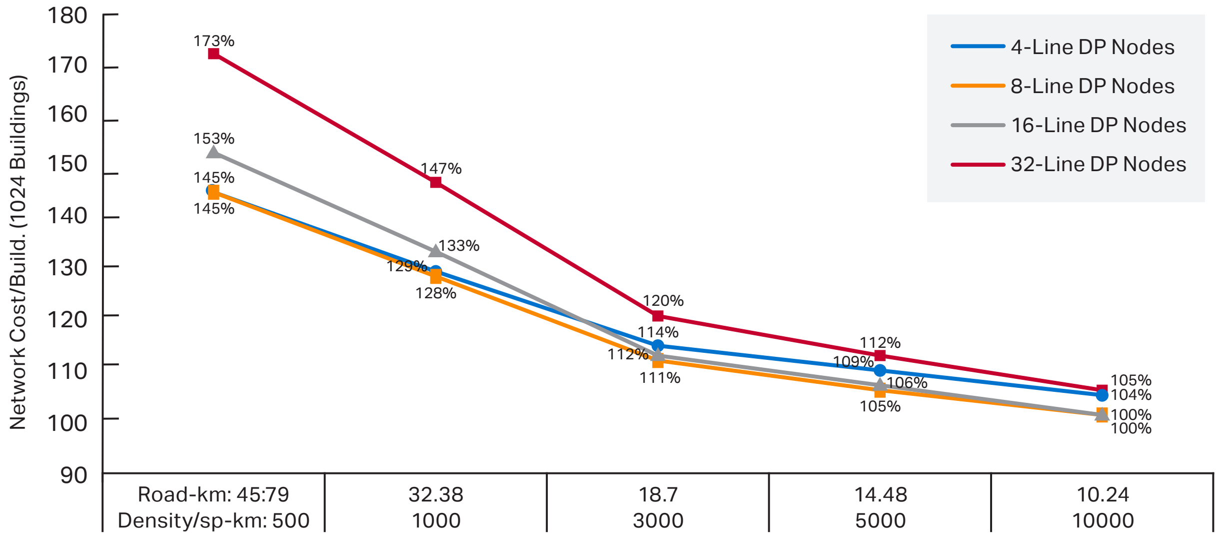


Figure 11a. Use case1: Cost of PON FTTH access architecture per subscriber based on Ciena's 10G XGS-PON solution with a total optical splitting of 1:32 of a feeder fiber (service penetration rate: 100 percent)

8 Access loop model applications: Use cases: Analysis of results

8.1 Use case 1 (with 100 percent service penetration rate)

Use case 1 employs the following four logically equivalent PON FTTH access architectures:

1. PON Architecture #1: A 1:32 cascade split: Cabinet: 1:8; DPs: 1:4 (4-line capacity DP nodes)
2. PON Architecture #2: A 1:32 cascade split: Cabinet: 1:4; DPs: 1:8 (8-line capacity DP nodes)
3. PON Architecture #3: A 1:32 cascade split: Cabinet: 1:2; DPs: 1:16 (16-line capacity DP nodes)
4. PON Architecture #4: A 1:32 centralized/local convergence cabinet: No split; DPs: 1:32 (32-line capacity DP nodes)

Based on Ciena's 10G XGS-PON solution, Figure 11a shows the variation of the four PON FTTH access architecture costs per subscriber as a function of housing density and DP node termination capacity. The costs are normalized to the cost of the 8-line capacity DP nodes, which produces the lowest cost at a housing-density of 10,000 per sq. km.

Table 1: Use case 1: Cost of PON FTTH Architecture (based on Ciena's 10G XGS-PON solution: costs normalized to cost of 8-line DP nodes at housing density of 10,000/sq.-km; service penetration Rate: 100%

Density/sq-km	500	1000	3000	5000	10000
Road-km	45.79	32.38	18.7	14.48	10.24
HHP	1024	1024	1024	1024	1024
HHP with 100% Take Rate	1024	1024	1024	1024	1024
4-Line DP Nodes	145%	129%	114%	109%	104%
8-Line DP Nodes	145%	128%	111%	105%	100%
16-Line DP Nodes	153%	133%	112%	106%	100%
32-Line DP Nodes	173%	147%	120%	112%	105%
If PON Architecture Design is Nonoptimized: Maximum Cost (using 32-Line DP Nodes)	173%	147%	120%	112%	105%
If PON Architecture Design is Optimized: Minimum Cost (using 8-Line DP Nodes)	145%	128%	111%	105%	100%
Cost Difference/Penalty for Sub-optimally Designed PON Access Network	28%	19%	9%	6%	5%

Figure 11b. Use case 1: Cost of PON FTTH architecture based on Ciena's 10G XGS-PON solution: Costs normalized to cost of 8-line DP nodes at housing density of 10,000 per sq.km (service penetration rate: 100 percent)

Analysis of results: Use case 1

PON FTTH access architecture costs exhibit large inverse variation as a function of housing density.

Figures 11a and 11b show:

- The PON FTTH architecture cost exhibits an inverse variation with housing density; that is, PON FTTH architecture costs decrease as housing densities increase.
  - For example, for PON FTTH architecture with 8-line capacity DP nodes, the cost decreases by 45 percent (from 145 to 100 percent) as housing density increases from 500 per sq. km to 10,000 per sq. km.
  - For PON FTTH architecture with 32-line capacity DP nodes, the cost decreases by 68 percent (from 173 to 105 percent) as housing density increases from 500 per sq.km to 10,000 per sq.km.

PON FTTH access architecture costs exhibit high sensitivity to DP node termination capacity at low housing-densities.

At low housing density of 500 per sq. km, there is very large (28 percent) cost difference between the minimum cost achieved with 8-line/4-line capacity DP nodes and the maximum cost achieved with 32-line capacity DP nodes (Figure 11b).

However, at very high housing densities of 5,000 per sq. km and 10,000 per sq. km, there is little difference in the cost of the architectures as a function of the termination capacity of the DP nodes—a difference of only five to six percent.

Network operators have been able to cost-effectively deploy PON FTTH in the access loop in dense urban networks because of the following reasons:

- First, in high housing-density networks, the end-to-end network costs are cheaper because of shorter loop distances.
- Hence, there is little cost penalty or impact for selecting a sub-optimal PON architecture—only about six percent at very high housing densities of 5,000 per sq.km.

However, at low housing density of 500 per sq. km, the selection of a sub-optimal PON architecture has a very high cost impact—a cost penalty of 28 percent.

Therefore, in networks of low housing density such as the suburban U.S., PON access network design cannot be based on some established practices for outside plant design. At low housing densities, PON access network cost is highly sensitive to several factors, including:

- Demographics: Housing density (or equivalently, road km) of the network serving area
- Service penetration rates
- OSP/ODN material and installation costs
- DP nodes termination capacity

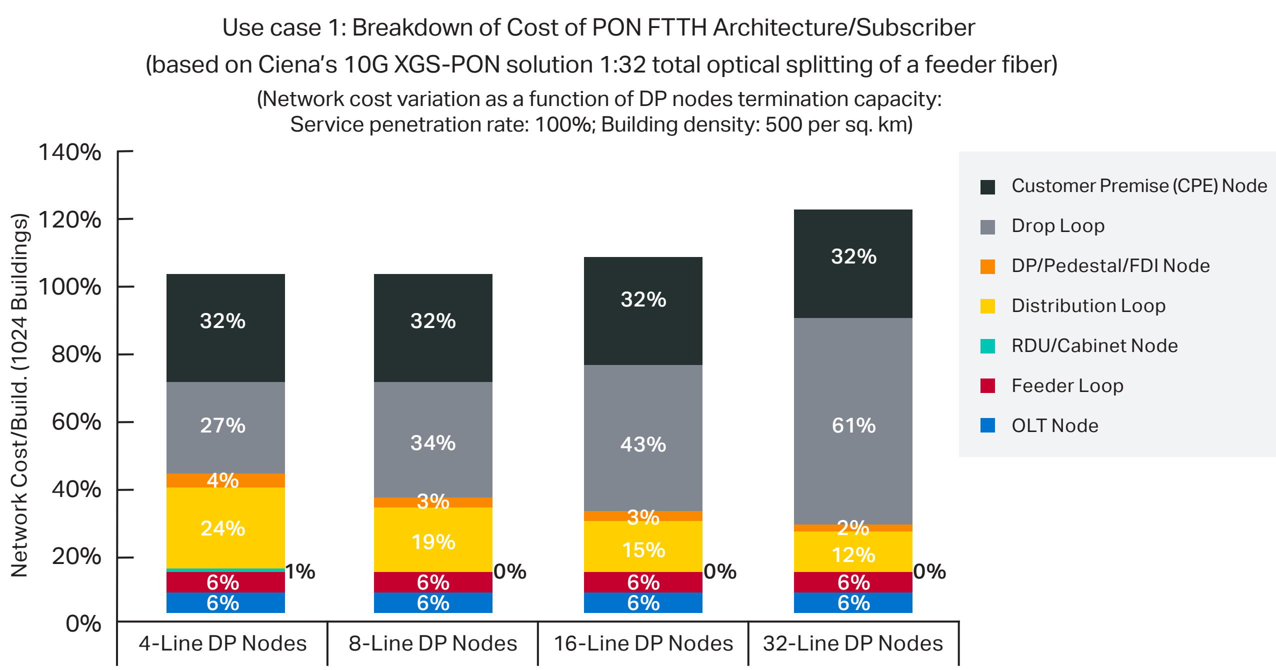


Figure 11c. Use case 1: Breakdown of cost of PON FTTH architecture/subscriber (based on Ciena's 10G XGS-PON solution 1:32 total optical splitting of a feeder fiber (service penetration rate: 100 percent)

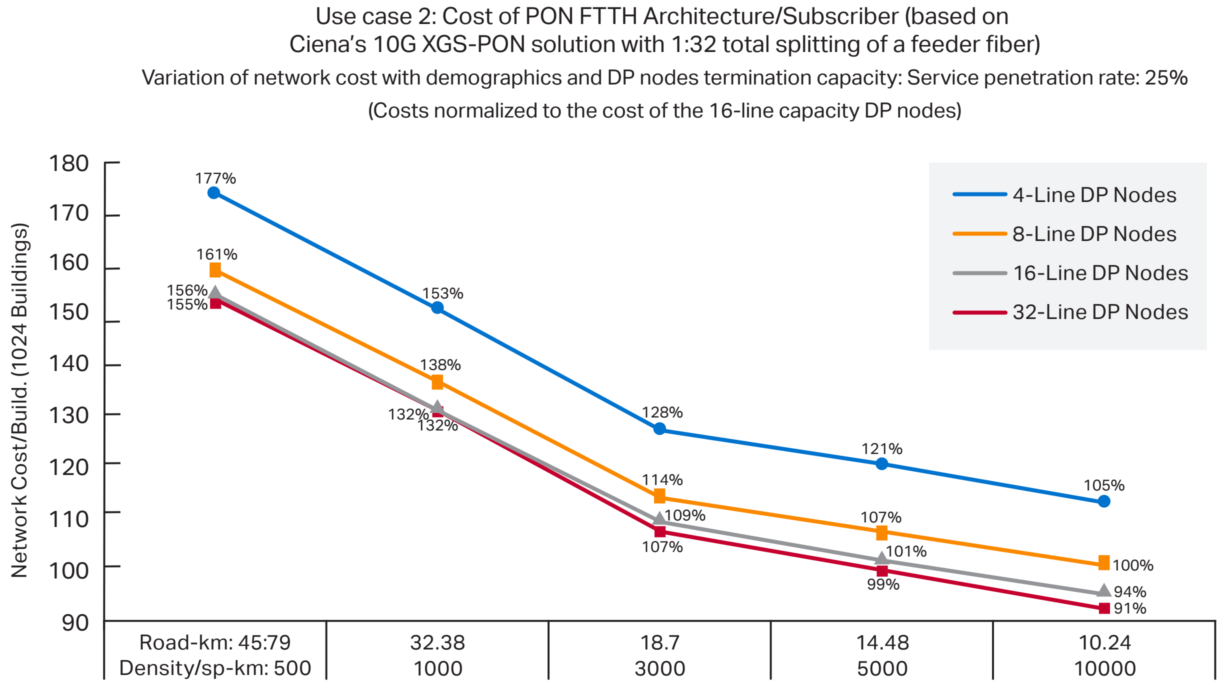


Figure 12a. Use case 2: Cost of PON FTTH access architecture per subscriber based on Ciena's 10G XGS-PON solution) with a total optical splitting of 1:32 of a feeder fiber (service penetration rate: 25 percent)

The access loop model presented in this white paper can help network operators design PON access networks optimally by determining the PON architecture(s) that minimize network cost as a function of these variables.

Cost drivers

Figure 11c shows that the major cost driver at a low housing density of 500 per sq. km is the drop loop and has the most impact on 16-line and 32-line capacity DPs nodes, which comprise 43 and 61 percent of end-to-end network costs, respectively.

8.2 Use case 2 (with 25 percent service penetration rate)

Use case 2 employs the same four logically equivalent PON FTTH access architectures from use case 1.

Figure 12a shows the variation of the four PON FTTH access architecture costs per subscriber as a function housing density and DP node termination capacity, based on Ciena's 10G XGS-PON system solution.

Table 2: Use case 2: Cost of PON FTTH Architecture (based on Ciena's 10G XGS-PON solution: Costs normalized to cost of 16-line DP nodes at housing density of 10,000/sq.-km

Density/sq-km	500	1000	3000	5000	10000
Road-km	45.79	32.38	18.7	14.48	10.24
HHP	1024	1024	1024	1024	1024
HHP with 100% Take Rate	256	256	256	256	256
4-Line DP Nodes	188%	163%	136%	128%	120%
8-Line DP Nodes	171%	147%	122%	114%	106%
16-Line DP Nodes	165%	140%	115%	108%	100%
32-Line DP Nodes	166%	140%	114%	106%	101%
If PON Architecture Design is Nonoptimized: Maximum Cost (using 4-Line DP Nodes)	188%	163%	136%	128%	120%
If PON Architecture Design is Optimized: Minimum Cost (using 16-Line DP Nodes)	165%	140%	114%	106%	100%
Cost Difference/Penalty for Sub-optimally Designed PON Access Network	24%	22%	22%	22%	20%

Figure 12b. Cost normalized to cost of 16-line DP/pedestal nodes (minimum cost)

The costs are normalized to the cost of the 16-line capacity DP nodes, which produces the lowest cost at a housing density of 10,000 per sq. km.

Analysis of results: Use case 2

As was the case in use case 1 with 100 percent service penetration rate, use case 2, with 25 percent service penetration rate, shows that the PON FTTH access architecture costs exhibit a large inverse variation as a function of housing density.

Figures 12a and 12b show that the PON FTTH architecture cost exhibits an inverse variation with housing density—that is, PON FTTH architecture costs decrease as housing densities increase. For example, for PON FTTH architecture with 16-line capacity DP nodes, the cost decreases by 65 percent (from 165 to 100 percent) as housing density increases from 500 per sq. km to 10,000 per sq. km.

When service penetration rates are low, PON FTTH access architecture costs exhibit high sensitivity to DP node termination capacity, both at low and high housing densities.

At low housing density of 500 per sq. km, there is very large (24 percent) cost difference between the minimum cost achieved with 16-line/32-line capacity DP nodes and the maximum cost achieved with 4-line capacity DP nodes.

At very high housing densities of 5,000 per sq. km, there is also a similarly high cost difference of 22 percent between the minimum cost achieved with 16-line capacity DP nodes and the maximum cost achieved with 4-line capacity DP nodes.

Consequently, a combination of low housing densities and low service penetration rates pose the greatest challenge for network operators in deploying PON access architectures because of high sensitivity of PON OSP/ODN cost with regard to both low housing densities and low service penetration rates, as well as the DP nodes termination capacities, which impact distribution and drop loop costs. Therefore, the selection of wrong DP nodes termination capacities leads to a sub-optimally designed PON access network architecture, with a very high cost impact/penalty.

Hence, in networks with a combination of low housing density and low service penetration rates, trying to design PON access networks based on some established practices for outside plant design will most likely lead to sub-optimally designed networks, with costs pushing higher by 20 percent or more than necessary. This is because PON access network cost is highly sensitive to several factors, including:

- Demographics: Housing density (or, equivalently, road km) of the network serving area
- Service penetration rates
- OSP/ODN material and installation costs
- DP nodes termination capacity

The access loop model presented in this white paper can help network operators design PON access networks optimally by determining the PON architecture(s) that minimize network cost as a function of these variables.

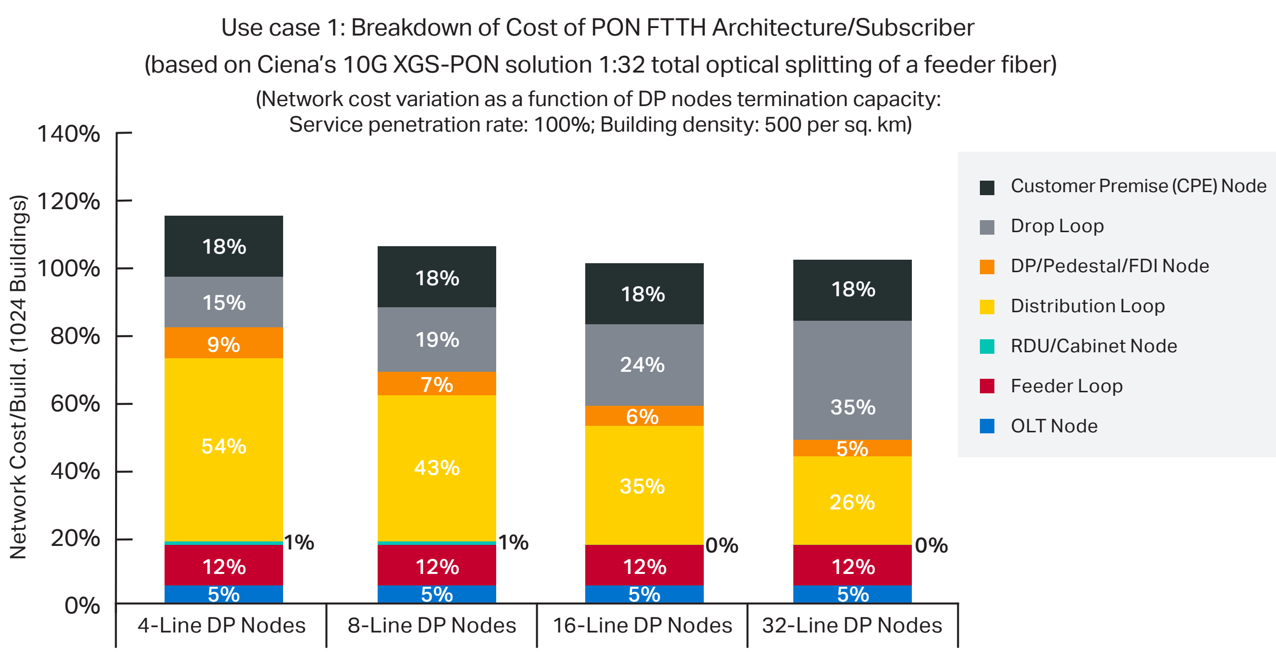


Figure 12c. Use case 2: Breakdown of cost of PON FTTH architecture/subscriber based on Ciena's 10G XGS-PON solution 1:32 total optical splitting of a feeder fiber (service penetration rate: 25 percent)

Cost drivers

Figure 12c shows the major cost drivers at a low housing density of 500 per sq. km and low penetration rate of 25 percent. In this case, the main cost driver is now the distribution loop cost, which is very high for 4-line and 8-line DP nodes at 54 and 43 percent of end-to-end network costs, respectively. In use case 1, the drop loop was the main cost driver and had the most impact on 16-line and 32-line capacity DPs nodes, which comprise 43 and 61 percent of end-to-end network cost, respectively.

9. Conclusions

This white paper presents an access loop model for the techno-economic analysis and optimal (minimum cost) design of PON FTTx and Fixed Wireless Access (FWA) network architectures. It examines two use cases based on Ciena's 10G XGS-PON solution. This examination highlights the major challenge for network operators: the very high cost of deploying fiber in access loop networks in low housing density demographic areas such as the suburban U.S., where high network costs are driven primarily by OSP/ODN cost.

The paper demonstrates how to employ this model to minimize the cost of a PON FTTH networks by analyzing a number of logically equivalent PON access network architectures, but whose OSP/ODN physical designs/implementations result in wide differences in network costs as housing density and/or service penetration rates vary.

9.1 Key takeaways

In networks with high housing densities and high service penetration rates, PON access network cost has limited sensitivity to the OSP/ODN design.

Figure 13 outlines how PON access network architecture cost varies as a function of housing densities and service penetration rates for optimally designed and sub-optimally designed PON architectures. The costs are normalized to costs at a housing density of 5,000 per sq. km and 100 percent penetration rate.

At a very high housing density of 5,000 per sq. km, the cost penalty—that is, the difference between the cost of an optimally designed (or minimum-cost) a sub-optimally designed PON access architecture—is only approximately six percent.

When housing density is high and the network design is for a service penetration rate of 100 percent, the penalty for a sub-optimal PON architecture design is minimal. Therefore, there is little cost penalty to the network operator for sub-optimally designed PON access networks in high-density areas. Network operators do not require any special sophistication or established practices for outside plant design, and rule of thumb is largely sufficient.

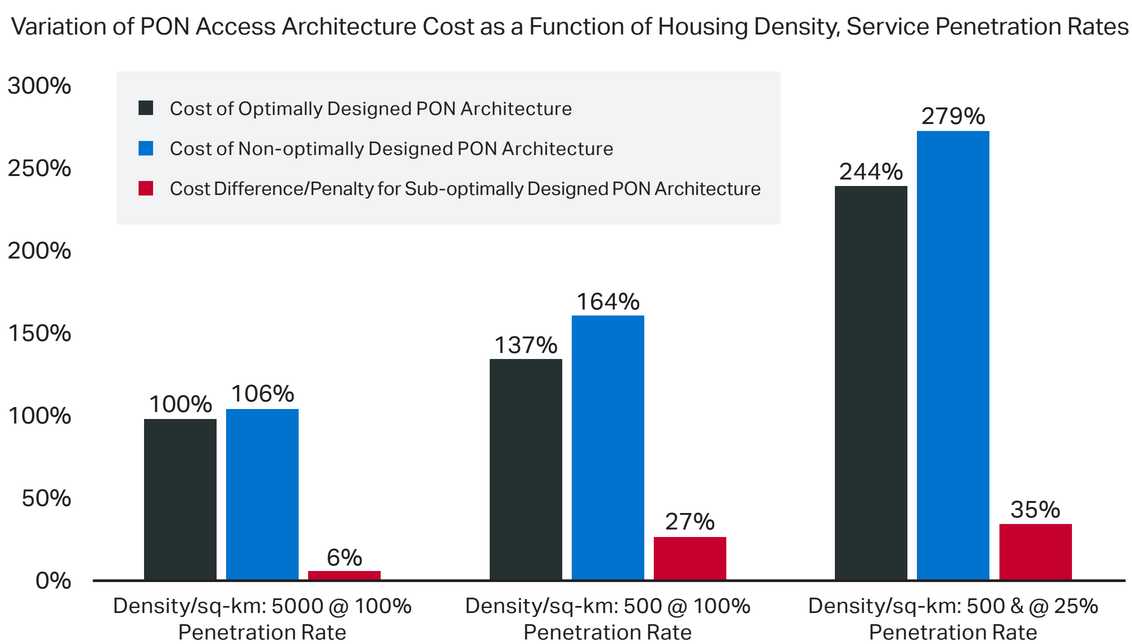


Figure 13. Variation of PON access architecture cost as a function of housing density, service penetration rates

Cost Penalty for Sub-optimally Designed PON Access Network Architecture	Sub-optimal PON Architecture Design	Optimal (Minimum Cost) PON Architecture Design	Cost Difference/Penalty
Density/sq-km: 5000 @ 100% Penetration Rate	106%	100%	6%
Density/sq-km: 500 @ 100% Penetration Rate	164%	137%	27%
Density/sq-km: 500 & @ 25% Penetration Rate	279%	244%	35%

Figure 14. Cost penalty for sub-optimally designed PON access network architecture

This explains why network operators have been able to cost-effectively deploy PON FTTH in the access loop in dense urban networks cost-effectively. However, deploying PON FTTH networks in the access loop in low housing density areas (especially in the suburban U.S.) has been particularly challenging for network operators for the reasons below.

In networks with low housing densities and/or low service penetration rates, PON access network cost is highly sensitive to the OSP/ODN design, and sub-optimally designed PON access architectures under these scenarios can increase cost dramatically, by 27 to 35 percent.

As shown in Figure 13, at a low housing-density of 500 per sq. km and 100 percent penetration rate, when the PON architecture is designed optimally, the cost is 37 percent higher than the cost at a housing density of 5,000 per sq. km (see Figure 14). However, if the PON architecture is sub-optimally designed, the cost at low housing density of 500 per sq. km is 64 percent higher than if the housing density were 5,000 per sq. km. The cost penalty for sub-optimally designed PON access architecture jumps to 27 percent at a low housing density of 500 per sq. km, compared to just six percent at a high housing density of 5,000 per sq. km.

Also, as shown in Figure 14, at a low housing density of 500 per sq. km and a low service penetration rate of 25 percent, when the PON architecture is designed optimally, the cost is 114 percent higher than the cost at a housing density of 5,000 per sq. km and 100 percent penetration rate.

If the PON architecture is sub-optimally designed, the cost at a low housing density of 500 per sq. km and low service penetration rate of 25 percent is 179 percent higher than the cost at a housing density of 5,000 per sq. km and 100 percent penetration rate. The cost penalty for sub-optimally designed PON access architecture jumps to 35 percent at a low housing density of 500 per sq. km and low service penetration rate of 25 percent, compared to a cost-penalty of just six percent at a high housing density of 5,000 per sq. km with a 100 percent service penetration rate.

This presents a challenge to network operators trying to deploy PON access networks in areas of varying housing densities and/or low service penetration rates. The cost penalty for deploying sub-optimally designed PON access architectures is very high. Consequently, in networks of low housing density such as suburban America, PON access network design cannot be based on some established practices or rule-of-thumb for outside plant design because at low housing densities, the PON access network cost is highly sensitive to several factors including:

- Demographics: Housing density (or equivalently, road km) of the network serving area
- Service penetration rates
- OSP/ODN material and installation costs
- DP nodes termination capacity

The access loop model presented in this white paper can help network operators design PON access networks optimally by determining the PON architecture(s) that minimize network costs as a function of these variables. This versatile access loop model is also used for the minimum cost design of 5G mmWave small cell hybrid fiber/FWA networks where several conflicting variables such as spectrum frequency, spectrum cost, small cell size, and fiber backhaul densification requirements need to be considered to minimize costs.

Was this content useful? Yes No